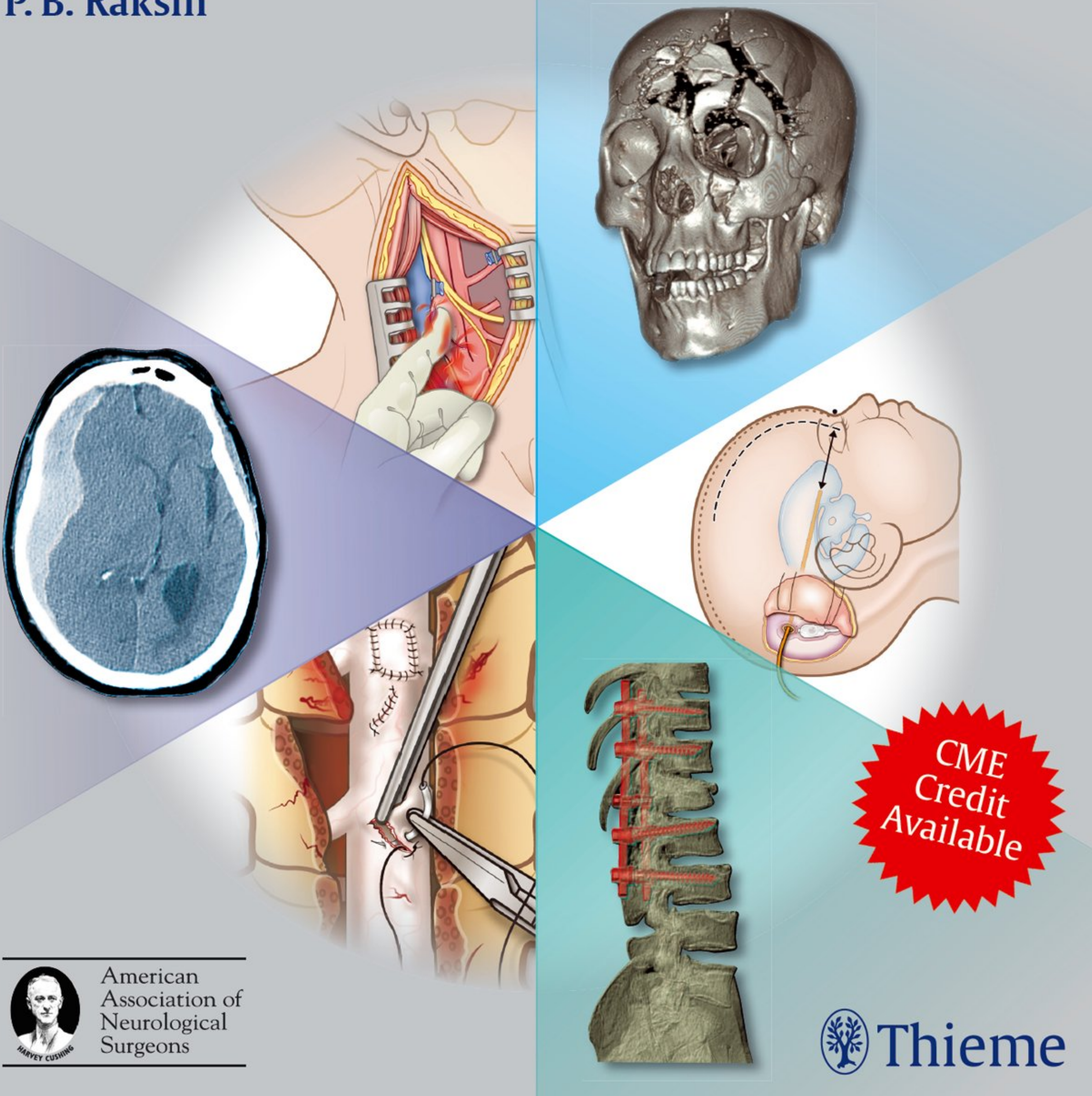
Atlas of Emergency Neurosurgery

Jamie S. Ullman
P. B. Raksin



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American Association of Neurological Surgeons

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Contents

Continuing Medical Education Credit Information and Objectives

Objectives

1. Identify neurosurgical conditions which require emergent or urgent intervention
2. Evaluate the various options for managing spine trauma in the cervical, thoracic, and thoracolumbar regions.
3. Apply provided techniques when performing urgent interventions for the brain and spine
4. Recognize key issues of applying brain and spinal trauma surgical techniques to military and pediatric populations.

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Casey Madura, MD

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I Cerebral Trauma and Stroke

1 Surgery for Epidural and Subdural Hematomas

Shelly D. Timmons

Introduction

Rapid evacuation of extra-axial hematomas after trauma can be a life-saving intervention. While there is no absolute cut-off time after which patients fare worse, many studies have demonstrated better outcomes with earlier evacuation. Surgical planning must take into consideration the presence of other intracranial lesions and the patient's clinical status. The presence of polytrauma, the patient's hemodynamic status,[1] and the presence of coagulopathy must be considered and addressed while not delaying surgical intervention.

Indications

- Surgical intervention is appropriate for *epidural hematomas* (EDH) with the following characteristics[2]
  - Glasgow Coma Scale (GCS) score ≤ 8 and anisocoria → operating room as soon as possible
  - Hematoma volume ≥ 30 cm^3
  - Hematoma volume , 30 cm^3 but accompanied by:
    - Thickness ≥ 15 mm
    - Midline shift ≥ 5 mm
    - GCS ≤ 8
    - Focal motor deficit
  - Effaced cisterns
  - Deteriorating neurologic status
- Surgical intervention is appropriate for *subdural hematomas* (SDH) with the following characteristics[3]
  - Thickness ≥ 10 mm
  - Midline shift ≥ 5 mm
  - Thickness , 10 mm and midline shift , 5 mm but accompanied by:
    - Neurologic worsening by 2 or more points on the GCS
    - Asymmetric pupils
    - Fixed and dilated pupils
    - Intracranial pressure (ICP) ≥ 20 mm Hg

Preprocedure Considerations

Radiographic Imaging

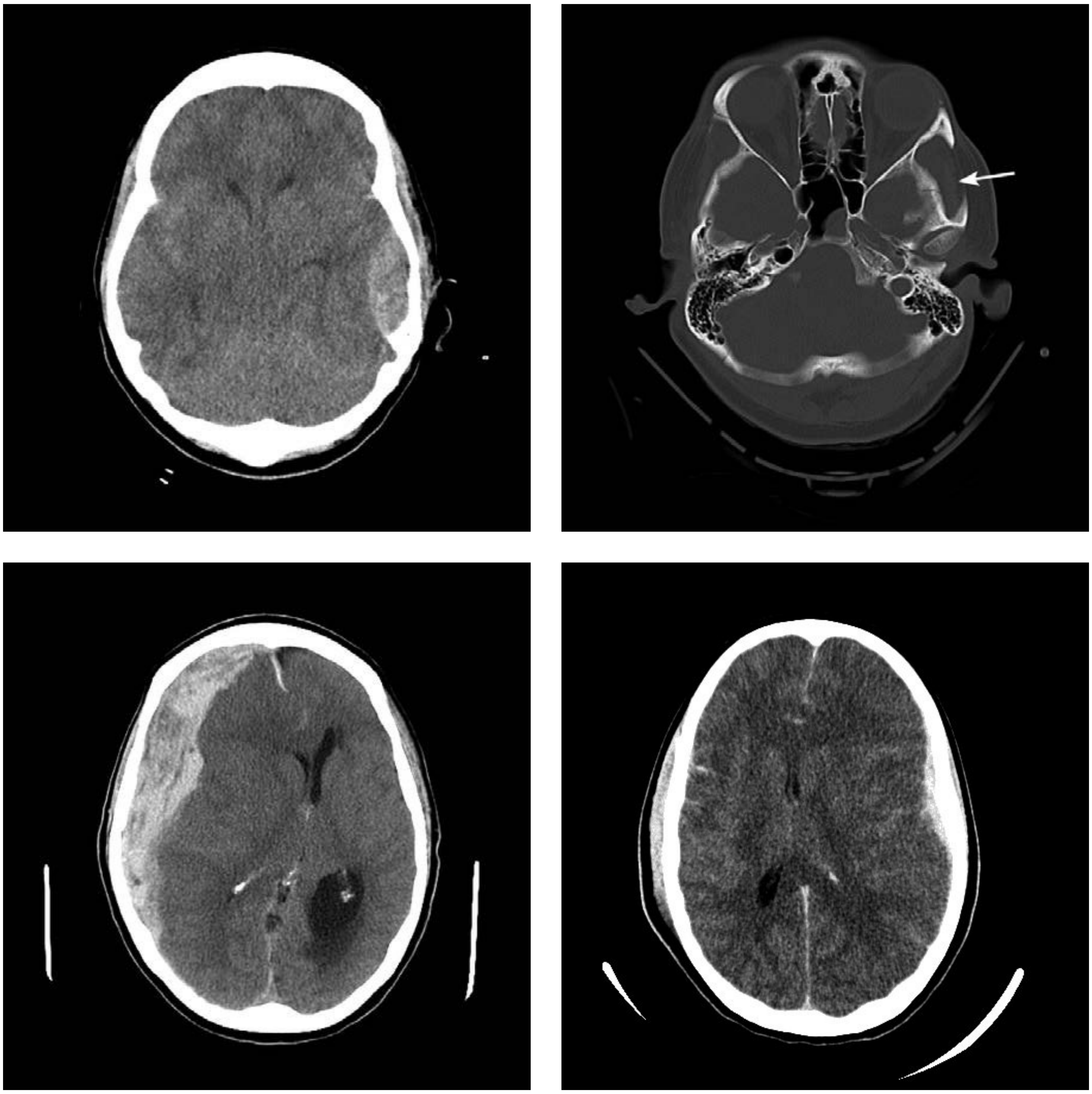
- Computed tomography (CT) is essential to evaluate for:
  - The presence and size of extra-axial hematoma
  - Degree of midline shift
  - Appearance of perimesencephalic cisterns
  - Presence of other space-occupying lesions
- Preoperative imaging (**Fig. 1.1**).

Medications

- Preoperative antibiotics: either a cephalosporin or vancomycin (if penicillin allergic) should be given.
- The patient should be given seizure prophylaxis at earliest opportunity after arrival to the hospital. Evidence-based guidelines support the utilization of anticonvulsants for 7 days in patients following traumatic brain injury.[4]
- Fresh frozen plasma and/or other blood products/factors should be administered preoperatively and intraoperatively as needed to correct coagulopathy.

Operative Field Preparation

- The head may be positioned on a doughnut or horseshoe head holder, rather than a three-pinion head holder, to facilitate more rapid progression to brain decompression.
- The operative field should be prepared using an iodine-based sterile prep solution, provided the patient has no iodine allergies.
- The use of chlorhexidine is controversial; product insert information bars the use for procedures exposing the cerebral meninges. In cases with known betadine or iodine allergies, chlorhexidine or alcohol prep can be used.
- The incisions are marked and, after final sterile draping, infiltrated with 1% lidocaine with epinephrine 1:100,000.



a b c d

Fig. 1.1a–d CT scan is the modality most commonly utilized in the perioperative setting. **(a)** Epidural hematomas demonstrate a characteristic convex shape (due to adherence of the dura at the suture lines) and are typically accompanied by a **(b)** fracture (arrow). **(c)** Subdural hematomas by contrast, are not bound by sutures and assume a crescentic appearance, layering over the convexity. **(d)** A small subdural hematoma may be accompanied by disproportionate mass effect and midline shift.

Operative Procedure

Positioning (Fig. 1.2a, b)

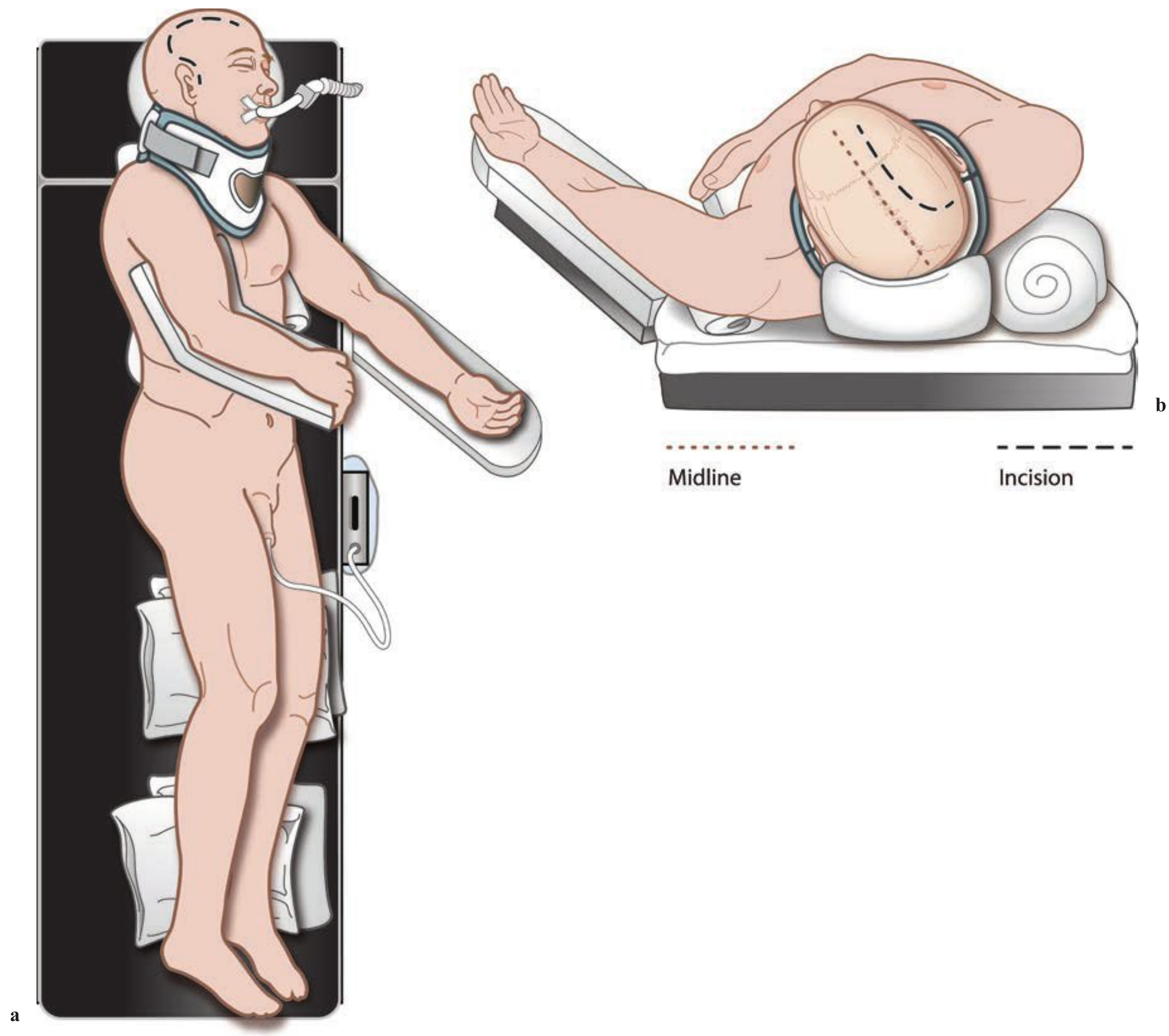


Figure	Procedural Steps	Pearls
Fig. 1.2	**(a, b) The head is turned so as to expose the operative hemicranium. The patient whose neck has not yet been cleared can be positioned in the cervical collar by placing a bolster under the ipsilateral shoulder and the ipsilateral arm across the chest. Pressure points should be padded appropriately. The head may be placed on a foam or gel doughnut to expedite positioning.**	• Discuss positioning with the anesthesiology team. The endotracheal tube (ETT) should exit the contralateral side of the mouth if placed orally, and should be secured in place using tape, ETT collar, etc. The eyes should be protected from corneal abrasion by placing ointment under each lid and taping the lids shut. • Allowance for central venous catheters, peripheral intravenous catheters, and arterial lines should be made, with these positioned toward the anesthesiology team if possible. Foley catheters should always be placed and should be accessible to the anesthesia team. • Pin fixation may also be used, but positioning on a doughnut or horseshoe head holder may expedite decompression of the brain. • The head should be positioned just at or slightly overhanging the end of the table and the sterile craniotomy drape placed so that it hangs vertically to facilitate drainage of irrigation by gravity. Final draping should exclude the anesthesia setup, using a vertical drape. • An exit site for a subgaleal drain should be included in the area exposed by the sterile draping. • Reverse Trendelenburg positioning may be used to provide elevation of the head to help reduce cerebral edema.

Skin Incision (Fig. 1.3)

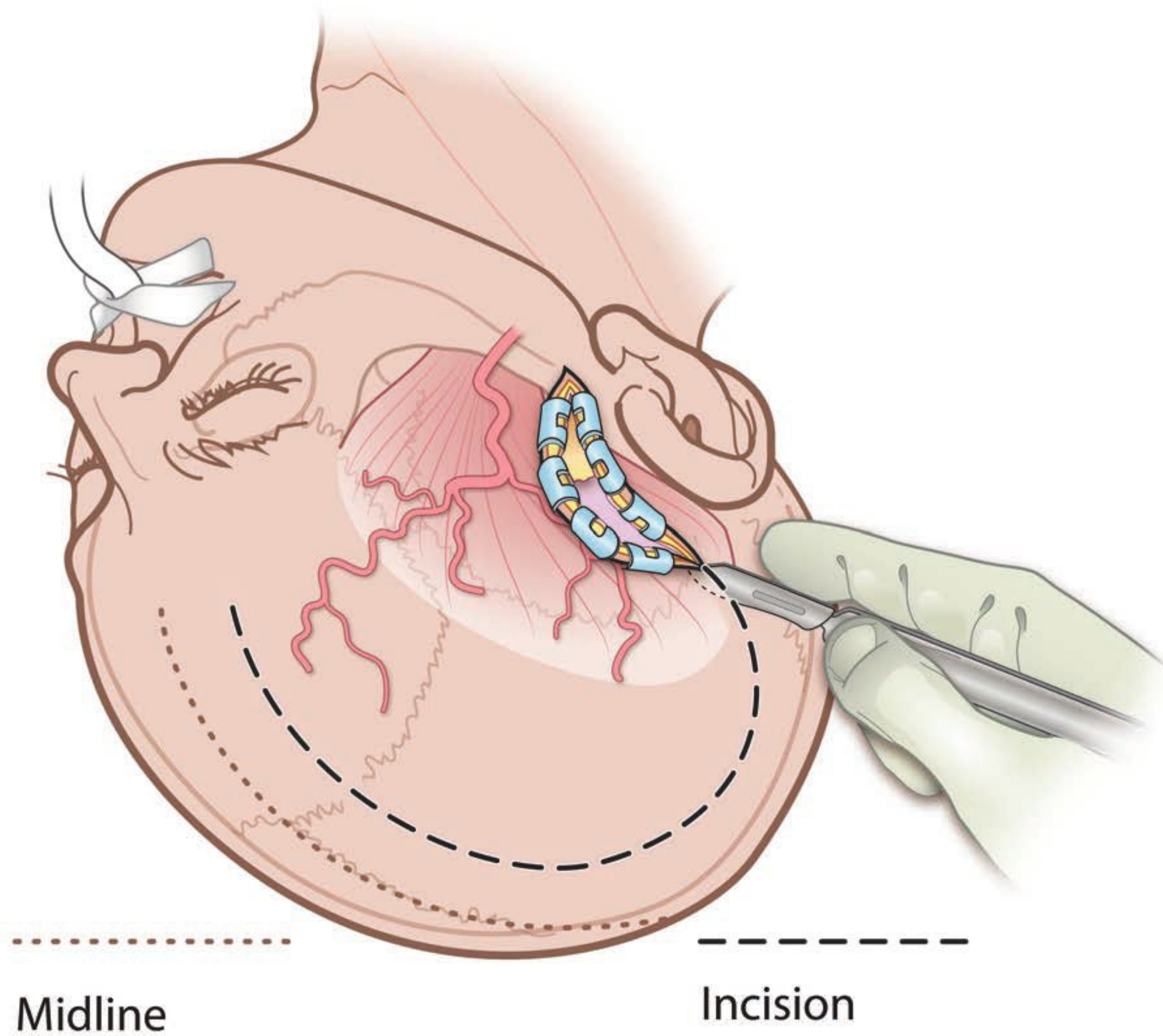


Figure	Procedural Steps	Pearls
Fig. 1.3	**The skin incision should be planned to create a craniotomy sufficient to access the entire hematoma. The question mark or reverse question mark incision (illustrated here) is used commonly to access large traumatic extra-axial hematomas.**	• Other skin incisions may be utilized to evacuate smaller hematomas. However, before committing to a more limited exposure, consideration should be given to the degree of brain swelling anticipated. • When using a question mark incision, care should be taken not to place the incision too close to the pinna of the ear. A margin of at least 1 cm should be used. Likewise, the vertical limb of the incision should be placed at least 1 cm anterior to the tragus. The scalp may be elevated off of the underlying bone and retracted out of the way. • Scalp clips may be applied to the scalp edges to aid in hemostasis. • Prior to opening the scalp over the temporalis muscle, an instrument may be passed over the muscle fascia and the skin divided down to the level of the instrument with a scalpel. The temporalis may then be divided in parallel with the incision using Bovie cautery. • Branches of the superficial and middle temporal arteries may be encountered and may be ligated and divided sharply, or cauterized with the bipolar cautery.

Subcutaneous Dissection (Fig. 1.4)

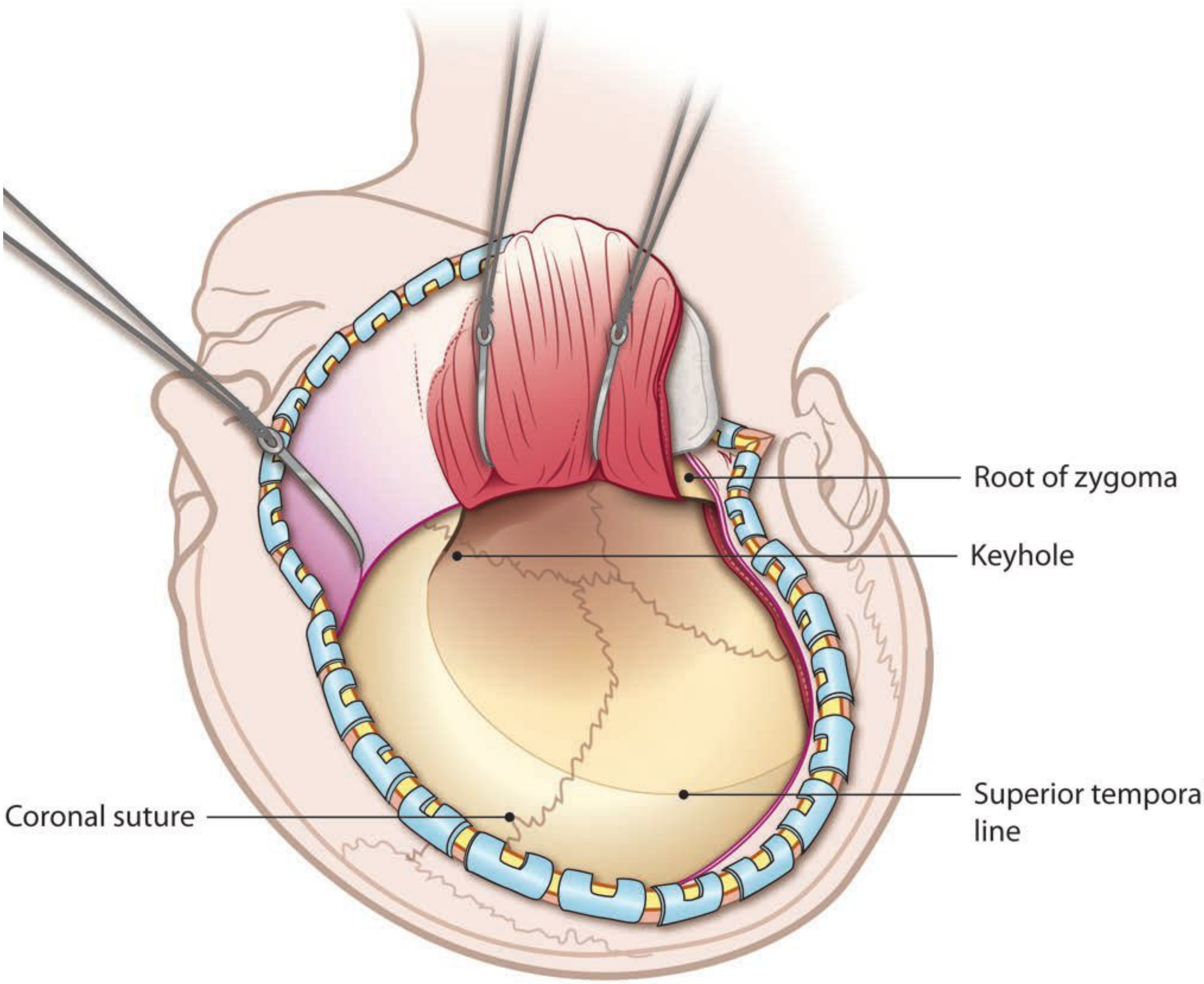


Figure	Procedural Steps	Pearls
Fig. 1.4	**For rapid opening, the temporalis muscle may be elevated simultaneously with the scalp flap.**	• The temporalis muscle may be elevated off of the underlying bone using a sharp periosteal elevator, such as a Langenbeck, or using the Bovie cautery. • The musculocutaneous flap should be protected from strangulation by placing dry sponges (counted) behind the flap, which is then secured using fishhooks. A sponge soaked with irrigation infused with epinephrine may be placed on the undersurface of the galea and muscle to aid in hemostasis. • Bipolar cautery may be used sparingly on scalp and muscle vessels, taking care not to shrink the galea.

Craniotomy (Fig. 1.5a, b)

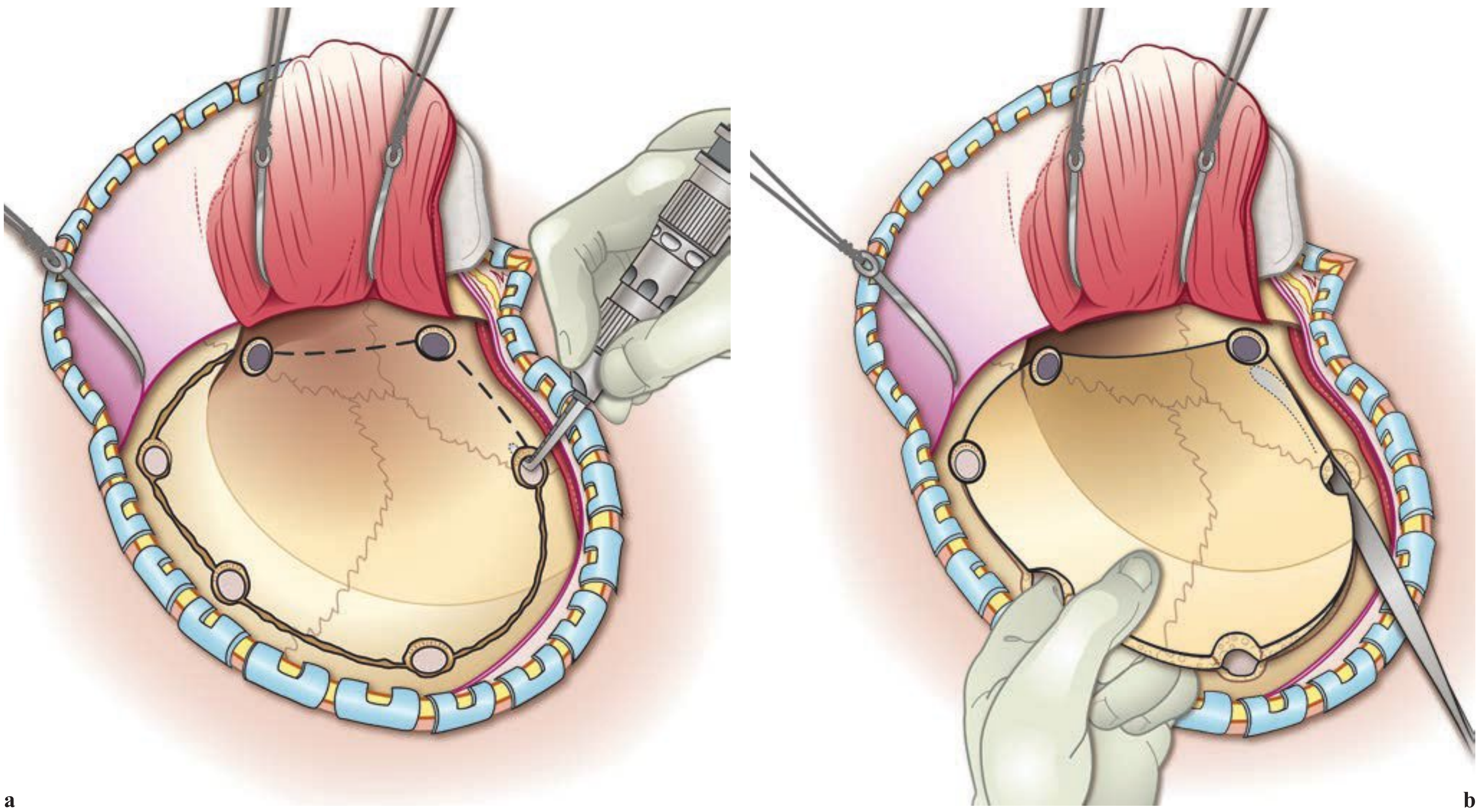


Figure	Procedural Steps	Pearls
Fig. 1.5	**(a) Bur holes are placed at the perimeter of the planned bone flap, leaving sufficient bony margins so that the plating hardware is not located immediately under the skin incision at closure.** **A no. 3 Penfield dissector is used to strip the dura off of the undersurface of the bone at each bur hole. If possible, the Penfield should be used to make a communication, in this same plane, between adjacent bur holes. The high-speed drill attachment is converted to a cutting bit with a footplate and used to connect each pair of bur holes circumferentially.** **The bone flap should be secured in place with a finger prior to making the final cut.** **(b) As the bone flap is elevated off of the center dura, again using a no. 3 Penfield, the edge of the flap should be securely grasped and eventually removed from the exposure.**	• After creation of the bur holes using a high-speed drill, bone wax is applied to the raw bone edges where necessary. Excess wax is removed, along with any obstructive bone edges deep in the bur holes, with a cup curette. • A larger instrument, such as a Langenbeck periosteal elevator, may be used to elevate the flap, as long as the underlying dura is protected from the sharp edge of the instrument. The explanted bone flap should be cleared of hematoma and blood and placed in irrigation infused with antibiotics on the back table until ready to be replaced. • Center holes may be made later in the bone flap for epidural tack-up sutures.

Evacuation of Epidural Hematoma (Fig. 1.6)

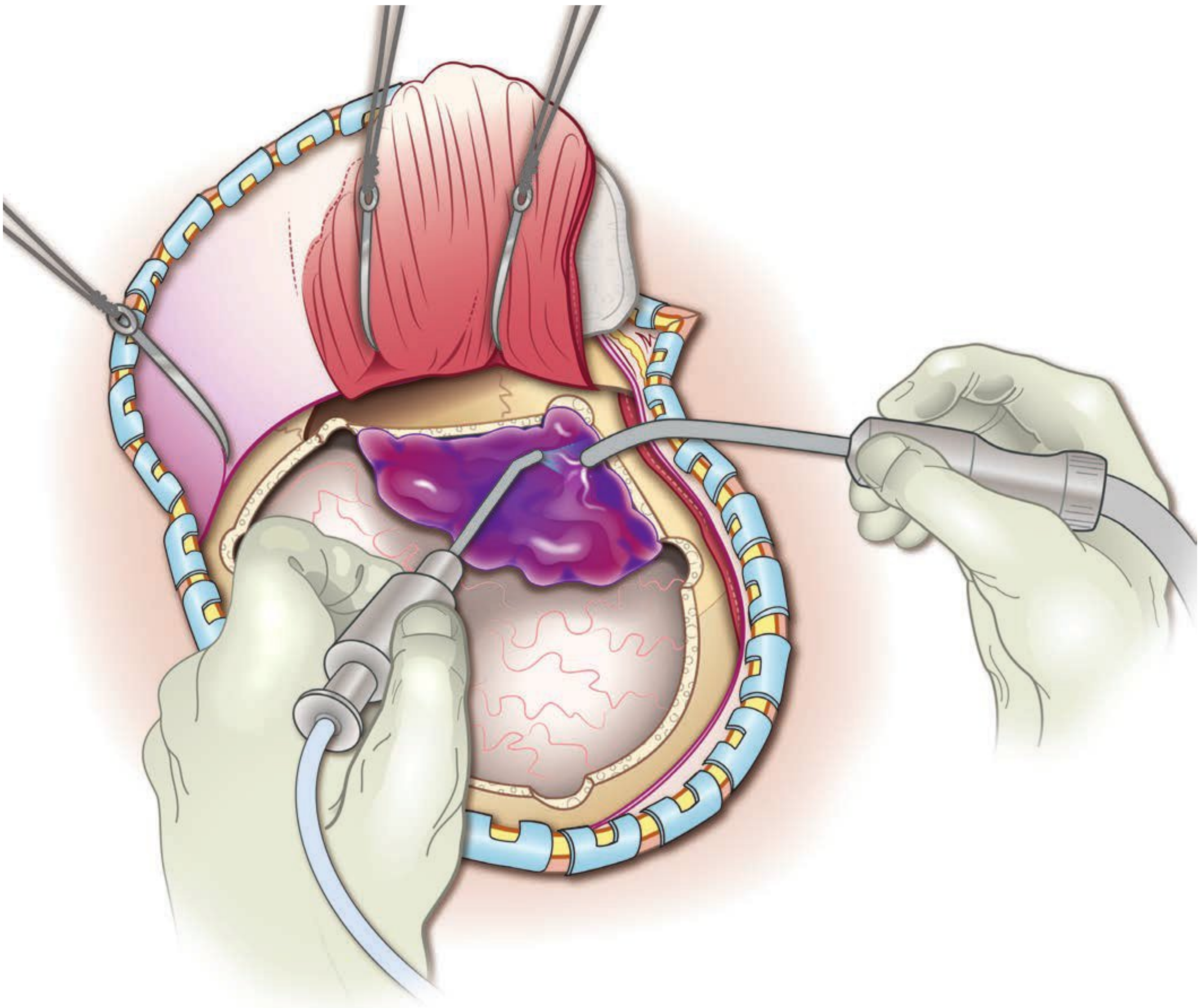


Figure	Procedural Steps	Pearls
Fig. 1.6	**As the bone flap is elevated, an epidural hematoma will be appreciated immediately in the extradural space. This may be removed using irrigation and suction.** **The source of bleeding should be addressed as quickly as possible, utilizing bipolar cautery on the vessel itself, and/or bone wax on the foramen spinosum where the vessel enters the cranium.**	• Evacuation of an epidural hematoma will often yield both organized hematoma and liquid blood. The hematoma is often adherent to the bleeding vessel, commonly the middle meningeal artery in the anterior temporal area. This, in turn, may be associated with a fracture of the squamous portion of the temporal bone. • Other sources of epidural hematomas may be handled similarly. Venous epidural hematomas sometimes require application of gel foam soaked in thrombin and gentle pressure, or Bovie cautery or bone wax to bleeding bone edges.

Dural Opening (Fig. 1.7)

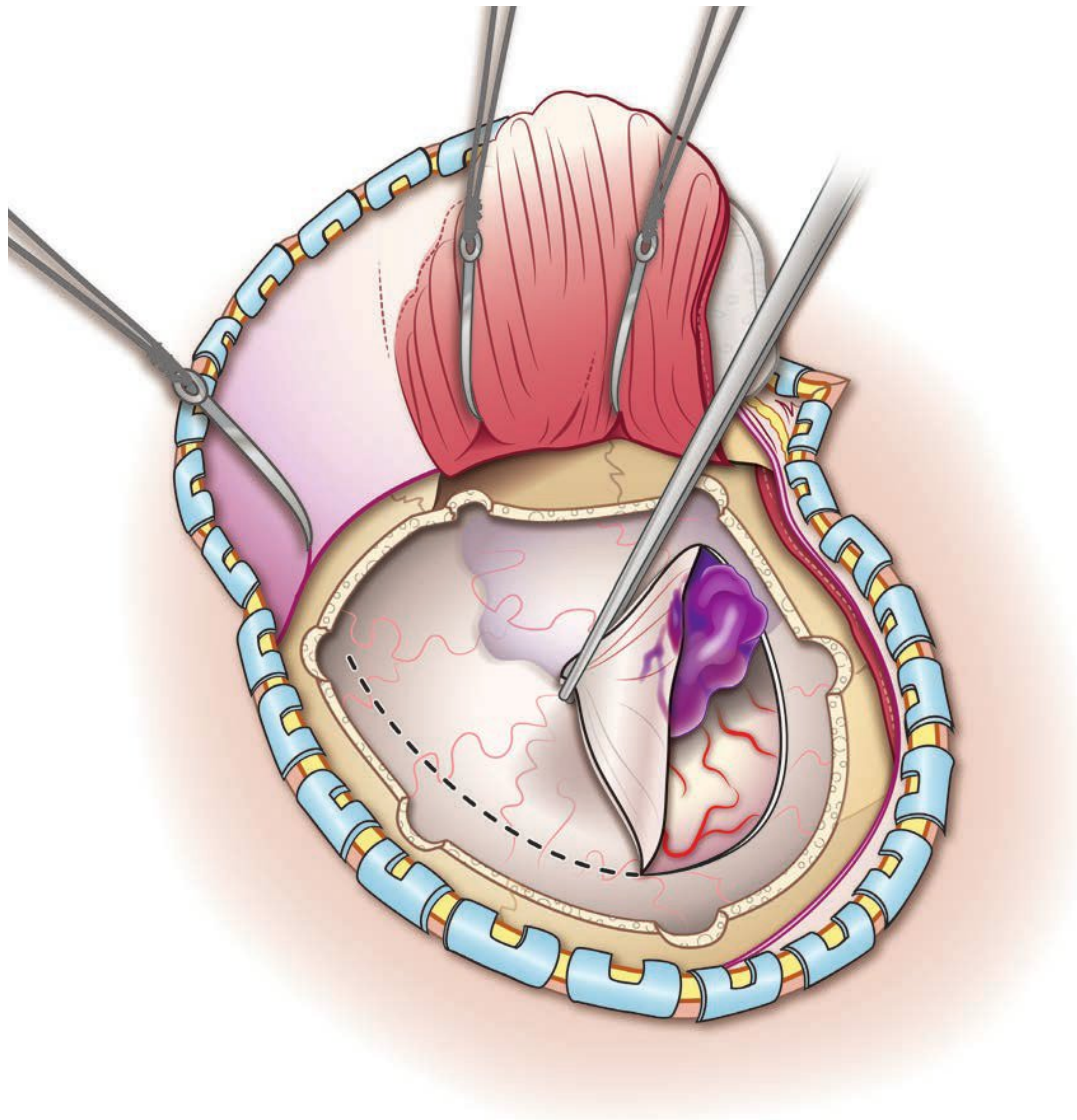


Figure	Procedural Steps	Pearls
Fig. 1.7	**The dura is opened widely enough to allow access to as much of the subdural space as possible in the craniotomy exposure.** **The initial dural opening may be made with a no. 11 scalpel. The dural edges may then be grasped with fine-toothed forceps, elevated, and the remainder of the opening performed with fine Metzenbaum or tenotomy scissors. Occasionally, if the brain is very edematous, the opening may be made with a no. 11 scalpel over a groove director.**	• For curvilinear incisions, at least 1 cm of dura should be left between the durotomy and the bone edge to prevent retraction, causing difficulty with closure. If the brain is significantly edematous and the dura is taut, relaxing incisions may be made in the perimeter of a curvilinear incision to prevent strangulation of the underlying brain by the dural edge. • The dural edges should be secured with 4-0 braided nylon sutures, and held in place with mosquito hemostats, either to gravity or secured to the drapes without undue tension. • The dural flap or flaps should be weighted with hemostats in order to prevent shrinkage during the procedure as much as possible. • Dural vessels may be coagulated with the bipolar at the edges of the cut dura.

Evacuation of Subdural Hematoma (Fig. 1.8)

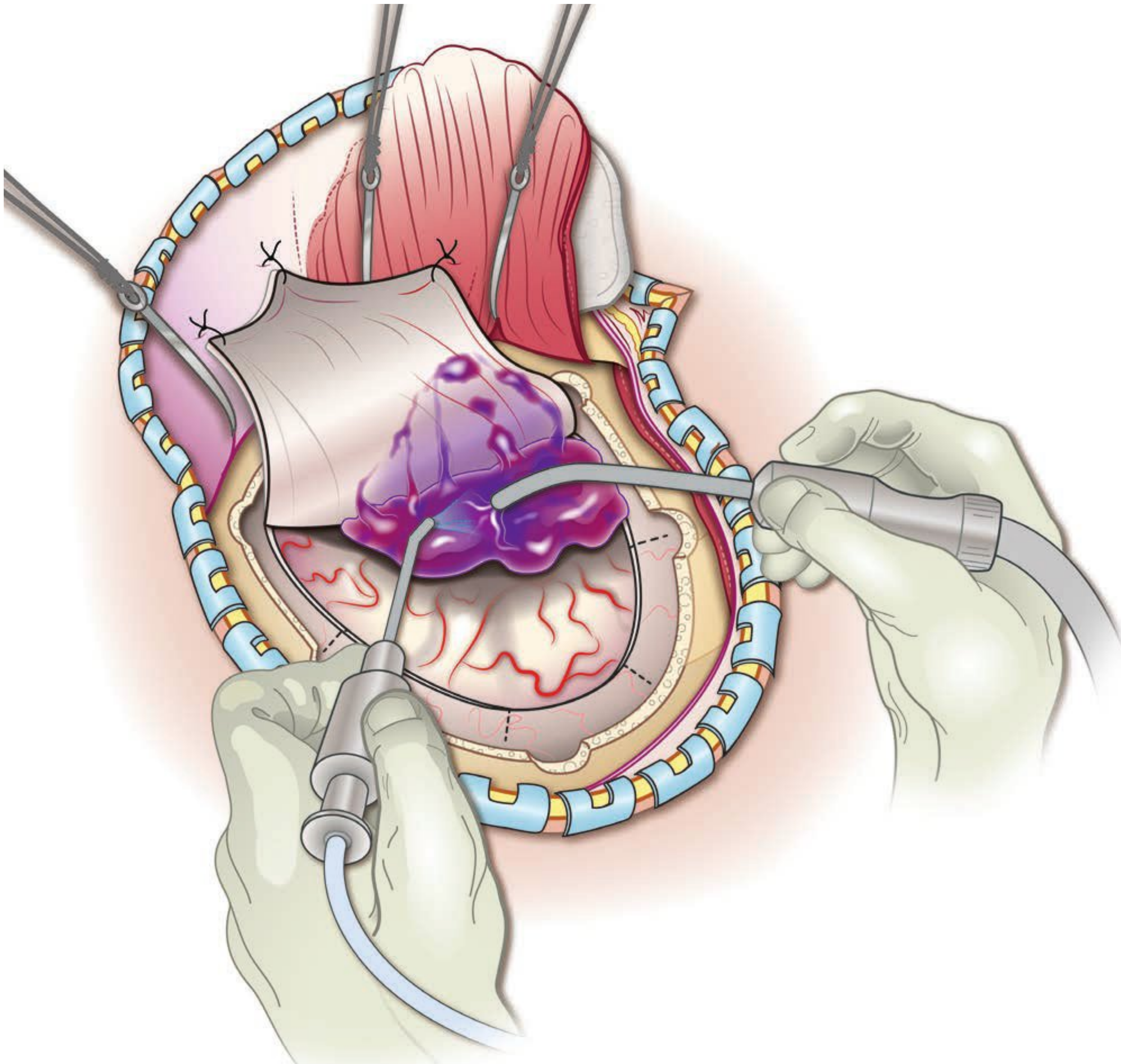


Figure	Procedural Steps	Pearls
Fig. 1.8	**The subdural hematoma (SDH) is seen overlying the surface of the brain and is evacuated with irrigation and suction.**	• The source of any SDH should be sought. The source is often a cortical surface vein or artery. SDHs occasionally may emanate directly from a surface contusion. • Gentle irrigation with sterile saline should be used and the entire perimeter of the dural exposure explored with adequate lighting to ensure that the hematoma has been completely evacuated. A brain retractor blade may be used to gently depress the brain during this phase. Well-formed hematomas may be grasped with biopsy forceps and gently elevated from the brain surface while flushing the area with ample irrigation. • If an active bleeding source is identified (which is not always possible), the bleeding should be stopped with bipolar electrocautery, gelatin sponge soaked in thrombin, and gentle pressure with a cotton pattie. The site should be irrigated again to ensure no active bleeding prior to dural closure.

Dural Closure (Fig. 1.9)

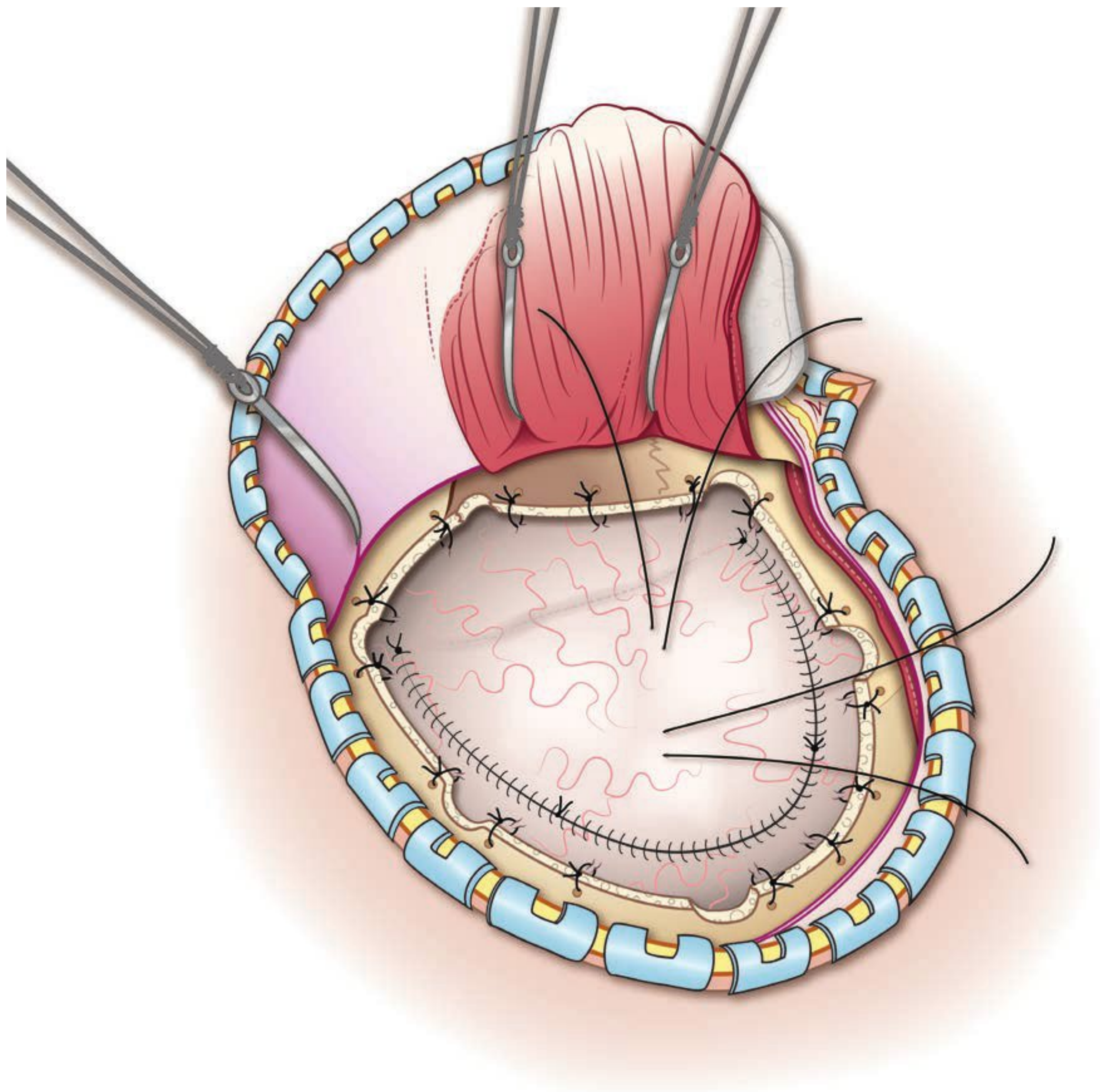


Figure	Procedural Steps	Pearls
Fig. 1.9	**After adequate evacuation of the hematoma, the dura is closed with 4-0 braided nylon suture.** **Epidural tack-up sutures are placed through small drill holes placed around the perimeter of the craniotomy. A central epidural tacking stitch may be brought out through two holes drilled in the bone flap.**	• Closure of the dura should be affected in a watertight fashion if possible. Over the convexity, watertight closure is not imperative. The dura may be closed with simple running, running-locking, or interrupted sutures. • For large dural defects not amenable to primary closure due to shrunken dura, torn or adherent dura (common in the elderly), and/or brain swelling, a variety of dural substitute materials are available. The dura may be patched with suturable graft materials or autograft from the patient's own galea or muscle fascia, or closed with graft materials alone. • Prior to placing the final few sutures, the subdural space should be irrigated a final time. When a large subdural potential space remains (as in the case of an elderly patient and/or one with a slack brain), a small amount of irrigation may be left in the subdural space to lessen the risk of extensive postoperative pneumocephalus.

Bone Flap Replacement (Fig. 1.10)

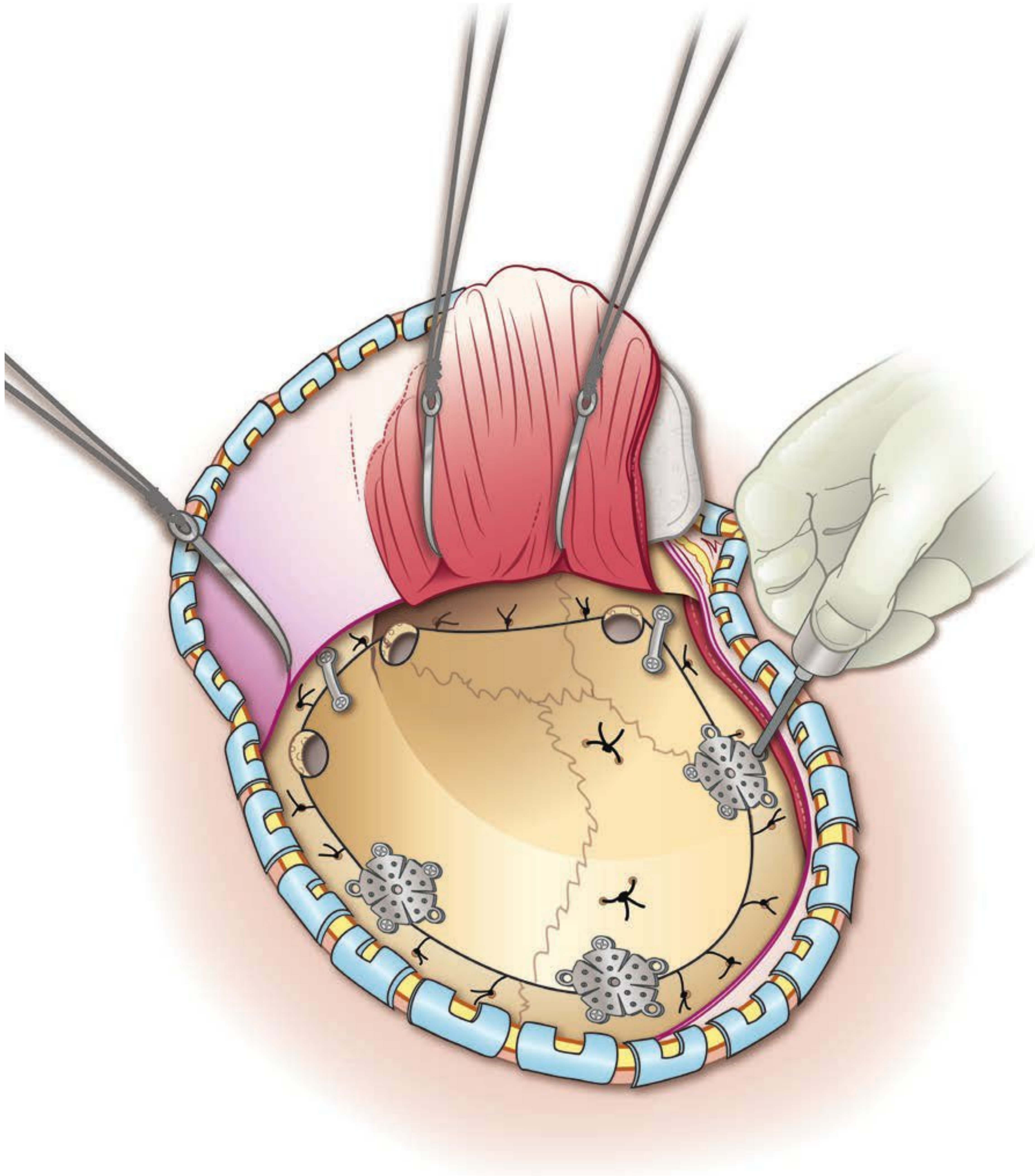


Figure	Procedural Steps	Pearls
Fig. 1.10	**Following evacuation of either an epidural or subdural hematoma, the bone flap is replaced in its anatomic position, using a cranial plating system. The central epidural tacking stitch is secured.**	• Many types of cranial plating systems, with a variety of plate shapes and sizes, are available. These are generally made of titanium, which is nonmagnetic, allowing for later magnetic resonance imaging. • Resorbable plates and screws are available for children. Alternatively, the bone flap may be replaced with silk suture to avoid rigid fixation in the growing skull.

Drain Placement (Fig. 1.11)

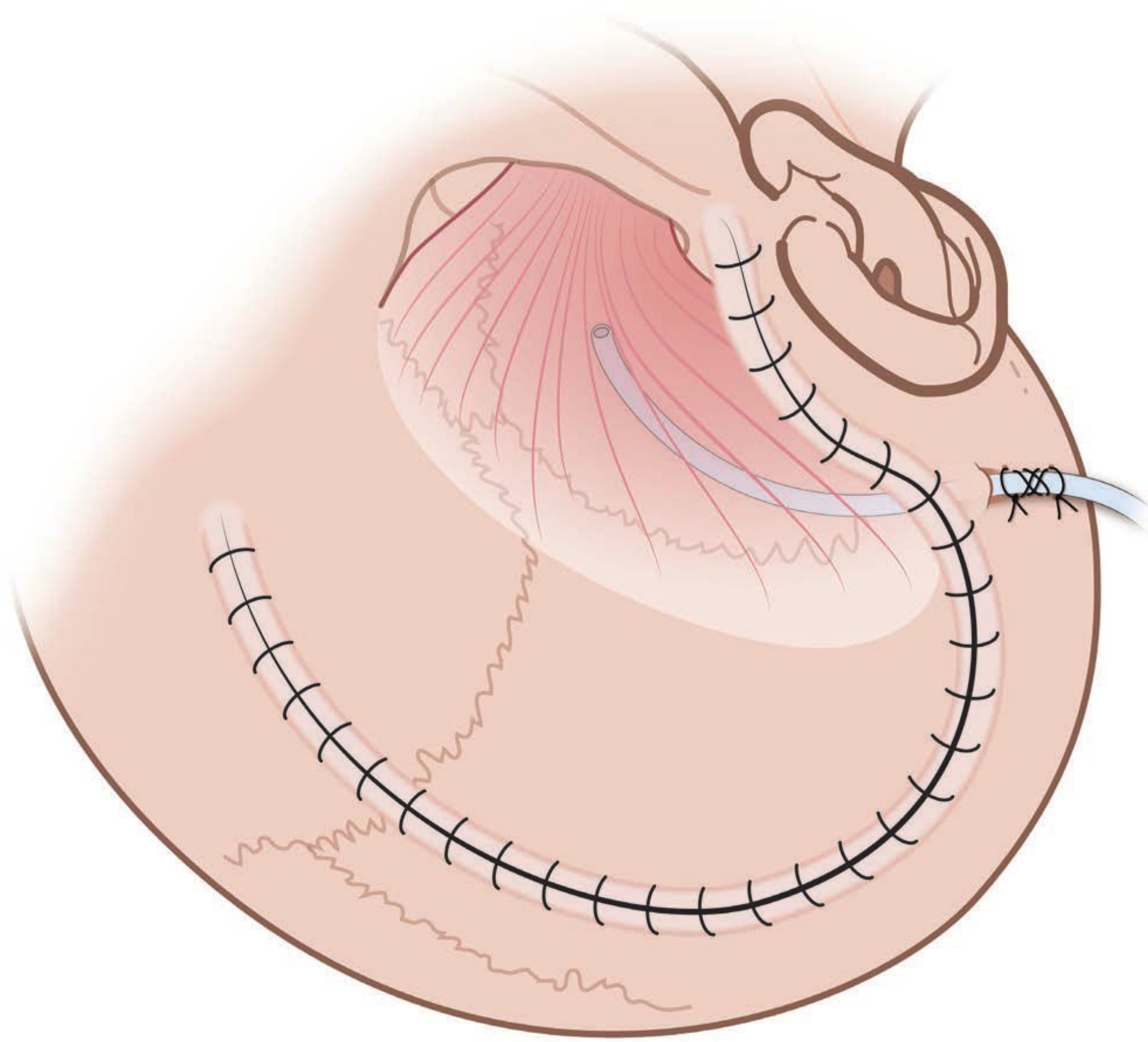


Figure	Procedural Steps	Pearls
Fig. 1.11	**For large flaps, a subgaleal drain may be used to lessen the risk of postoperative subgaleal hematoma.**	• The drain should exit from a separate stab incision, formed with a trocar or no. 11 knife, and should be secured at its skin exit site with a nylon stitch. The drain is attached to bulb suction.

Closing

- If mass effect has been relieved adequately and the brain is slack (creating dead space in which blood may accumulate postoperatively), the patient's end-tidal CO_2 level should be allowed to rise gradually to 30 to 35 mm Hg (roughly equivalent to pCO_2 of 35 to 40 mm Hg) during closure.
- If ongoing coagulopathy is observed, measures should be taken to correct clotting parameters intraoperatively.
- Sterile saline irrigation is utilized in the intradural space.
- After dural closure, copious amounts of sterile saline infused with antibiotic solution (e.g., bacitracin) are used to irrigate the wound.
- Temporalis muscle and fascia are reapproximated with 0-gauge braided absorbable suture. The galea is closed with interrupted, inverted, 2-0 braided absorbable suture. As the scalp closure proceeds, the scalp clips may be removed successively, by spreading with the scalp clip applier or a hemostat.
- The skin may be closed with nylon or other nonbraided suture, or with staples. External suture is required on the scalp, as there is not a well-developed subcuticular layer.
- The wound may be dressed in a variety of ways. The author prefers to apply a strip of nonadherent petrolatum gauze over sutures or staples to prevent pulling. This base dressing, in turn, is covered with narrow gauze bandages to absorb minor oozing postoperatively. The dressing is secured with stretchy dressing tape, applied under slight tension to assist incisional hemostasis. Strips of dressing tape may be used to follow the curvature of the head parallel to the incision for close adherence. The dressing is removed after 24 hours, and the patient is allowed to cleanse the wound with mild soap and water.

Postoperative Management

Monitoring

- The patient should be monitored in the post-anesthesia care unit (recovery room), progressive care unit, or intensive care unit with frequent neurologic checks, occurring at least hourly initially. The patient's preoperative status and postoperative course will dictate the timing of transition to less intensive monitoring.
- Patients with severe injuries will likely have additional invasive neuromonitoring (an ICP, external ventricular drain, brain tissue oxygen monitor, or a combination thereof) to guide management. Invasive hemodynamic monitoring (arterial line, central venous line, Swan-Ganz catheter) may be indicated to assist management in critically ill patients.
- Drains should be monitored for output every 4 hours for the first 8 hours and then every 8-hour shift.
- The incision and/or dressing should be monitored for bleeding initially, and for erythema, exudate, and/or edema subsequent to the initial postoperative period.

Medication

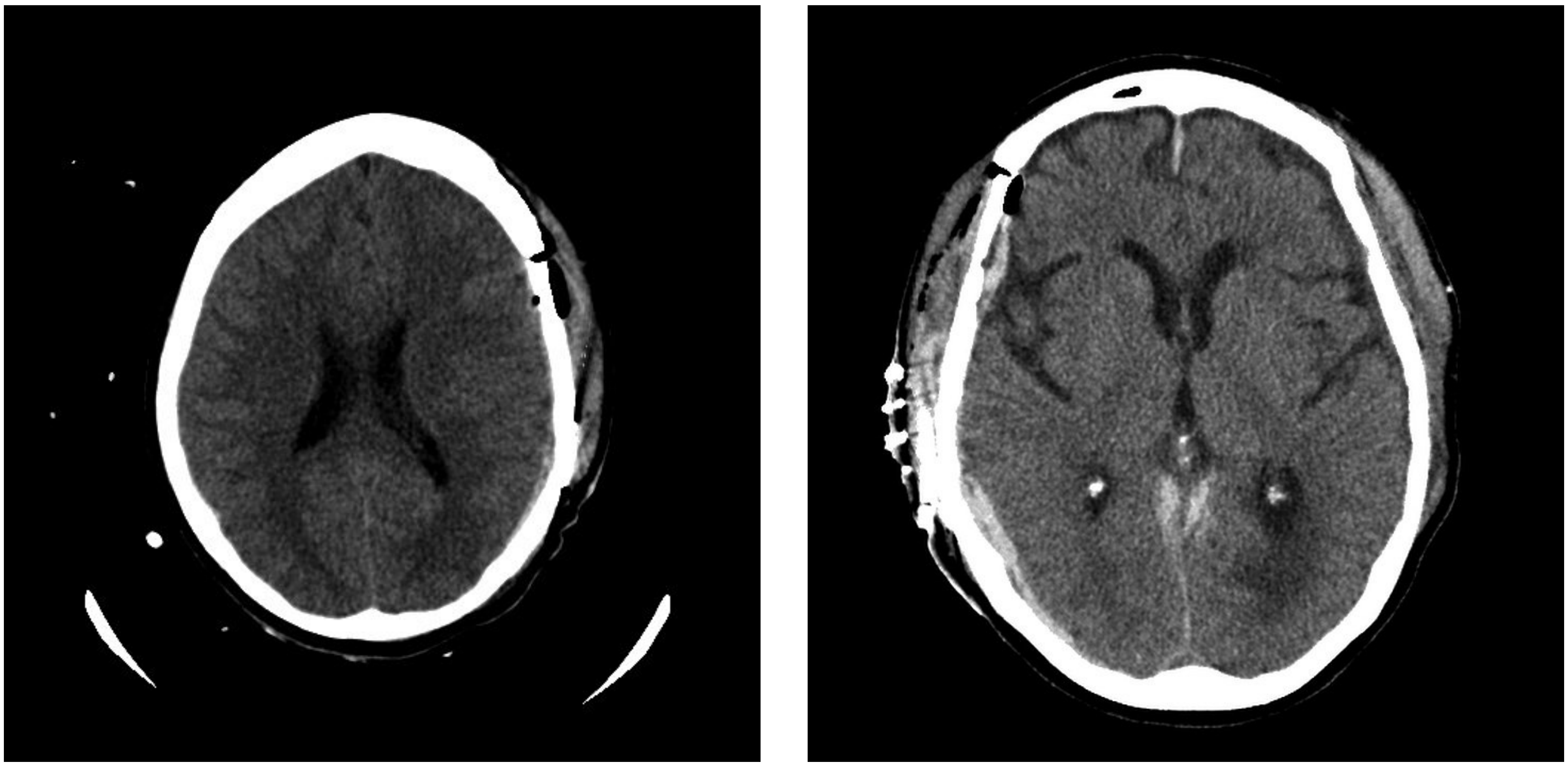
- Postoperative antibiotics are continued for 24 hours unless there was gross contamination present at the time of surgery, in which case this period may be extended.
- Seizure prophylaxis should be continued for a total of 7 days for patients with EDH or SDH. The presence of documented seizures may provide an indication to continue therapy beyond this window.
- Hyperosmolar therapy—mannitol and/or hypertonic saline—may be indicated for ICP control depending on the clinical picture.
- Sedation and/or neuromuscular paralytics may be indicated to assist ICP control depending on the clinical picture.
- Pressor support may be necessary to maintain adequate cranial perfusion pressure depending on the clinical picture.
- Ongoing coagulopathy should be corrected with fresh frozen plasma or other appropriate blood products/factors.

Radiographic Imaging

- Postoperative imaging **(Fig. 1.12)**.

Further Management

- Drains are removed on the first postoperative day, provided input has slowed sufficiently. If there is significant output, removal may be delayed another 1 to 2 days.
- The dressing is removed and the wound is cleansed with warm water and mild soap or shampoo after 24 hours.
- Skin sutures or staples are removed on or about postoperative day 10 to 14.



a b

Fig. 1.12a, b Axial CT images demonstrating resolution of **(a)** epidural hematoma and **(b)** subdural hematoma.

Special Considerations

Preoperative planning is important in the management of traumatic SDHs. Planning for possible decompressive craniectomy must often be incorporated into the positioning, incision, and bone flap creation (see Chapter 4). Patients who are likely to require the bone flap to be left out include those with midline shift out of proportion to the thickness of the SDH, those with effaced cisterns, those with blunt vascular injury or ischemia to the affected hemisphere, or those with a significant amount of underlying contusion.

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2 Chronic Subdural Hematomas

Branko Skovrlj, Jonathan Rasouli, A. Stewart Levy, P.B. Raksin, and Jamie S. Ullman

Introduction

Chronic subdural hematoma (CSDH) is one of the most commonly treated neurosurgical disorders in the world. The 2006 *American Association of Neurological Surgeons* procedural survey reported over 43,000 bur holes performed for the evacuation of extra-axial (subdural/epidural) hematomas.[1] The most common patient characteristics are elderly males with or without a history of head trauma.[2,3] Additional risk factors include a history of alcoholism, the presence of an internal cerebrospinal fluid (CSF) shunt, and acquired or congenital bleeding diathesis.[4] CSDHs are often unilateral, but present as bilateral in approximately 16 to 25% of cases.[3,5] The most common presenting symptoms include headache, ataxic gait, confusion, aphasia, and various nonspecific complaints. If the CSDH is large and causes significant mass effect, paresis, seizure, and coma may ensue. Mortality statistics vary among institutions, but generally range from 5 to 16%[6,7]

Several theories exist to explain the pathogenesis of CSDH. The prevailing hypothesis is that most start as acute subdural bleeds that trigger a local inflammatory response in the surrounding meninges. Inflammation triggers the migration of fibroblasts, which then create membranes that organize the clot and secrete vascular endothelial growth factor (VEGF) that, in turn, promotes the formation of capillaries within these membranes.[8] Over time, these membrane capillaries bleed and prevent the blood from being reabsorbed. Hemoglobin eventually is broken down into hemosiderin, leading to the characteristic appearance of CSDH on computed tomography (CT)/magnetic resonance (MR) imaging (**Fig. 2.1**).

Management of CSDH typically involves surgical evacuation of the clot and placement of postsurgical drains to prevent reaccumulation of blood in the subdural space. In particular, the use of drains after bur hole evacuation of CSDH has been shown to reduce both recurrence and mortality at 6 months.[9] Several operative approaches are available. Bur hole drainage is performed most commonly. A "mini"-craniotomy may augment visualization of the subdural space. When the radiographic appearance is favorable, bedside procedures—such as minimally invasive twist drill catheter placement or suction evacuation—can be used to good effect. In addition to these surgical techniques, several small studies have suggested that dexamethasone therapy might show some promise in treating CSDH.[10,11] Newer pharmacological treatment, such as the use of tranexamic acid (an antithrombolytic agent), is investigational.[12] CSDH recurrence rates vary among institutions, but generally range from 8 to 16%[13,14] Several studies have suggested that CSDH recurrence rates are higher with bilateral CSDH, with large volumes of pneumocephalus after evacuation, and with use of anticoagulation therapy.[13,14]

Indications

All Procedures

- Subacute or chronic subdural hematoma with maximum thickness . 10 mm and/or midline shift . 7 mm
- Subacute or chronic subdural of any thickness causing mass effect, midline shift, or neurologic signs and symptoms.

Minimally Invasive

- Favorable CT imaging characteristics—a uniformly isodense or hypodense collection in the subdural space—are present. This suggests the subdural hematoma is sufficiently liquefied to permit drainage via a ventriculostomy catheter.
- The presence of an isodense, or even slightly hyperdense, "ground glass" appearance is not necessarily a contraindication to catheter drainage. This phenomenon is seen sometimes in the setting of a subacute or "acute on chronic" subdural hematoma, often with a gradual gradient from anterior hypodensity to posterior hyperdensity (reflecting dependent acute blood mixed with the predominantly chronic hematoma). These usually can be drained effectively with a bedside catheter or suction evacuation procedure.
- A small amount of acute, hyperdense subdural blood within a larger, mostly chronic, hypodense collection is not necessarily a contraindication.
- While adequate drainage can be achieved even in the presence of a few subdural membranes, extensive membranes and multiple layers of subdural hematoma (SDH) of different ages or densities may pose a challenge. Bur hole drainage or craniotomy should be considered in this setting.

Preprocedure Considerations

Radiographic Imaging (Figs. 2.1, 2.2, and 2.3)

- **X-ray:** In general, X-ray is a poor diagnostic tool for CSDH. Occasionally, a plain film of the skull may reveal a calcified CSDH.[15]
- **CT:** CT is the gold-standard imaging modality for diagnosing CSDH. SDHs classically demonstrate a crescentic configuration, as their distribution over the cortical convexity is not bounded by suture lines (in contrast to epidural bleeds). Mass effect, cortical buckling, and midline shift may also

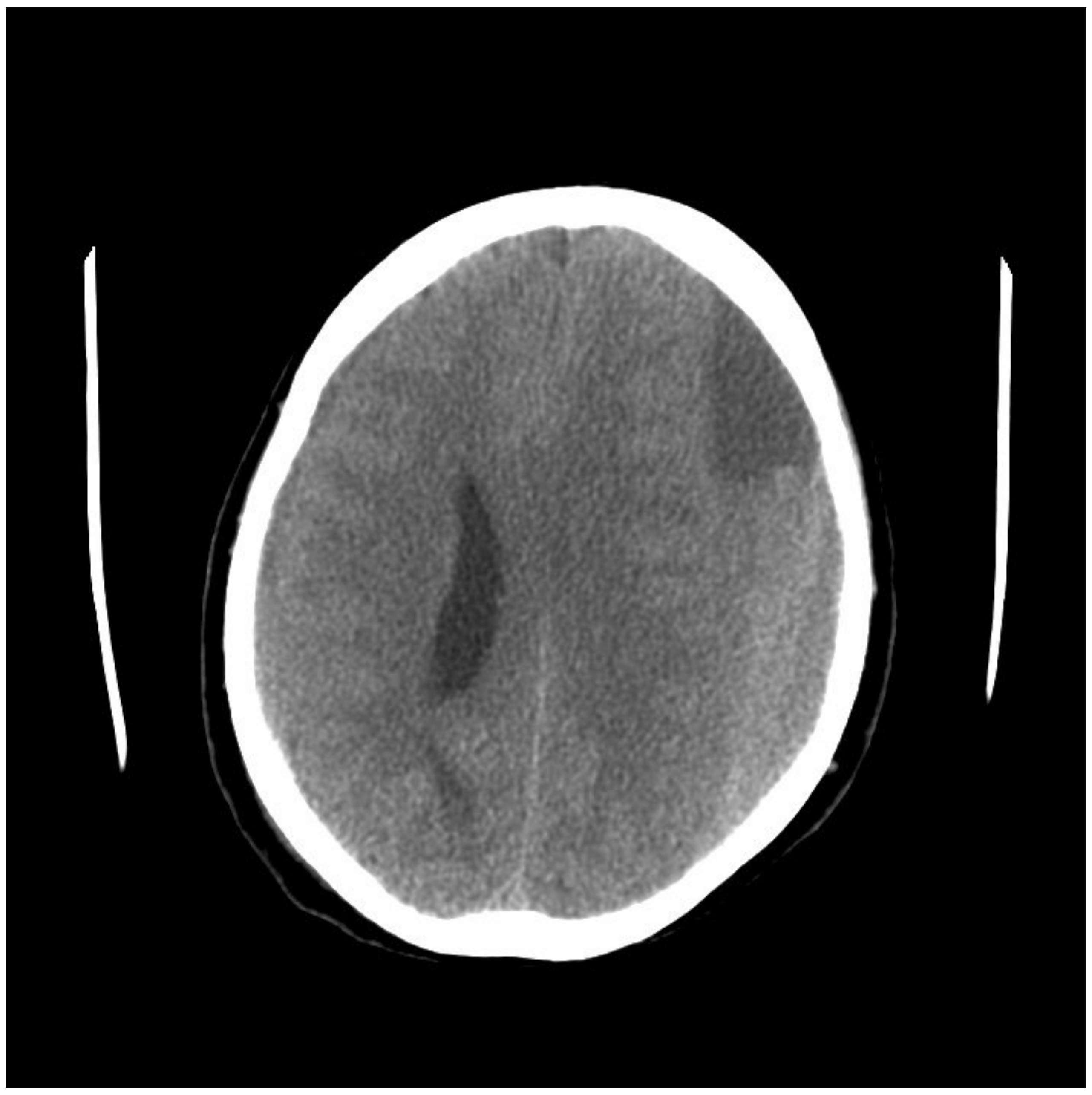


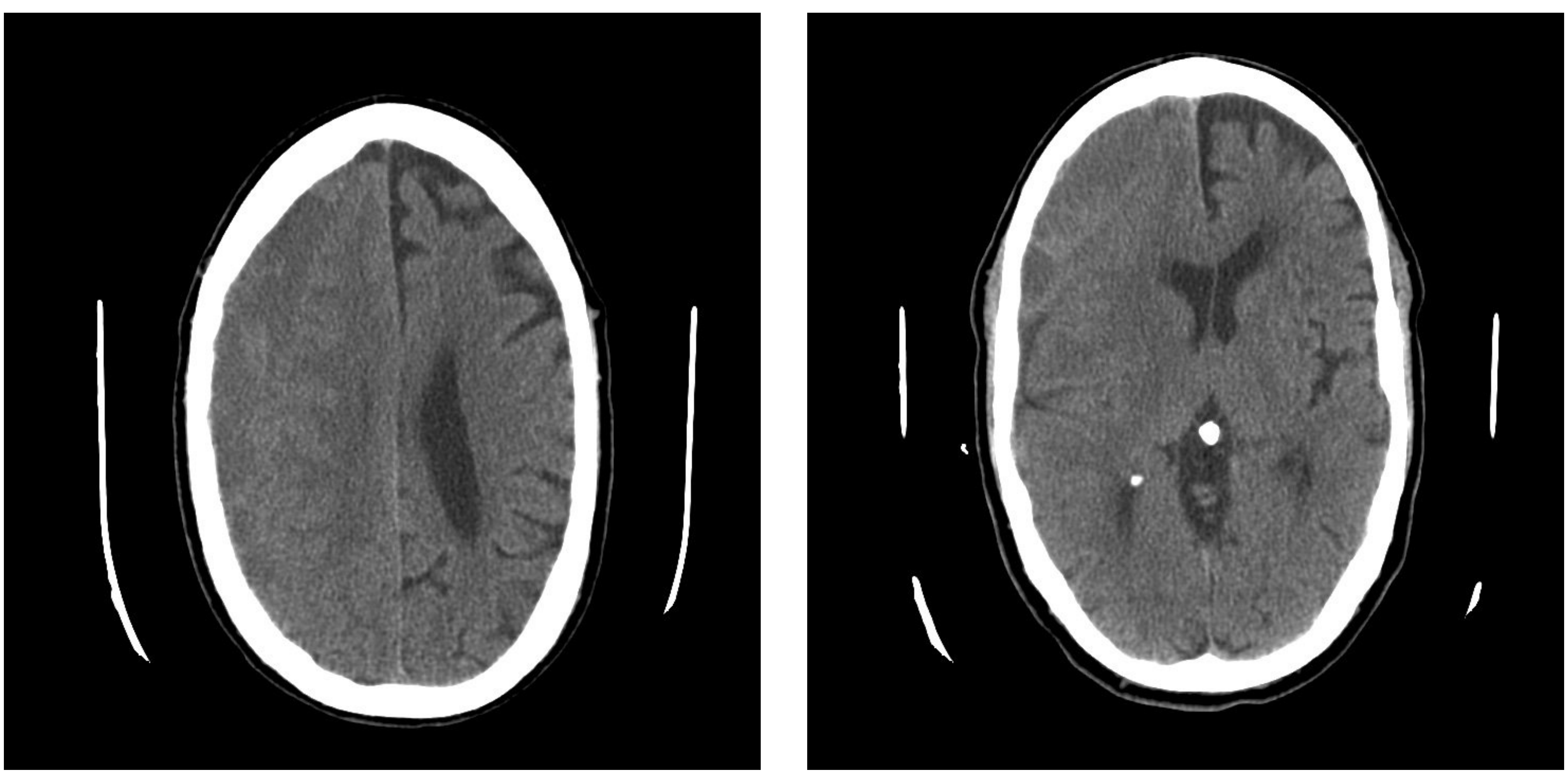
Fig. 2.1 Patient with subacute subdural hematoma with a so-called "hematocrit" effect with blood of different densities layering in a dependent fashion. There is mass effect causing mild shift and left ventricular effacement. This patient was deemed a good candidate for bur hole drainage.

appear depending on the thickness and size of the clot. The appearance of blood on CT scan will change over time as the blood products age (**Table 2.1**); subacute blood appears isodense and chronic blood, hypodense relative to brain. The degree of midline shift and thickness of subdural blood are useful radiographic markers to assist clinical decision making regarding operative intervention. Noncontrast CT usually is adequate to assess the age of the blood present, and therefore, the likelihood that it will be drained successfully via minimally invasive or open means. Contrast-enhanced imaging should be considered if there is concern for subdural empyema or for clarity in the setting of a subacute subdural hematoma that is isodense with respect to the brain tissue. Enhancement of cortical veins helps to define the boundary between cortex and hematoma. Contrast may also demonstrate the presence of membranes.

- **MRI:** Magnetic resonance imaging (MRI) is similarly sensitive and specific for diagnosing CSDH as CT scan; it is potentially more sensitive in determining size and internal structure.[16] CT generally is preferred due to the high cost of MR imaging as well as the time required to perform the study. Similarly to CT scanning, the appearance of subdural blood will also change over time (**Table 2.2**). MRI may be considered for more detailed evaluation of membranes and layers if there is concern regarding the feasibility of catheter drainage.

Medications

- Intravenous (IV) antibiotics should be given within 1 hour prior to incision. The use of prophylaxis in the setting of minimally invasive bedside procedures is left to the discretion of the surgeon.
- Antiepileptic drug prophylaxis should be administered.
- Sedation for bedside procedures should be administered with caution. Minimize dosing or avoid sedation, if possible, as patients with CSDH may be particularly sensitive to its effects. One of the benefits of the bedside SDH drainage procedure is the possibility to witness rapid neurologic improvement



a b

Fig. 2.2a, b Large right frontoparietal subdural hematoma causing mass effect and right ventricular effacement. There are some septations within the mixed density subdural. A small craniotomy was chosen to evacuate the collection.

Fig. 2.3 CT scan of a patient's head with a homogenous right hemispheric subdural hematoma and right to left midline shift. This case was selected for twist drill craniostomy.

when minimal or no sedating medications are used. This stands in contrast to the delayed emergence some (often elderly) patients experience after bur hole drainage under general anesthesia. Bur hole procedures in the operating room can be performed under conscious sedation or general anesthesia as per surgeon preference or patient tolerance. Craniotomies typically are performed under general anesthesia.

Operative Field Preparation

- The hair overlying the affected hemisphere is clipped with electric clippers.
- Sterile skin preparation is performed with povidone iodine or chlorhexidine.
- The planned incision sites are infiltrated with 1% lidocaine with 1:100,000 epinephrine.
- Available imaging should be studied carefully to determine the ideal entry point for the twist drill craniostomy. The target is almost always more lateral than the typical insertion site for a ventriculostomy or intracranial pressure (ICP) monitor.

Table 2.1 CT appearance of subdural blood over time[17]

Time	Appearance relative to brain parenchyma
Hyperacute (, 24 hours)	Hypo-/isodense
Acute (1–2 days)	Hyperdense
Subacute (2–13 days)	Isodense
Chronic (. 14 days)	Hypodense

Table 2.2 MR appearance of subdural blood over time[18]

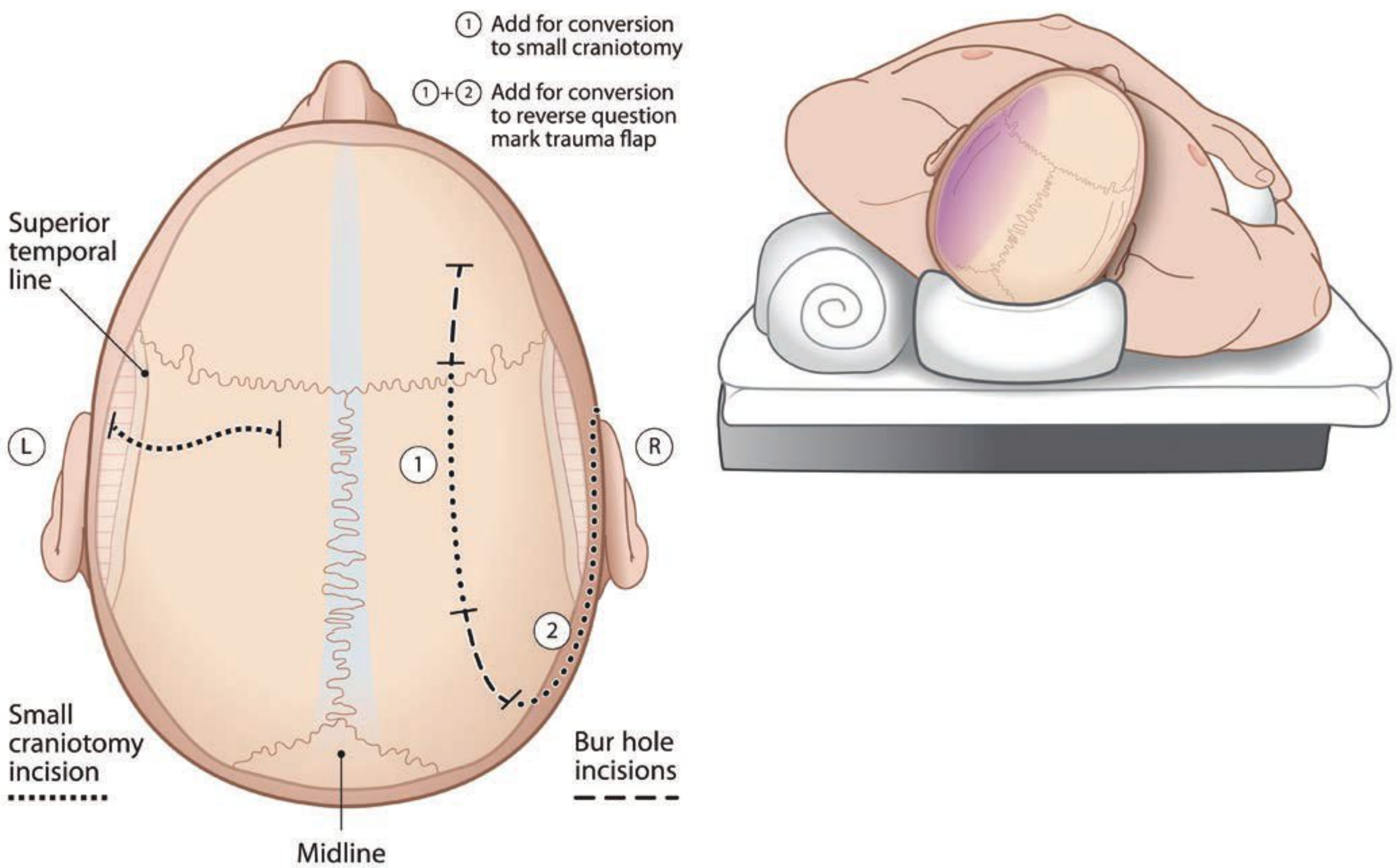
Time	T1	T2
Hyperacute (, 24 hours)	Hypo-/isointense	Hyperintense
Acute (1–3 days)	Hypo-/isointense	Hypointense
Early subacute (3–7 days)	Hyperintense	Hypointense
Late subacute (8–13 days)	Hyperintense	Hyperintense
Chronic (. 14 days)	Hypointense	Hyptointense

H – D B
A – D D
ES – B D
LS – B B
C – D D

Operative Procedure

Bur Hole Drainage

Positioning and Skin Incision (Fig. 2.4a, b)



a

b

Figure	Procedural Steps	Pearls
Fig. 2.4	**The patient is positioned supine on a donut or a horseshoe, with the head rotated approximately 30 degrees to the contralateral side. A shoulder roll is placed longitudinally beneath the ipsilateral shoulder. The back of the bed is elevated slightly.** <u>**Bur Holes (Right)**</u> **Two incisions—each approximately 3 cm in length—are planned along a line that bisects the interval between midline and superior temporal line. The anterior incision is positioned just anterior to coronal suture and the posterior incision, over the parietal eminence.** <u>**Small Craniotomy (Left)**</u> **A "lazy 'S'" incision is begun from approximately 1 cm below the superior temporal line extending superiorly approximately 2 cm lateral to the midline in the parietal region approximately 1 cm posterior to the coronal suture. The incision can be further tailored to the location and size of the hematoma.**	• For bilateral procedures, the head is kept in a neutral position. • Trace out a reverse question mark–type incision over the affected hemisphere. This will facilitate a more extensive opening, if necessary. The planned bur hole incision sites should fall along the superior limb of the question mark. • If the CT appearance of the extra-axial fluid is both hypodense and homogeneous, it may be possible to drain the collection through a single bur hole.

Incisions and Bur Holes/Craniotomy (Fig. 2.5)

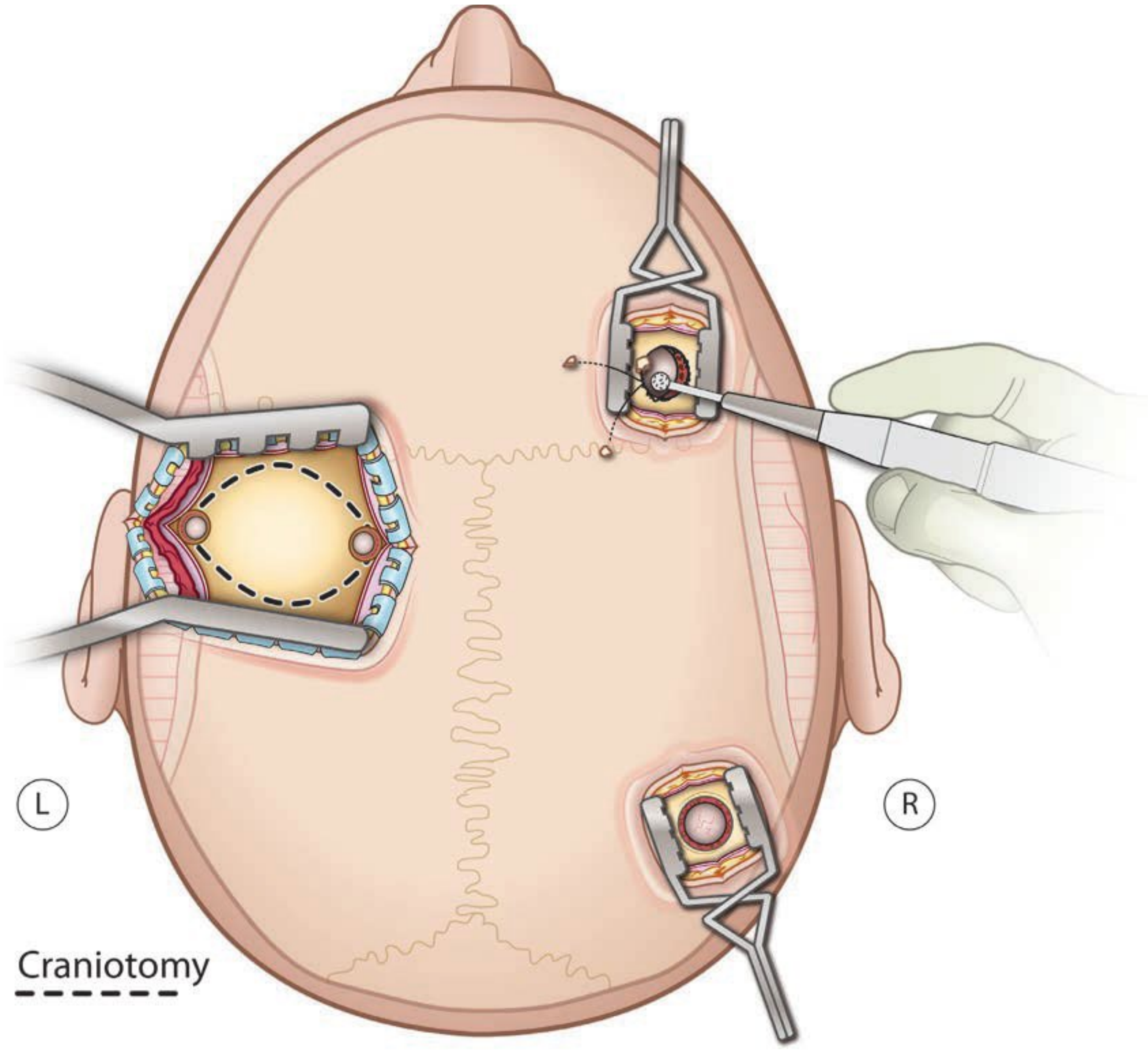


Figure	Procedural Steps	Pearls
Fig. 2.5	**A no. 10 blade is used to open each incision to the level of pericranium. The pericranium is opened with Bovie electrocautery and swept to either side with a periosteal elevator. For the craniotomy, scalp clips are applied to the scalp edges. The temporalis is incised and is reflected with the skin incision. Self-retaining retractors are placed.**	
	<u>**Bur Holes (Right)**</u> **Place a single bur hole at each incision site, using a round or matchstick bur, perforator, or acorn drill. Apply bone wax to the bony edges as necessary.**	• **Bur Holes** ◦ Bur holes should be 1.5 to 2 cm in diameter.
	<u>**Small Craniotomy (Left)**</u> • **Place bur holes at the apices of the exposed calvarium. A footplate attachment, dental tool, or Penfield no. 3 is used to free the underlying dura from the bone. Use the craniotome to create a small bone flap, limited to the size of the opening.** • **The craniotome is used to create a roughly ovoid flap. The bone is elevated—using a blunt surgical tool to dissect any remaining dural attachments to the undersurface of the bone—and set aside in antibiotic solution.**	• **Craniotomy** ◦ Resistance may be encountered at the level of coronal suture, where the dura is more firmly adherent to bone. ◦ The bone flap will be 4 to 5 cm in diameter.

Dural Opening (Fig. 2.6)

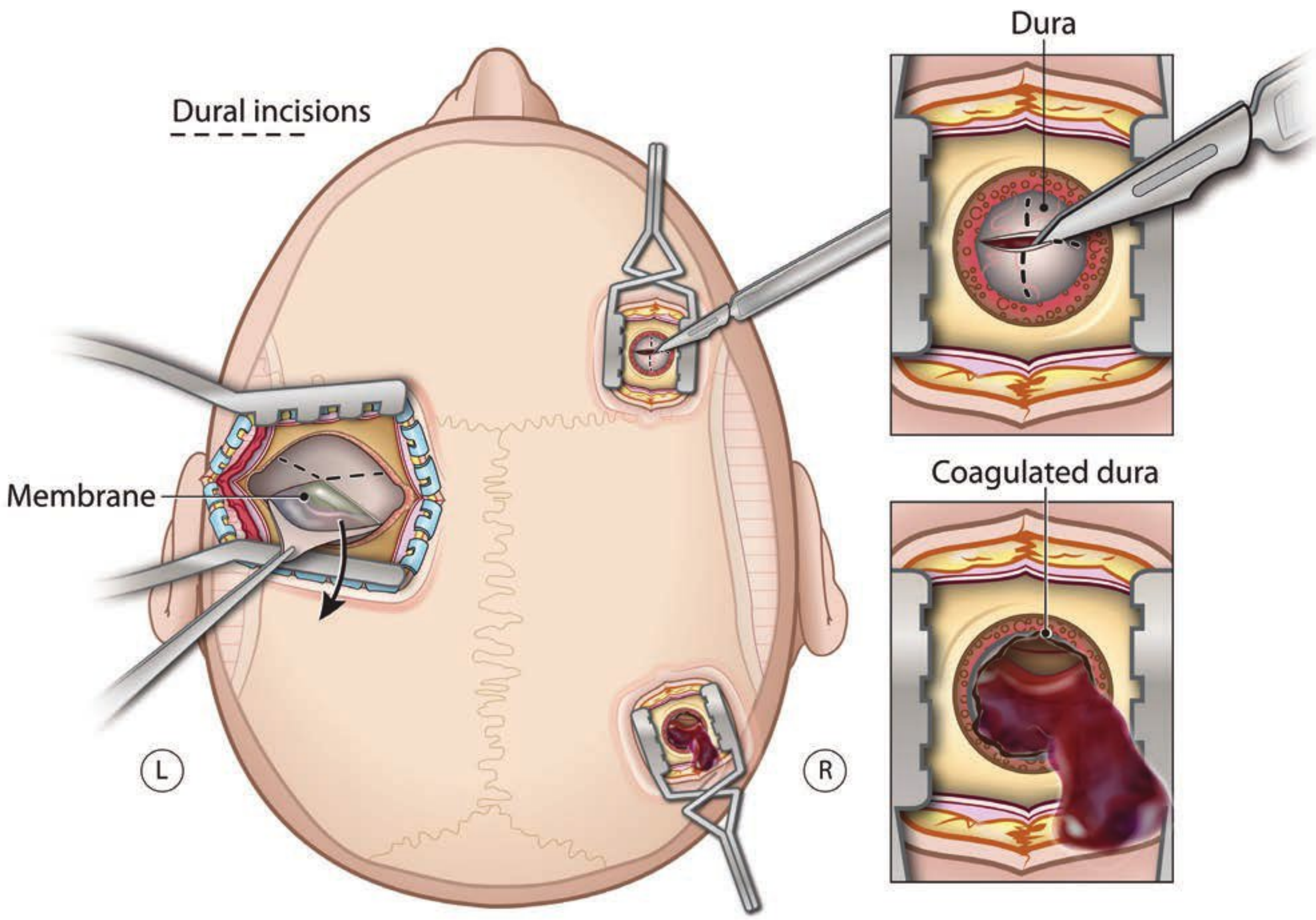


Figure	Procedural Steps	Pearls
Fig. 2.6	<u>Bur Holes (Right)</u> • **Coagulate the exposed dura with bipolar electrocautery at each bur hole site.** • **Open the dura in a cruciate fashion with a no. 11 blade. Coagulate the dural leaflets with bipolar electrocautery to prevent bleeding into the subdural space and to ensure opening of the dura across the full surface area of the bur hole.** • **Upon opening the dura, there may be immediate expulsion of liquid hematoma. If not, a membrane is likely present. The membrane should be coagulated with bipolar electrocautery and opened sharply with a no. 11 blade.**	• **Bur Holes** ◦ The posterior site should be opened first to encourage gravitational drainage. ◦ Attach one suction unit to a Luken's trap prior to opening the dura in order to facilitate collection of a specimen for pathology.
	<u>Small Craniotomy (Left)</u> • **Drill holes circumferentially at the periphery of the craniotomy site. Line the edges of the craniotomy site with thin strips of gelatin sponge soaked in thrombin. Place epidural tacking stitches circumferentially with 4-0 braided nylon sutures.** • **Open the dura in a cruciate fashion, with a no. 11 blade, followed by tenotomy scissors.** • **An outer membrane may be present upon opening of the dura. Usually, it is possible to develop a distinct plane between the undersurface of the dura and the membrane, using a dissector and cotton patties.** • **Reflect the resulting dural flaps to each quadrant and secure them with 4-0 braided nylon sutures.**	• **Craniotomy** ◦ When subdural hematoma is present, the dura will have a bluish hue. ◦ A 4-0 silk suture, passed through the periosteal dural layer, may be used to lift the dura away from the underlying structures to facilitate opening. ◦ The subdural membrane often has a brown-green hue.

Hematoma Evacuation (Fig. 2.7)

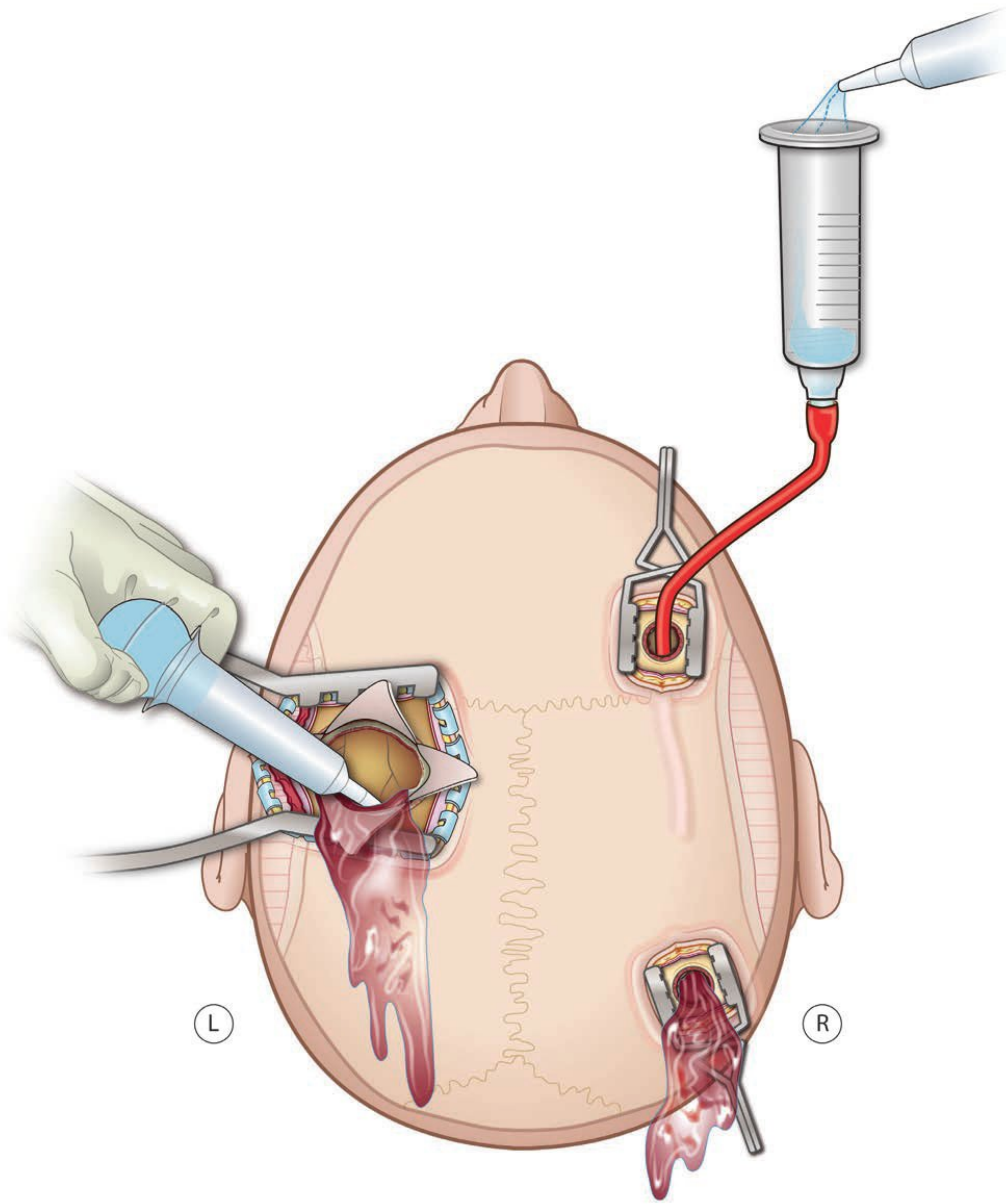


Figure	Procedural Steps	Pearls
Fig. 2.7	<u>**Bur Holes (Right)**</u> • **Once the initial egress of fluid subsides, inspect each bur hole site.** • **Provided the brain has not expanded to fill the subdural space, a small red rubber catheter may be introduced—under direct vision.** • **Gravity irrigation may be performed with lukewarm saline. Affix a 10- to 20-mL syringe—with the plunger removed—to the open end of the red rubber catheter. Elevate the syringe, fill the open end with irrigation, and allow it to funnel through the catheter, into the subdural space. Monitor the bur hole sites during this process to ensure that there is communication within the subdural space between the two holes. Alternatively, the surgeon may elect simply to flush irrigate between the two bur holes.** • **Reorient the catheter within the subdural space as necessary to permit access to additional hematoma.** • **Continue irrigation until the returning fluid is predominantly clear in all directions.**	• Additional holes may be placed along the distal 2 to 3 cm of the red rubber catheter, taking care not to sever the tubing. • If the fluid introduced through one hole does not exit the second hole, there may be an additional membrane that is limiting communication. Halt irrigation and reassess. • The red rubber catheter may be guided in any direction where there is presumed to be hematoma; however, if resistance is encountered, do not force the catheter into position. It is possible for the catheter to penetrate brain parenchyma or to tear a bridging vein, resulting in hemorrhage. • If acute hemorrhage is suspected (and the fluid does not clear with continued irrigation), consideration must be given to conversion from bur holes to a full craniotomy.
	<u>**Small Craniotomy (Left)**</u> • **Coagulate the surface of the membrane and open it widely—within the craniotomy field—with the bipolar and scissors.** • **There will be immediate expulsion of liquid hematoma. Collect a specimen in the Luken's trap for pathology. (Consider taking a specimen of membrane as well.)** • **Use bulb irrigation with lukewarm saline to flush additional clot from the subdural space at the periphery of the craniotomy site. Membranes and septations can be broken apart with bipolar coagulation.** • **Irrigation with a red rubber catheter in a systematic, circumferential fashion under the craniotomy edge is performed until the returning fluid is clear in all directions.** • **Address bleeding points along the membrane and cortical surface with bipolar electrocautery and/or adjuvant hemostatic agents as necessary.**	• The membrane does not need to be cut beyond the edges of the craniotomy. The vascularized membrane can bleed, and such bleeding may be difficult to control if remote from the craniotomy. • Craniotomy also facilitates flushing out of more organized rests of hematoma not accessible via bur holes. • The inner membrane, if present, is not stripped from the surface of the brain due to the risk of precipitating cortical bleeding. • It is important to control active bleeding. Placing gelatin sponge soaked in thrombin in small pieces or strips along the undersurface of the bone can be helpful in stopping bleeding from membranes in difficult-to-reach areas.

Drain Placement (Fig. 2.8)

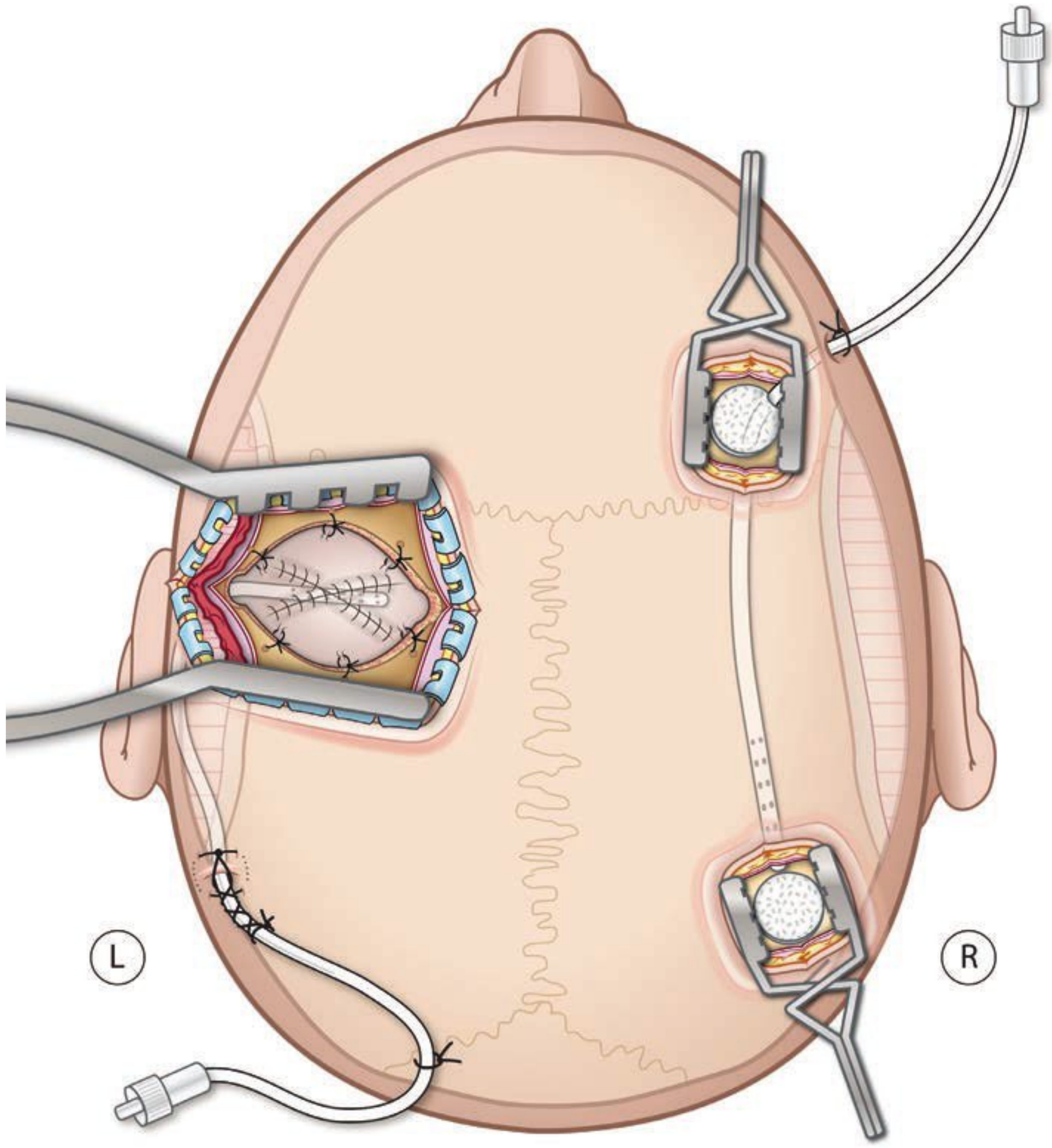


Figure	Procedural Steps	Pearls
Fig. 2.8	<u>Bur Holes (Right)</u> • **A small Jackson-Pratt drain or ventricular catheter may be introduced into the subdural space at the frontal site and advanced, over a Penfield no. 3, until it is visualized at the parietal bur hole. The drain can be advanced further if no resistance is encountered.** • **Irrigate the bur holes with normal saline (using a syringe with an angiocatheter tip) to flush out air within the subdural space. Cover each dural opening with a piece of gelatin sponge to prevent further air or blood from entering the subdural space.**	• **Bur Holes** • On occasion, the brain expands to fill the subdural space, leaving little or no room for a drain. In such circumstances, the risk of placing a subdural drain may outweigh the benefits of ongoing drainage.
	<u>Small Craniotomy (Left)</u> • **A flat or soft round small Jackson-Pratt drain is carefully placed in the subdural space under direct visualization without resistance depending on how much brain expansion is encountered. The dura is closed in an interrupted or running fashion. The cavity is irrigated to remove most of the air. Gelatin sponge is placed over the cavity prior to replacing the bone flap to prevent air and blood from getting into the subdural space during closure.**	• **Craniotomy** • Compressed gelatin sponge can be used to overlap the craniotomy edges especially if a watertight dural seal cannot be achieved. • A subgaleal drain may be left in place as needed to help prevent a postoperative subgaleal hematoma or leakage of subgaleal blood into the subdural space.

Closing

- Superficial skin and subcutaneous bleeding is controlled using bipolar electrocautery.
- The incision site is irrigated with antimicrobial solution.
- For the small craniotomy:
  - The bone flap is secured to the skull with titanium plates and screws. The subdural drain should exit via a bur hole. It is sometimes necessary to create a groove (with a match-stick bur) on the undersurface of the bone flap—at the bur hole site—in order to avoid kinking of the drain at its exit site.
  - The temporalis muscle, if breached, is reapproximated using 2-0 braided nylon sutures.
- The galea and subcutaneous tissue are approximated in an interrupted fashion using inverted 3-0 braided absorbable suture.
- The skin is closed with staples or with 3-0 nylon sutures in a vertical mattress fashion.
- A 2-0 braided suture is placed in a pursestring fashion around the subdural drain exit site to anchor the drain to the skin and seal the space around the drain, preventing inadvertent drain removal, as well as leakage of blood and/or CSF from the drain site.
- A similar suture is placed around the subgaleal drain, if present, at its exit site.
- The skin around the incisions is cleaned of all blood products and surgical debris.
- A sterile dressing is applied.

Operative Procedure

Twist Drill Craniostomy

Positioning and Skin Incision (Fig. 2.9)

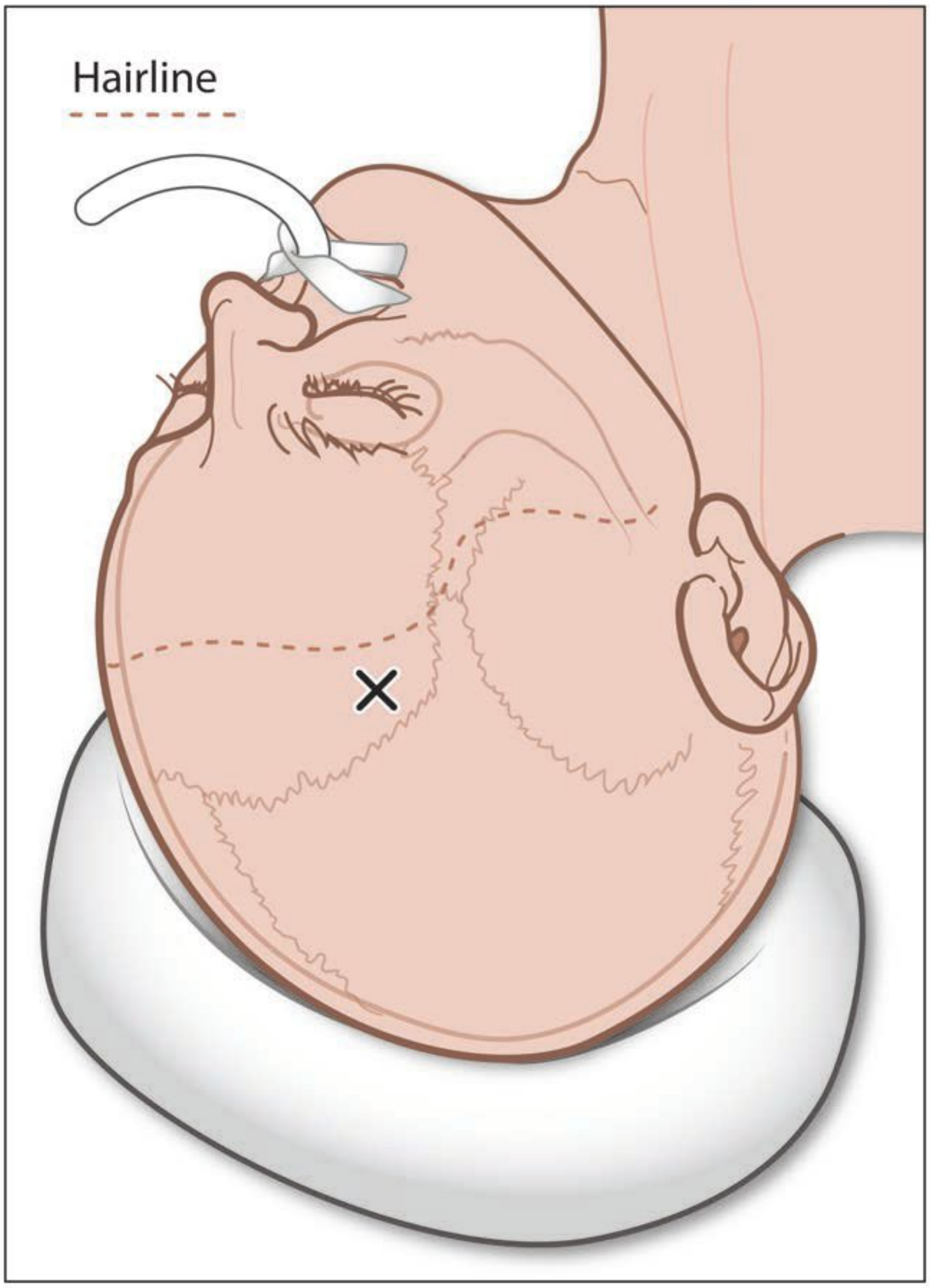
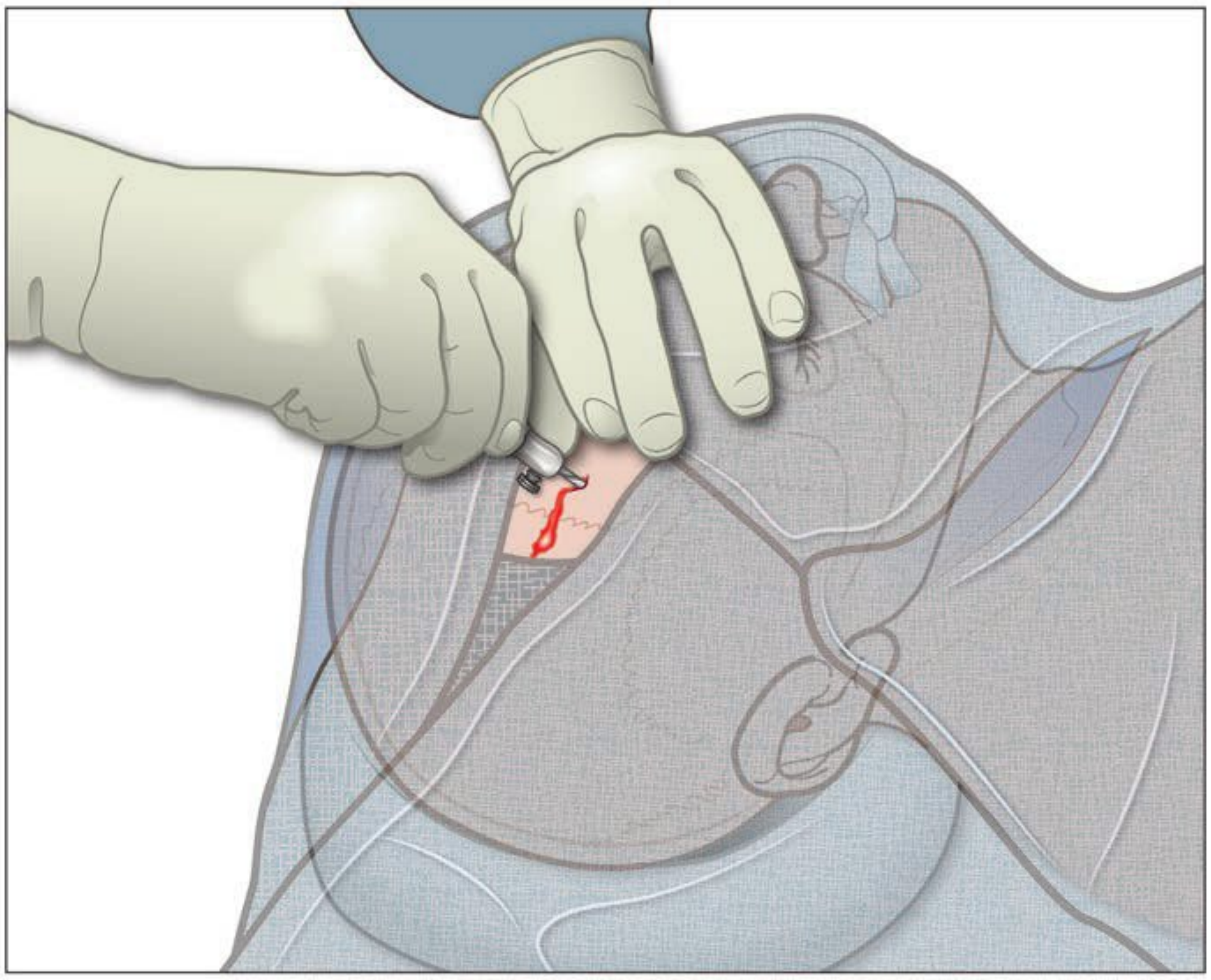


Figure	Procedural Steps	Pearls
Fig. 2.9	**The patient's head is positioned on a firm surface, such as a folded blanket or gel donut, and turned 15 to 30 degrees to the contralateral side (60 degrees if a more posterior parietal entry point is required). Make a small stab incision at the desired insertion site with a no. 15 blade. The entry point for the catheter insertion is chosen over a relatively thick part of the SDH that is safely accessible, usually in the frontal region, about 2 cm in front of the coronal suture and 4 to 8 cm off midline.**	• Soft restraints are often necessary to prevent the patient from inadvertently reaching into the sterile field. An assistant may be useful to stabilize the patient's head during the procedure, with hands placed gently on either side of the patient's jaw, under the drapes. • The ideal entry point is usually similar to a ventriculostomy entry point, but more lateral. Occasionally, a predominantly posterior SDH will require a parietal entry point.

Drilling (Fig. 2.10a, b)



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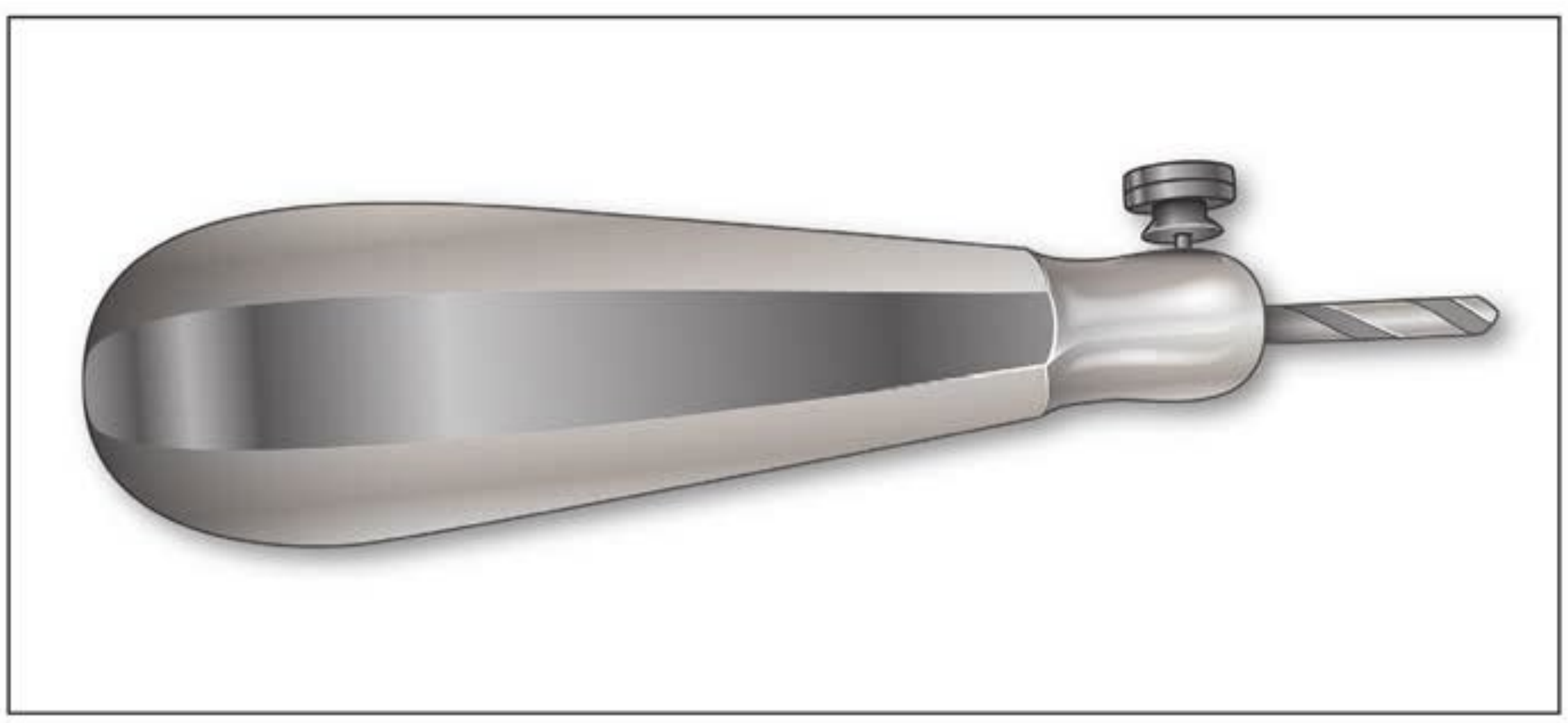


b

Figure	Procedural Steps	Pearls
Fig. 2.10	**(a) A hand-operated twist drill is positioned at the desired entry point and a small hole is drilled through the skull. The twist drill can be started in the usual perpendicular angle, but once the hole is started and the drill bit is stable enough in the hole to not slide, the drill angle can be carefully adjusted off the perpendicular angle and into the direction in which you wish the catheter to enter. Usually this means tilting the drill tip posteriorly in order to angle the hole posteriorly, thereby directing the catheter into the subdural space and toward the posterior dependent portion of the chronic SDH collection.** **The dura is usually penetrated with the drill bit. Alternatively, a no. 11 blade or spinal needle can be used.**	• Angling the drill helps to guide the catheter into the subdural space smoothly, and also helps to avoid inadvertently passing the catheter through the surface of the brain. **(b)** The "Kindt Drill" type of short straight-axis hand drill (**Fig. 2.10b**) is ideally suited for facilitating precise control of the drill position and angle; this is done by using the dominant hand to twist the drill while resting the nondominant hand on the patient's head to stabilize the drill position and angle.

Catheter Placement (Fig. 2.11a, b)

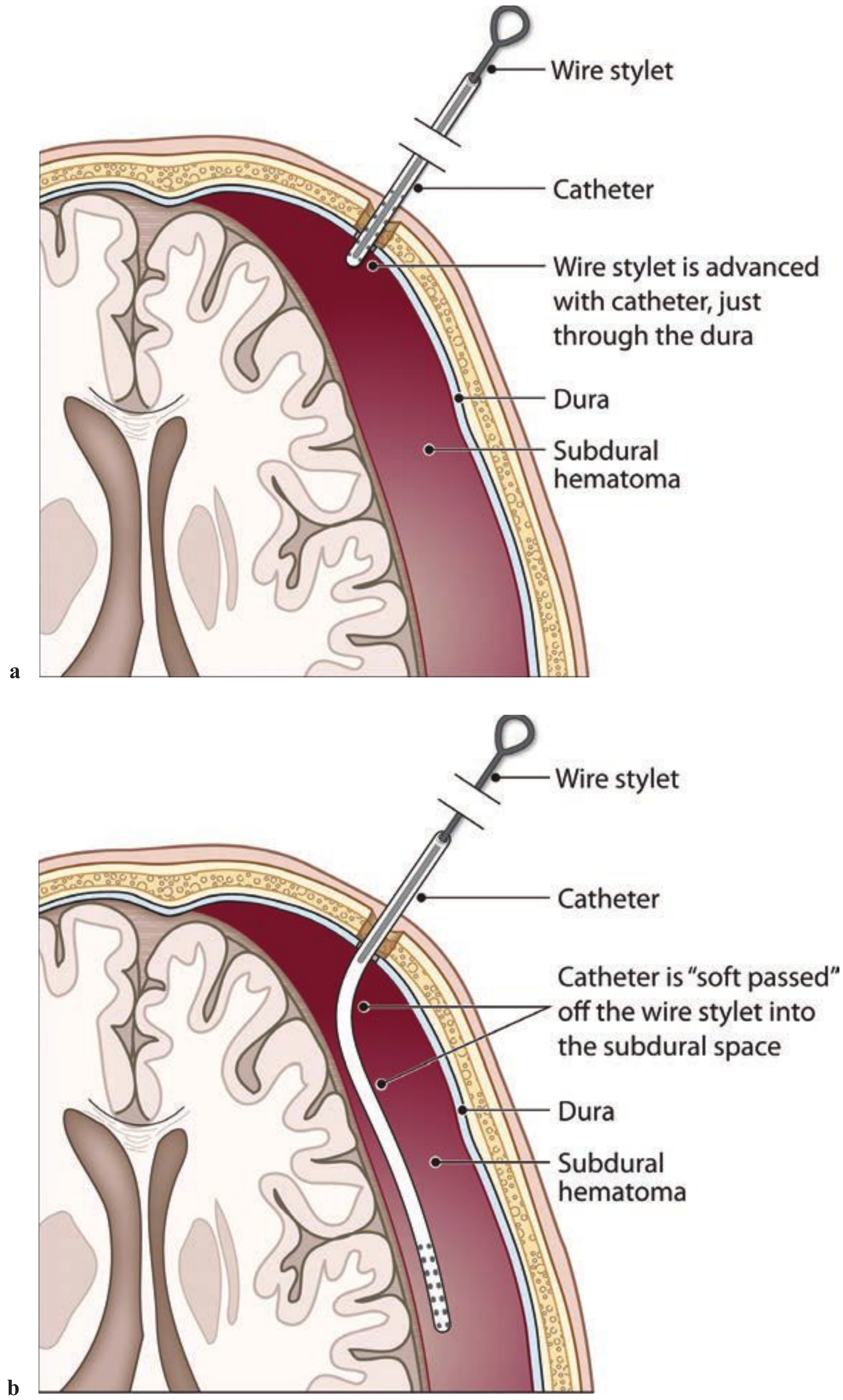


Figure	Procedural Steps	Pearls
Fig. 2.11	**A ventriculostomy-type catheter is inserted through the hole in the skull and the dura and into the subdural space. (a) The wire stylet is used to advance the catheter through the dura. (b) As soon as the catheter has passed through the dura, the catheter should then be advanced off the stylet and "soft passed" into the subdural space, to minimize the risk of advancing the catheter into the brain parenchyma.**	• Choose a ventricular catheter with a larger inner diameter (e.g., 1.5–1.9 mm) and larger side hole perforations to maximize the ability to drain thicker CSDH contents. • Since the catheter is usually in place for only 12 to 48 hours, the author (ASL) usually does not tunnel the catheter, but some may prefer to do so.

Closing

- The insertion site is closed around the catheter with 3-0 monofilament nylon sutures, which are also used to anchor the catheter in place.
- Since the catheter is usually in place for only 12 to 48 hours, the author (ASL) prefers to place a closing stitch where the catheter exits (while the site is still anesthetized), so that it can be easily closed when the catheter is removed, without the need for opening another suture and needle holder. Tip: Place this stitch prior to the anchoring stitch so you can move the catheter aside and position the stitch where the catheter will be once it relaxes back into position. Throw a surgeon's knot (two overhand throws in the same direction) without pulling it tight, so that the suture will stay in place, and you can easily pull it tight once the catheter is removed (**Fig. 2.12**).
- Dress the site with a dry gauze dressing and a head wrap. The latter provides a secure dressing with which to anchor the external drainage tubing. A complex external ventricular drain system is not required since ICP will not be measured; a simple drainage collection bag is sufficient.

Fig. 2.12 The closing stitch. A suture is placed in position to serve as a closing suture for after the catheter is removed. A surgeon's knot (two overhand throws in the same direction) is placed but not pulled tight until after the catheter is removed, usually the next day.

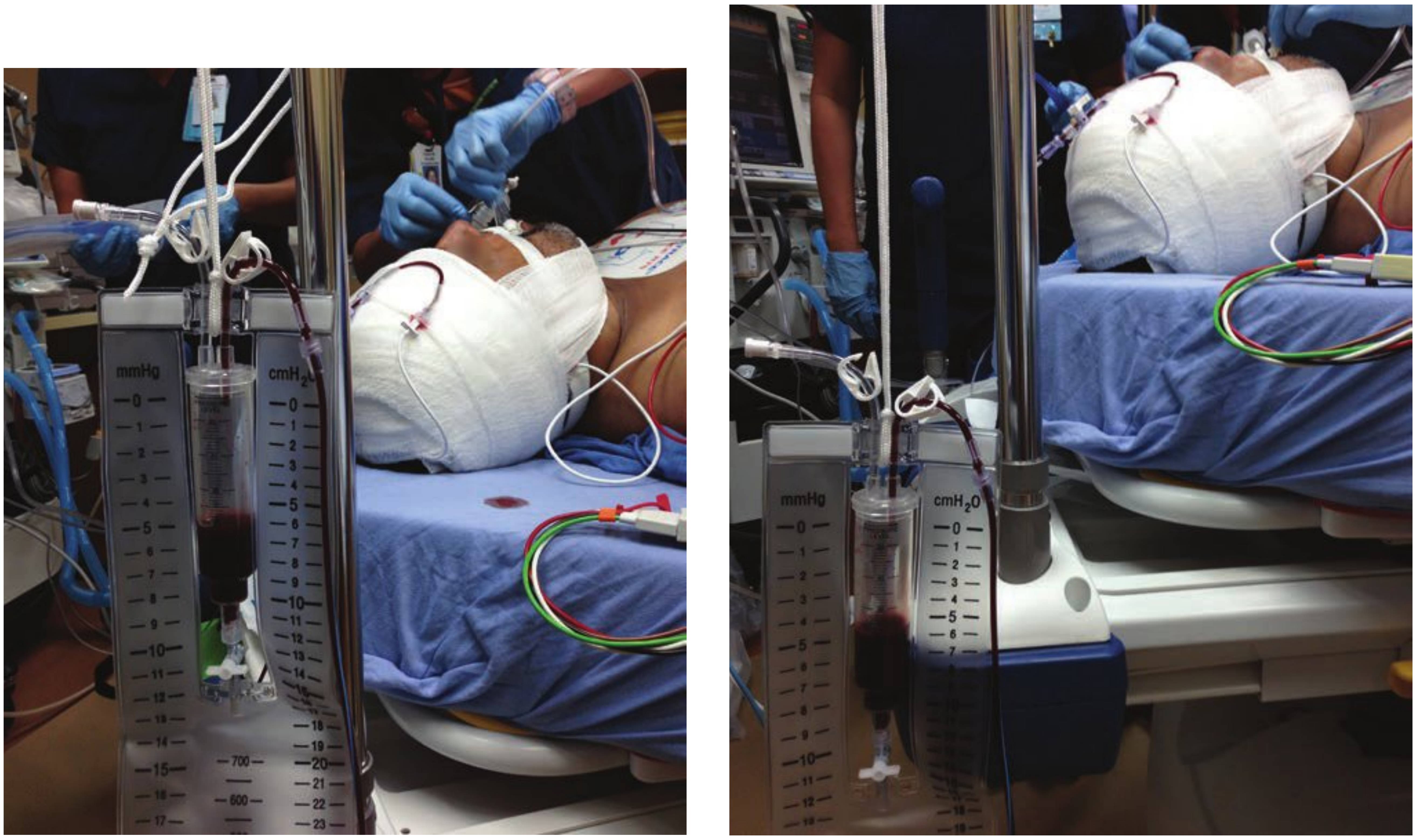
Postoperative Management

Monitoring

- Patients are monitored in an intensive care unit to observe for changes in neurologic status and hemodynamic parameters.
  - Seizure activity and postoperative re-bleed are the two most common complications.
- Patients are maintained relatively flat in bed (0–20 degrees) until the drains are removed.
- Drains are removed in a sterile fashion, usually within 48 hours.
  - All drain sites must be closed tightly using 3-0 nylon sutures to prevent egress of CSF and/or entry of air.
- Skin staples or sutures are removed after 1 to 2 weeks.

Twist Drill Craniostomy

- The patient is monitored in the intensive care unit, with hourly neurologic checks as long as the drain is in place, and usually for 12 to 24 hours after the drain is discontinued.
- The head of the bed is kept flat to promote gravity drainage of the SDH, and to avoid negative pressure aspiration of air back into the subdural space. The patient can be log rolled side-to-side. Changes in position may actually facilitate drainage of the SDH. The patient can be allowed to raise the head of the bed to 10 to 15 degrees for eating, if neurologically indicated.
- The drain is placed to gravity drainage, starting at or just below the patient's ear (**Fig. 2.13a**), and the level is adjusted to maintain a steady drainage rate. It will become necessary to lower the drain gradually (over several minutes to several hours) as the pressure in the subdural space decreases (**Fig. 2.13b**). The author (ASL) prefers to adjust the drain level in order to maintain an SDH drainage rate of approximately 1 drop of SDH fluid per second. This gives the nurses a clear objective goal in order to make safe and appropriate adjustments to the drain level, and results in a slow, gradual evacuation of the SDH. Patients seem to better tolerate slow drainage of the SDH, with decreased risk of headache, nausea, neurologic deterioration, or contralateral hemorrhage. The drainage collection bag will end up at or near floor level as the last of the SDH is drained; the rate will decrease below 1 drop per second and, ultimately, stop.
- When the SDH drainage has ceased or slowed significantly, and follow-up CT demonstrates adequate drainage of the SDH (usually 50–90%), the drain is removed. The skin is prepared in a sterile fashion. The catheter-anchoring suture is cut free from the catheter and the catheter is removed, but the stitch itself is left in place in the skin to keep that part of the incision closed. The previously placed closing suture is tied tightly to complete the closure of the exit site.
- In rare cases, xanthochromic-appearing CSF may continue to drain indefinitely. The drain should be discontinued after 2 to 4 days, regardless of the volume of continued drainage, and follow-up imaging will be required to determine if any additional therapy is indicated. Usually the remaining subdural fluid will resolve spontaneously over time (weeks to months), and a subdural shunt is very rarely required.



a b

Fig. 2.13a, b (**a**) The drain collection bag is initially leveled with the drip chamber "0" mark at or just below the level of the patient's ear. Note the approximately 20-mL chronic subdural hematoma fluid already in the drip chamber. (**b**) As more SDH is evacuated, and the pressure decreases in the subdural space, the drip chamber is gradually lowered.

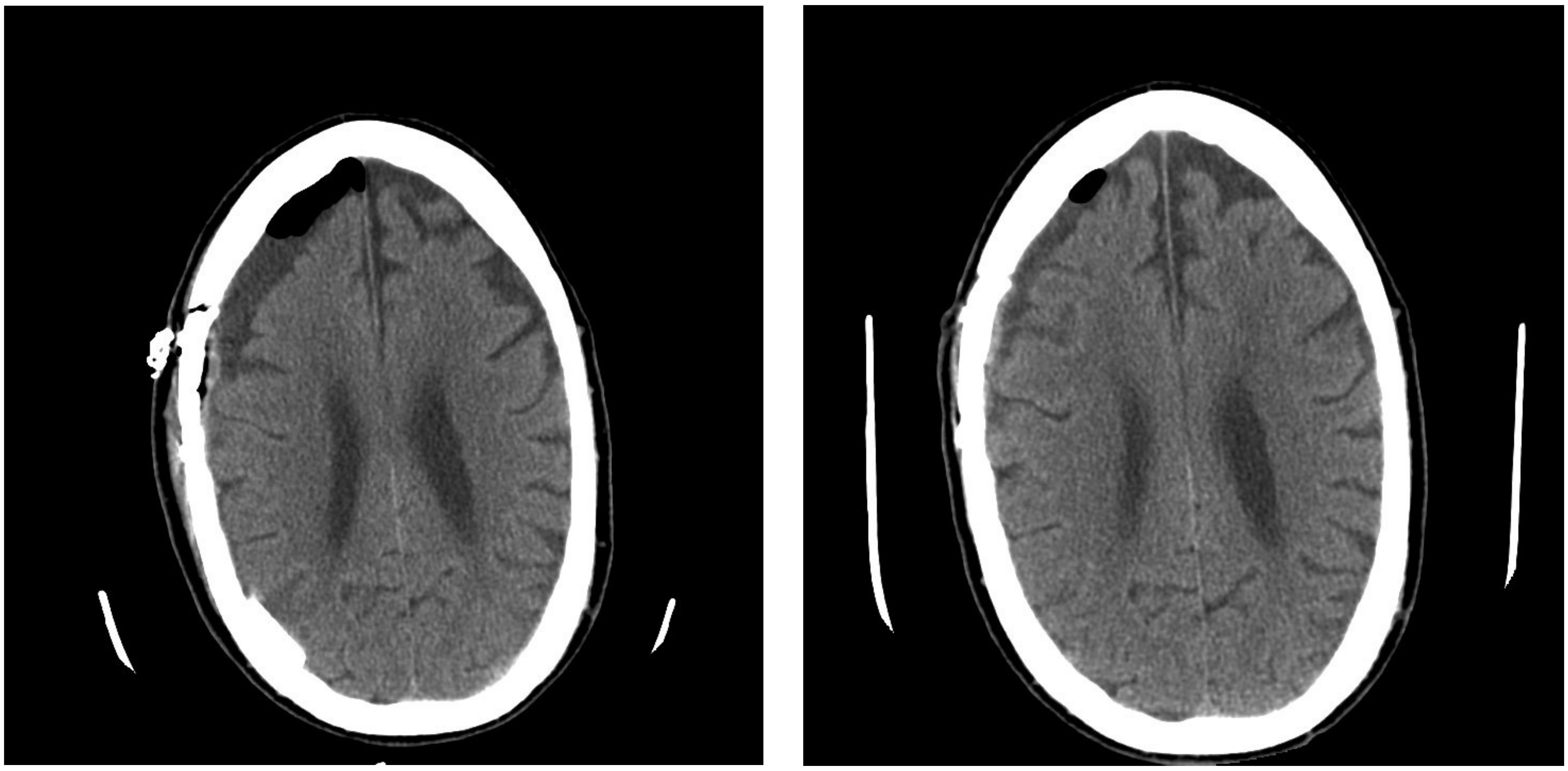
Medication

- Anticonvulsants are administered for a total of 7 days.
- For craniotomies and bur holes, antibiotics are continued for 24 hours postoperatively.
- Dexamethasone, in a 2-week tapering dose, may be used if mild expansion of the residual collection is noted in the postoperative period.
- It is recommended that patients remain off anticoagulant/antiplatelet agents until the residual subdural collections resolve.

Radiographic Imaging

- A postoperative CT scan is performed to evaluate the extent of subdural hematoma evacuation, as well as to exclude new postoperative subdural or epidural hemorrhage (**Figs. 2.14** and **2.15**).
- For twist drill craniostomies, once SDH drainage has slowed or ceased, a follow-up CT scan of the head is obtained (usually the next morning) (**Fig. 2.16**).
- Consider a repeat CT scan about 3 days after drain removal to evaluate for reaccumulation.
- Barring a change in neurologic status, additional CT scans are usually obtained at 2 to 4 weeks, 2 to 3 months, and then as needed until the SDH is completely resolved.

Fig. 2.14 Postoperative CT scan of the patient in **Fig. 2.1** undergoing bur hole drainage with drain in place. There is pneumocephalus and improvement in mass effect. The patient also has a smaller subacute right parietal subdural collection which was treated conservatively.



a b

Fig. 2.15a, b (**a**) Postoperative CT of patient in **Fig. 2.2** undergoing craniotomy for subdural evacuation. There is a Jackson-Pratt drain in the subdural space and mild pneumocephalus with improvement in mass effect. (**b**) Delayed scanning after drain removal revealed further decrease in the residual collection.

Special Considerations

Subdural reaccumulation is a known risk of operative treatment. Reoperation may be necessary. A second reaccumulation may require subdural–peritoneal shunting (without a valve), which most often resolves this difficult problem.

Fig. 2.16 Post-drainage CT of patient in Fig. 2.3 shows a significant decrease in the size of the chronic subdural hematoma, and decreased midline shift. The tip of the subdural catheter can be seen in the subdural space (arrow).

While the focus of this chapter does not include the medical treatment of subacute and chronic subdural hematomas, it is worth mentioning the use of corticosteroids as an adjunct to surgery. The rationale for the use of corticosteroids is based on the antiangiogenic properties and inhibition of the inflammatory reaction, presumed to play a key role in hematoma formation and maintenance.[1,2] Five observational studies provide class III evidence that suggests that treatment with corticosteroids for CSDH might be as safe and effective as surgery, and therefore beneficial in the treatment of CSDH.[3] However, no randomized controlled trials examining the use of corticosteroids for this indication have been published. Primary treatment with an oral antifibrinolytic, tranexamic acid, has been demonstrated to be effective in a small series.[12]

A subdural suction evacuation system is commercially available. This minimally invasive approach has indications similar to the twist drill craniotostomy, but does not involve placement of devices within the intracranial cavity. The kit contains detailed instructions regarding its use and insertion. This technique provides yet another option in the management of patients with CSDH and offers the possibility of immediate relief of pressure if a patient becomes severely lethargic or obtunded.

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3 Surgery for Cerebral Contusions of the Frontal and Temporal Lobes, Including Lobar Resections

Pal S. Randhawa and Craig Rabb

Introduction

Cerebral contusions are observed in up to 8.2% of all traumatic brain injuries[1,2] and are more common (13–35% of patients) in the setting of severe traumatic brain injury.[1,3–7] While contusions can occur in almost any lobe, most occur in the frontal and temporal lobes.[8,9] Most small lesions will not require surgical intervention[1,3,10,11]; the majority will reabsorb in 4 to 6 weeks.

Indications

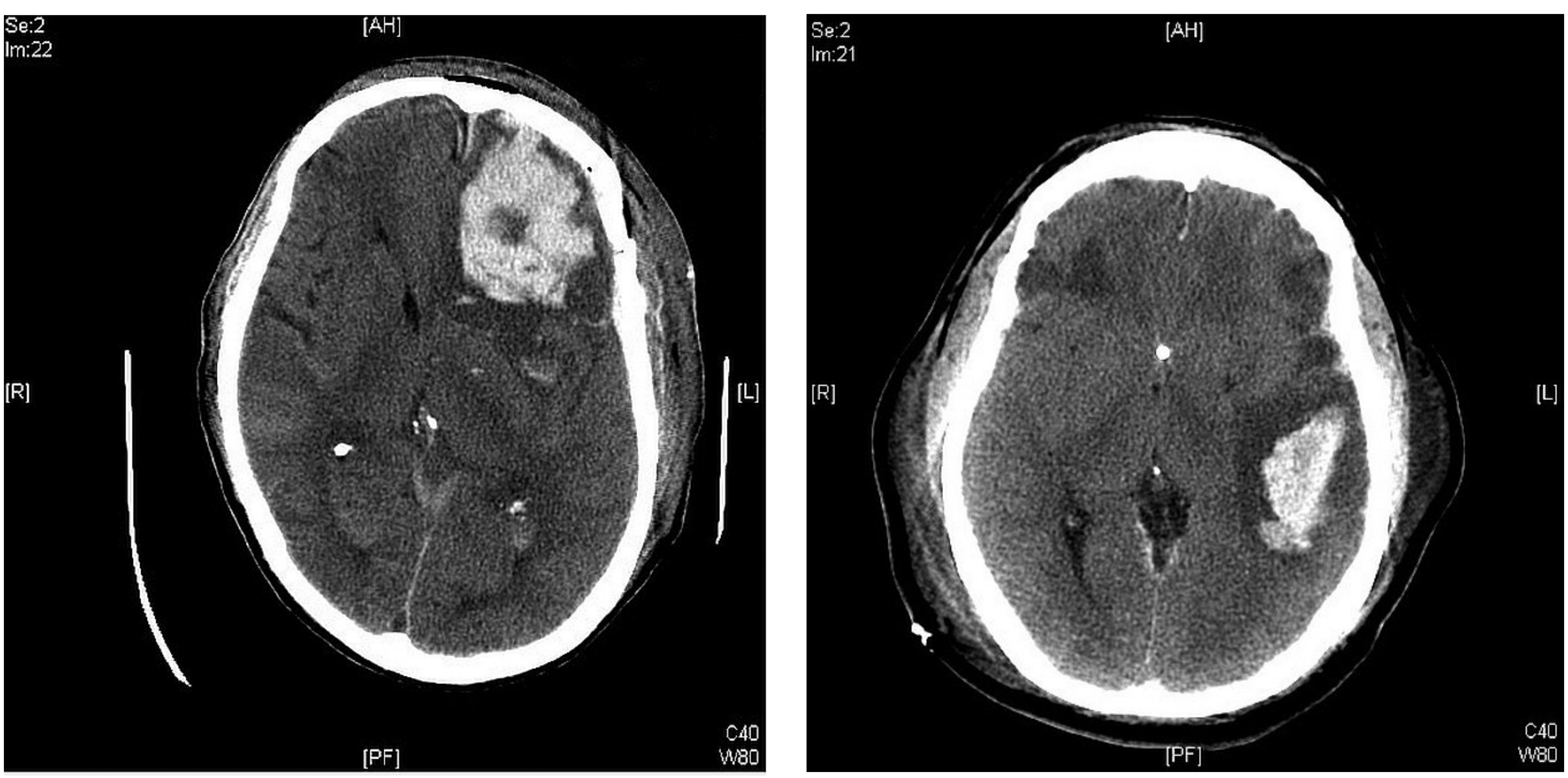
- Guidelines may assist clinical decision making with respect to which contusions might require surgical intervention.[1]
- Operative intervention is indicated in the setting of:
  - A frontal or temporal contusion of greater than 20 cm^3 in volume and associated with any of the following:
    - Glasgow Coma Scale (GCS) score 6 to 8
    - Midline shift at least 5 mm
    - Cisternal compression
  - Any lesion calculated to be greater than 50 cm^3 in volume
  - A parenchymal mass lesion that is associated with:
    - Progressive neurologic decline attributable to the lesion
    - Refractory intracranial hypertension
    - Mass effect on computed tomography (CT) scan
  - A temporal lobe hematoma greater than 30 mL, with or without any midline shift or elevation of the middle cerebral artery. These patients are particularly at risk for transtentorial herniation given the limited space of the middle cranial fossa.

Preprocedure Considerations

Radiographic Imaging

Noncontrast head CT is vital in the evaluation of all severe traumatic brain injuries. CT allows for anatomic localization of surgical pathology and, in turn, facilitates planning of patient positioning and operative approach.

- **Preoperative imaging (Fig 3.1).**



a b

Fig. 3.1a, b Axial CT images demonstrating (**a**) frontal and (**b**) temporal lobe cerebral contusions.

Medication

- The authors prefer the use of vancomycin for antibiotic prophylaxis, provided the patient does not have renal failure or any other contraindications. Given the increasing prevalence of methicillin-resistant *Staphylococcus aureus*, it is possible that the skin can or will be colonized by this microorganism.
- Antiepileptic prophylaxis should be provided. Fosphenytoin may be administered in a loading dose of 17 to 20 mg phenytoin equivalents (PE)/kg in nonallergic patients who are not on standing antiepileptic medication; alternately, levetiracetam may be administered at a loading dose of 20 mg/kg.

Choice of Surgical Approach

- Two different approaches—bicoronal and modified pterional—are outlined in the Operative Procedure section; the choice of approach will depend on the site of the pathology.
- Bilateral or unilateral, medial contusions of the frontal lobes may be addressed optimally by a bicoronal approach.
- A far lateral frontal contusion may be approached by a modified pterional approach.
- Temporal contusions generally can be approached via a modified pterional approach.

Operative Field Preparation

- Alcohol prep is performed before the application of povidone iodine or chlorhexidine.
- The planned incisions are marked and infiltrated with 1% lidocaine with 1:100,000 epinephrine.

Operative Procedure

Bicoronal Approach

Positioning (Fig. 3.2)

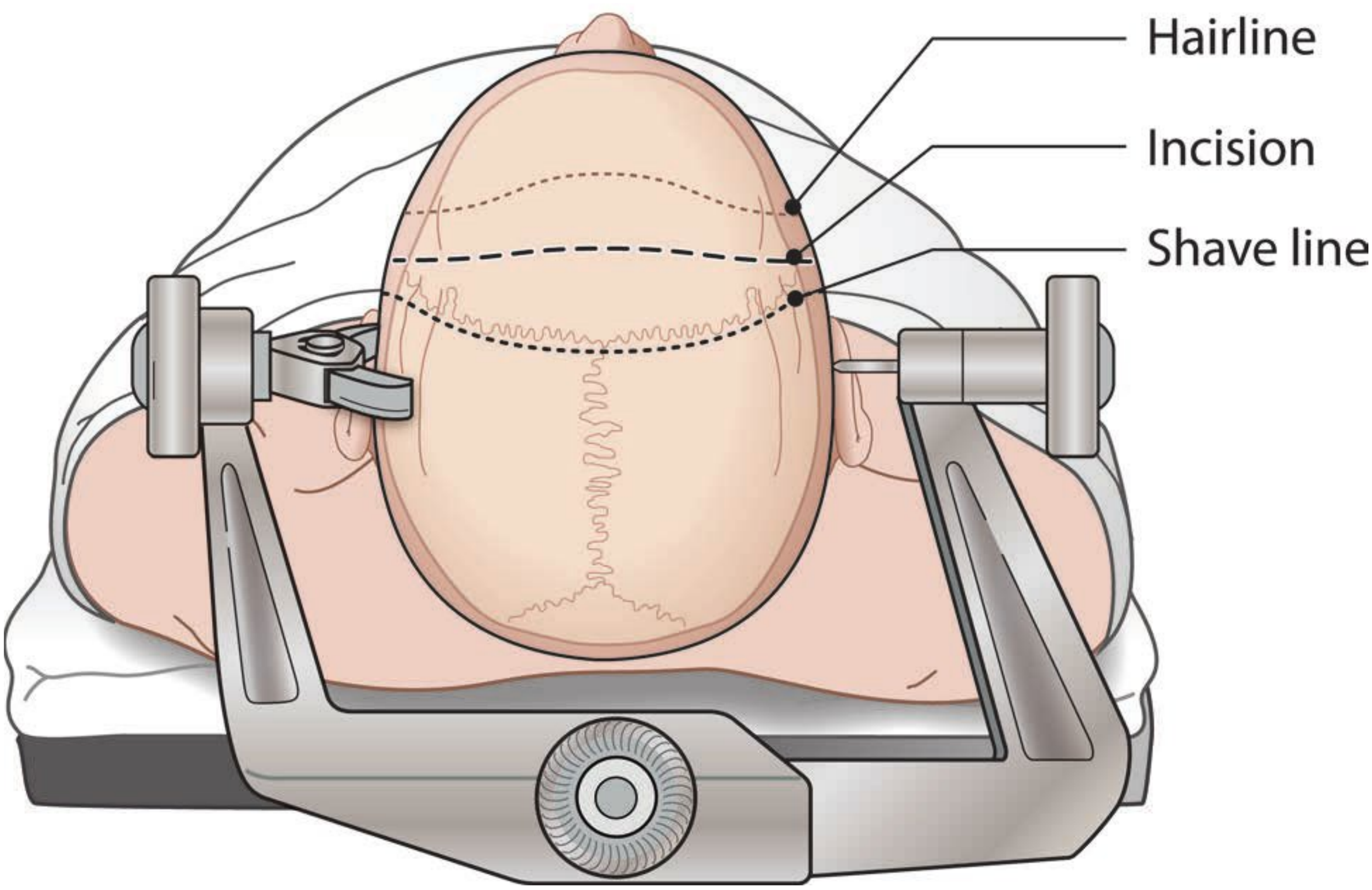


Figure	Procedural Steps	Pearls
Fig. 3.2	**The patient is positioned supine, with the head in a neutral, upright position. The head is stabilized with Mayfield three-point fixation. The head of bed is elevated slightly.**	• Consider using a horseshoe headrest to facilitate more rapid decompression in the emergency setting, or if a skull fracture prevents use of a Mayfield three-point fixation.

Skin Incision (Fig. 3.3)

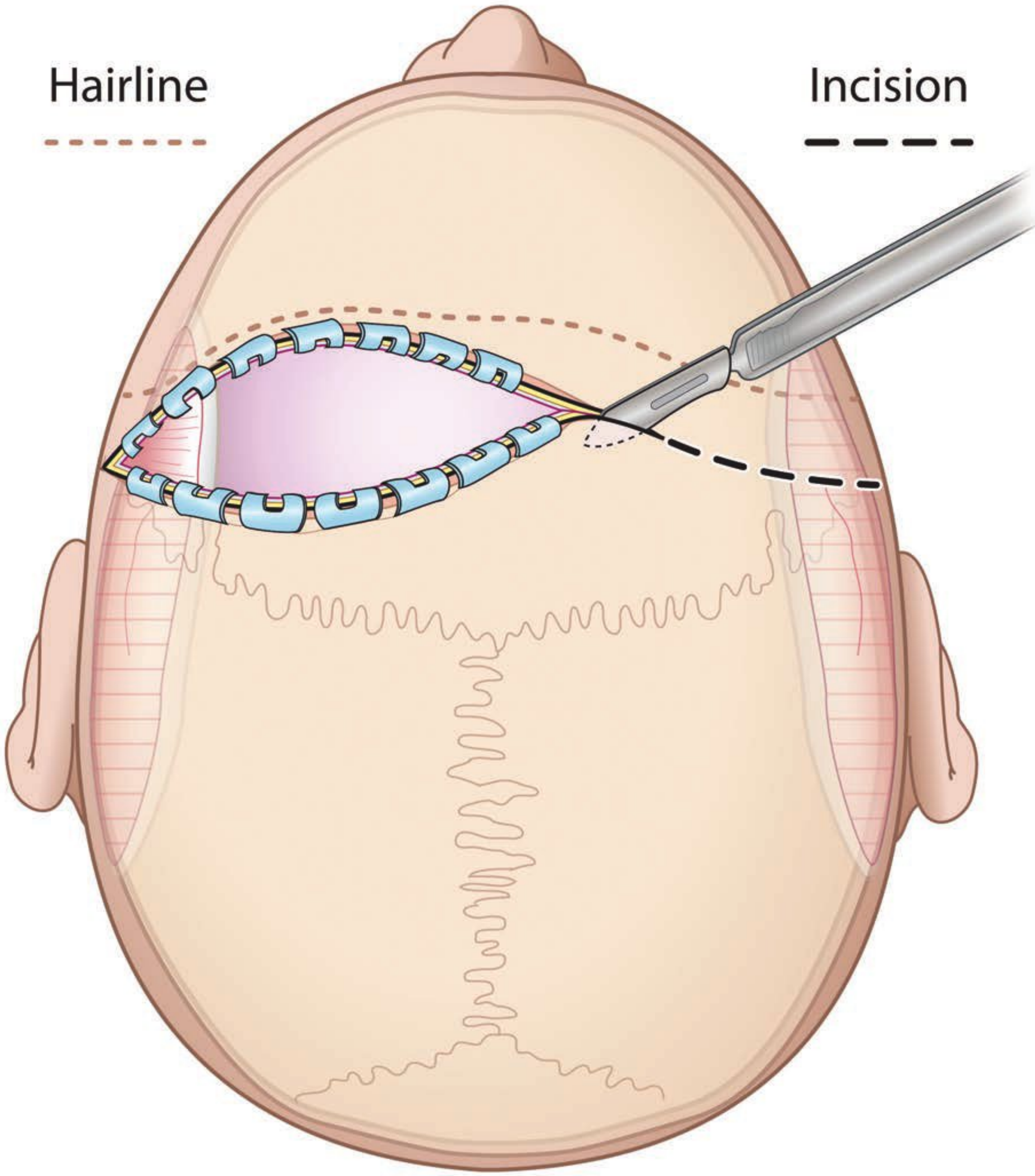


Figure	Procedural Steps	Pearls
Fig. 3.3	**Mark out a bicoronal incision, starting at the level of zygoma and extending superiorly toward the midline, just posterior to the hairline. Carry the incision across midline, in a mirror fashion, to the contralateral zygoma.** **Initiate the skin opening with a no. 10 blade. Carry the incision down to the pericranium above the superior temporal line and down to the temporalis fascia in the temporal region.**	• Scalp clips are applied to the skin edges to assist hemostasis.

Subcutaneous Dissection (Fig. 3.4)

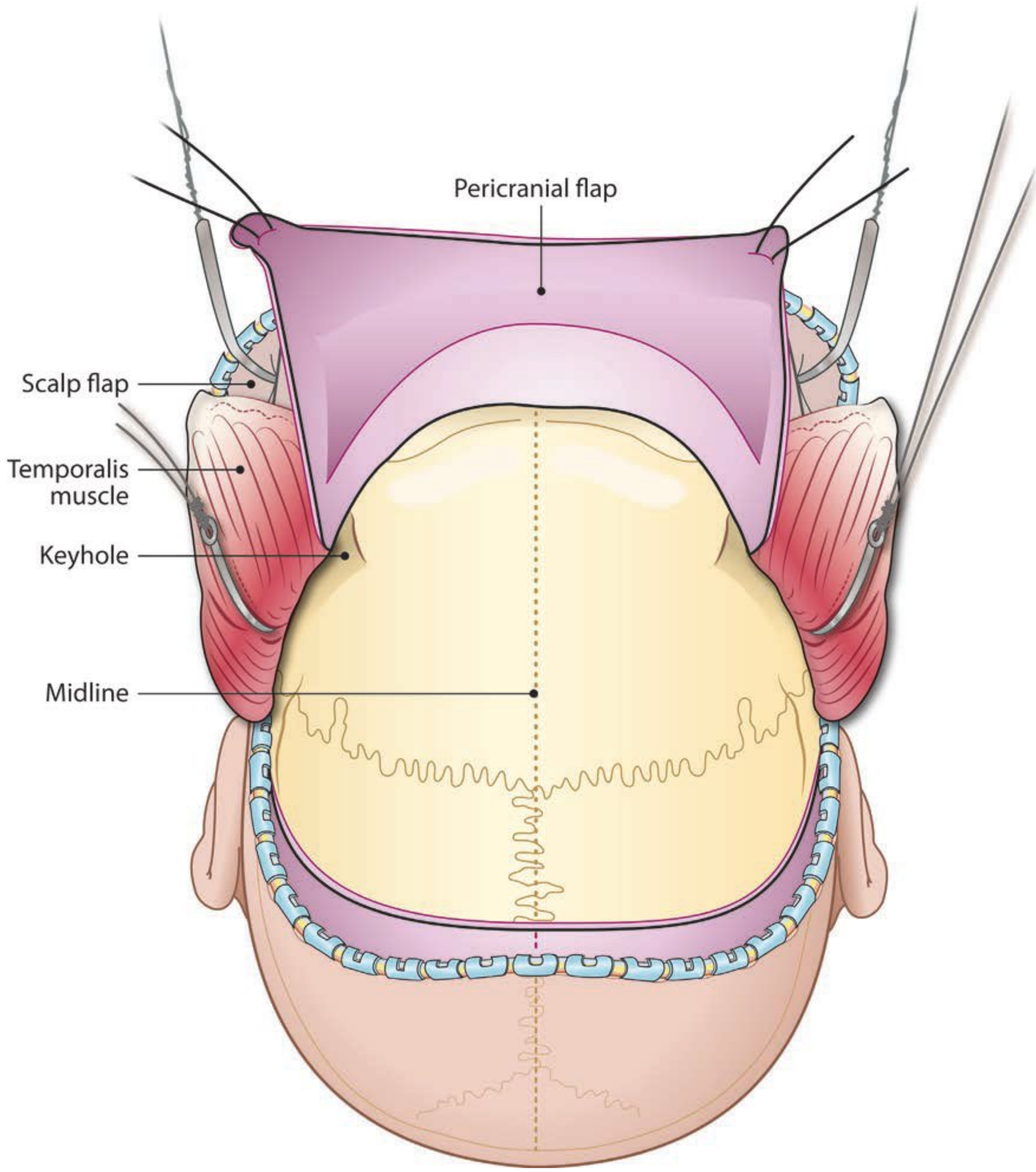


Figure	Procedural Steps	Pearls
Fig. 3.4	**The pericranium is opened with monopolar electrocautery, in line with the scalp incision. The superficial temporal fascia and temporalis muscle are opened, likewise, using monopolar electrocautery. Pericranium and muscle are advanced with a combination of periosteal elevator and monopolar electrocautery. Leave the frontalis muscle intact if possible.** **The myocutaneous flap is reflected anteriorly until the anterior middle fossa and supraorbital areas are accessible. The flap is secured with mini-towel clips, hooks, or suture.**	• Special care must be taken to avoid compromising the frontalis branch of the facial nerve. Remain above the zygoma when approaching the inferior aspect of the incision. • A few rolled sponges are placed beneath the flap as it is reflected and secured.

Bur Hole Placement (Fig. 3.5)

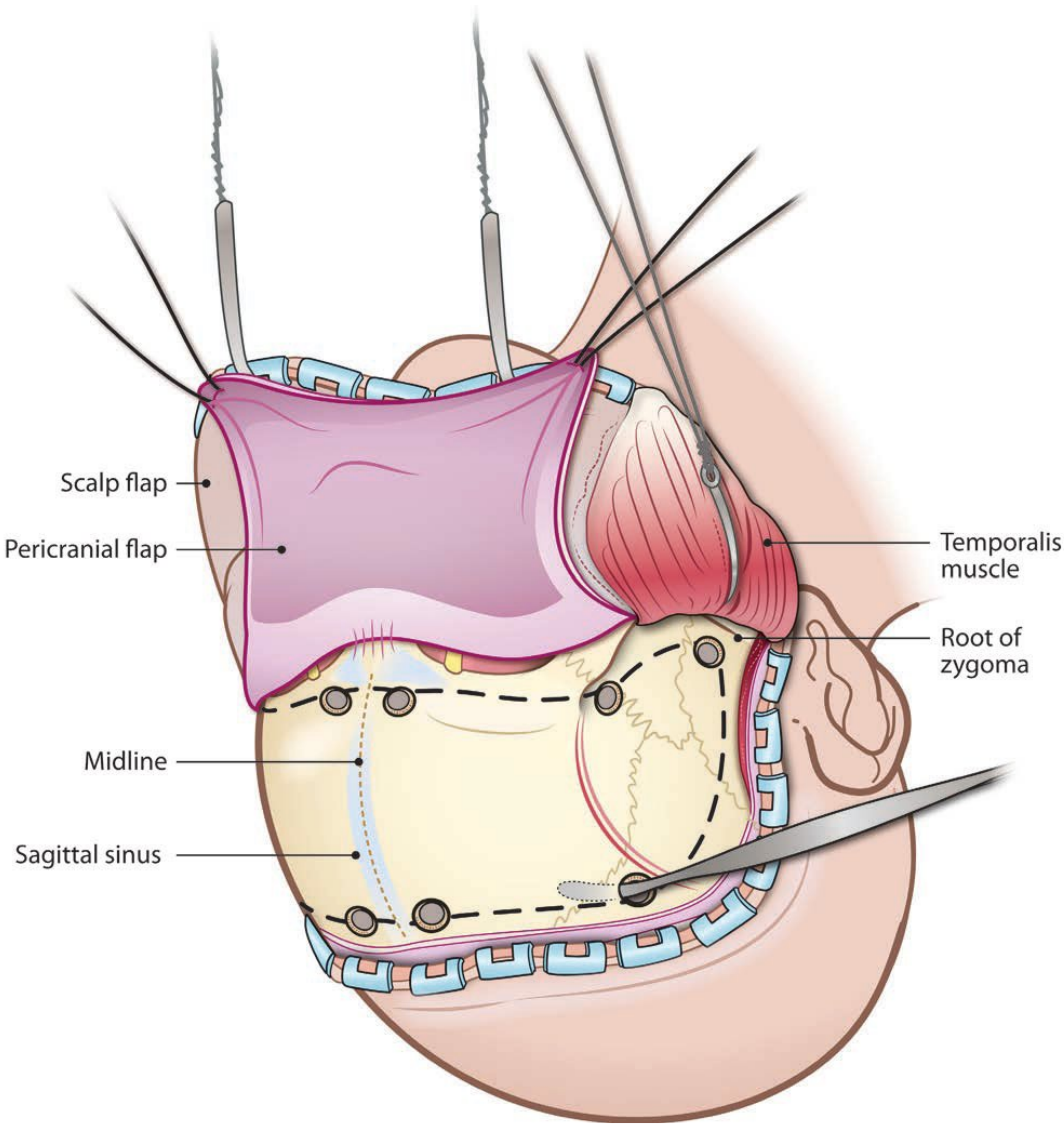


Figure	Procedural Steps	Pearls
Fig. 3.5	**Bur holes are placed with a high-speed drill at the following sites: just above the root of zygoma; at the keyhole; and just above superior temporal line, anterior to coronal suture. An additional pair of holes are placed straddling the midline, anterior to coronal suture. The base of each hole is cleared with a curette. The dura is stripped from the undersurface of the bone, locally and between each pair of holes, with a separator (e.g., Penfield no. 3, Hoen, or similar).**	• Exercise particular care when stripping the dural attachments between the two paramedian holes overlying the sagittal sinus.

Craniotomy (Fig. 3.6)

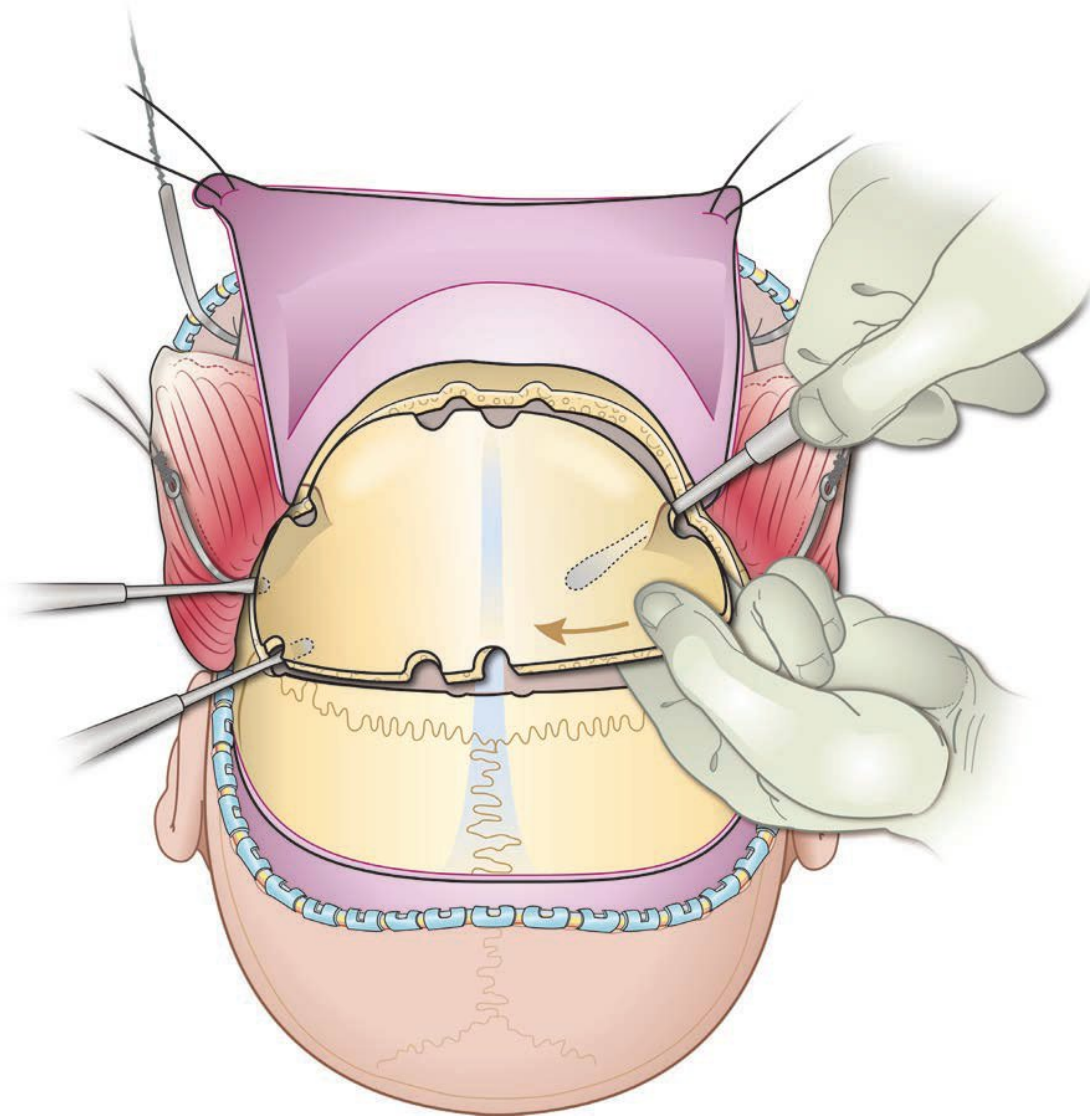
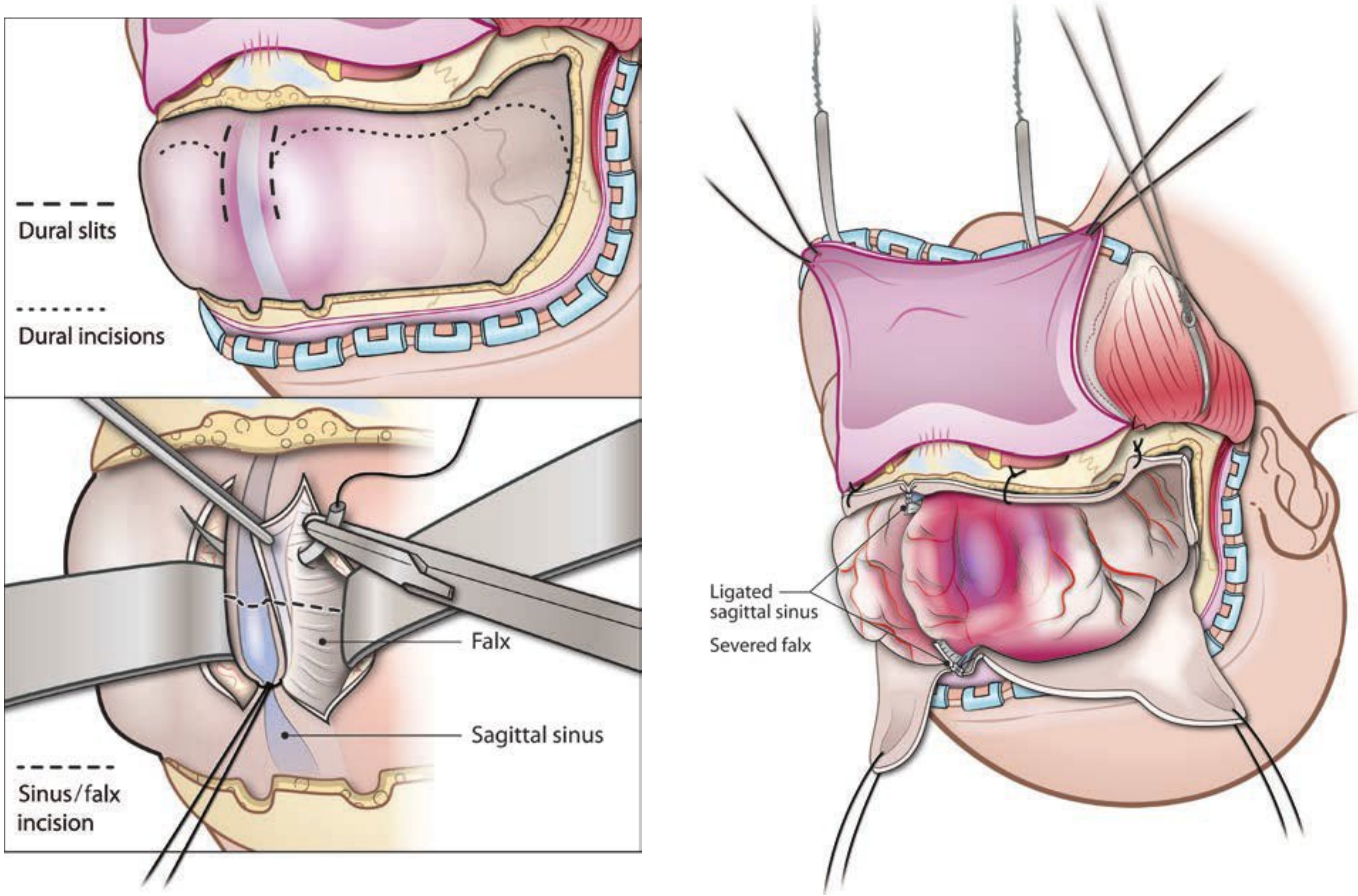


Figure	Procedural Steps
Fig. 3.6	**The craniotome is used to connect each pair of bur holes circumferentially, taking care to stay low in the frontal and temporal regions and making the final cut in the region of the superior sagittal sinus. The bone flap is carefully elevated away from the underlying dura and set aside in antibiotic solution.** **Bone wax is applied to the bony edges where necessary. Bleeding along the midline sagittal sinus may be controlled with a combination of fibrillar hemostatic material, thrombin-soaked gelatin sponge, and hemostatic matrix sealant. If all other measures fail, the superior sagittal sinus may be ligated anteriorly, at the level of the crista galli.**

Dural Opening (Fig. 3.7a–c)



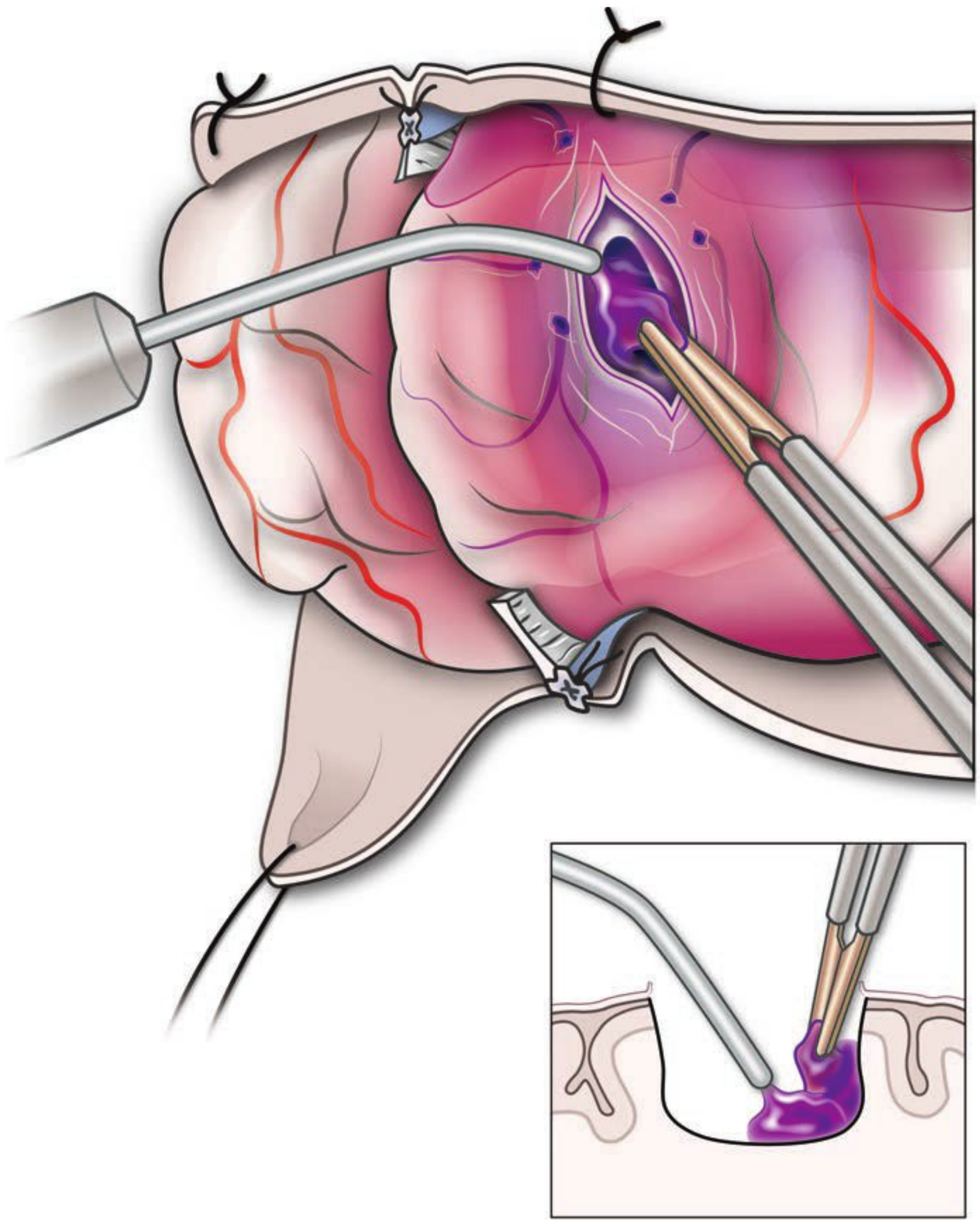
a

b

c

Figure	Procedural Steps	Pearls
Fig. 3.7	**Pilot holes are drilled circumferentially at the periphery of the craniotomy to create dural tack-up sites.**	• Dural tacking stitches help prevent the formation of postoperative epidural hematomas. However, do not take time at this point in the procedure to place the actual stitches.
	(a) The dural opening is initiated with a no. 15 blade and enlarged with tenotomy scissors. A strip of moistened nonadherent bandage or a cotton pattie may be introduced into the subdural space to protect the underlying cortex. A trap-door type opening (flapped toward the midline) provides wide access to the frontal lobe. If access to the temporal fossa is necessary and/or ligation of the sagittal sinus anticipated, dural slits are made initially parallel to the anterior portion of the sinus and the dural opening extending laterally and inferiorly toward the middle fossa on either side. The dural flaps are secured under modest tension with 4-0 braided nylon stitches.	
	(b) It may be necessary to divide the superior sagittal sinus and falx in order to achieve adequate decompression of the frontal lobes. After release of the sinus, use a double ligature technique to occlude the sinus, using a 2-0 polypropylene or nylon suture. Make a double circular course across the falx, just below the level of the sinus, and cinched tightly to occlude the sinus. Repeat this process with a second stitch, anterior to the first.	• The sinus should be targeted for ligation and division at a point well forward of the coronal suture (along the anterior one-third of the sinus). • The second needle pass should be more superficial (within the falx) than the first.
	(c) Sever the sinus between the ligatures and divide the subadjacent falx in its entirety to complete the exposure.	• Alternatively, ligation may be performed with a hemostatic double surgical clip at the inferior insertion of the sinus into the falx, near the crista galli. Attention must be paid to ensure that the clips cross the sinus completely.

Address the Contusion (Fig. 3.8a, b)



a

b

Figure	Procedural Steps	Pearls
Fig. 3.8	**(a) Inspect the cortical surface. Select your site for entry—an area of obvious contusion or cortical disruption is ideal.** **Cauterize the superficial vessels and pia mater at the planned entry site. Use a no. 11 or no. 15 blade to open the pia. Approach the hematoma cavity in the subpial plane with a combination of gentle suction and bipolar electrocautery.** **(b) Upon entry to the hematoma, suction out any liquid clot and remove solid clot in a piecemeal fashion. Continue evacuation of hematoma until gliotic brain is visible on all sides.**	• If the cortical surface appears undisturbed, consider the use of ultrasound to localize the most superficial extent of the hematoma. • A handheld malleable retractor—introduced over a saline-moistened 1- 3 3-cm cotton pattie (to protect the friable tissue along the cavity wall)—may assist visualization during contusion resection and hemostasis. • Always be mindful of position relative to the anterior horn of the lateral ventricular while evacuating hematoma from deep subcortical spaces. Avoid entry to the ventricle if feasible.

Anterior Frontal Lobectomy (Fig. 3.9)

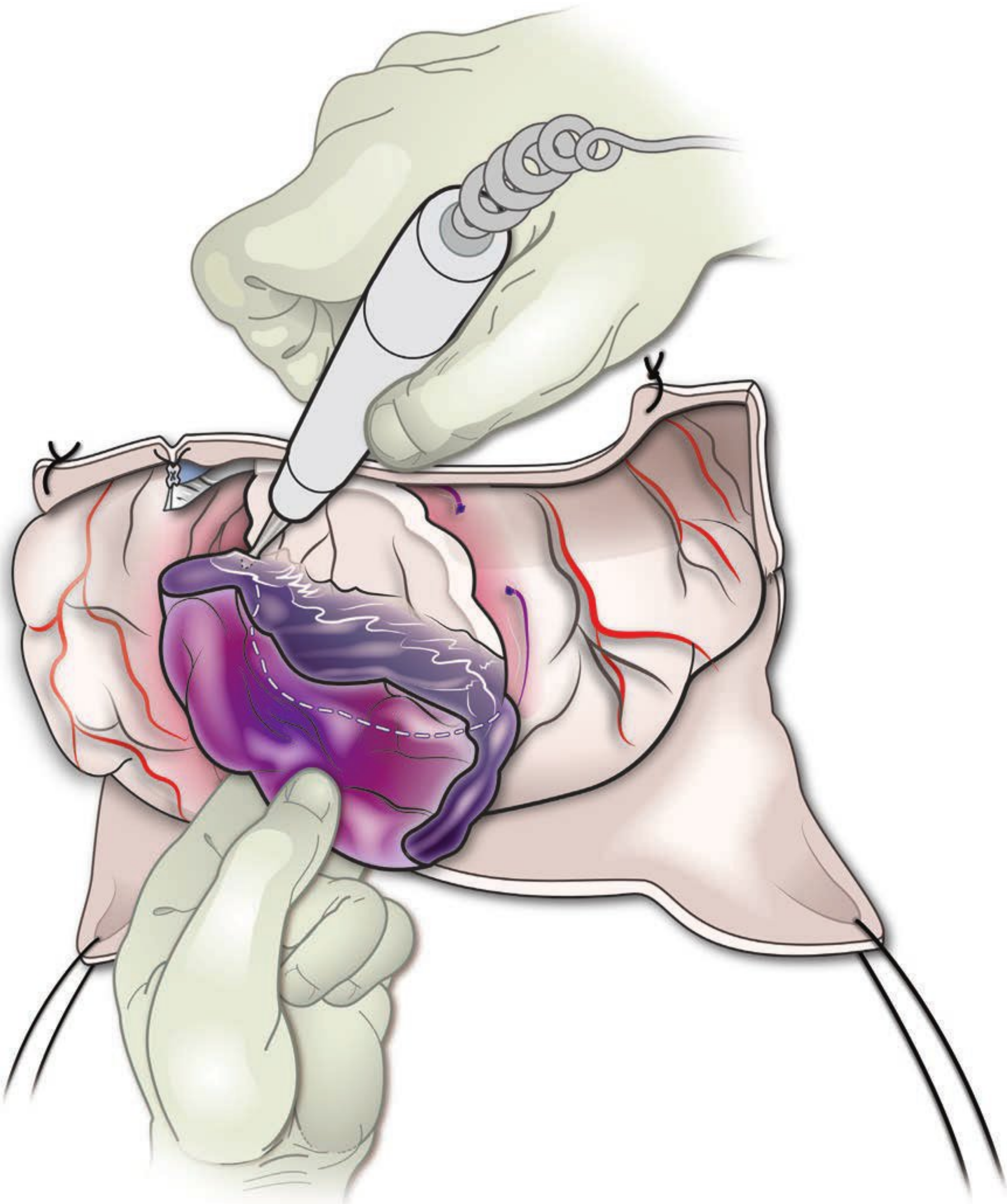


Figure	Procedural Steps	Pearls
Fig. 3.9	**In the event that the frontal lobe is extensively contused, consideration may be given to a frontal lobectomy. The margin of resection will depend on the size and appearance of contused frontal lobe. Alternatively, if contusion is diffuse, one may begin the cortical incision 7 to 8 cm from the frontal pole and extend laterally to the level of the lesser wing of the sphenoid. If it is desired to avoid entry into the lateral ventricle, the medial aspect of the cortical incision should be made where the two frontal lobes are clearly separate.**	• In the setting of significant intraoperative or anticipated postoperative swelling, consider frontal polectomy to ensure adequate decompression.

Modified Pterional Approach

Positioning (Fig. 3.10)

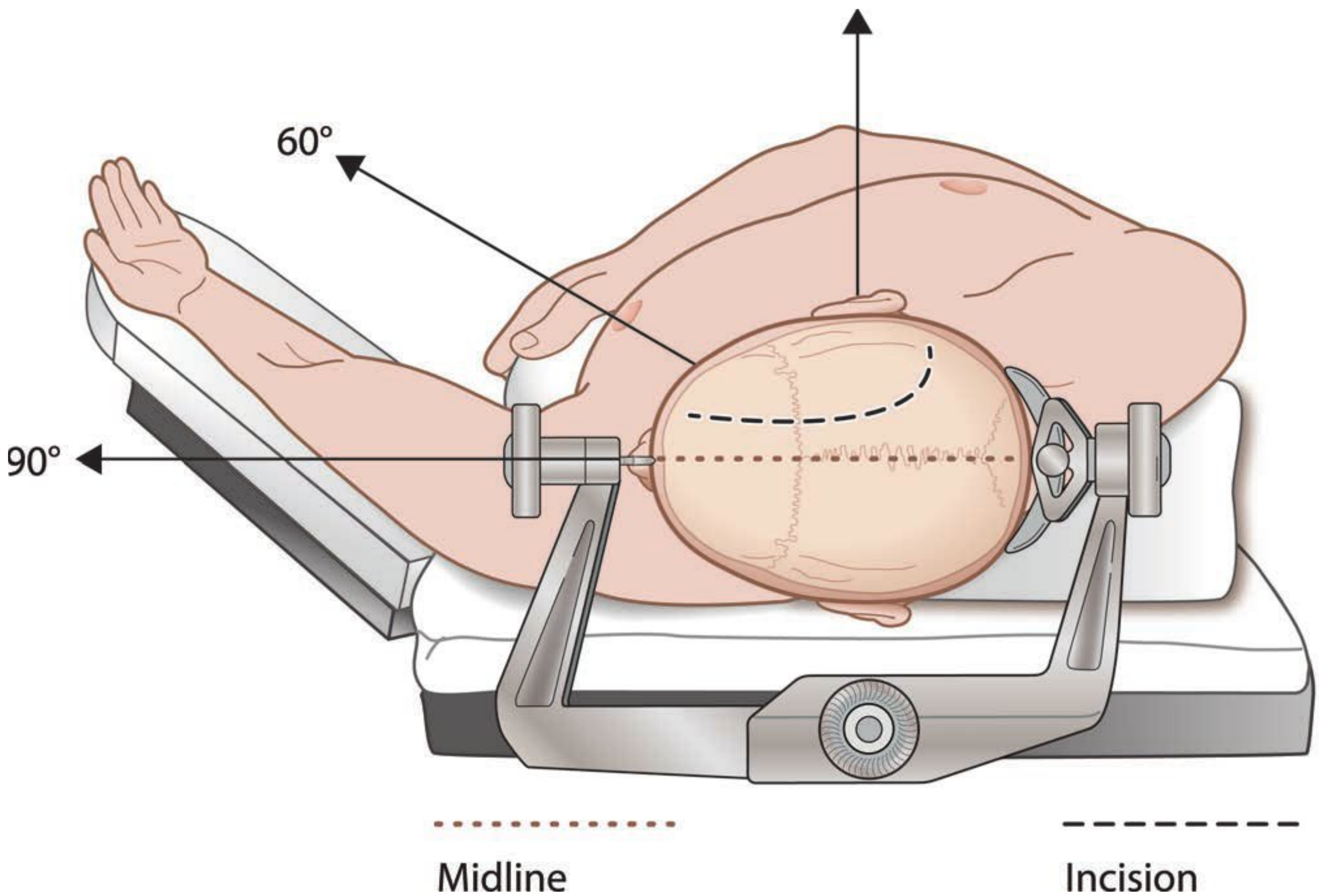


Figure	Procedural Steps	Pearls
Fig. 3.10	**The patient is placed on the table in a supine position. The head is turned 60 to 90 degrees away from the side of the approach to help provide better surgical visualization. A roll is placed longitudinally beneath the ipsilateral shoulder. The head is stabilized with a three-pinion head holder.**	• If the cervical spine has not been cleared, maintain the rigid collar and rotate head and body as a unit (a larger shoulder roll may be necessary) to provide the necessary exposure. • A horseshoe headrest may decrease time to decompression in the emergent setting.

Skin Incision (Fig. 3.11)

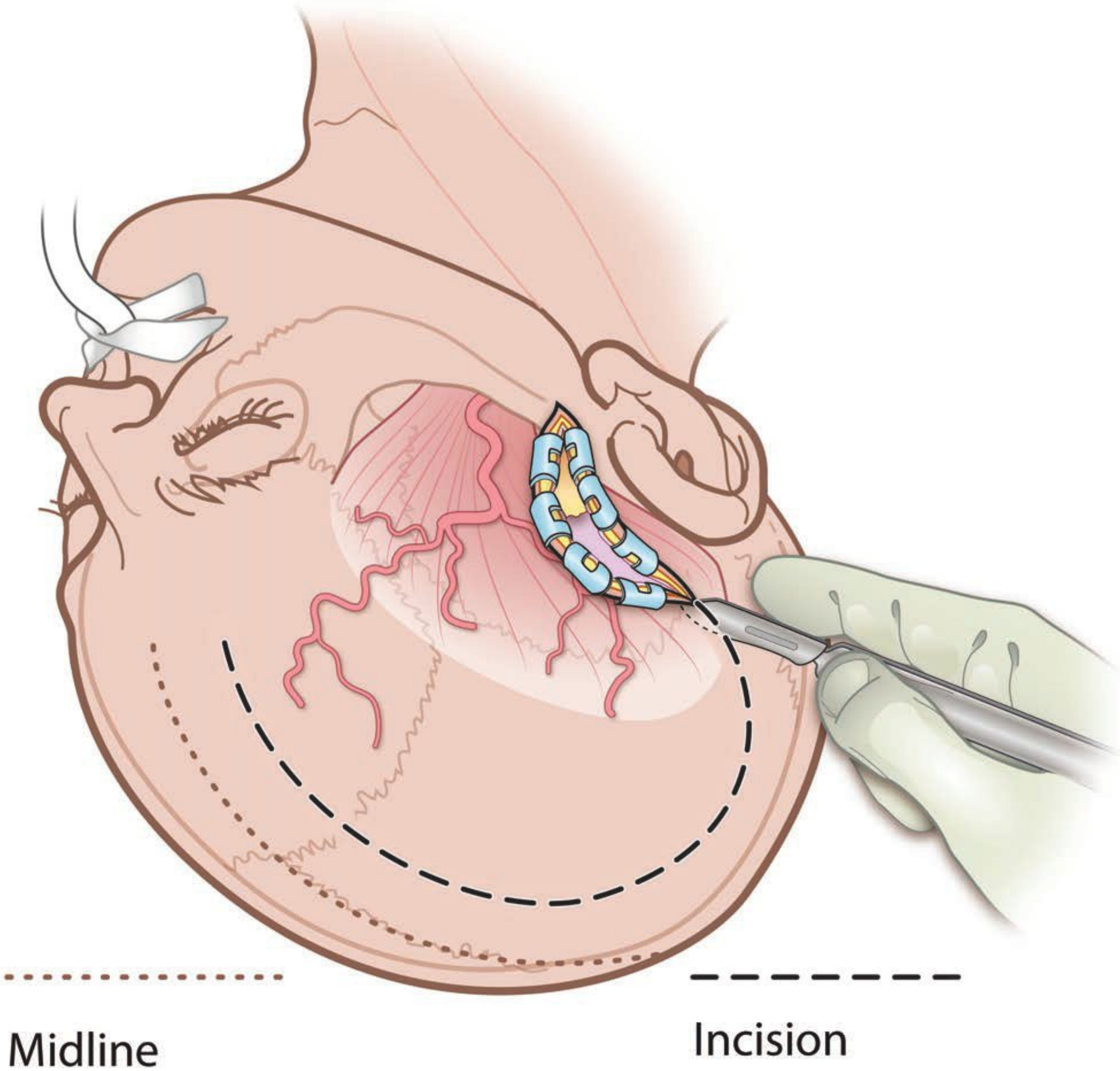


Figure	Procedural Steps	Pearls
Fig. 3.11	**Hair is clipped with an electric razor over the hemicranium of interest.** **A reverse question mark–type incision (i.e., trauma flap) is planned, starting 1 cm anterior to the external auditory meatus and within 1 cm of the superior aspect of the zygoma, extending posteriorly toward the parietal eminence and curving superiorly toward the midline, ending just behind the hair line.** **The incision is initiated with a no. 10 blade and carried down to the level of pericranium superiorly and temporalis fascia inferiorly. Scalp clips are applied to the skin edges.**	• Preserve the frontalis branch of the facial nerve as well as the main trunk of the superficial temporal artery.

Subcutaneous Dissection (Fig. 3.12)

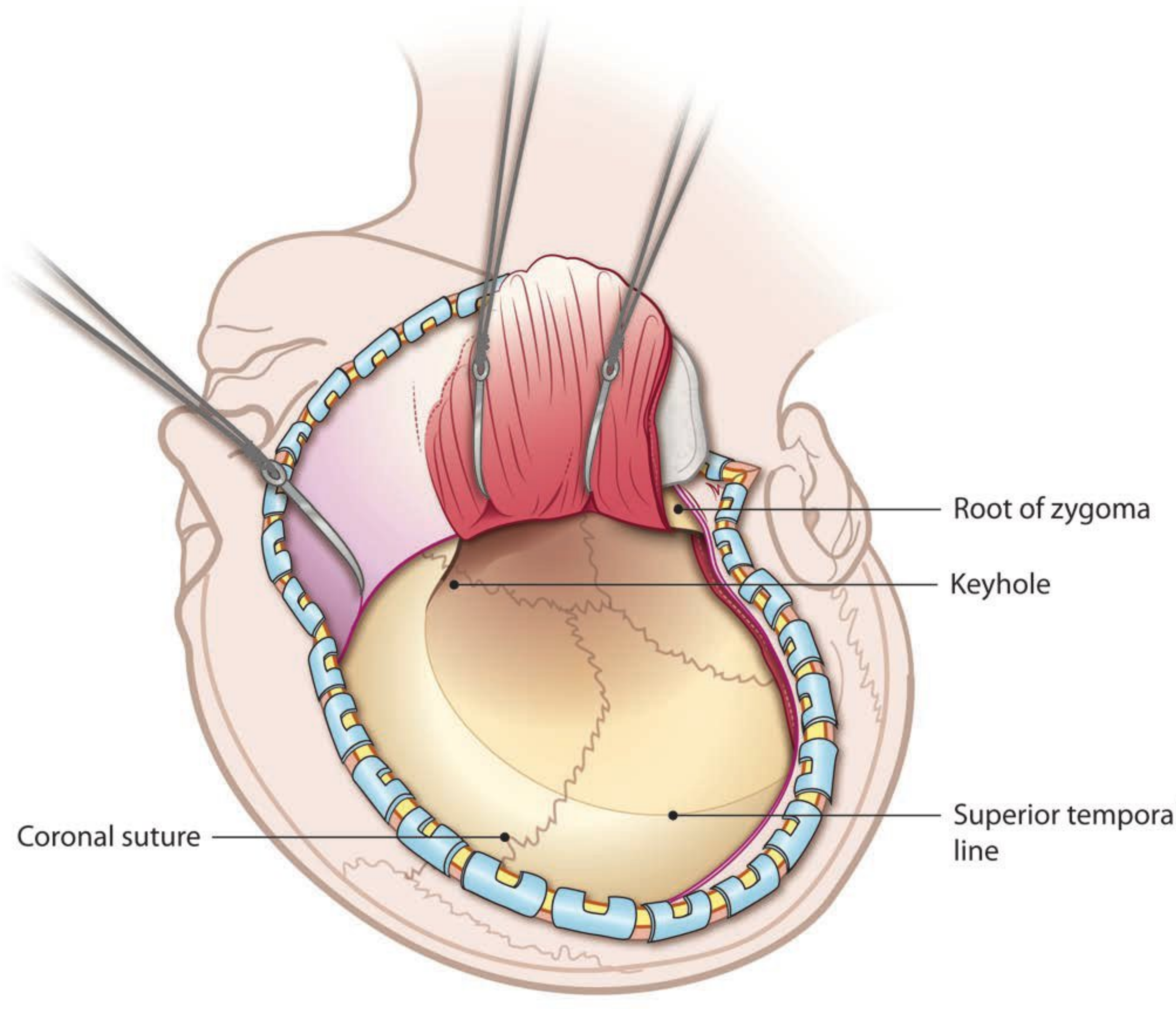


Figure	Procedural Steps	Pearls
Fig. 3.12	**The pericranium and temporal fascia and muscle are opened in line with the scalp incision, using monopolar electrocautery.** **The resulting myocutaneous flap is dissected subperiosteally and advanced forward until the root of zygoma and keyhole are visible. The flap is secured with mini towel clips, hooks, or suture.**	• Some advocate mobilizing the temporalis off the superior aspect of the zygomatic arch by approximately 1 to 2 cm.

Bur Hole Placement (Fig. 3.13)

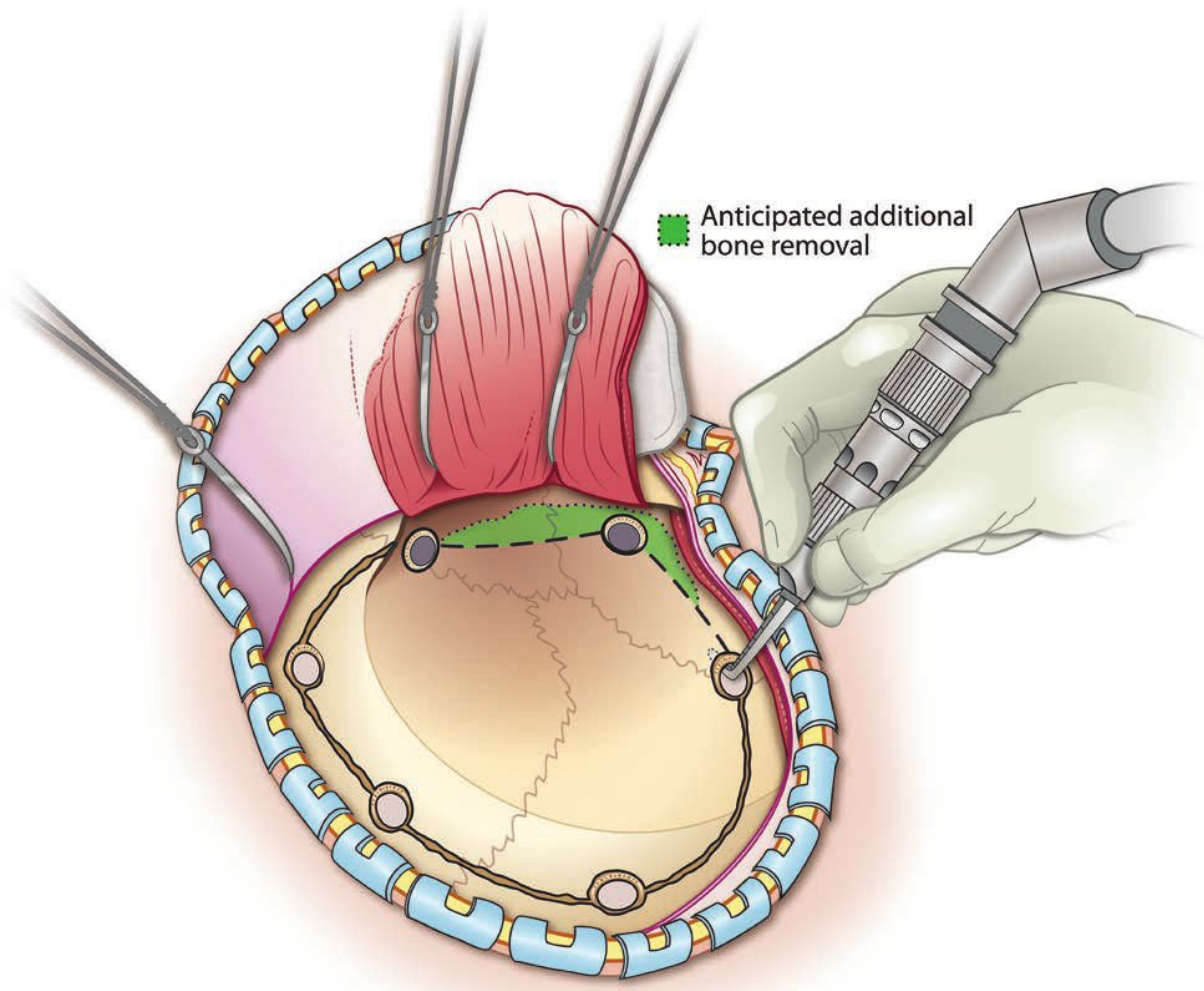


Figure	Procedural Steps
Fig. 3.13	**Bur holes are placed with a high-speed drill at the following sites: just above the root of zygoma; at the keyhole; over the parietal eminence; and at a point ~1 cm lateral to the midline and anterior to coronal suture. The base of each hole is cleared with a curette. The dura is stripped from the undersurface of the bone, locally and between each pair of holes, with a separator (e.g., no. 3 Penfield, Hoen, or similar).**

Craniotomy (Fig. 3.14)

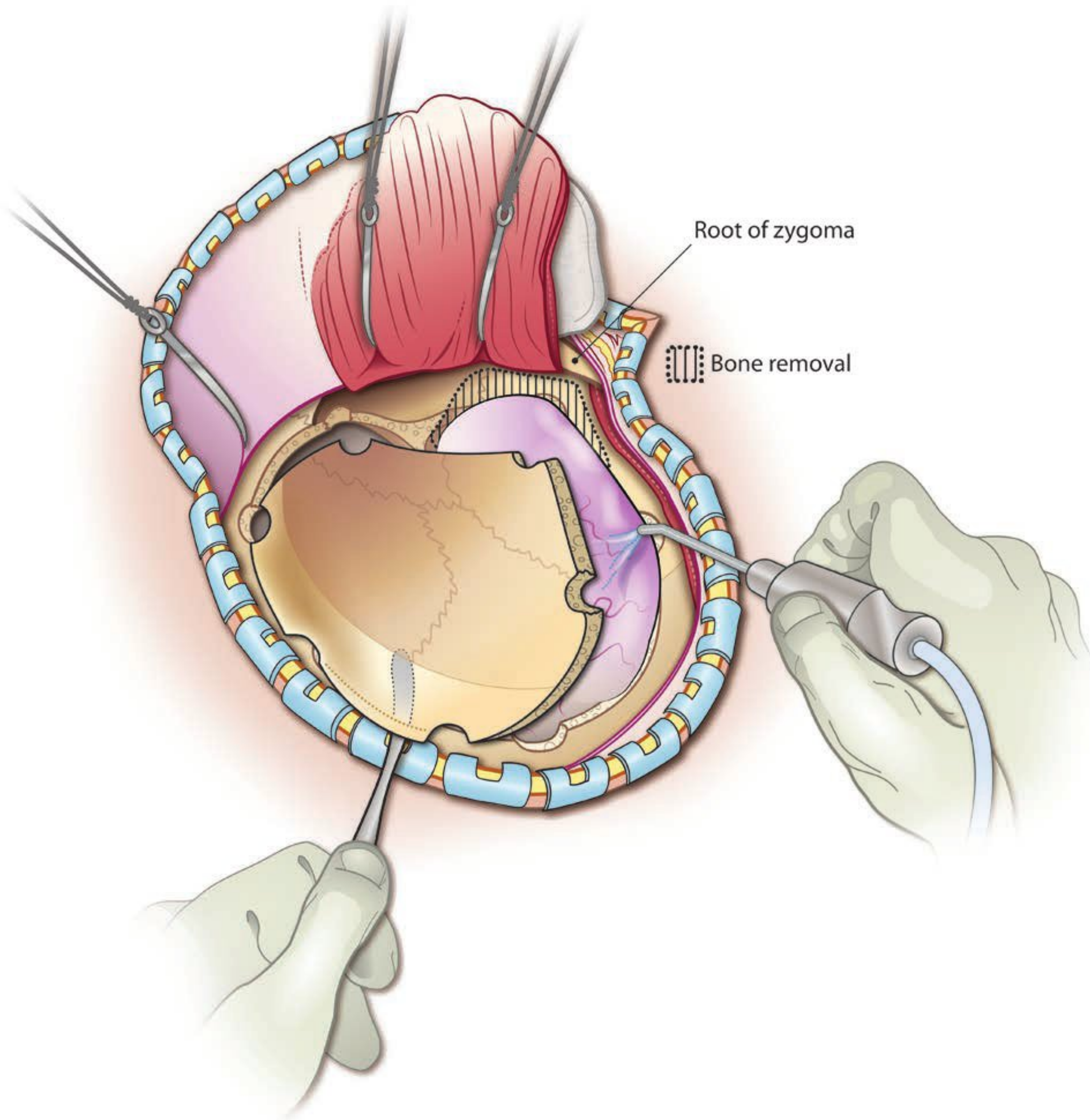


Figure	Procedural Steps	Pearls
Fig. 3.14	**The craniotome is used to connect each pair of bur holes circumferentially. It may be necessary to thin the bone crossing the sphenoid ridge with a bur. A no. 3 Penfield or small, curved periosteal may be introduced along the posterior margin of the craniotomy to initiate elevation of the bone flap away from the underlying dura. Once removed, the bone flap is set aside in antibiotic solution.** **The dural surface is irrigated. Branches of the middle meningeal artery observed on the exposed dural surface are coagulated with bipolar electrocautery.** **Bone wax is applied to the bony edges where necessary.**	• Temporal exposure may be augmented by removal of additional bone with a Leksell rongeur until flush with the middle fossa floor and anterior temporal dura. • Pay particular attention to any open air cells at the temporal bone margins. Pack and seal any observed opening.

Dural Opening (Fig. 3.15)

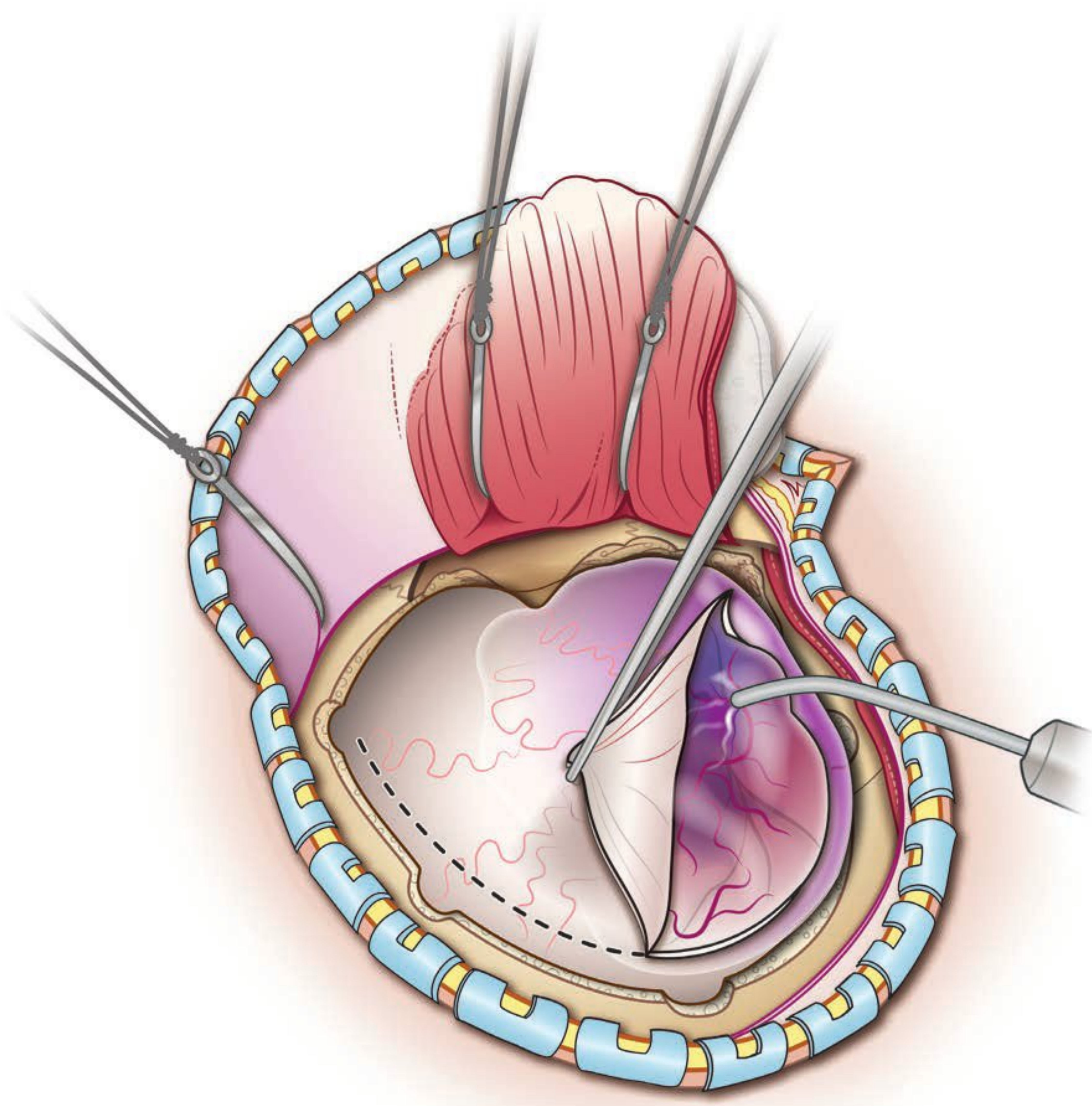
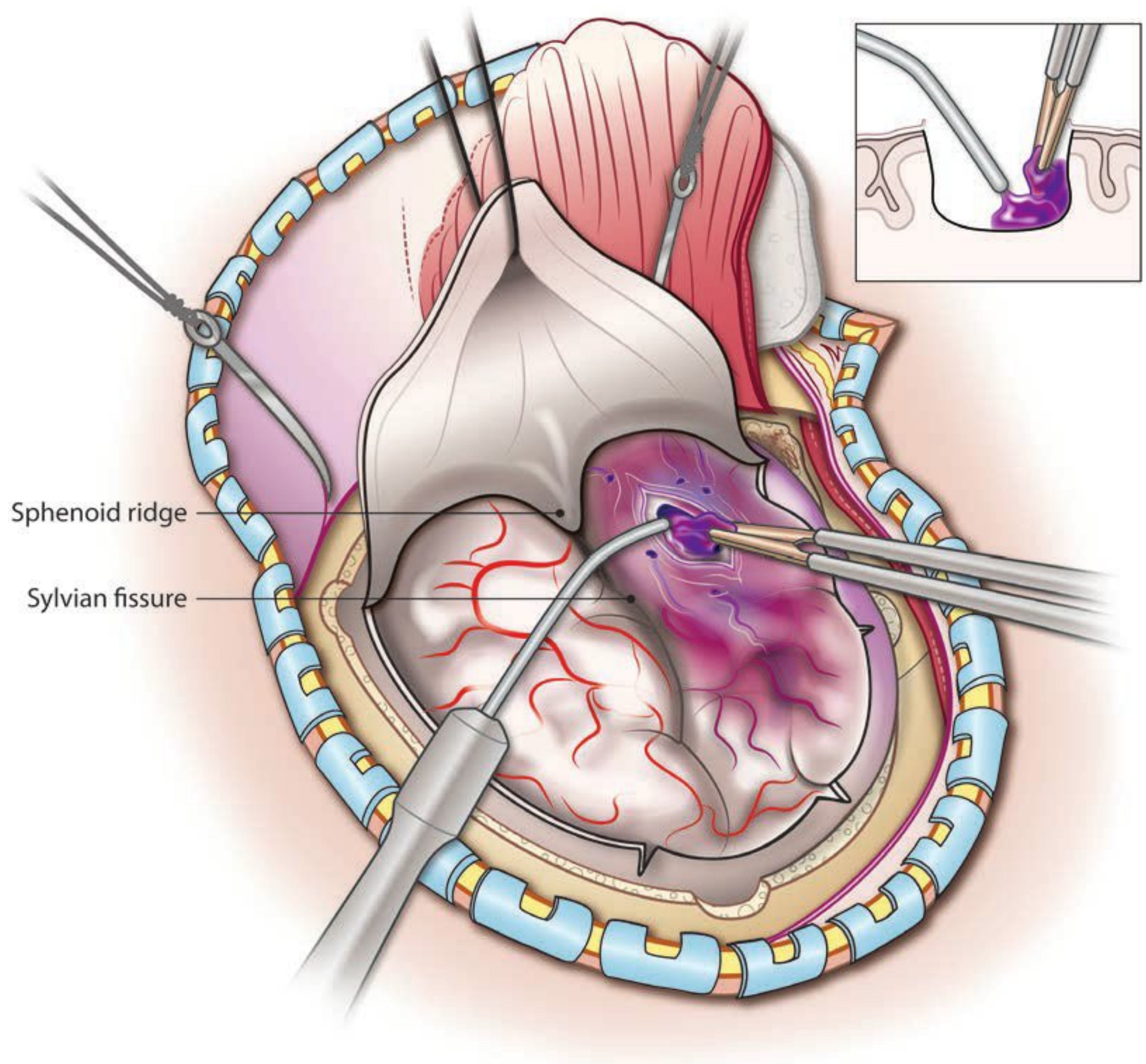


Figure	Procedural Steps	Pearls
Fig. 3.15	**Pilot holes are drilled circumferentially at the periphery of the craniotomy to create dural tack-up sites.**	• Do not take time at this point in the procedure to place the tacking stitches unless active bleeding from the epidural space beneath the bony edge is observed.
	A reverse C–shaped dural flap (reflected onto the sphenoid ridge) is planned.	• A flap fashioned in this manner will maximize the vascular supply and, therefore, its viability.
	The dural opening is initiated over the frontal area with a no. 15 blade and enlarged with tenotomy scissors. A strip of moistened nonadherent bandage or a cotton pattie may be introduced into the subdural space to protect the underlying cortex. The dural flap is secured under modest tension with 4-0 braided nylon stitches.	• Allow a dural margin of at least 0.5 cm with respect to the craniotomy edge to permit primary closure after decompression. • Keep the reflected dural flap moistened with a damp sponge to minimize shrinkage.

Address the Contusion (Fig. 3.16a, b)



b

a

Figure	Procedural Steps	Pearls
Fig. 3.16	**(a) Identify the Sylvian fissure. This is best done in relation to the location of the sphenoid ridge. It may be necessary to drill the bone of the sphenoid ridge until flush with the anterior and middle fossae to augment the surgical exposure.** **Inspect the cortical surface. Select your site for entry. An area of obvious contusion or cortical disruption is ideal.** **Cauterize the superficial vessels and pia mater at the planned entry site. Use a no. 11 or no. 15 blade to open the pia. Approach the hematoma cavity in the subpial plane with a combination of gentle suction and bipolar electrocautery.** **(b) Upon entry to the hematoma, suction out any liquid clot and remove solid clot in a piecemeal fashion. Continue evacuation of hematoma until gliotic brain is visible on all sides.**	• The sphenoid ridge separates the anterior temporal lobe from the adjacent frontal lobe and, in general, serves as a more stable landmark for identifying the Sylvian fissure than does the middle cerebral vein. • If the cortical surface appears undisturbed, consider the use of ultrasound to localize the most superficial extent of the hematoma. • A handheld malleable retractor—introduced over a saline-moistened 1-3 3-cm cotton pattie (to protect the friable tissue along the cavity wall)—may assist visualization during contusion resection and hemostasis.

Anterior Temporal Lobectomy (Fig. 3.17)

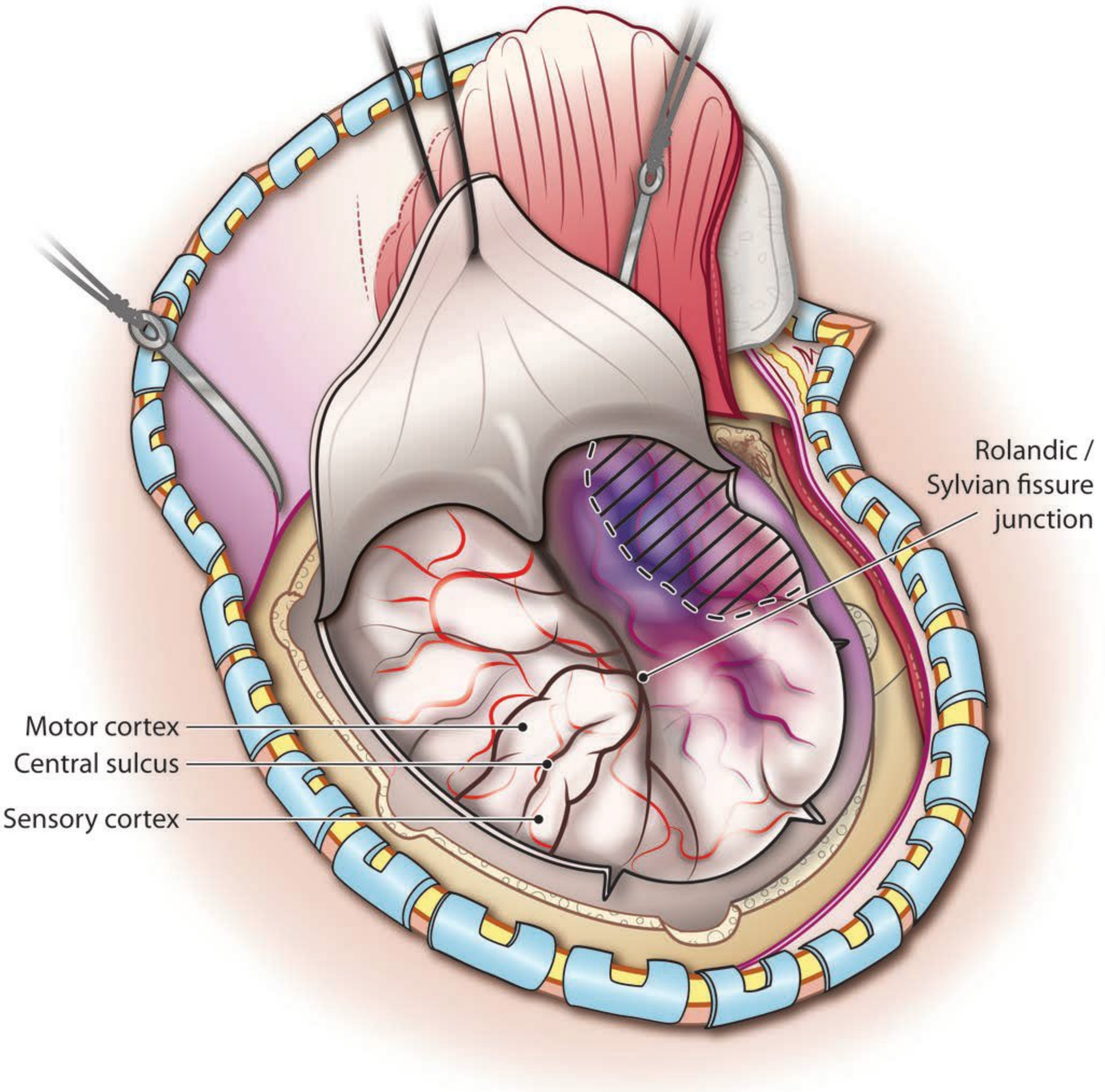


Figure	Procedural Steps
Fig. 3.17	**In the event that the temporal lobe is severely contused, consideration may be given to an anterior temporal lobectomy. While one may resect up to 5 to 6 cm of the anterior, nondominant temporal lobe—carrying out the resection to the junction of the Rolandic and Sylvian fissures to demarcate the posterior limit of resection (as in tumor cases)—the posterior limit ultimately will depend on what the surgeon feels necessary for the patient's survival.**

Closing

- Hemostasis is attained within the hematoma cavity using a combination of mechanical and chemical techniques. Focal bleeding points are controlled with bipolar electrocautery. Temporary packing with gelatin sponge soaked in thrombin may be augmented with hemostatic matrix sealant and saline-moistened cotton patties. Half-strength hydrogen peroxide or normal saline-soaked cotton balls may be used to tamponade generalized oozing as well. Once adequate hemostasis has been achieved, the walls of the hematoma cavity are lined with small pieces of a fibrillar hemostatic material.
- In the absence of significant swelling, the dura may be reapproximated with 4-0 braided absorbable or braided nylon sutures in the standard “water-tight” fashion. The dural closure can be supplemented with dural graft material (either autogenous or artificial).
- If there is significant swelling, the dura may be left open and a dural patch graft sutured to the margins of the native dura. Consideration should be given to leaving the bone flap out at the time of closure.
- Pilot holes are drilled at regular intervals around the periphery of the craniotomy site. Epidural tacking stitches are placed with 4-0 braided nylon sutures.
- The bone flap is reapproximated with a mini-plate system.
- The temporalis muscle is reapproximated with 2-0 braided absorbable sutures.
- The galea and subcutaneous tissue are reapproximated with 2-0 braided absorbable sutures in an inverted, interrupted fashion.
- The skin is closed either with staples or with 3-0 nylon (in a vertical mattress or running fashion).
- Bacitracin ointment, with a dressing of choice, is then placed over the incision site.
- If the patient is comatose, a ventriculostomy should also be placed.

Postoperative Management

Monitoring

- It is the authors’ practice to place the patient in a monitored setting (e.g., the intensive care unit) overnight in the postoperative period to observe for seizure activity or evidence of intracranial bleeding or any other neurologic complications.
- It is also authors’ practice to give three doses of prophylactic antibiotics in the immediate postoperative period.

Medication

- Antiepileptic prophylaxis of choice (phenytoin or levetiracetam) is maintained for a total of 7 days.

Radiographic Imaging

- Postoperative imaging **(Fig. 3.18)**.

Further Management

- Skin sutures or staples are removed after 2 weeks.

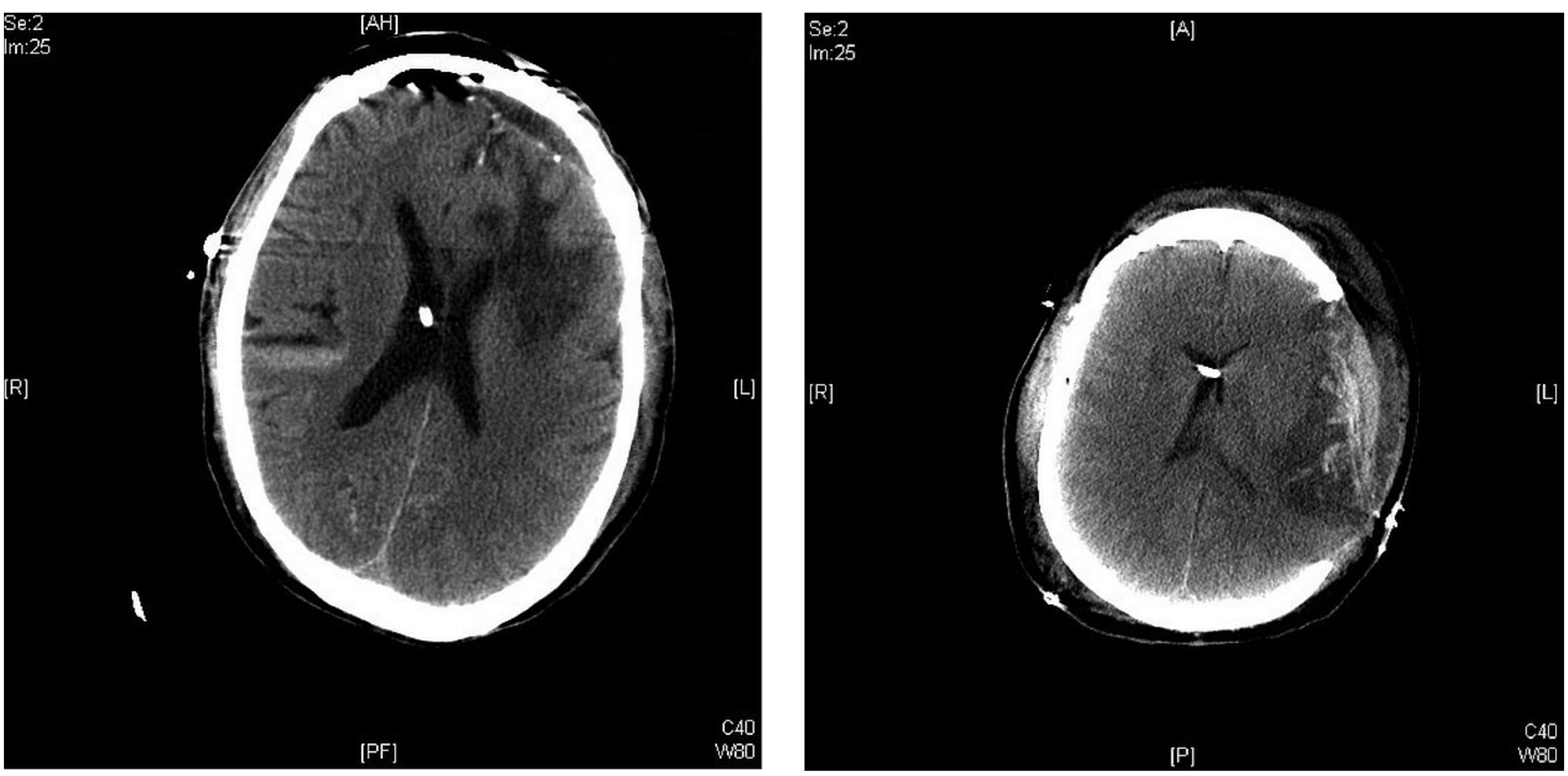
a  b

Fig. 3.18a, b Axial CT images after evacuation of (**a**) frontal and (**b**) temporal lobe contusions. In each case, an external ventricular drain has been placed to facilitate monitoring of intracranial pressure and therapeutic drainage of cerebrospinal fluid.

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4 Decompressive Craniectomy for Intracranial Hypertension and Stroke, Including Bone Flap Storage in Abdominal Fat Layer

Roberto Rey-Dios and Domenic P. Esposito

Introduction

The use of a decompressive craniectomy to treat the symptoms of intracranial hypertension was first proposed in the late 19th century by Sir Victor Horsley.[1] Kocher popularized its use in Europe. Cushing introduced it in the United States in the early 20th century as a palliative treatment for multiple conditions causing intracranial hypertension, including tumors, hydrocephalus, and trauma.[2] The operation fell into disfavor as advances in neurosurgery during the first half of the 20th century transformed most of the original indications for decompressive craniectomy into treatable conditions. In the 1970s, advances in life support increased the survival of patients with severe head injuries. This operation was revisited with the goal of treating traumatic brain injury patients with intracranial hypertension not responsive to “medical treatment.”[3,4] A collection of good results over the past two decades[5–7] has turned decompressive craniectomy surgery into an accepted option for the management of severe traumatic brain injury with refractory intracranial hypertension; new indications are being explored. Several studies have demonstrated a decrease in mortality and improved outcomes when this operation is performed in the correct patient population.[8–10]

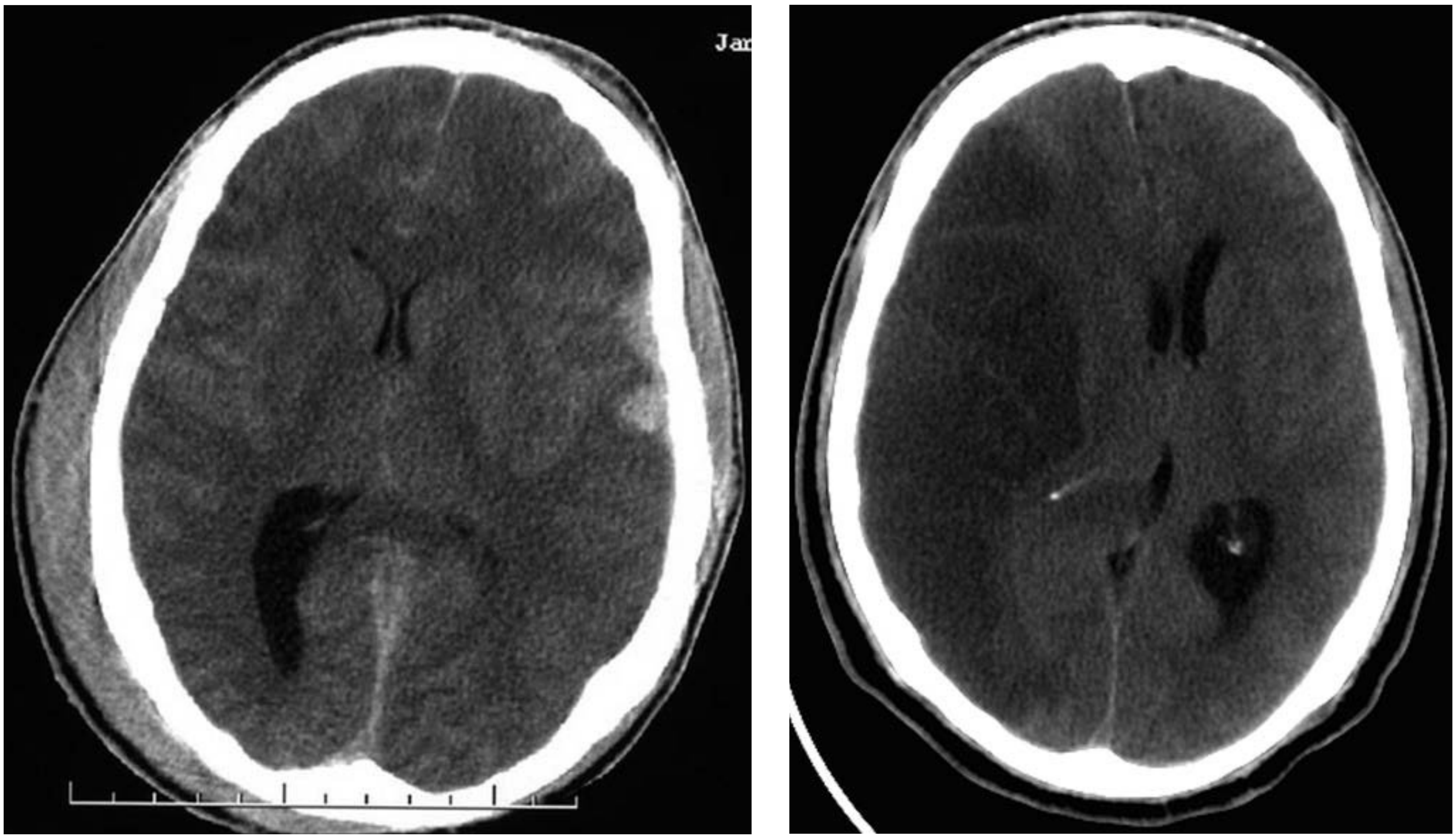
Indications

- There is accumulated evidence to support the use of decompressive craniectomy for the following pathologies:
  - Traumatic brain injury with diffuse or localized cerebral edema or multiple contusions refractory to medical therapy.[10]
  - Large cerebral infarctions resulting in severe edema and mass effect.[11,12]
  - Some studies have shown promising results using decompressive craniectomy for other pathologies presenting with diffuse cerebral edema like aneurysmal subarachnoid hemorrhage,[13] venous thrombosis,[14] or infectious encephalitis,[15] but the available evidence is not strong enough to allow for a standard indication.
- Two primary types of decompressive craniectomies are performed:
  - Frontotemporoparietal (occipital) decompressive hemicraniectomy. This procedure is indicated for traumatic lesions or edema concentrated in one hemisphere with midline shift and risk of uncal herniation. This type of craniectomy may also be performed in the setting of an ischemic cerebrovascular event involving a unilateral, large vascular territory (usually middle cerebral artery [MCA] or internal carotid artery [ICA])
  - Bifrontal decompressive craniectomy. This procedure is indicated in cases of diffuse, bilateral cerebral edema or in the setting bilateral frontal lesions with associated severe edema.
- Decompressive craniectomy may be performed early or late[16]:
  - Early decompressive craniectomy is performed soon after the patient arrives to the emergency department. Early craniectomy should be considered in patients with more than 5 mm of midline shift or if the midline shift is out of proportion to the size of the extra-axial mass lesion (usually hematoma) to be evacuated.[10]
  - Late decompressive craniectomy is usually performed within 48 hours of the original insult, in the setting of medically refractory elevated intracranial pressure (ICP; defined as ICP . 30 mm Hg for greater than 20 minutes by protocol at the authors’ medical center). Late decompressive craniectomy should only be considered after failure of primary tier therapy for intracranial hypertension.
  - “Later” decompressive craniectomy—longer than 48 hours after the initial insult—may be indicated for patients who develop malignant edema following ischemic stroke, delayed expansion of contusions, or delayed malignant cerebral edema and/or hyperemic brain syndrome.

Preprocedure Considerations

Radiographic Imaging

- Computed tomography (CT) is the most common imaging modality used to evaluate potential candidates for a decompressive craniectomy. CT images not only demonstrate acute intracranial pathology but also provide information concerning bony anatomic landmarks—useful for surgical planning—and allow for identification of skull fractures that might complicate the operation.



a b

Fig. 4.1a, b Axial CT images for two patients—(**a**) one with traumatic brain injury and (**b**) one with a large right MCA stroke—selected for decompressive craniectomy.

- CT angiography can be useful to diagnose major vascular occlusions and vascular injuries associated with head injuries, particularly when skull base fractures are present.
- Magnetic resonance imaging (MRI) is used more sparingly in the context of trauma due to the added difficulty of organizing the logistics for life support in the MRI suite and the long duration of the study, which a critically ill patient may not tolerate. MR diffusion-weighted images are useful for early detection of large ischemic strokes. Early involvement of the neurosurgeon in such cases is essential in the event that later neurologic deterioration might provide an indication for emergent decompressive craniectomy.
- **Preoperative imaging** (**Fig. 4.1**).

Medication

- If the patient is showing signs of imminent neurologic deterioration (dilated nonreactive pupil, hemiparesis, decerebrate or decorticate posturing), a bolus dose of mannitol (0.5 to 1 g/kg) can be administered as a temporizing measure en route to the operating room.
- Perioperative antimicrobial prophylaxis should be administered within 1 hour of skin incision. The authors prefer cefazolin. In the setting of an open skull fracture and/or penetrating brain injury, triple antibiotic coverage (gram-positive, gram-negative, and anaerobic organisms) is initiated.

Operative Field Preparation

- The hair is clipped with an electric razor. Any foreign bodies may be removed from the scalp at this time.
- Hexachlorophene (or similar) soap is used to cleanse the skin, and then 70%alcohol is applied.
- The skin incisions are marked, and povidone iodine or chlorhexidine may be applied as a final prep.
- The surgeon also needs to make a decision at this time about how the bone flap will be preserved for future skull reconstruction. There is not enough evidence in the literature to support the preferential use of subcutaneous or cryopreservation.[17,18] In most institutions, sterile deep-freezing storage (2 80°C) is available. If storage is not available, or if the patient is anticipated to continue treatment at a different institution before the anticipated time of reconstruction, the surgeon should proceed to prep the abdomen for subcutaneous storage. We prefer to store the bone flap in the right lower quadrant of the abdomen. Many patients who sustain a traumatic brain injury will eventually need a gastrostomy tube, so the left side should be avoided. The right upper quadrant should be reserved in the event that the patient might require a ventriculoperitoneal (VP) shunt in the future.
- Consideration should be given to perioperative placement of an invasive pressure monitor, contralateral to the planned surgical site. When feasible, placement of an external ventricular drain (EVD) is preferred. An EVD will permit both continuous assessment of ICP to guide therapy and therapeutic drainage of cerebrospinal fluid (CSF) for treatment of intracranial hypertension.

Operative Procedure

Decompressive Hemicraniectomy (Frontotemporoparietal [Occipital] Craniectomy)

Positioning (Fig. 4.2)

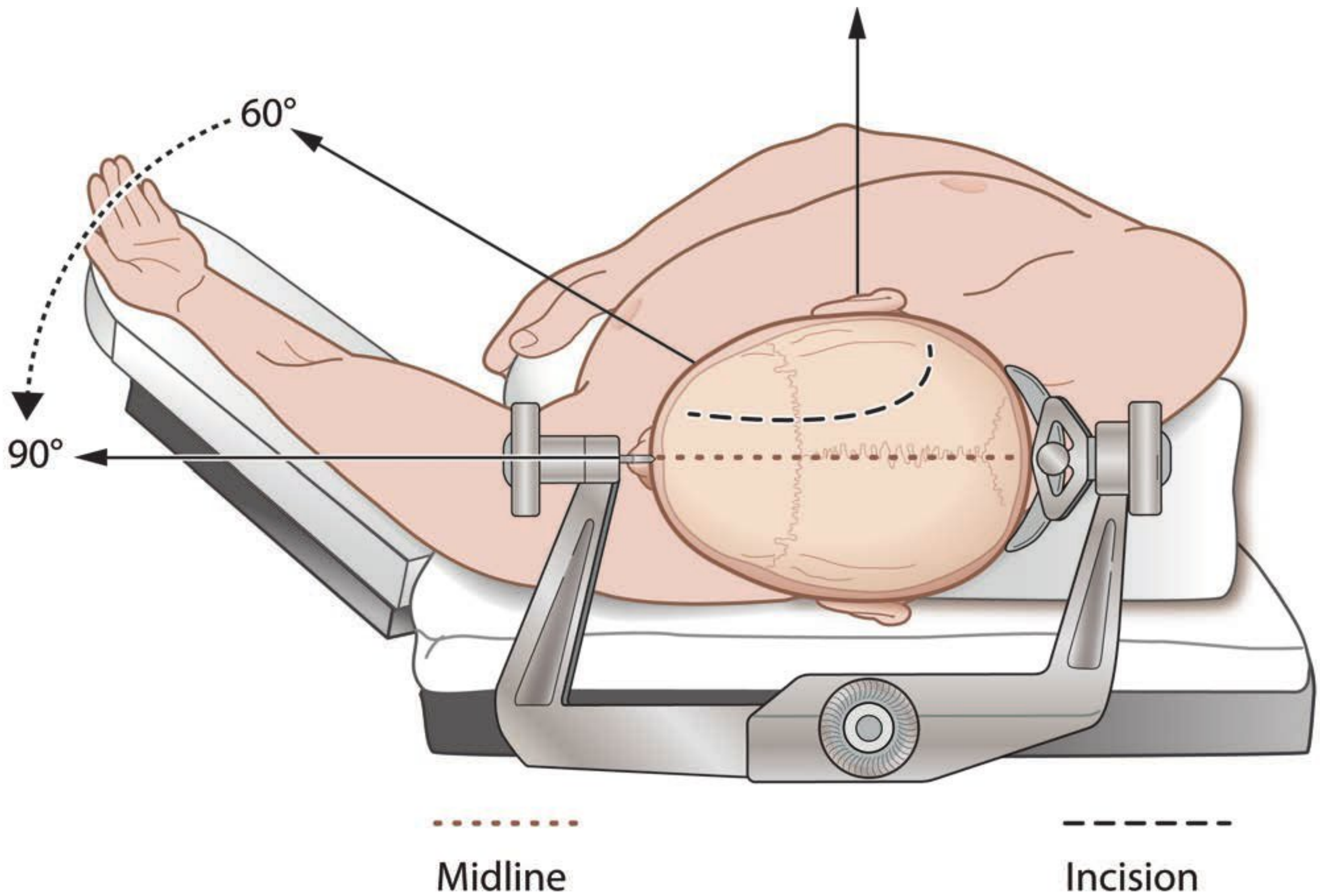


Figure	Procedural Steps	Pearls
Fig. 4.2	**The patient is positioned supine on the operating table. The head is secured with a three-point head holder and turned a minimum of 60 degrees (ideally 90 degrees) to the opposite side of the planned operation. Depending on the body habitus and flexibility of the neck, a roll under the ipsilateral shoulder may be needed to achieve the proper position. Ideally, the parietal eminence should be near parallel to the floor to avoid posterior sagging of the brain after the dural opening.**	• The frontal pin is placed on the midpupillary line contralateral to the side of the planned craniectomy. The two posterior pins should straddle the midline, above the transverse sinus. The posterior pins should not be placed laterally, toward the side of the craniectomy, to prevent compromising the posterior extent of the craniectomy. • If an ICP monitor has not been placed already, now is the time to do so. Usually, an entry point contralateral to the craniectomy is chosen. The catheter or wire should be tunneled away from midline to avoid interference with the incision.

Skin Incision (Fig. 4.3)

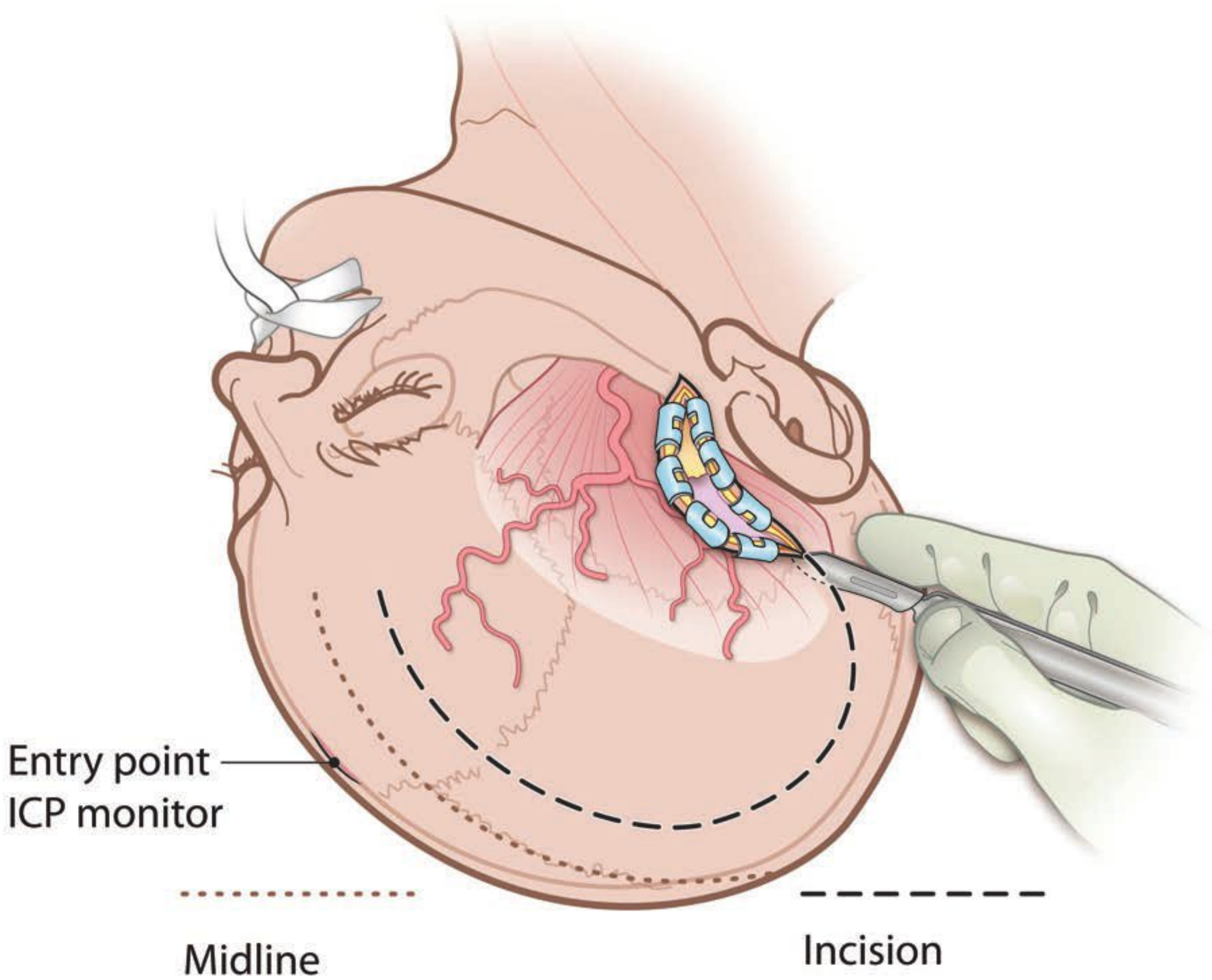


Figure	Procedural Steps	Pearls
Fig. 4.3	**For a standard hemicraniectomy, the incision will start at the level of the zygomatic arch, 1 cm in front the tragus, and extend superiorly and posteriorly in a reverse question mark fashion. The incision will end anteriorly at the hairline, close to midline.** **The skin opening technique varies with surgeon preference. The most expedient method that still minimizes blood loss should be used, since trauma patients often have already suffered severe hemorrhage and may be acutely anemic and hypovolemic. The authors prefer to open the skin with a no. 10 blade and to advance through the subcutaneous tissue with the monopolar. Focal bleeding points are controlled with both mono- and bipolar electrocautery. Scalp clips are applied immediately to the skin edges to assist hemostasis.**	• In many patients, the superficial temporal artery (STA) can be palpated, and the incision designed to avoid it. Maintaining a patent STA will increase the viability of the flap. The posterior portion of the question mark should be kept uniform in width with the frontotemporal base of the flap to avoid a narrow, poorly vascularized distal end of the flap. This is achieved by allowing the reverse question mark to turn superiorly all the way to midline rather than directing it inferiorly into the territory mainly supplied by the occipital artery. A narrow or too caudally directed distal portion of the flap can result in tenuous perfusion, poor wound healing, or frank skin necrosis. • In cases of trauma, the flap should extend as posteriorly as possible to include the parietal eminence. In cases of ischemic stroke, the decompression area should be tailored to the margins of the infarcted area, allowing only the devitalized brain to bulge through the defect. • Once the whole incision is open and hemostasis has been achieved, the monopolar is used to cut the pericranium along the incision line. The temporalis muscle and fascia are also cut following the incision line.

Subcutaneous Dissection (Fig. 4.4)

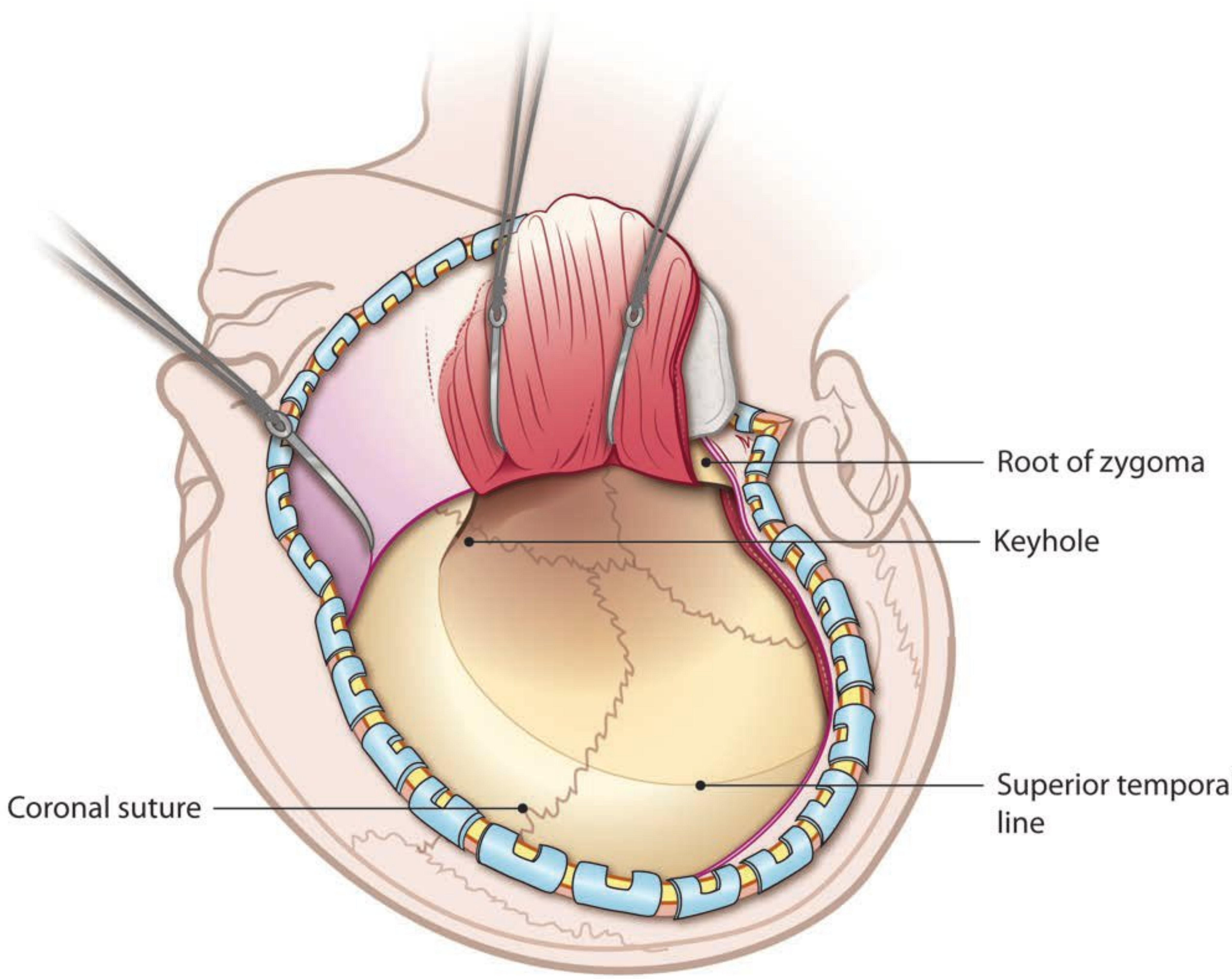


Figure	Procedural Steps	Pearls
Fig. 4.4	**The pericranium is carefully separated from the skull using a Langenbeck type (square) periosteal elevator. A Hoen type (round) periosteal elevator is used to dissect the temporalis muscle. At the superior temporal line, the monopolar is often needed to dissect the more tenacious muscle insertion.** **The resultant myocutaneous flap is reflected anteriorly to expose the bone. Retraction can be applied by using Fisch hooks or mini-towel clamps.**	• The pericranium must be dissected carefully, without creating tears, since it will be used for the expansive duraplasty. The temporalis muscle must be dissected caudally until the root of the zygoma can be easily palpated to allow for access to the middle fossa. • A rolled lap sponge must be placed at the base of the flap, before applying retraction, to prevent kinking of the arterial supply and hypoperfusion of the flap during the procedure.

Bur Hole Placement (Fig. 4.5)

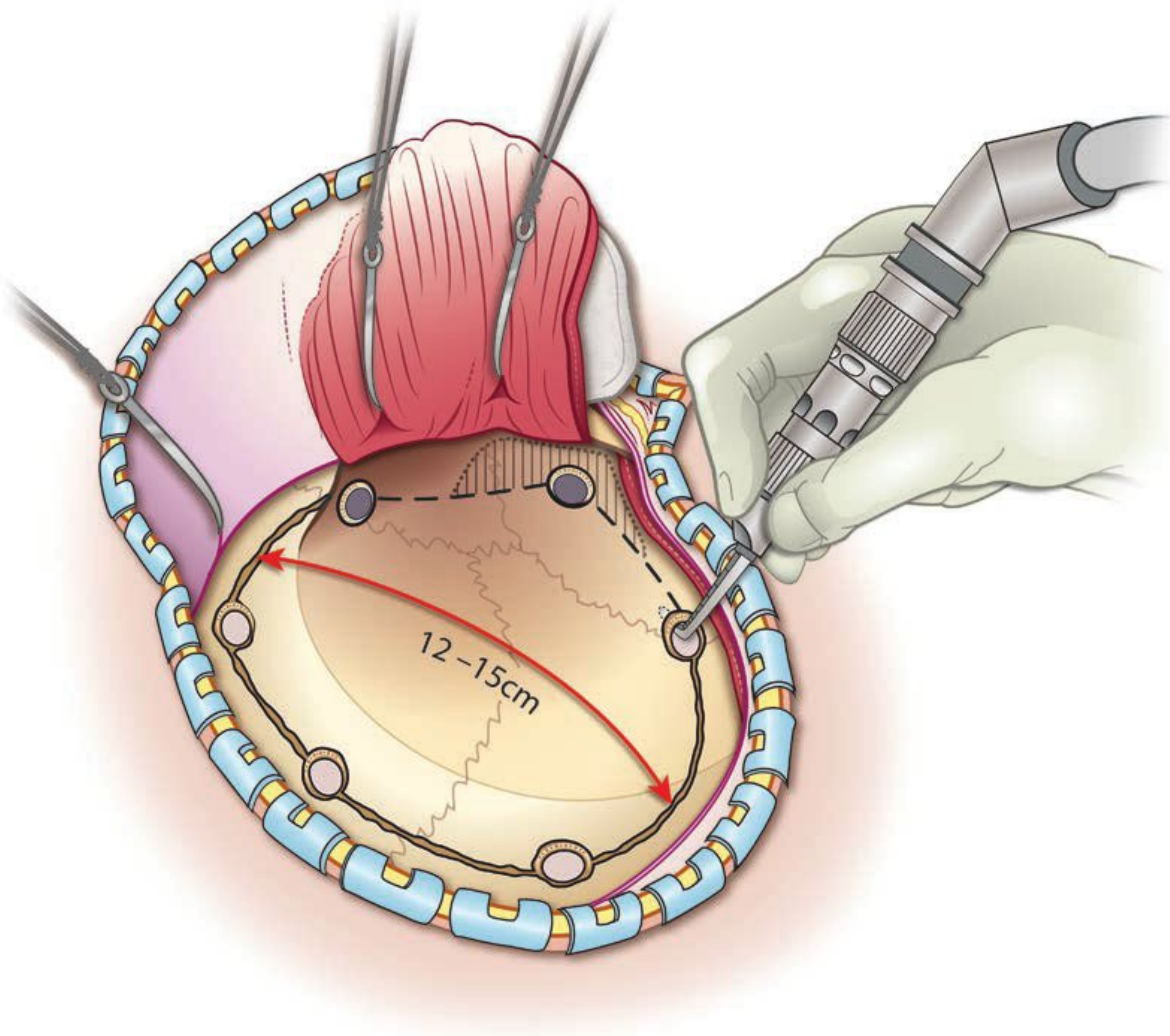


Figure	Procedural Steps	Pearls
Fig. 4.5	**Bur holes are placed in the following locations:** **1. Key hole.** **2. Above the mastoid posteriorly, high enough to avoid air cells.** **3. As low as possible on the squamous portion of the temporal bone, just above the root of zygoma.** **4. Two or three bur holes spanning the frontoparietal high convexity, about 2 cm lateral to midline to avoid bleeding from veins draining into the sagittal sinus.** **A no. 3 Penfield is used to strip the dural attachments from the undersurface of the calvarium at each bur hole site (and between holes, where feasible). The craniotomy is performed using a craniotome. At the level of the sphenoid wing, a small bur can be used to thin the bone between the craniotome cuts above and below the ridge.**	• Ideally, the craniectomy should extend 12 to 15 cm in the anteroposterior dimension and from the floor of middle fossa to 2 to 3 cm from midline to avoid injury to the sagittal sinus. There is evidence to suggest that smaller craniectomy defects are associated with worse outcomes.[19] A measuring tape should be used to confirm the measurements before placing the bur holes.

Elevation of the Bone Flap (Fig. 4.6)

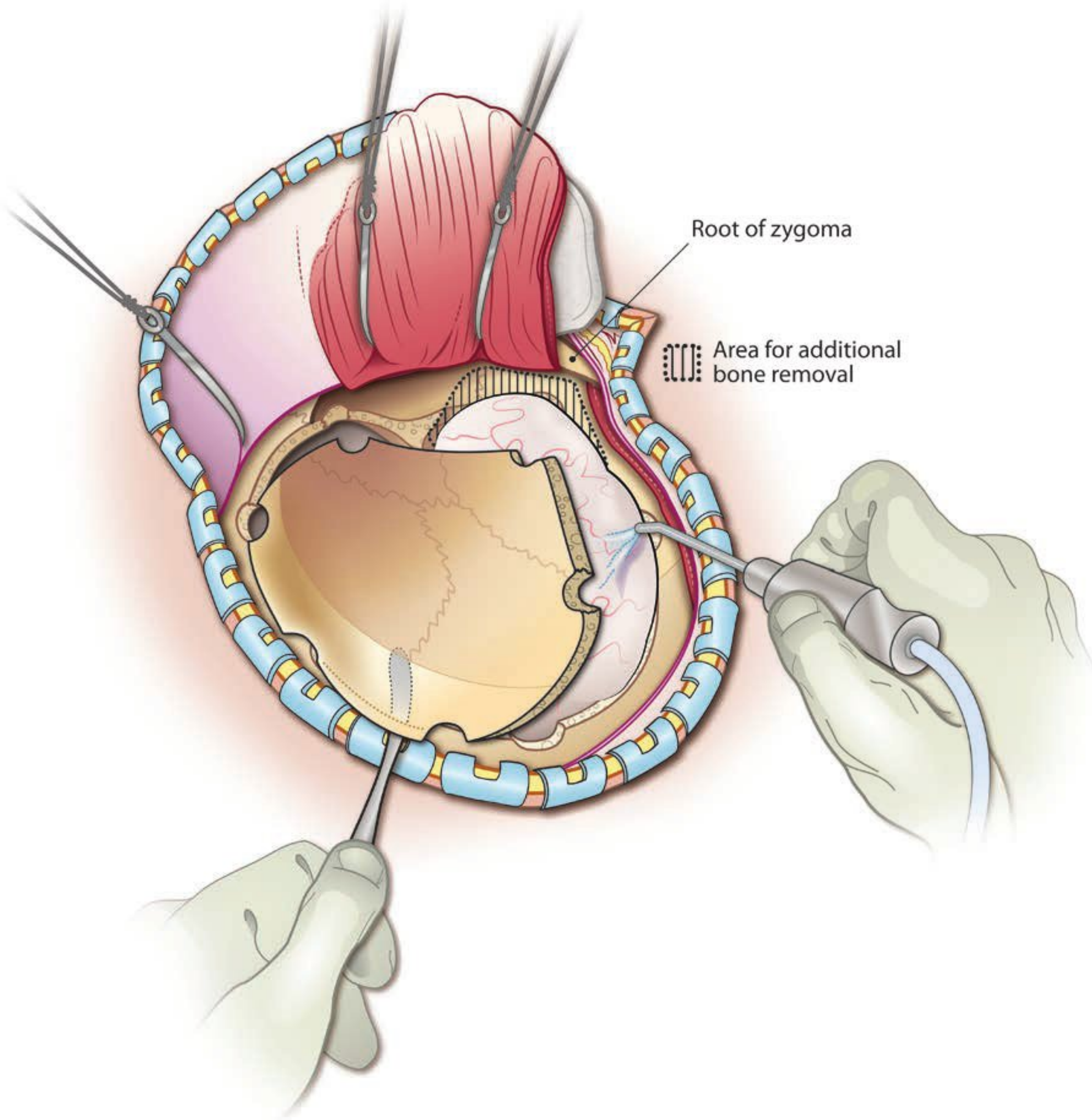


Figure	Procedural Steps	Pearls
Fig. 4.6	**A periosteal elevator or similar tool is introduced along the posterior edge of the craniotomy and used to elevate the bone flap away from the underlying dura. Remaining dural attachments are severed and gentle leverage applied until the corner of the sphenoid wing fractures easily. The explanted bone flap is rinsed with a saline and bacitracin solution. If freezing is planned, the bone flap can be handed off at this time. If abdominal storage is planned, the flap is kept in antibiotic solution until the time of implantation.**	• The sphenoid ridge should fracture with minimal force. If resistance is encountered, the bone should be thinned further with a bur. Excessive leverage may cause a fracture through the sphenoid wing with medial extension and the potential for severe complications. • Elevation of the bone flap alone should produce a demonstrable drop in ICP.

Refinement of the Temporal Craniectomy (Fig. 4.7)

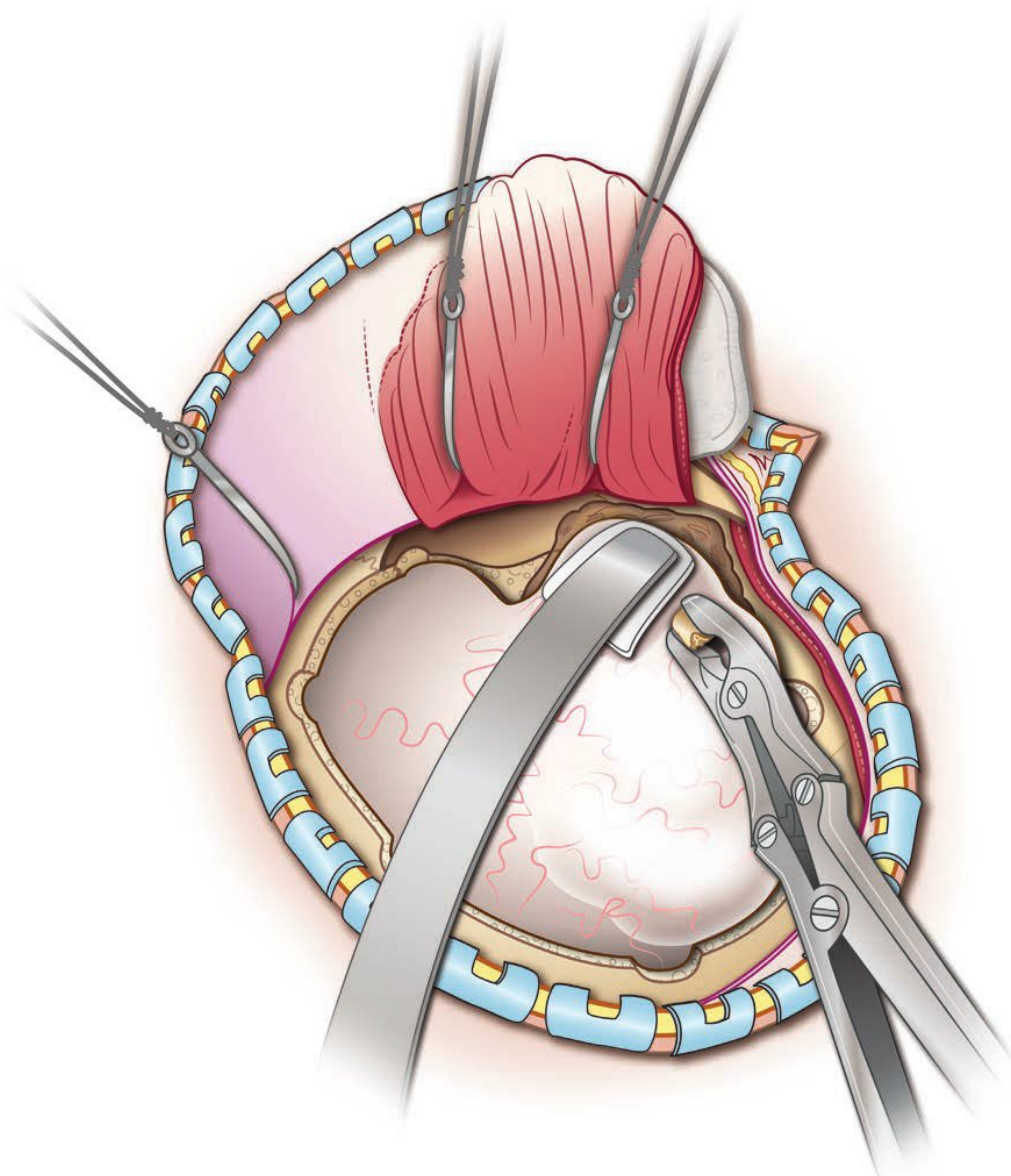


Figure	Procedural Steps	Pearls
Fig. 4.7	**Once the bone flap is removed and hemostasis is achieved, the remainder of the squamous portion of the temporal bone must be removed to allow for a subtemporal decompression. This portion of the craniectomy can be performed with a Leksell rongeur or with the drill, depending on the surgeon's preference.**	• The squamous portion of the temporal bone must be removed until flush with the floor of middle fossa. If mastoid air cells are exposed, bone wax should be applied until completely sealed.

Dural Opening (Fig. 4.8)

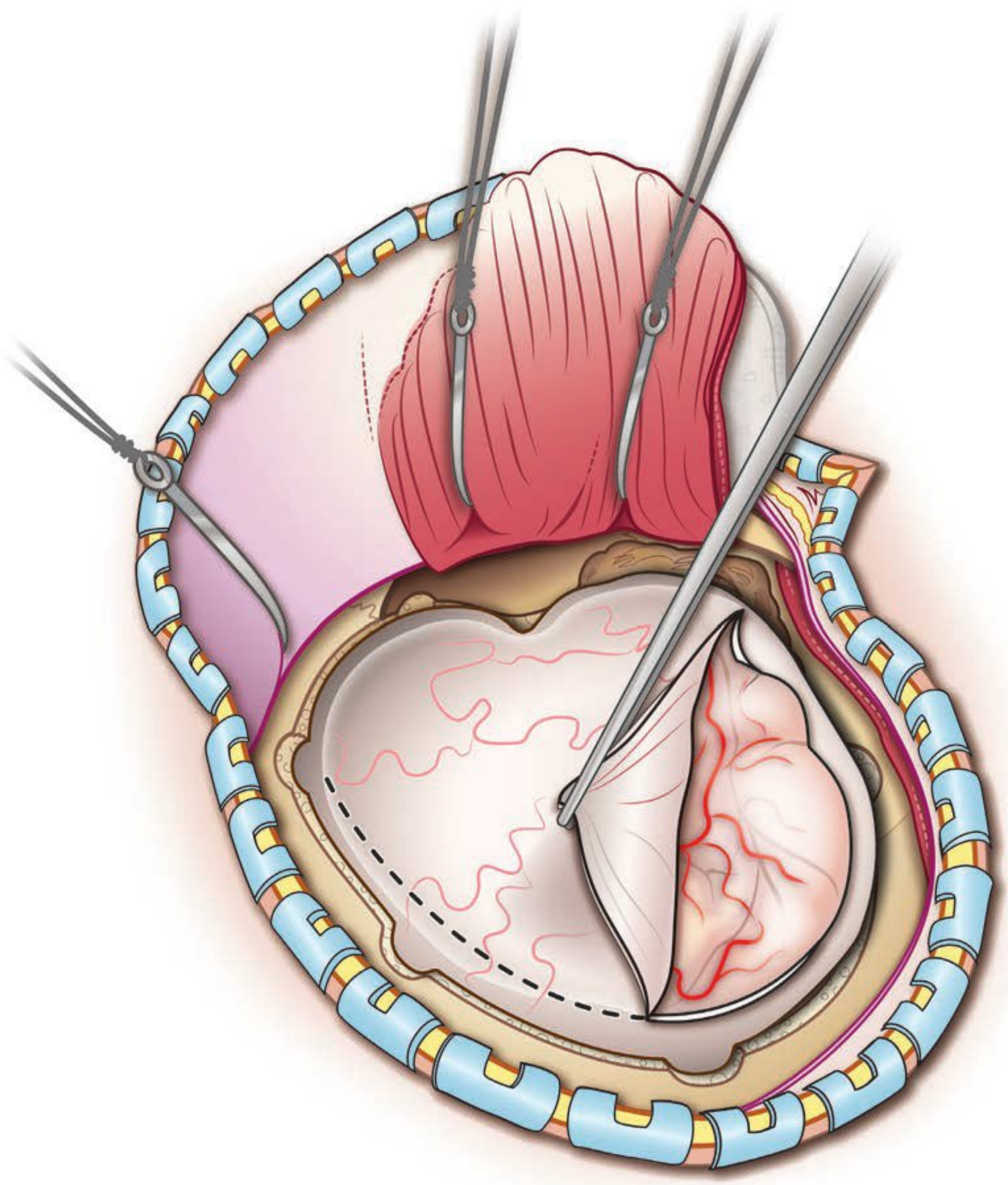


Figure	Procedural Steps	Pearls
Fig. 4.8	**The dura can be opened in several different patterns. The most common is in a U-shape, with the base attached to the temporal edge of the craniotomy defect. Other patterns include a medially based flap or stellate opening.**	• This is the key portion of the operation. • When opening the dura, it is important to leave a generous cuff from the bony edge to facilitate the closure.

Duraplasty (Fig. 4.9)

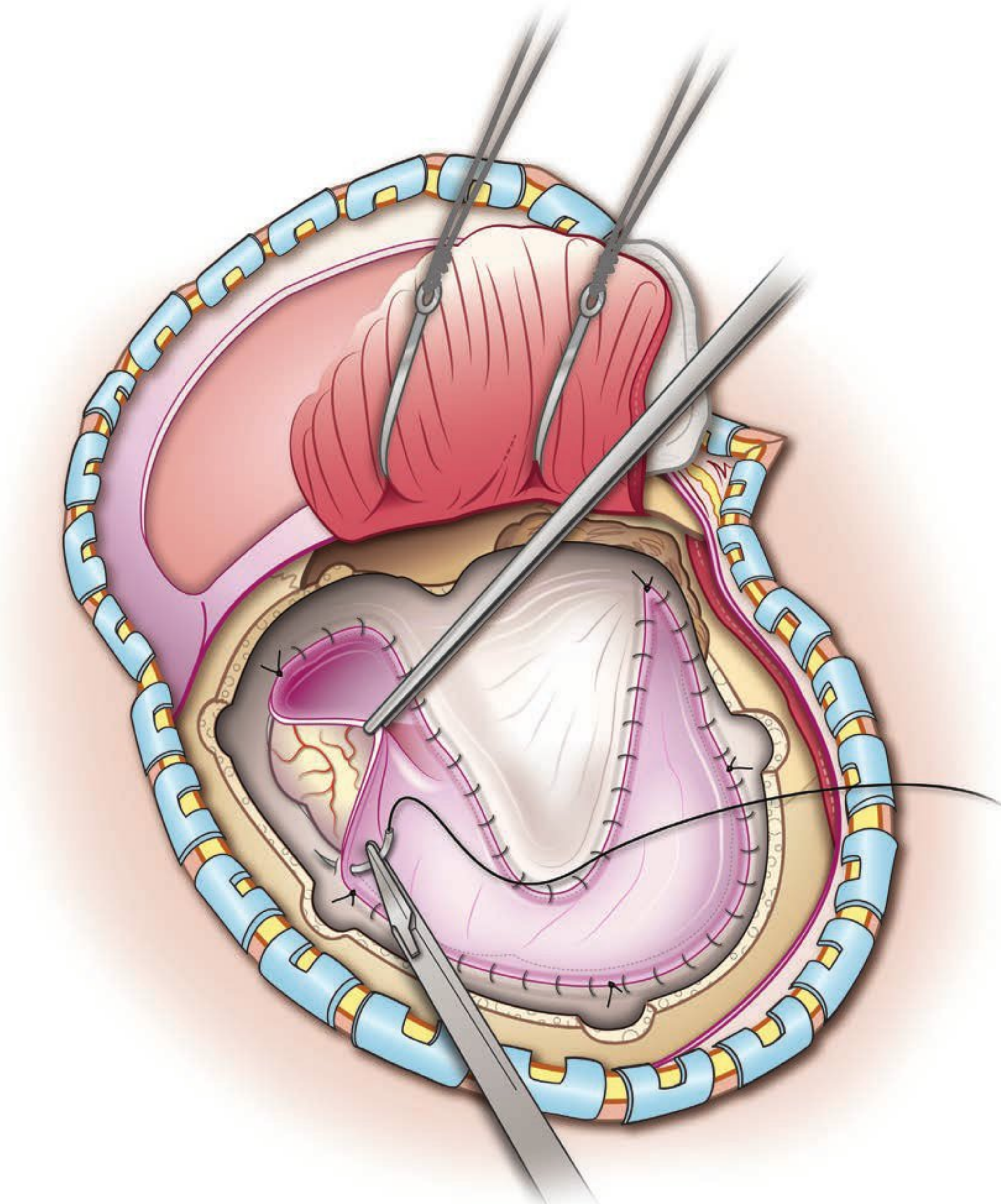
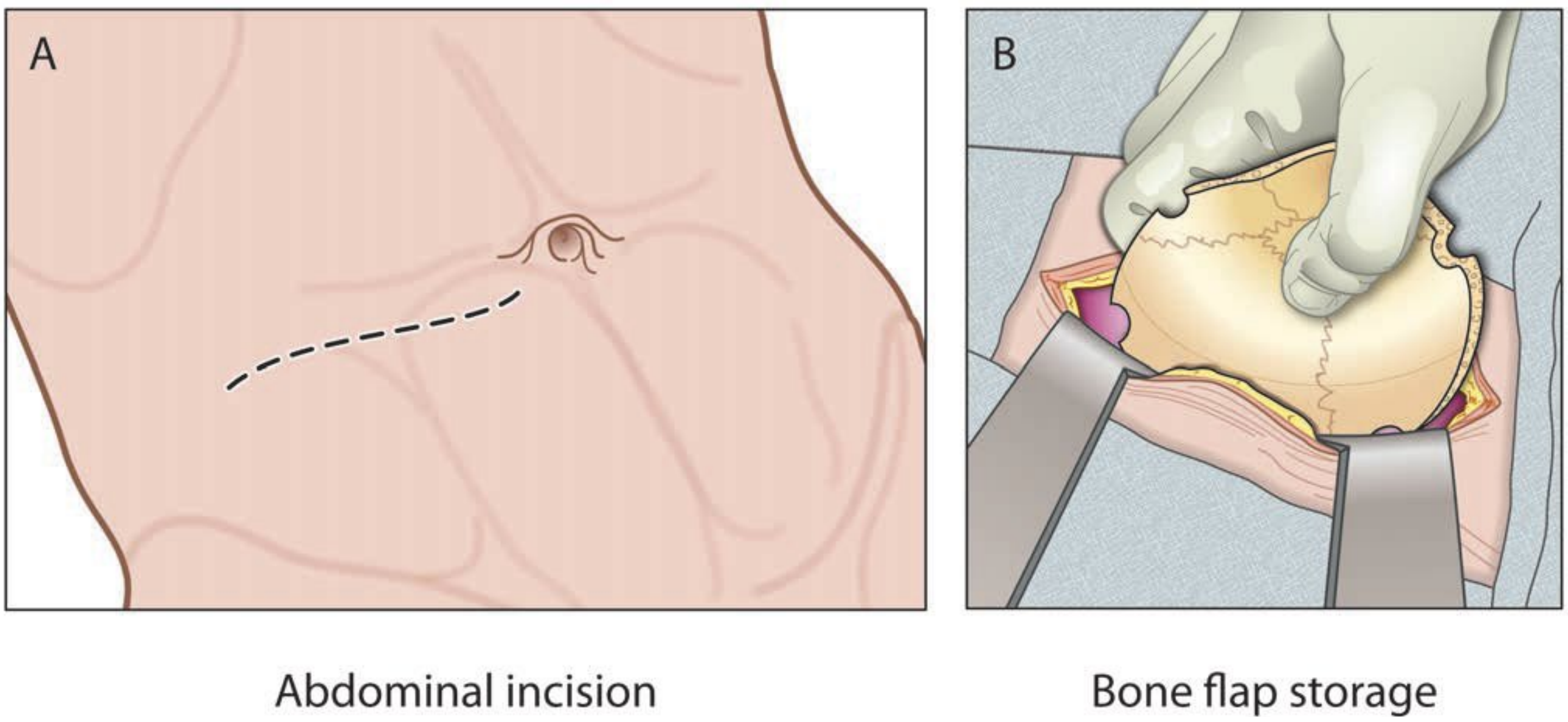


Figure	Procedural Steps	Pearls
Fig. 4.9	**Once the dura is open, the surface of the brain is inspected for subdural hematoma. If present, it should be evacuated. The duraplasty can be performed with autogenous materials (e.g., pericranium) or synthetic, suturable implants. Pericranium can be harvested easily from its galeal attachment by sharp dissection with Metzenbaum scissors. If the pericranium is damaged or contaminated (e.g., open skull fractures, scalp avulsions, etc.), an artificial implant should be considered.**	• If the ICP is high, the dura should be opened slowly, 1 or 2 inches at a time. While the brain is decompressing, the pericranial graft can be sutured in placed as the opening is slowly being made. • In the authors' experience, a watertight duraplasty, using an autologous pericranial graft, produces the best results. We use 4-0 braided nylon suture in a running fashion for this purpose. The expansive duraplasty should be made as generous as possible.

Bone Flap Storage (Fig. 4.10a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 4.10	**(a) A linear incision is performed in the previously designated area of the right lower quadrant. The monopolar is used to create a pocket of adequate size within Camper's fascia. Good hemostasis must be achieved to prevent formation of hematomas. (b) The bone flap is introduced—convex side out—into the subcutaneous pocket. The skin should be closed in at least two layers, according to the surgeon's preferences.**	• This part of the operation can be performed by an assistant surgeon during the cranial closure or immediately after the closure is completed. • The subcutaneous pocket should be of sufficient size that there is not tension on the skin edges when reapproximation is attempted. In a particularly small and/or skinny patient, it may be necessary to split the bone flap in half and "stack" the pieces in the pocket.

Bifrontal Decompressive Craniectomy

Positioning (Fig. 4.11)

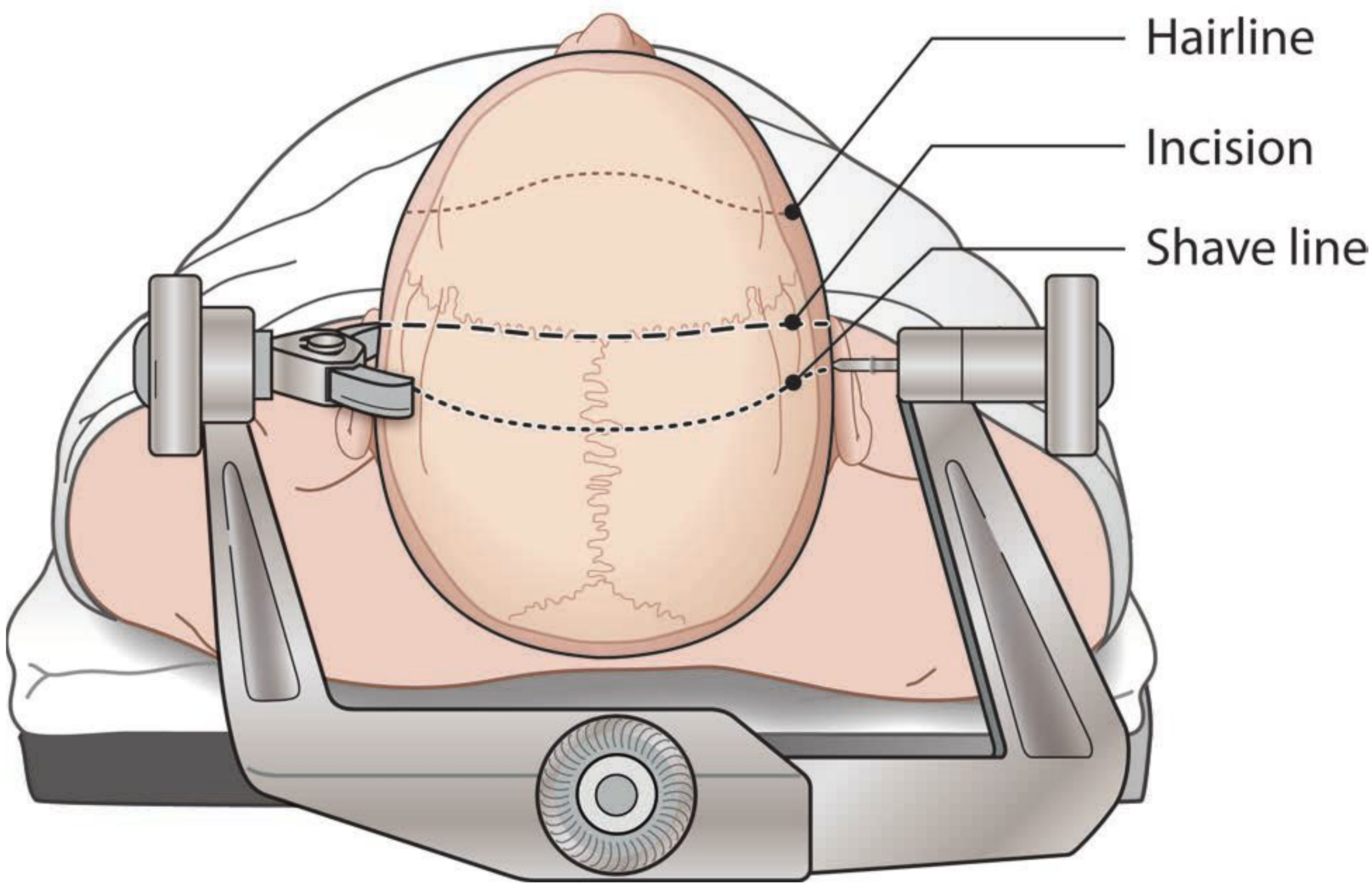


Figure	Procedural Steps
Fig. 4.11	**The patient is positioned supine on the operating table. The head is secured with a three-point head holder, in a slightly flexed position. The pins are placed on the equator of the skull, in a slightly posterior position in order to allow for access to middle fossa.**

Incision Planning (Fig. 4.12)

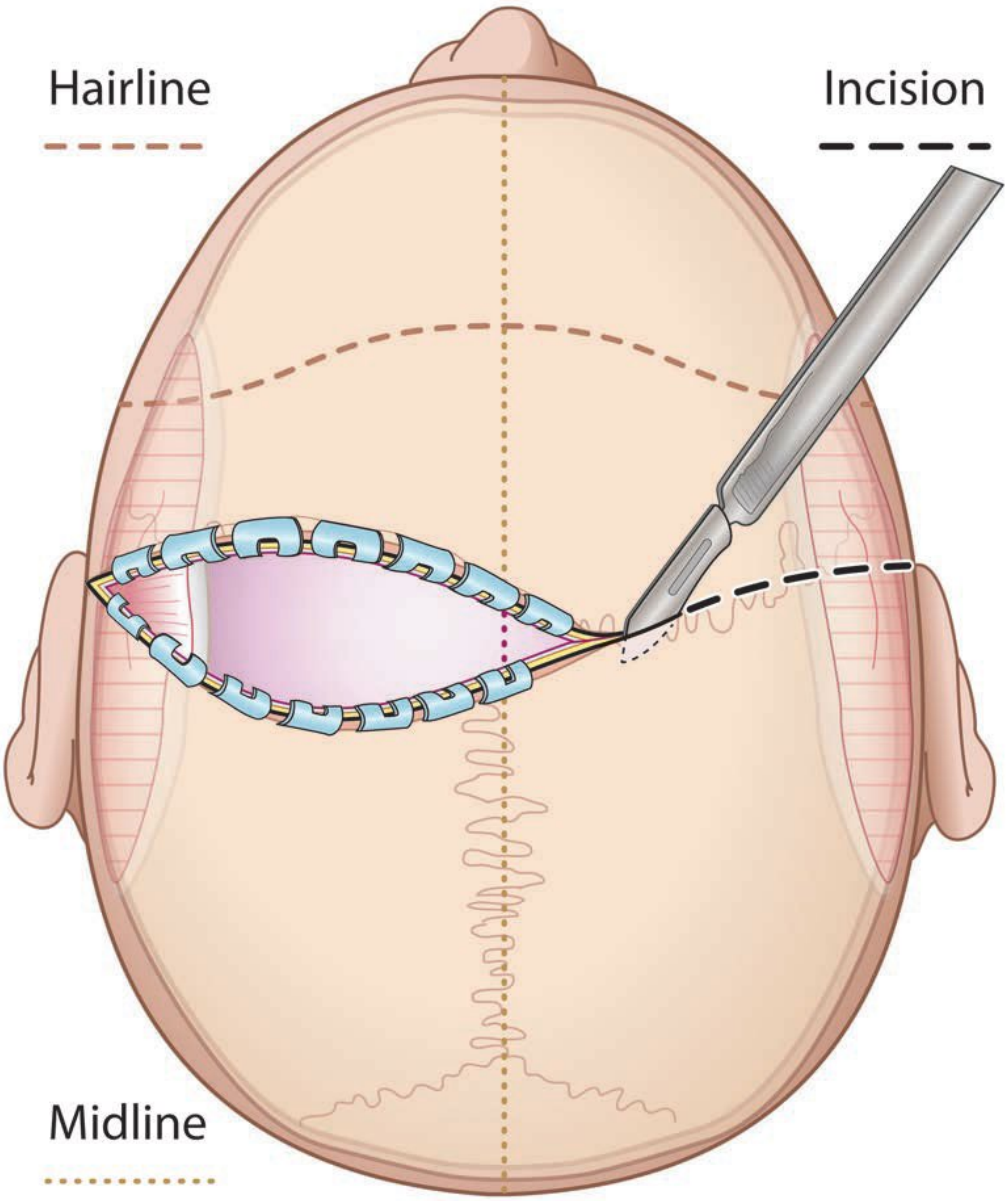


Figure	Procedural Steps	Pearls
Fig. 4.12	**A large, bicoronal incision is planned, with the limbs positioned behind the hairline at approximately the level of the coronal suture, extending bilaterally 1 cm in front of the tragus and inferiorly to the zygoma.**	• If the preoperative CT provides evidence of temporal lobe injury or edema with threatened uncal herniation, a more posterior incision (up to 3 to 5 cm posterior to the coronal suture) should be planned to allow for temporal bone exposure and subtemporal decompression.

Subcutaneous Dissection (Fig. 4.13)

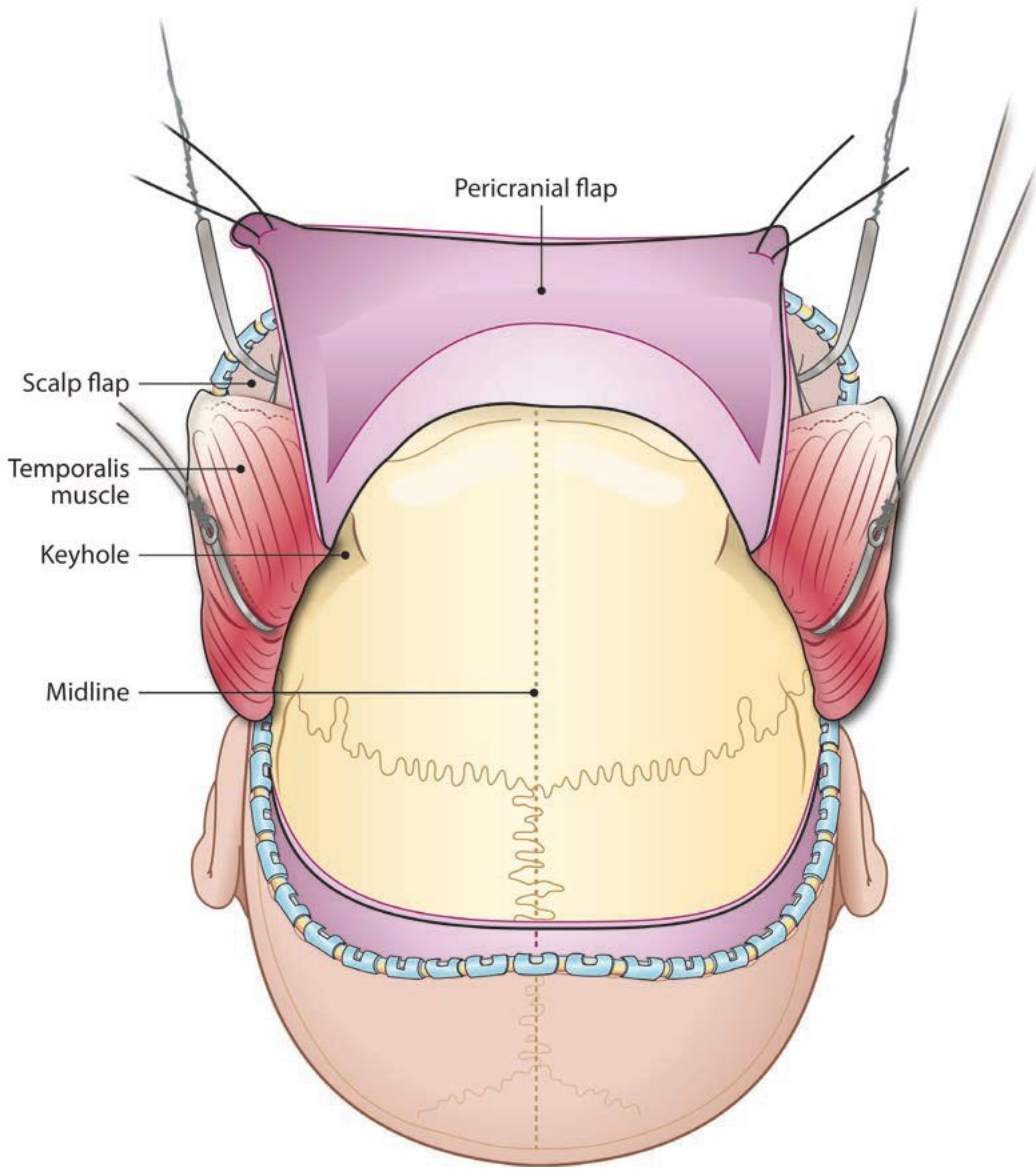


Figure	Procedural Steps	Pearls
Fig. 4.13	**A skin incision is made along the previously marked line and clips applied to the skin edges to assist hemostasis. The incision is carried down to the level of pericranium superiorly and temporalis fascia inferiorly. The pericranium is opened with monopolar cautery—1 to 2 cm posterior to the scalp incision. The temporalis muscle and fascia, likewise, are opened in line with the scalp incision. A periosteal elevator is used to carefully separate the pericranium and anterior belly of the temporalis muscle from the skull, advancing the myocutaneous flap forward.**	• The dissection should be carried anteriorly to the level of the supraorbital ridges. Fisch hooks, mini-towel clamps, or heavy silk sutures can be used to maintain the flap retraction. • Opening the pericranium a few centimeters posterior to the scalp incision gains a few extra centimeters of graft material for later use.

Craniotomy (Fig. 4.14)

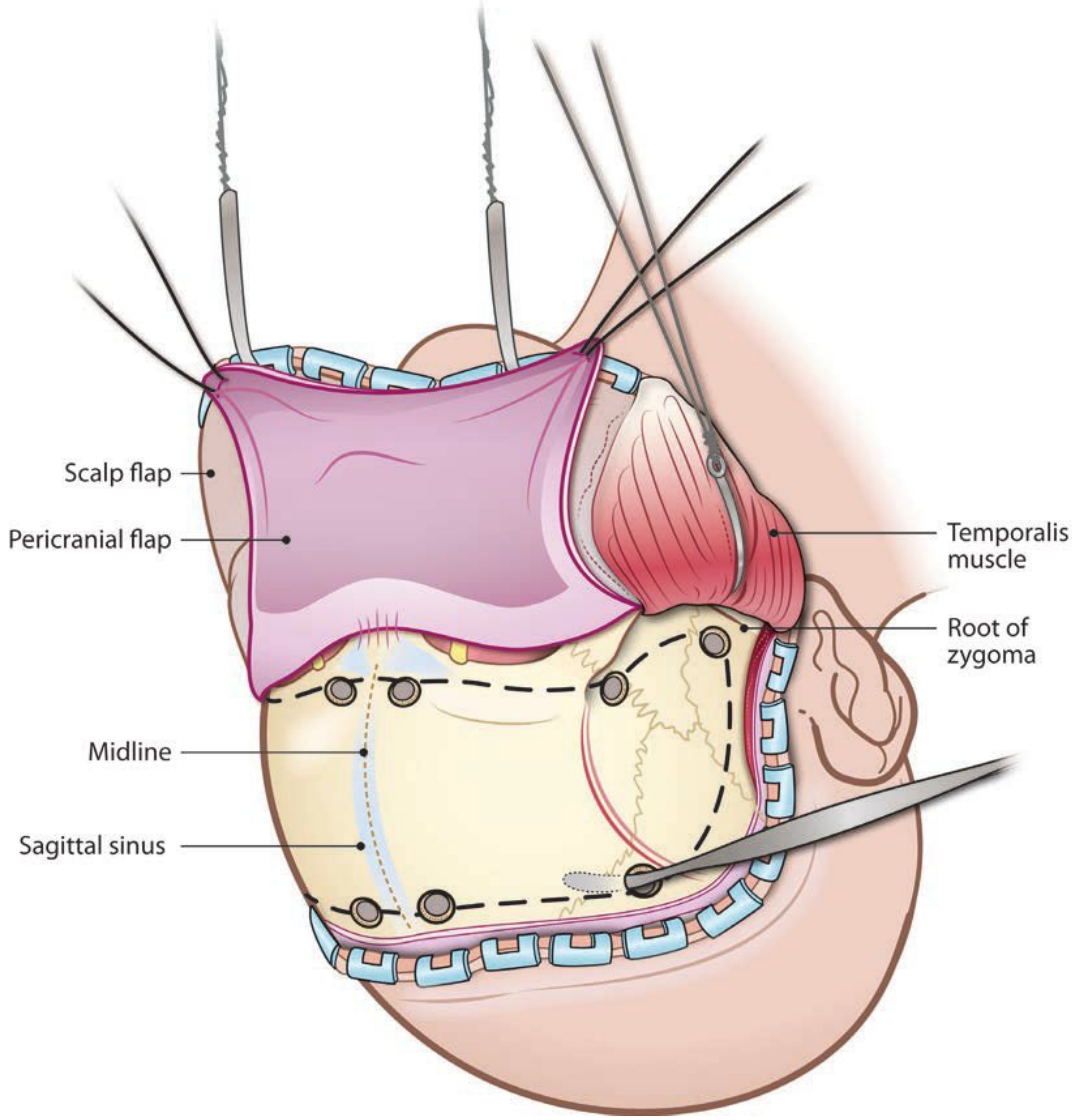
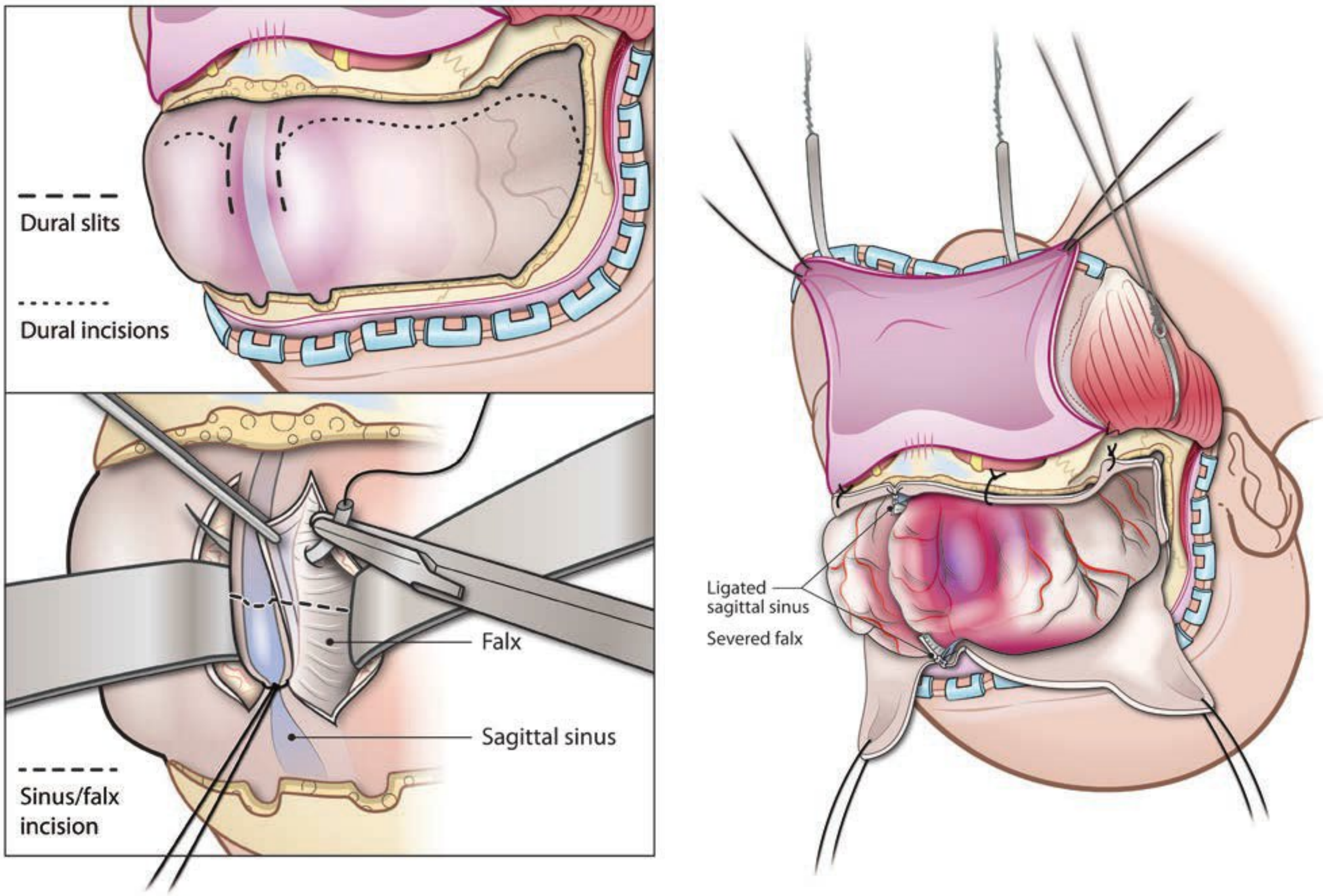


Figure	Procedural Steps	Pearls
Fig. 4.14	**Bur holes are placed in the following locations and in this order:** **1. Bilateral keyhole** **2. Bilateral temporal—in the line of the coronal plane from the sagittal sinus bur holes** **3. One or two just above the frontal sinus** **4. One on either side of the sagittal sinus; these bur holes can be placed 1 to 5 cm behind the coronal suture, depending on the amount of exposure desired**	• It is imperative to localize the frontal sinuses on the preoperative CT and, whenever possible, to avoid them at the time of surgery. If the patient has an extensive, high-reaching frontal sinus system, intraoperative entry is inevitable. In this case, the surgeon should anticipate the need for cranialization of the sinuses before closure and use appropriate antibiotics to cover potential sinus pathogens. • We strongly recommend performing the craniotome cut between the two midline bur holes only after all the other cuts have been made. The dura between the two bur holes is stripped from the undersurface of the calvarium with a no. 3 Penfield and the cut made promptly. This maneuver allows for adequate exposure to permit immediate control of any bleeding from the sagittal sinus.

Dural Opening (Fig. 4.15a–c)



a b c

Figure	Procedural Steps	Pearls
Fig. 4.15	**(a) The dura is opened in a broad, U-shaped fashion with the base oriented posteriorly. The initial opening is made anteriorly, on either side of the midline. (b) The anterior portion of the sagittal sinus is ligated using two silk sutures and severed between the ligatures. (c) The opening is carried laterally and once enough exposure is obtained, the falx should be divided completely. At the temporal corners of the opening, a Y-shape incision can be performed to release tension and allow the dural flap to fall posteriorly.**	• The falx must be divided in its entirety in the anterior portion. Failure to do so will result in compression of midline structures, as the swollen frontal lobes will expand again.

Duraplasty (Fig. 4.16)

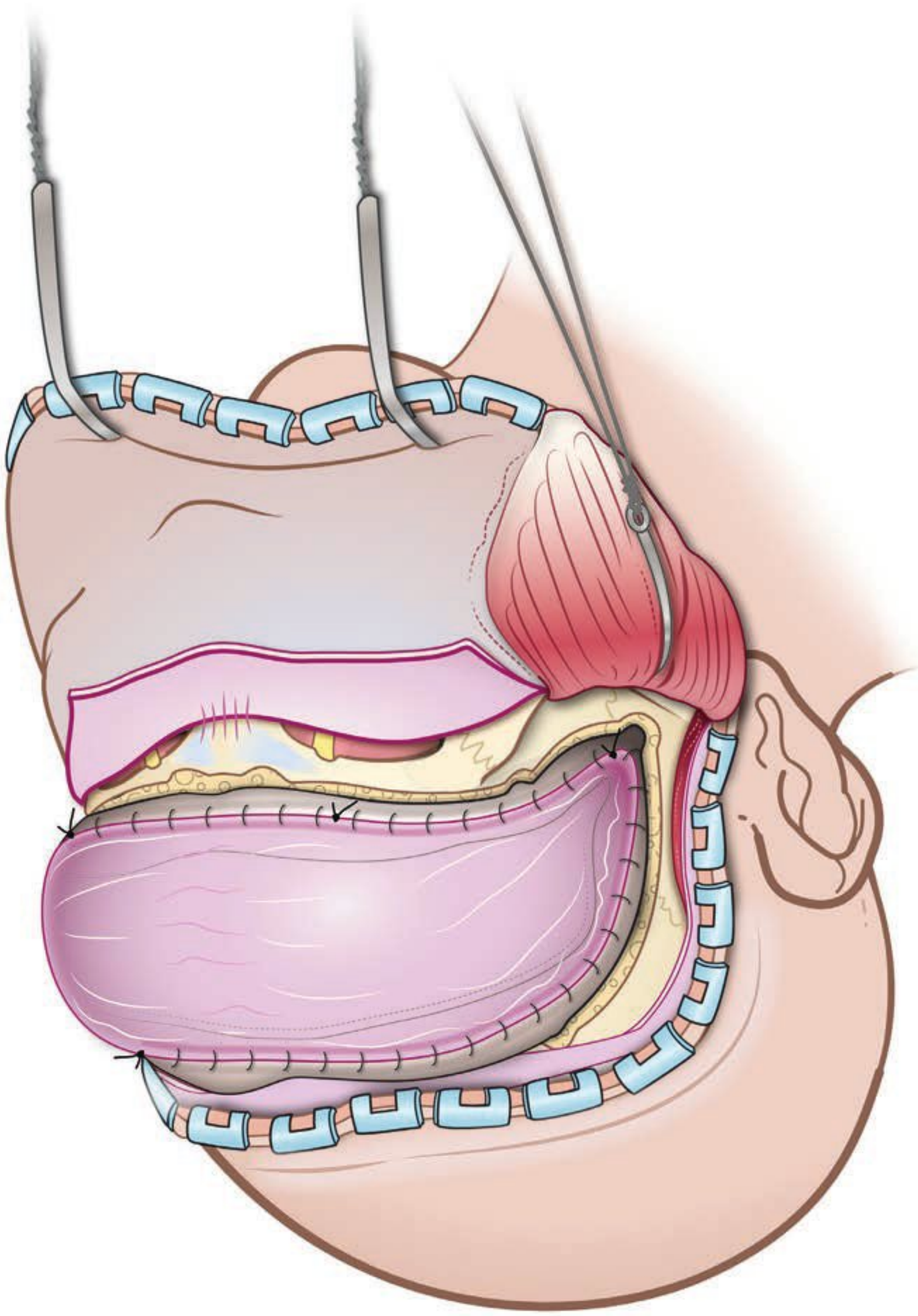


Figure	Procedural Steps	Pearls
Fig. 4.16	**The same principles described for the hemicraniectomy apply to the bifrontal craniectomy. Whenever possible, autogenous materials should be used. The pericranium can be easily harvested from the elevated scalp flap and usually cut into two pieces to allow coverage of the length of the durotomy. Again, watertight closure is recommended.**	• If the frontal sinuses have been violated, the surgeon must proceed to cranialize and obliterate them. This should be done after the duraplasty has been completed, to avoid entry of sinus contents into the CSF spaces. The mucosa is stripped with a curette and the posterior wall of the sinus is removed using rongeurs. The ostia of the sinuses can be obliterated by using temporalis muscle or fat. A vascularized pedicle of pericranium (usually there is enough left after harvesting the duraplasty graft) is draped over the cranialized sinuses and sutured to the dural cuff.

Closing

- Perfect hemostasis should be achieved on the galeal and temporalis muscle surfaces to avoid subgaleal hematoma accumulation, which would defeat the purpose of the operation.
- If active bleeding is present at the interface between the dura and bone edge, epidural tack-up sutures can be placed. This is mostly helpful along the superior frontoparietal edge (adjacent to the midline), where venous bleeding can sometimes be profuse.
- A subgaleal drain (usually a 10-mm Jackson-Pratt [JP]) is left in place.
- The scalp is closed in a single layer, using 2-0 vertical mattress monofilament sutures.

Postoperative Management

Monitoring

- Immediately postop, the blood pressure must be monitored closely and kept within a tight range—high enough to guarantee good cerebral perfusion pressure but not so high as to risk hemorrhage.
- Placement of an invasive pressure monitor is strongly recommended, if not already done, to permit accurate assessment of ICP in the postop period.
- JP drain output should be monitored. The drain is usually left in place for up to 48 hours. CSF in the drain is normal and actually beneficial—both for ICP control and to prevent leakage from the incision. Focal points of leakage along the incision line should be addressed promptly with suture reinforcement and, if persistent, prompt consideration of further radiographic investigation.
- Nursing staff must be instructed to exercise strict craniectomy precautions, including positioning of the head to prevent any pressure on the defect, avoidance of tight dressings, and removal of any equipment in the vicinity that could injure the unprotected brain.

Medication

- Adequate sedation and analgesia should be provided during the postoperative period, while the patient remains intubated and at risk for intracranial hypertension. Neuromuscular blockade can be introduced for patients with higher ICP values or severe respiratory complications.
- Hyperosmolar therapy—with mannitol or hypertonic saline—is appropriate if the ICP remains high after decompression and repeat CT identifies no space-occupying lesions amenable to surgical therapy.
- Perioperative antimicrobial prophylaxis is given for 24 hours (or until the JP drain is removed).
- If the patient presented with an open skull fracture, penetrating brain injury, or degloving injury of the scalp, a longer course of triple antibiotic therapy should be considered. There is insufficient evidence to recommend a specific regimen or duration of therapy.

Radiographic Imaging

- Mobilization of the patient during the first 24 hours must be minimized to prevent trauma to the exposed brain. The authors do not perform routine postoperative imaging for the first 48 hours unless a change in neurologic exam or a sustained increase in ICP suggests a complication that might be amenable to surgical intervention (e.g., subgaleal hematoma or blossoming of contusions). If imaging is considered necessary, CT is the modality of choice for the same reasons described in the preoperative evaluation section. MRI can be useful in ischemic stroke patients to evaluate for possible extension of the stroke volume if the patient's neurologic status deteriorates further and there is no CT evidence of any of the complications mentioned above.
- **Postoperative imaging** (**Fig. 4.17**).

Further Management

- The ICP monitor can be removed if the values have been stable and the neurologic status of the patient is stable.
- Posttraumatic hydrocephalus is a well-described phenomenon, and the incidence has been reported to be higher in patients undergoing decompressive craniectomy.[20]
- During the early postoperative period, patients experience a disturbance in CSF dynamics that may result in the appearance of extra-axial effusions—most often ipsilateral, but sometimes contralateral or interhemispheric—with or without an associated increase in ventricular size. This early presentation of "external" hydrocephalus is often benign and tends to resolve once the bone flap is replaced. The integrity of the wound in these cases can be protected by temporary CSF diversion. In some patients, resolution of the extra-axial effusions after cranioplasty is followed by the onset of symptomatic hydrocephalus, with an associated increase in ventricular size. This delayed presentation can occur weeks or even months after surgery. These patients typically come to medical attention due to an unanticipated plateau or regression in their neurologic recovery and usually require shunting.
- Sutures are usually removed 14 days after surgery. The incision should be monitored closely for any leaks, especially in patients known to have posttraumatic hydrocephalus. If CSF continues to leak despite suture reinforcement, hydrocephalus and infection should be ruled out. It is important to remember that patients with hydrocephalus who have an active leak might not have ventricular enlargement in imaging studies.
- When ready for mobilization, patients should be fitted for a protective helmet to be worn when out of bed and during transport.
- The patient should be evaluated for reconstruction of the cranial vault approximately 4 to 6 weeks post injury. Replacement of the bone flap is addressed in Chapter 25. Additional alloplastic techniques for cranial reconstruction are discussed in Chapter 26.

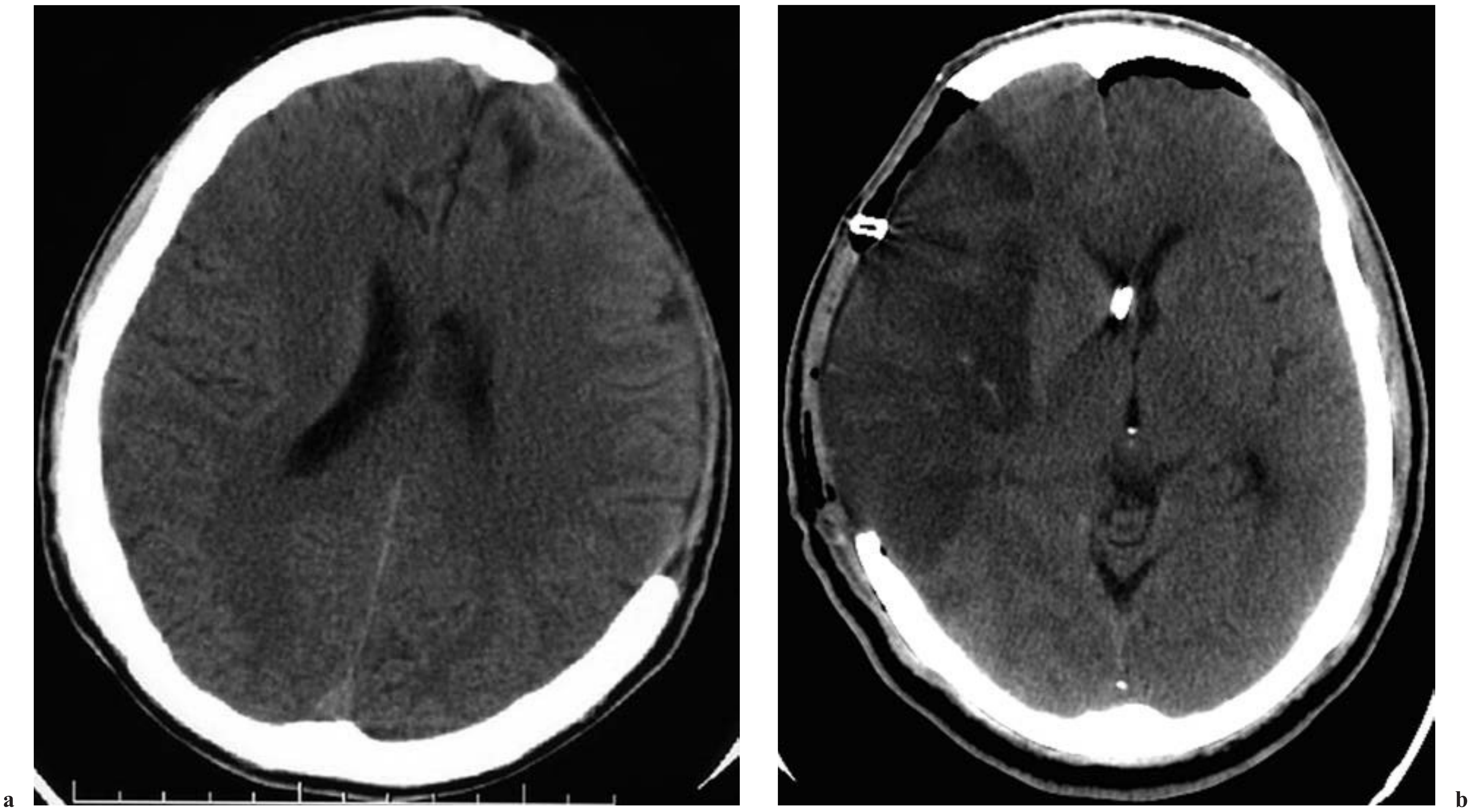


Fig. 4.17a, b Axial CT images for two patients who underwent decompressive craniectomies for (**a**) traumatic brain injury and for (**b**) a large MCA stroke. Note that in the case of the MCA stroke, the craniectomy was tailored to encompass the infarcted area only.

Special Considerations

- Malignant cerebral edema may be encountered upon opening of the dura. When this happens, it must be addressed expediently to prevent herniation of the brain and shearing against the dural and bone edge. Earlier in this chapter we explained our technique of slowly opening the dura as the duraplasty graft is being sutured in place to allow for gradual expansion of the brain. If the surgeon instead has opened the dura completely and brain herniation occurs, the following measures should be taken:
  1. Positioning: Elevate the head of the bed to improve venous drainage. Rule out kinking of the endotracheal tube and/ or neck.
  2. Ventilation: Check the airway pressure. The anesthesiologist should use the ventilation mode that achieves the lowest airway pressures possible.
  3. PCO_2: Check the end-tidal PCO_2. Hyperventilation can be performed for a brief period of time without detrimental effects, and it can buy some time.
  4. Hyperosmolar therapy: Mannitol, hypertonic saline, and loop diuretics can be used. Investigate the volume status of the patient and electrolytes.
  5. CSF drainage: If a ventricular catheter is in place, make sure it is open to drain and set as low as possible. Consider tapping the ventricle through the exposed anterior frontal lobe if a ventriculostomy was not previously inserted.
  6. Lowering of $CMRO_2$: Consider a bolus of barbiturates or etomidate.
  7. Undiagnosed mass lesion: Bear in mind that a hematoma—either extra-axial or intraparenchymal—may develop as a result of reperfusion achieved by opening the cranial compartment. Intraoperative ultrasound can be useful in this context. Postoperative imaging should be obtained as soon as possible.
- A severely damaged scalp and/or significant soft tissue loss may present a particular challenge in the setting of trauma. In such situations, collaboration with a plastics or head and neck surgeon is essential. Artificial grafts often are used as a temporary measure until tissues heal sufficiently and are clean enough to receive a permanent graft, if needed.
- The so-called "syndrome of the trephined" (or "sinking scalp flap syndrome") includes a combination of neurologic symptoms that can be directly related to the presence of a craniectomy defect and that eventually improve after cranioplasty. Patients usually become symptomatic when they start to sit up or ambulate. Most common symptoms are headache, discomfort in the region of the cranial defect, dizziness, seizures, and psychiatric alterations. Some patients will experience more severe symptoms, including orthostatic vegetative dysfunction and focal cranial nerve or motor deficits. Symptoms are usually triggered or aggravated by the upright position. Symptomatic patients should be evaluated for a cranial vault reconstruction as soon as possible.

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5 Surgery for Cerebellar Stroke and Suboccipital Trauma

Faiz U. Ahmad and Ross Bullock

Introduction

Acute cerebellar pathology—in the form of hemorrhage, swelling, and/or infarction—represents one of the most urgent and treacherous of neurosurgical emergencies. Patients presenting with these conditions can deteriorate rapidly and irreversibly. Posterior fossa hematomas and infarcts may compress the lower brainstem respiratory and cardiovascular centers, triggering respiratory arrest and cardiac instability.

Emergent surgical intervention is usually life-saving.[1–4] Timely intervention lends itself to a better overall prognosis in such patients because coma often results from hydrocephalus (usually reversible) and brainstem compression (rather than destruction).[5–10] Also, the fact that the cerebral hemispheres remain relatively unaffected allows many of these patients to retain their premorbid personalities and higher-order cognitive function despite presenting in coma before surgery.

Indications

Spontaneous Cerebellar Hemorrhage

Several factors must be considered before deciding to operate:

- Size of hematoma: Surgical intervention generally is indicated for lesions of greater than 3 to 4 cm to improve clinical condition and prevent secondary deterioration due to cerebellar swelling and herniation.[9,11]
- Neurologic status: The presence of signs and symptoms attributable to hydrocephalus (agitation, confusion, lethargy), brainstem compression (sixth or seventh nerve palsy, horizontal gaze paresis, hemiparesis), or coma should prompt emergent surgical intervention.
- Time since ictus: Patients presenting within 6 to 48 hours of hemorrhage often experience neurologic deterioration due to a combination of swelling and re-hemorrhage. By contrast, those presenting 5 to 7 days after the initial bleed typically improve or remain stable.
- Issues tangential to the primary pathology: Age, comorbidities, social situation, and advance directives also must be taken into account. A nursing home–confined, 80-year-old patient with dementia and multiple medical comorbidities, presenting in coma, may not an appropriate candidate for surgical management.[11–14]

Cerebellar Infarction

- The indications for decompressive surgery are broadly the same as those for hemorrhage. However, the clinical course tends to evolve more slowly.[15,16] Resection of the infarcted cerebellum itself is seldom helpful.
- Cerebellar hemisphere infarction (due to distal posterior inferior cerebellar artery [PICA] occlusion) causing brainstem compression should be differentiated—by computed tomography (CT) and/or magnetic resonance imaging (MRI)—from brainstem destruction due to proximal ischemia, as the latter will not improve with surgery.

Trauma

- Patients presenting with posterior fossa epidural hematoma (EDH) or acute subdural hematoma (SDH) who are awake and meet all of the following radiographic criteria can be managed conservatively, under close supervision: clot volume less than 10 mL, hematoma thickness less than 15 mm, and midline shift less than 5 mm.[17]
- Conversely, patients who present with a depressed level of consciousness, focal neurologic deficits, and/or ominous findings on CT scan (hydrocephalus, obliterated perimesencephalic cisterns, and/or a displaced fourth ventricle) are candidates for early surgical intervention.[1,3,6,18,19]
- The indications for operative intervention in the setting of traumatic intracerebellar hematomas are similar to those for spontaneous hemorrhage (see above).

Preprocedure Considerations

Radiographic Imaging

- Noncontrast CT provides adequate initial imaging in the setting of trauma or hemorrhage.
- MRI—in particular, diffusion-weighted imaging (DWI)—may be a useful adjunct in the setting of stroke to differentiate brainstem from cerebellar hemisphere ischemia.
- If the initial CT scan reveals evidence of subarachnoid hemorrhage and/or blood in the fourth ventricle, preoperative vascular imaging (angiogram or CT angiogram) should strongly be considered to rule out an underlying aneurysm or arteriovenous malformation. The presence of an underlying vascular lesion may dictate a change in operative plan and/or preoperative endovascular intervention.

- A patient with a known posterior fossa hematoma (traumatic or spontaneous) who is deteriorating rapidly should be taken to the operating room directly, without a repeat CT scan. The time required to complete an additional diagnostic study may not be worth the diagnostic yield in this setting.
- **Preoperative imaging (Fig. 5.1).**

Ventriculostomy

- The propensity of posterior fossa mass lesions to cause obstructive hydrocephalus means that a presurgical ventriculostomy is almost always mandatory before decompression. Failure to do so may result in massive herniation of the posterior fossa contents into the decompression, causing death on the operating table. The ventriculostomy should be inserted very rapidly to avoid delay in the deteriorating patient, and may be done as a part of the decompression (see below).
- Occasionally, in moribund patients, or in those with smaller posterior fossa hemorrhagic lesions, a ventriculostomy may be placed, and the patient observed and re-scanned in 3 to 4 hours to determine if definitive surgery is indicated (e.g., if clinical improvement or enlargement of hematoma occurs).
- Many authors advocate careful titration of the height of the drain (e.g., starting at 30 cm water and then lowering it by 5 cm water decrements every hour until 10 cm water is reached) in order to avoid "upward transtentorial herniation." This may be more important in the setting of neoplastic posterior fossa mass lesions, where edema and a more protracted clinical course make this complication much more common.

Medication

- The use of sedative-hypnotic agents should be avoided. Such medications may confound the clinical examination and precipitate respiratory depression.
- A stat bolus dose of mannitol (0.5–1 g/kg intravenous piggyback [IVPB]) may be given if clinical deterioration occurs. Otherwise, a bolus is administered prior to skin incision in the operating room.
- There is no role for preoperative antiepileptics unless there is concurrent supratentorial hemorrhage.
- Prophylactic antimicrobial prophylaxis (the authors prefer cefuroxime) to cover gram-positive organisms is given per hospital protocol.

Positioning and Operative Field Preparation

- To maintain adequate head flexion and rotation, a three-pinion head holder is essential. The cross bar should be padded to prevent pressure injury were slippage of the pins to occur (e.g., where the bridge of the nose or forehead would contact that cross bar).
- For evacuation of a predominantly unilateral hematoma, the lateral park bench position—with the head turned to the contralateral side and flexed—is suitable. For subdural or extradural hematomas extending bilaterally, and for unilateral cerebellar infarctions (where extensive foramen magnum decompression is needed), the prone position is chosen. For trauma cases, we attempt to reduce/minimize cervical flexion during positioning if the cervical spine has not been cleared. The cervical collar is replaced after the procedure.
- Either an iodine-based preparation or chlorhexidine/alcohol-based solution is used for skin preparation, taking care that the solution does not enter the eyes, especially in prone position. We use a transparent adhesive dressing film over the eyes to protect the cornea.
- The incision is marked and infiltrated with 1% lidocaine with epinephrine 1:100,000.

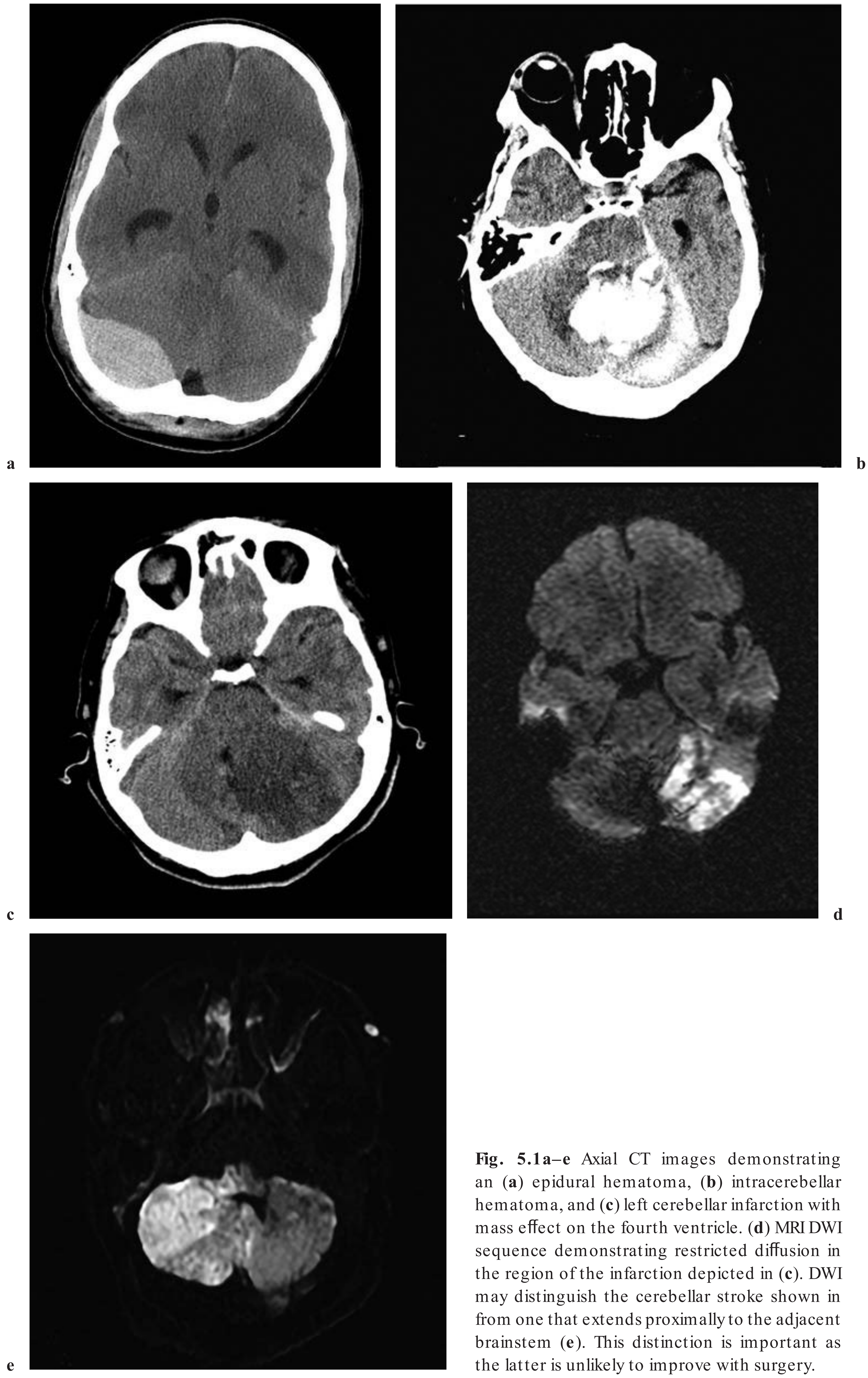

Fig. 5.1a–e Axial CT images demonstrating an (**a**) epidural hematoma, (**b**) intracerebellar hematoma, and (**c**) left cerebellar infarction with mass effect on the fourth ventricle. (**d**) MRI DWI sequence demonstrating restricted diffusion in the region of the infarction depicted in (**c**). DWI may distinguish the cerebellar stroke shown in from one that extends proximally to the adjacent brainstem (**e**). This distinction is important as the latter is unlikely to improve with surgery.

Operative Procedure

Positioning (Fig. 5.2a, b)

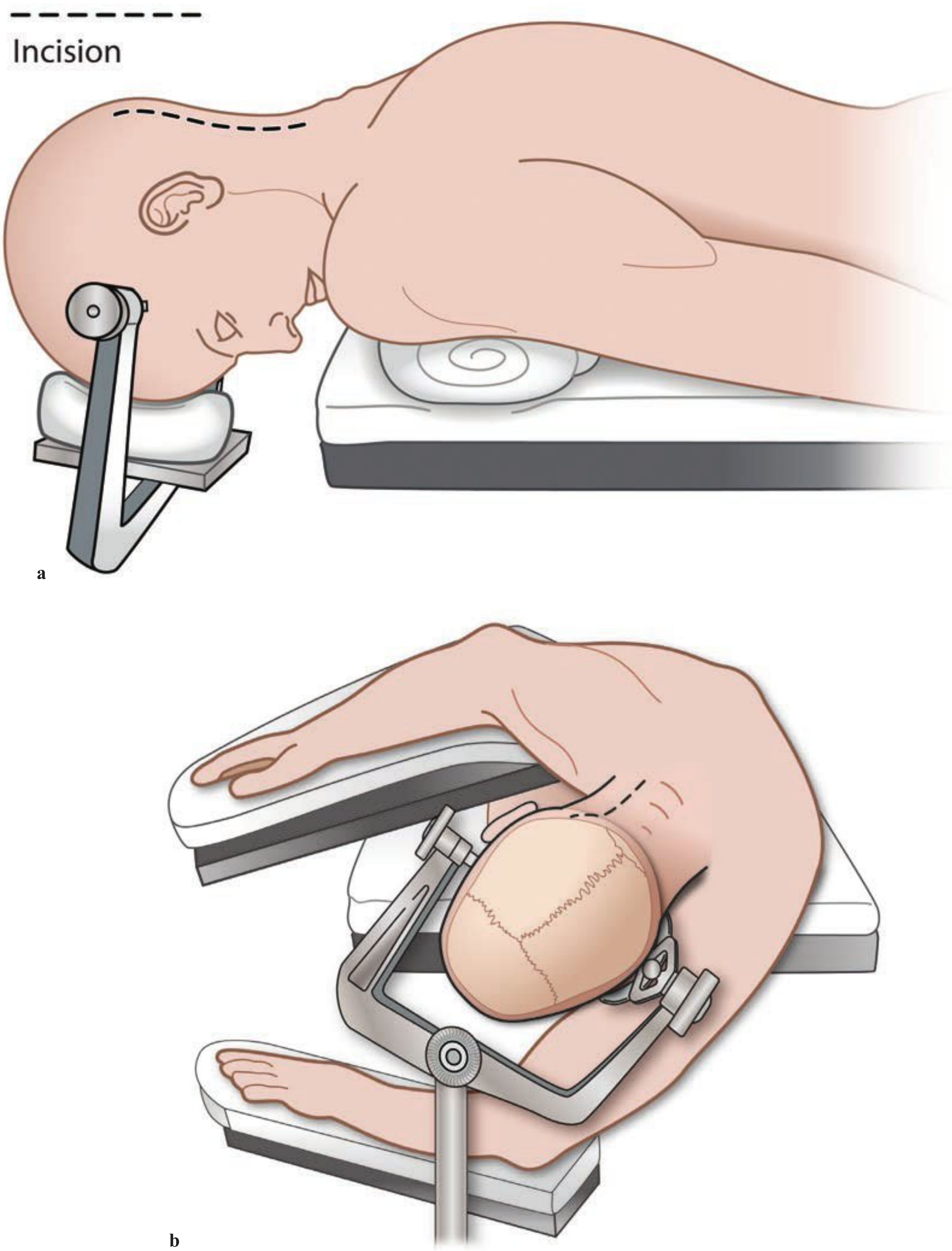

Figure	Procedural Steps	Pearls
Fig. 5.2	**Choice of the (a) prone or (b) lateral park bench position is dictated by the location of the clot, anticipated extent of exposure, and urgency of the situation (see above).**	• Make sure to protect the eyes, face, and cervical spine (if not cleared). Ensure that an armored endotracheal tube is used and secured well (by suture or tape and ties) to the external face and head holder.

Skin Incision (Fig. 5.3)

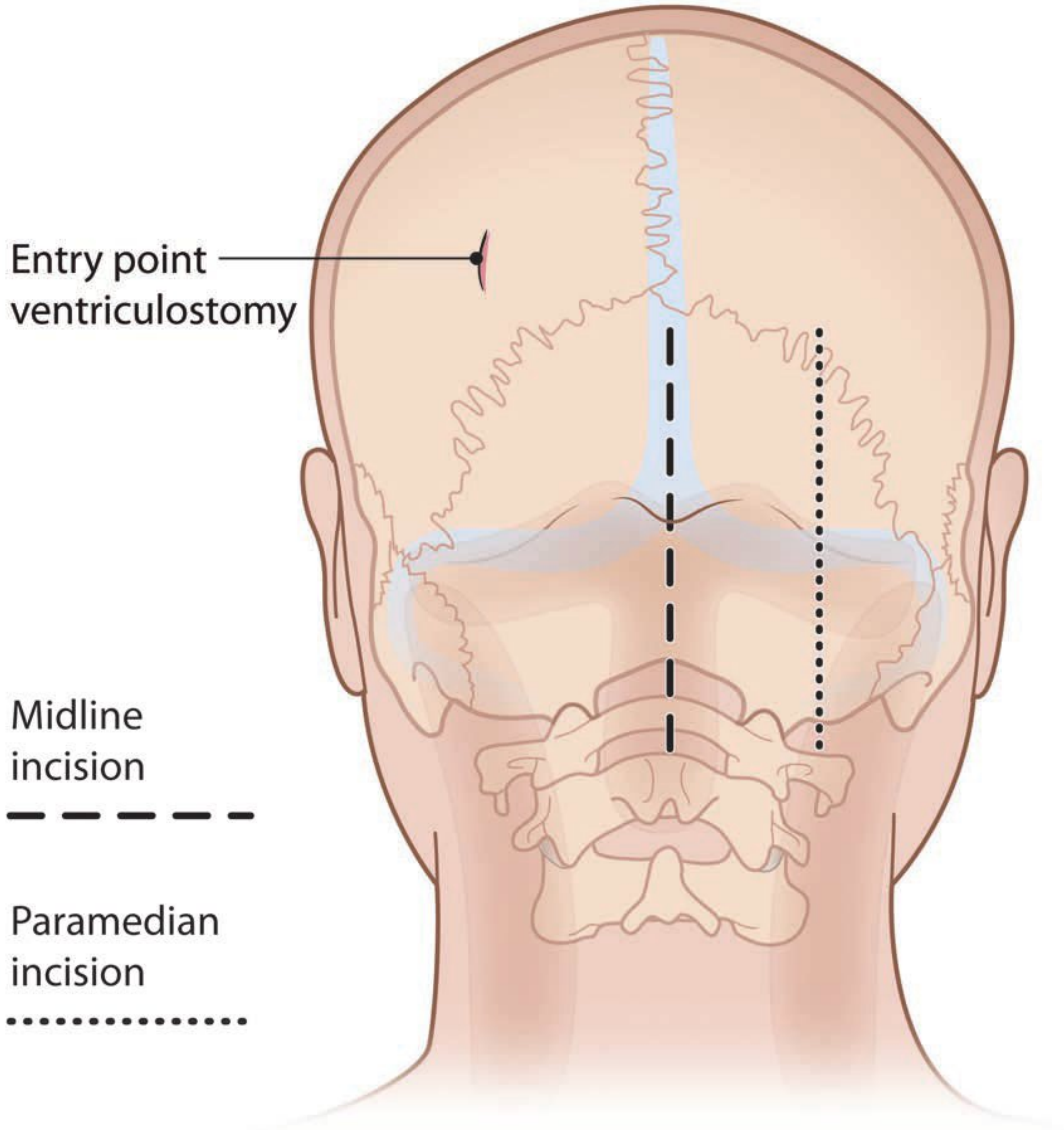

Figure	Procedural Steps	Pearls
Fig. 5.3	**The skin incision is always marked prior to skin preparation to avoid confusion after draping. If positioned prone, a midline incision is planned from the inion to the spinous process of C2. It can be extended later, if needed. A paramedian incision is used for unilateral intraparenchymal hematomas.** **The entry point for a ventriculostomy (if not placed preoperatively) should be planned and marked, using anatomic landmarks: 5 cm above the inion and 3 cm lateral to midline.** **A no. 10 blade is used to incise the skin along the previously marked line. The initial incision is carried down to the level of deep dermis.**	• Mark the midline and the position of transverse sinus (extrapolate from a line connecting the zygoma to the inion) prior to skin incision.

Subcutaneous Dissection (Fig. 5.4a, b)

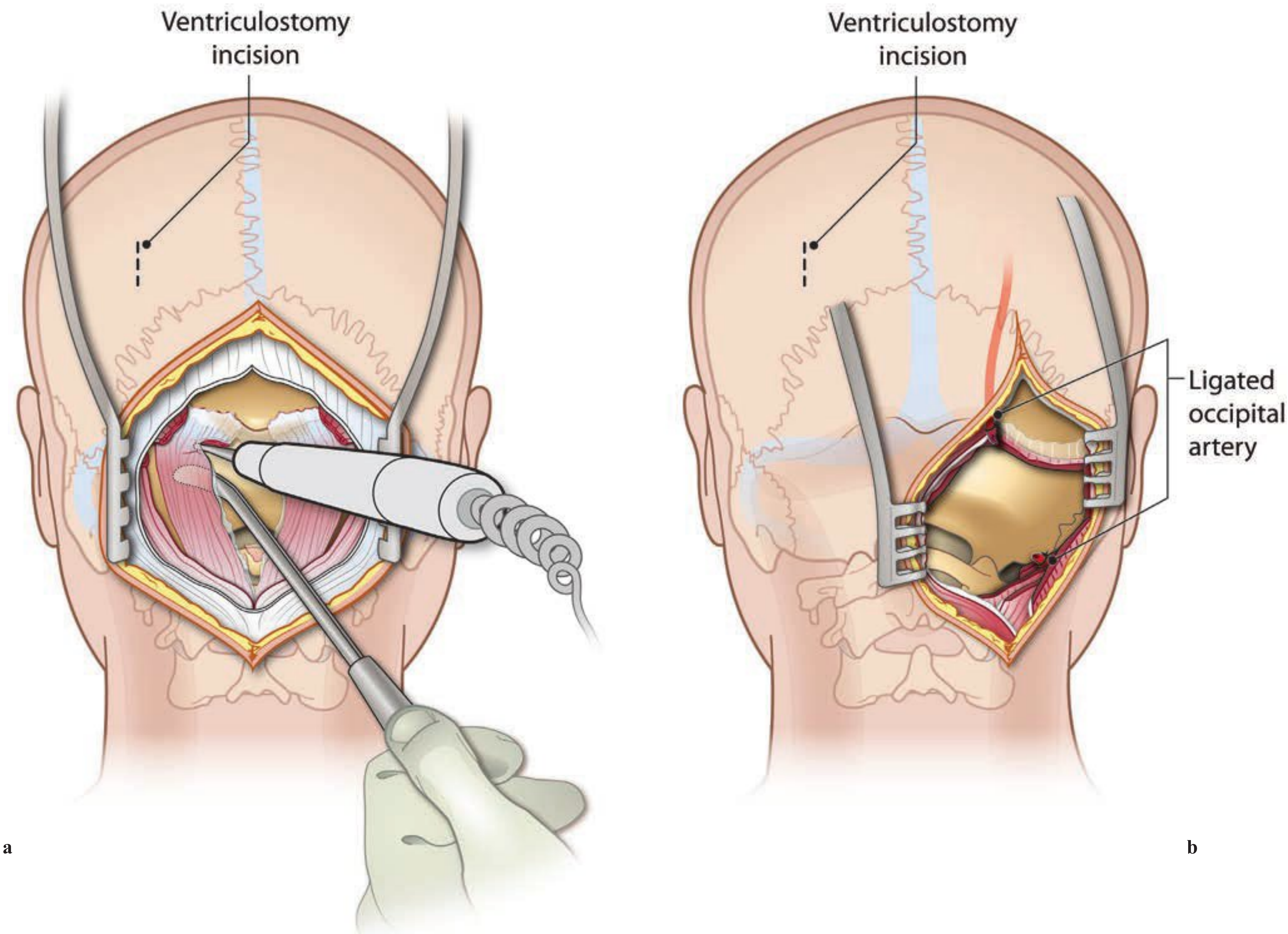

Figure	Procedural Steps	Pearls
Fig. 5.4	**(a) If using a midline approach, monopolar electrocautery is used to incise the subcutaneous fat and then deepen the incision in the avascular plane of ligamentum nuchae. The fascia should be cut sharply with a knife, instead of cautery, to avoid shrinkage. Self-retaining posterior fossa retractors assist retraction of the skin edges at this level. (b) If using a paramedian approach, muscle is divided in line with the skin incision, using monopolar electrocautery. The occipital branch of the external carotid artery (between the third and fourth layers of posterior cervical muscles) should be identified, coagulated with bipolar cautery, and divided sharply. Hemostasis is attained with monopolar or bipolar electrocautery.**	• Monopolar electrocautery should not be used when dissecting the tissue laterally at the level of foramen magnum and C1. Careful sharp dissection with Metzenbaum scissors (after thinning out the tissue by spreading) is recommended to avoid injury to the vertebral artery at this level.

Bony Exposure (Fig. 5.5)

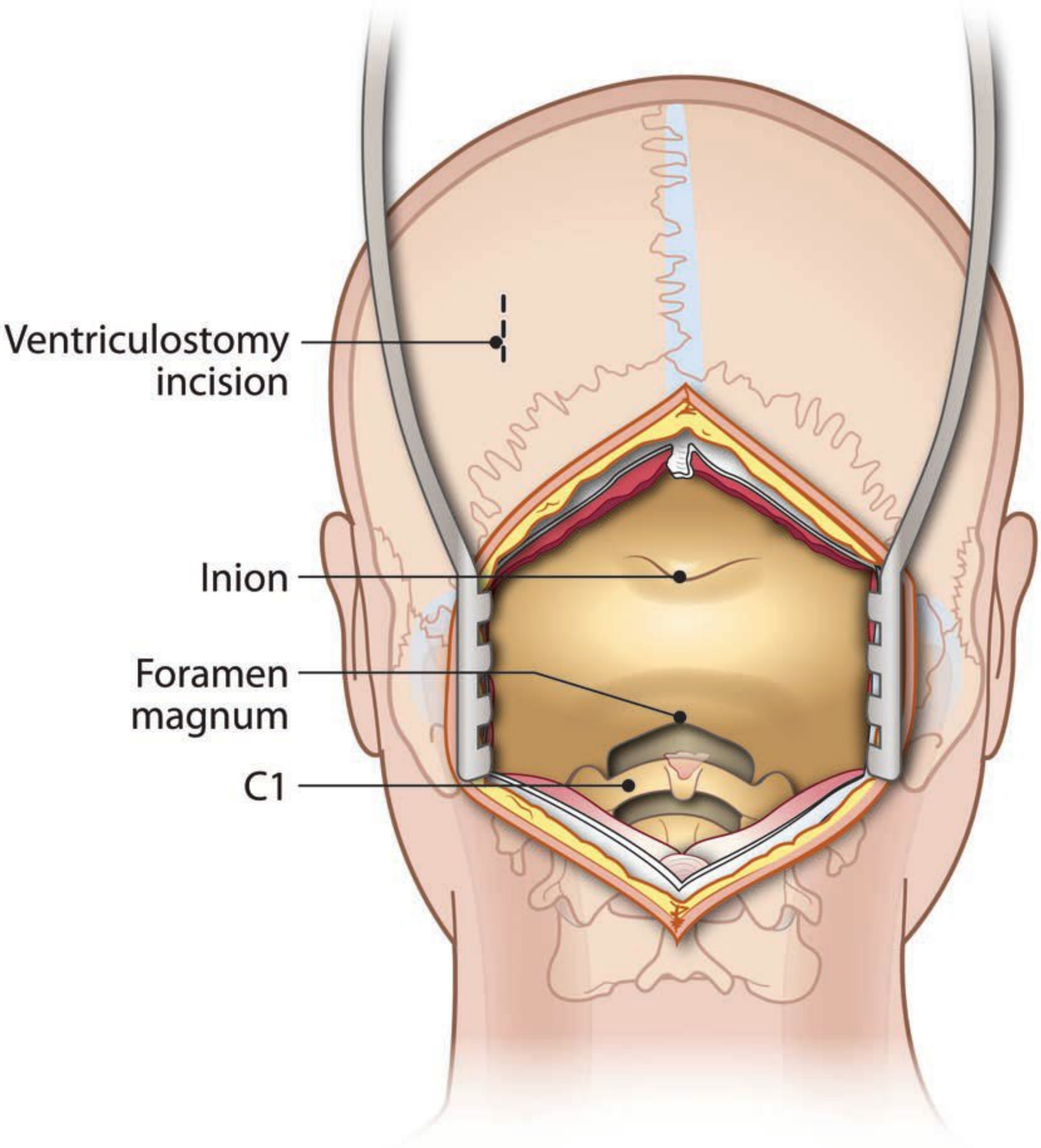

Figure	Procedural Steps	Pearls
Fig. 5.5	**The bony exposure should extend from the inion to the foramen magnum. A wide exposure is needed for cerebellar infarcts, extending laterally to a centimeter from the mastoid process. This essentially means incorporating the whole of the wide bony exposure into the craniotomy. A smaller exposure (either unilateral or bilateral depending upon the pathology) is needed for hematomas. Additional exposure can be obtained if necessary based on the CT scan findings.** **The C1 posterior arch is always exposed (20 mm on each side) but need not be resected. Deep cerebellar retractors spread the skin and dissected muscles at this level.**	• Care should be taken to avoid stripping the muscles off the spinous process and lamina of C2 as this is a major insertion point for many of the stabilizing muscles of the neck.

Bur Hole Placement (Fig. 5.6a, b)

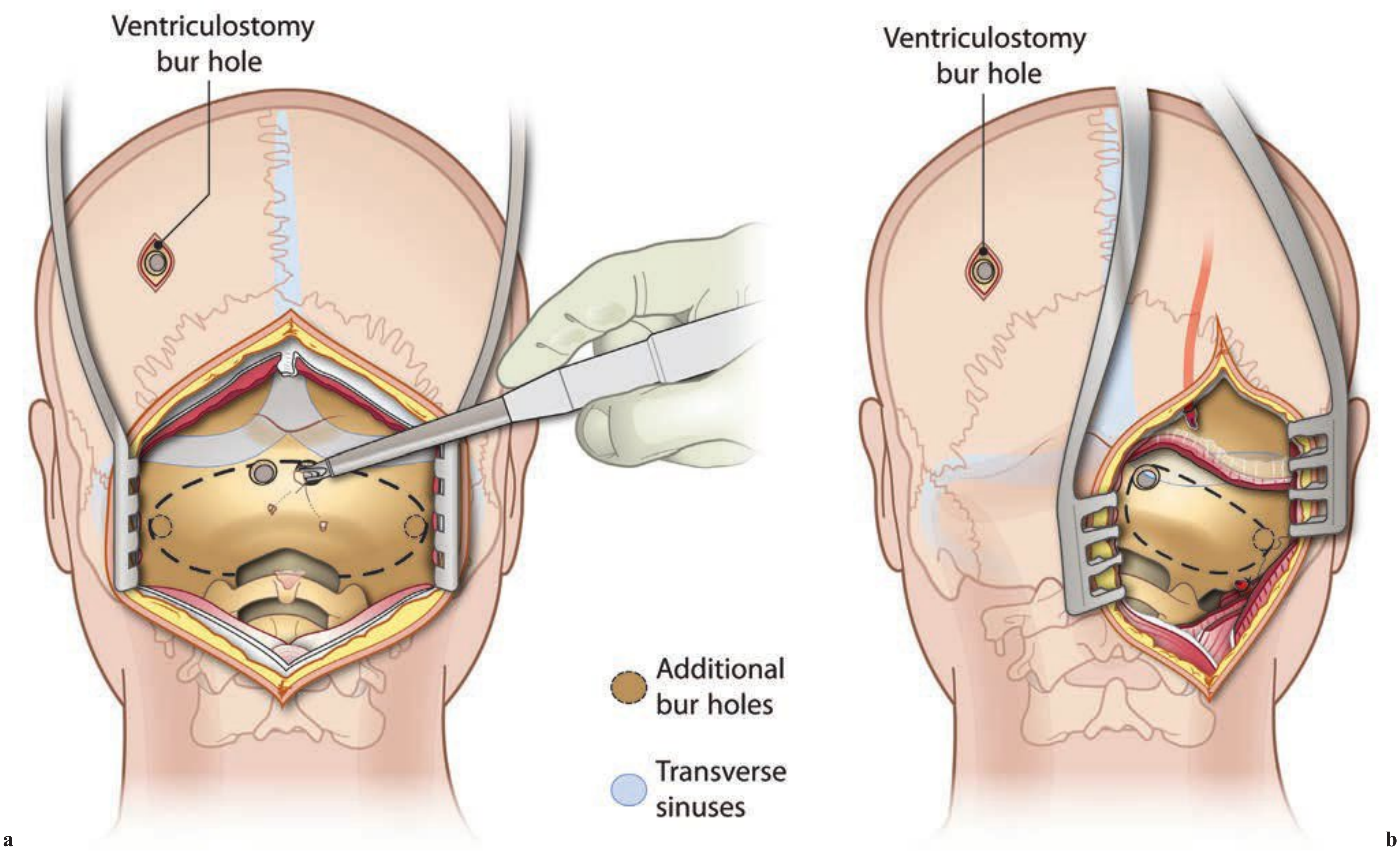

Figure	Procedural Steps	Pearls
Fig. 5.6	**(a) Bur holes are placed at the level of the transverse sinus (approximately 1 cm below the inion), to either side of midline. We typically use a perforator drill; alternately, a matchstick or acorn bur may be employed. A second set of bur holes can be made at the lateral edge of the craniotomy if the dura is very stuck to the bone, but typically only two are required. (b) For a paramedian approach, one bur hole is placed in the midline position and one at the lateral edge of the planned opening.**	• Protect the drill from slipping into the foramen magnum region during initial stages of the drilling.

Craniectomy (Fig. 5.7)

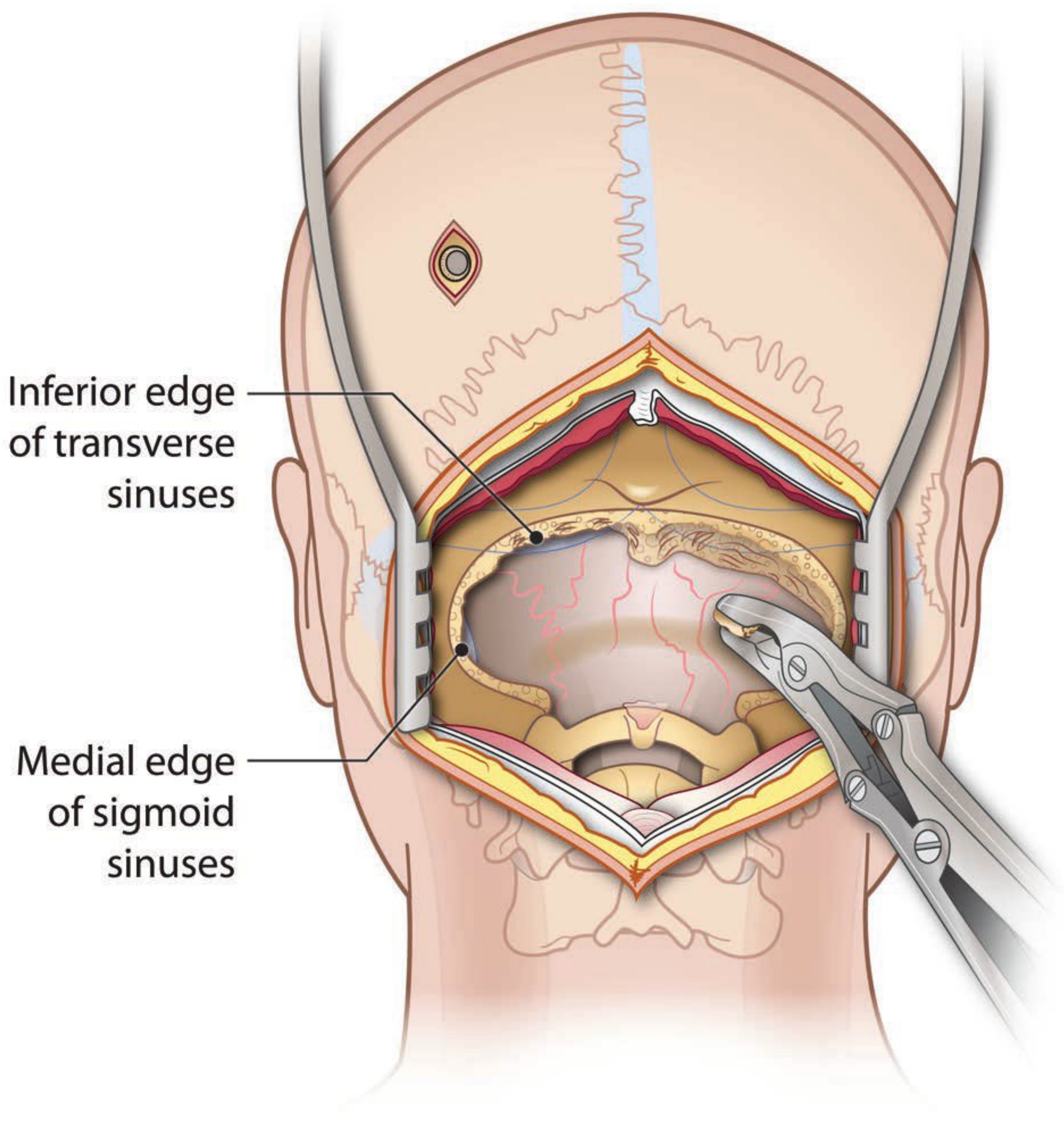

Figure	Procedural Steps	Pearls
Fig. 5.7	**An 8-mm acorn bur is used to thin the thick bone buttresses over the transverse sinuses and cerebellar convexities. When a thin shell of bone remains, a combination of Leksell rongeur and Kerrison punches may be used to complete the craniectomy.**	• The size of the craniectomy depends on the underlying pathology. Typically, infarction requires a larger exposure than hematoma.

Epidural Hematoma Evacuation (Fig. 5.8)

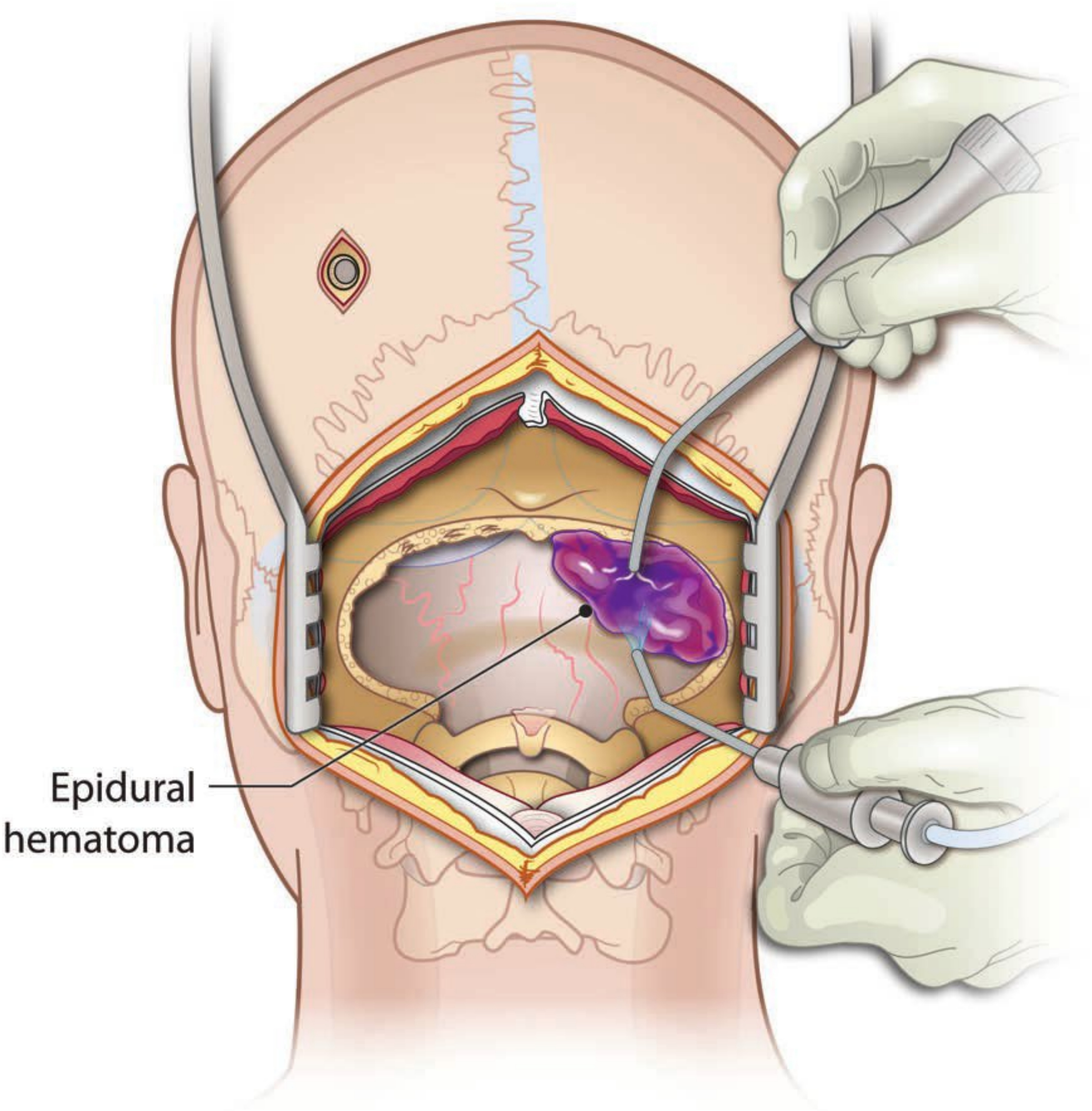

Figure	Procedural Steps	Pearls
Fig. 5.8	**In the case of an epidural hematoma, clot is immediately visible upon bony removal. Hematoma is evacuated by gentle suction. Focal bleeding points along the dural surface are identified and coagulated. Gelatin sponge powder (or bone wax, if powder is not effective) is applied to the bone edges.** **Clot removal over the sinus may produce heavy bleeding from a sinus tear. Small amounts of clot stuck to the sinuses should be left intact.** **There is no need to open the dura if the brain appears slack after evacuation of the epidural hematoma. However, if the dura is tense, subdural exploration is indicated to look for any additional clots (subdural or intracerebellar hematoma).**	• Rapid, partial decompression of the brain can be achieved by suctioning visible clot through the bur holes, prior to completion of the bony opening. However, care must be taken to avoid suctioning in the direction of the venous sinuses.

Dural Opening and Subdural Hematoma Evacuation (Fig. 5.9)

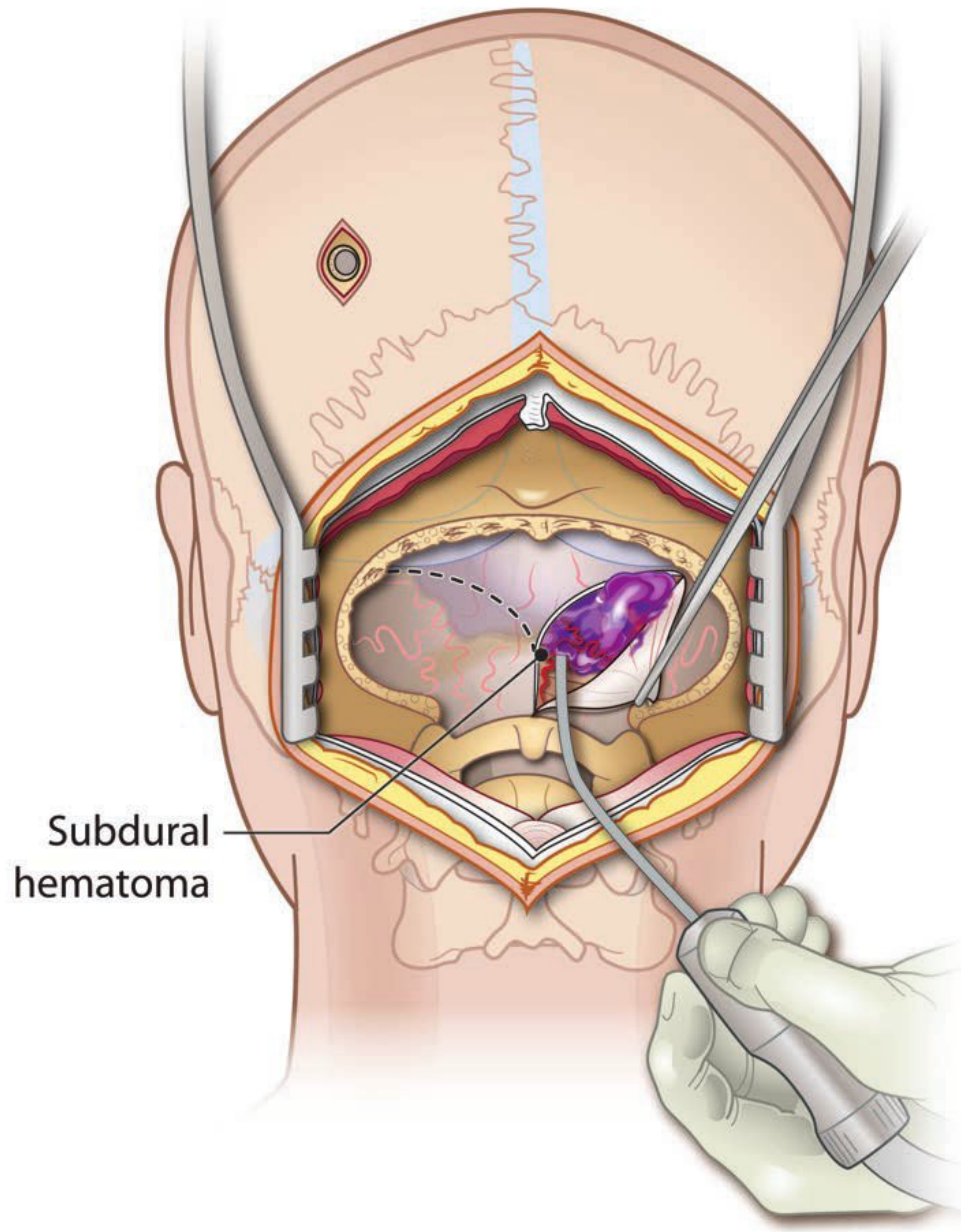

Figure	Procedural Steps	Pearls
Fig. 5.9	**The dura is opened in a Y-shaped fashion to gain adequate access to the posterior fossa contents. The superior limbs of the Y should commence just inferior to the transverse sinus. Either clot or cerebellum will usually bulge out from the dural opening at this stage. Complete the dural opening expediently while protecting the brain with a piece of nonadherent bandage or a cotton pattie to avoid incarceration between the dural edges. The inferior aspect of the opening (the stem of the Y) should extend to the foramen magnum. The dural edges may be held open with 4-0 braided nylon sutures.**	• The ventriculostomy should be opened to drain at a height of 10 to 15 cm water (zeroed to ear level) at this stage. • Be prepared for tears of the transverse sinus in trauma cases (ligating clip system, pressure, head up position). • A persistent circular sinus (or venous lakes within the dural leaves) can be a problem in children and occasionally may be encountered in adults. Coagulation with bipolar electrocautery and/or the use of ligating vascular clips may be necessary.

Intracerebellar Hematoma Evacuation (Fig. 5.10)

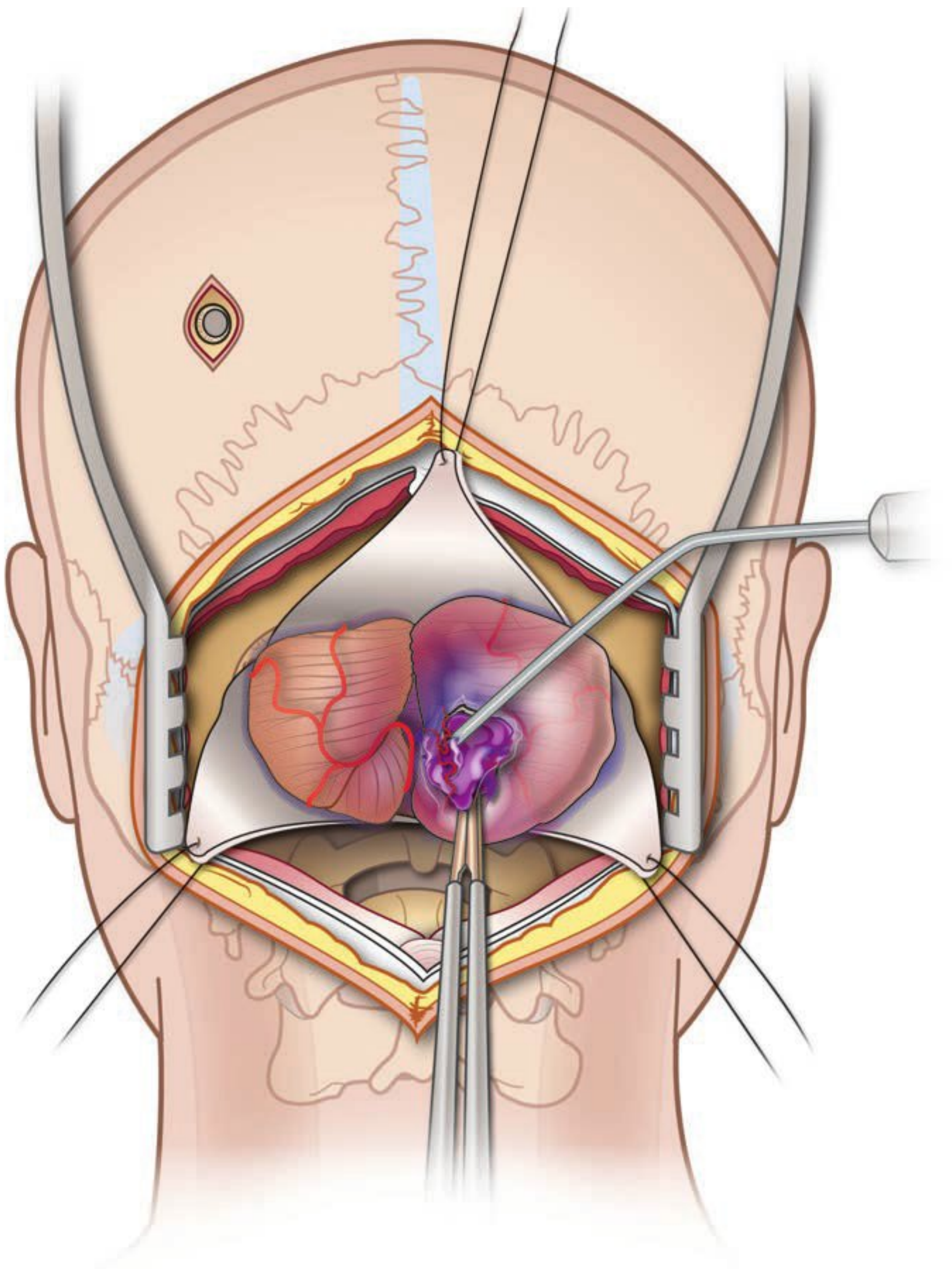

Figure	Procedural Steps	Pearls
Fig. 5.10	**In case of an intracerebellar hematoma, a 2- to 3-cm corticectomy is made over the site of clot presentation with a bipolar and microscissors/no. 11 blade. White matter is gently suctioned in the direction of the clot until the hematoma cavity is accessed. A brain cannula (e.g., Dandy) can be passed into the clot to assist in localization.**	• Ultrasound can be useful for smaller and/or deeply located hematomas, or if the hematoma is not found at the anticipated site after the corticectomy.
	The clot is gently suctioned out using no. 9 or no. 12 suction tips. Discrete bleeding points are identified and coagulated. Self-retaining brain retractors assist the exposure during hemostasis. Fukushima (teardrop side port) suction tips (e.g., no. 7) may be useful during the hemostasis stage.	• Surgical loupes and a headlight are useful adjuncts at this point.
	The brain will usually be slack after clot removal. If not, cerebrospinal fluid drainage from the cisterna magna should be attempted prior to resection of edematous cerebellum.	• Always keep in mind the location of the fourth ventricle while suctioning the depths of the hematoma cavity.

Decompression of Infarcted Brain (Fig. 5.11)

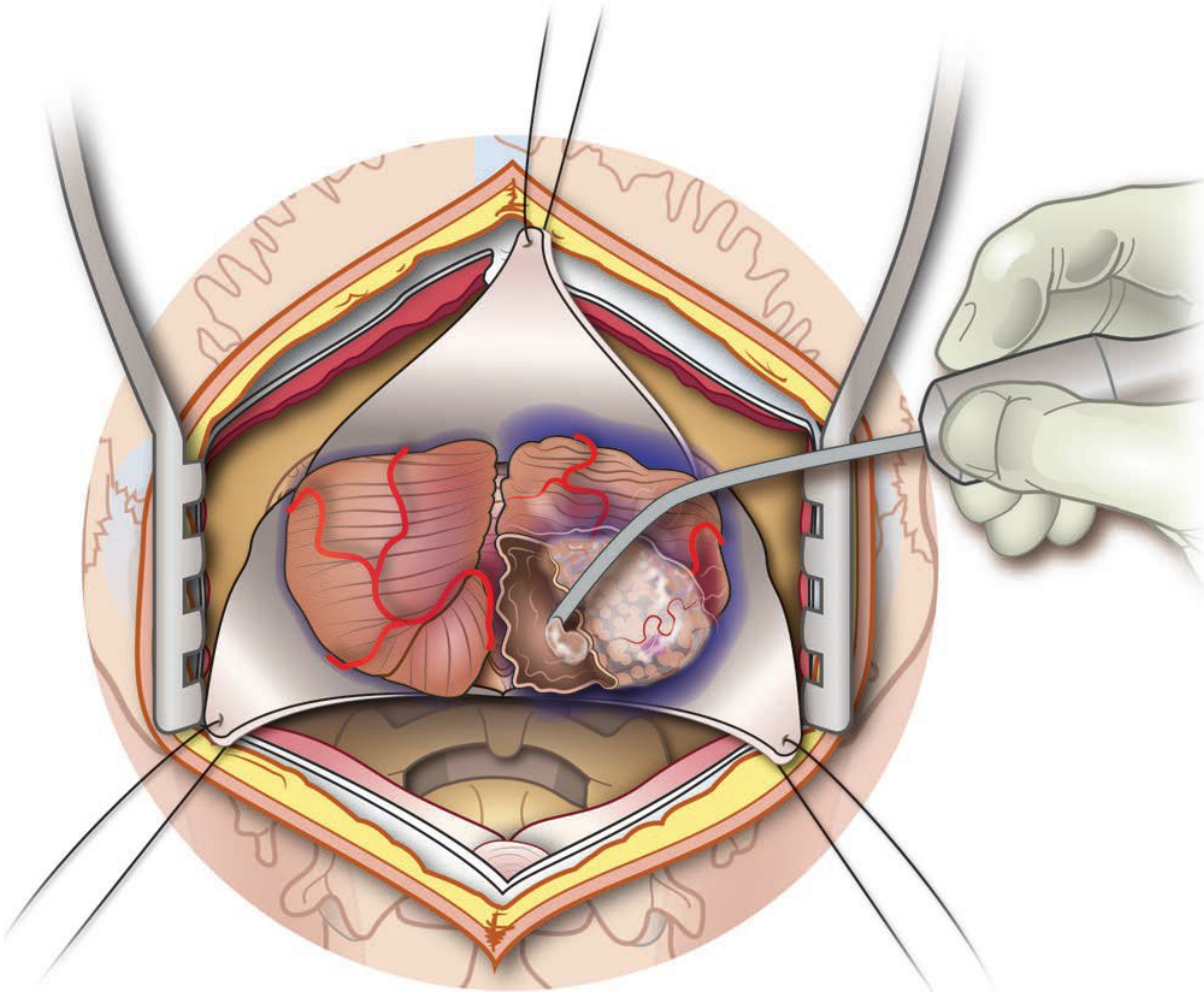

Figure	Procedural Steps	Pearls
Fig. 5.11	**In the case of surgery for infarction, wide decompression is the primary objective. The posterior rim of the foramen magnum should always be opened. Resection of infarcted cerebellum is required only if closure is difficult. Release of cerebrospinal fluid from the cisterna magna is more useful for infarcts than for hematoma.**	• In some cases, severe cerebellar swelling due to autonomic dysregulation can occur.

Hemostasis (Fig. 5.12)

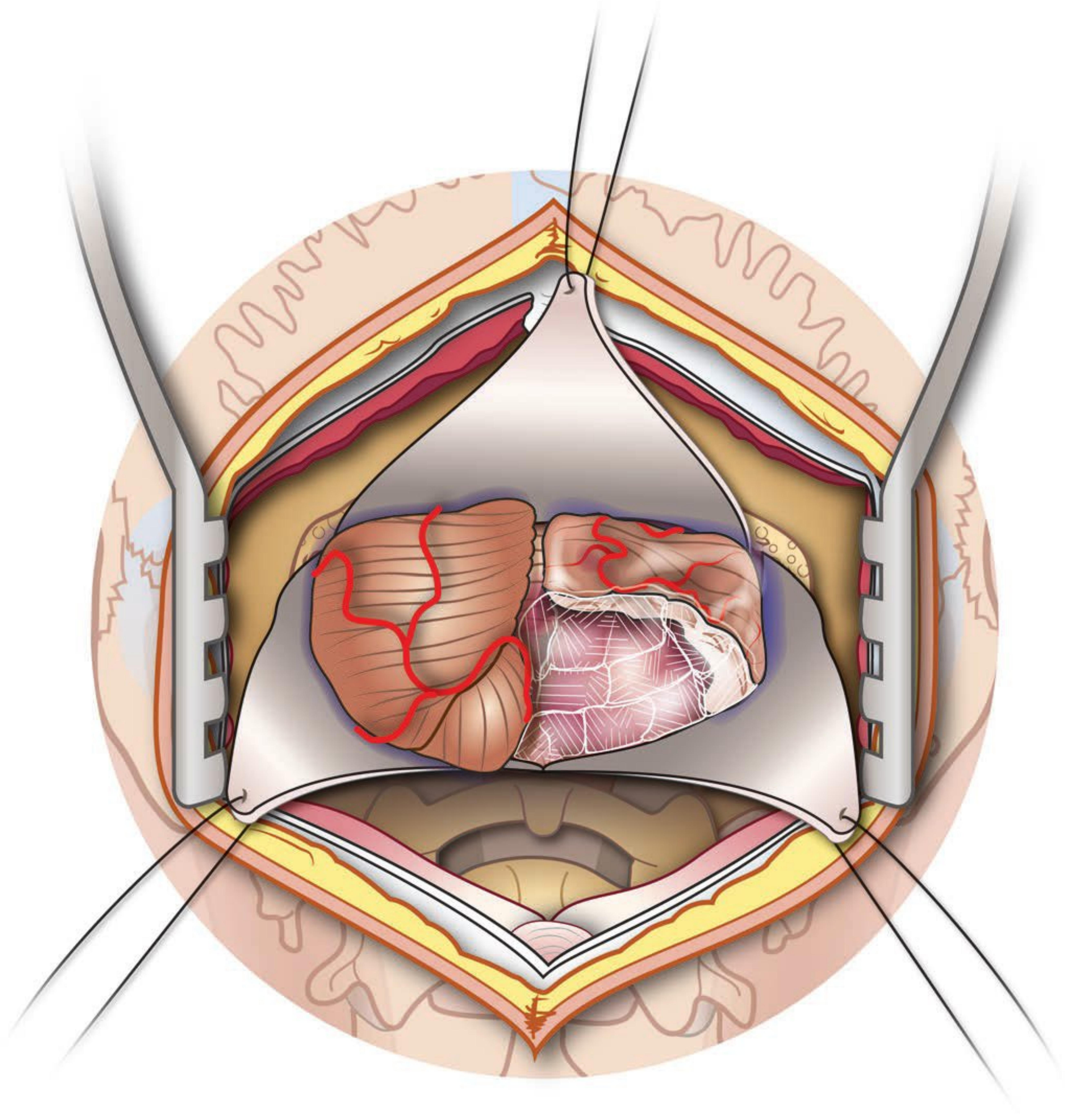

Figure	Procedural Steps
Fig. 5.12	**Hemostasis is attained within the resection cavity with pinpoint bipolar coagulation and again confirmed by Valsalva maneuver. The walls of the cavity then are lined with an absorbable hemostatic agent.**

Dural Closure (Fig. 5.13)

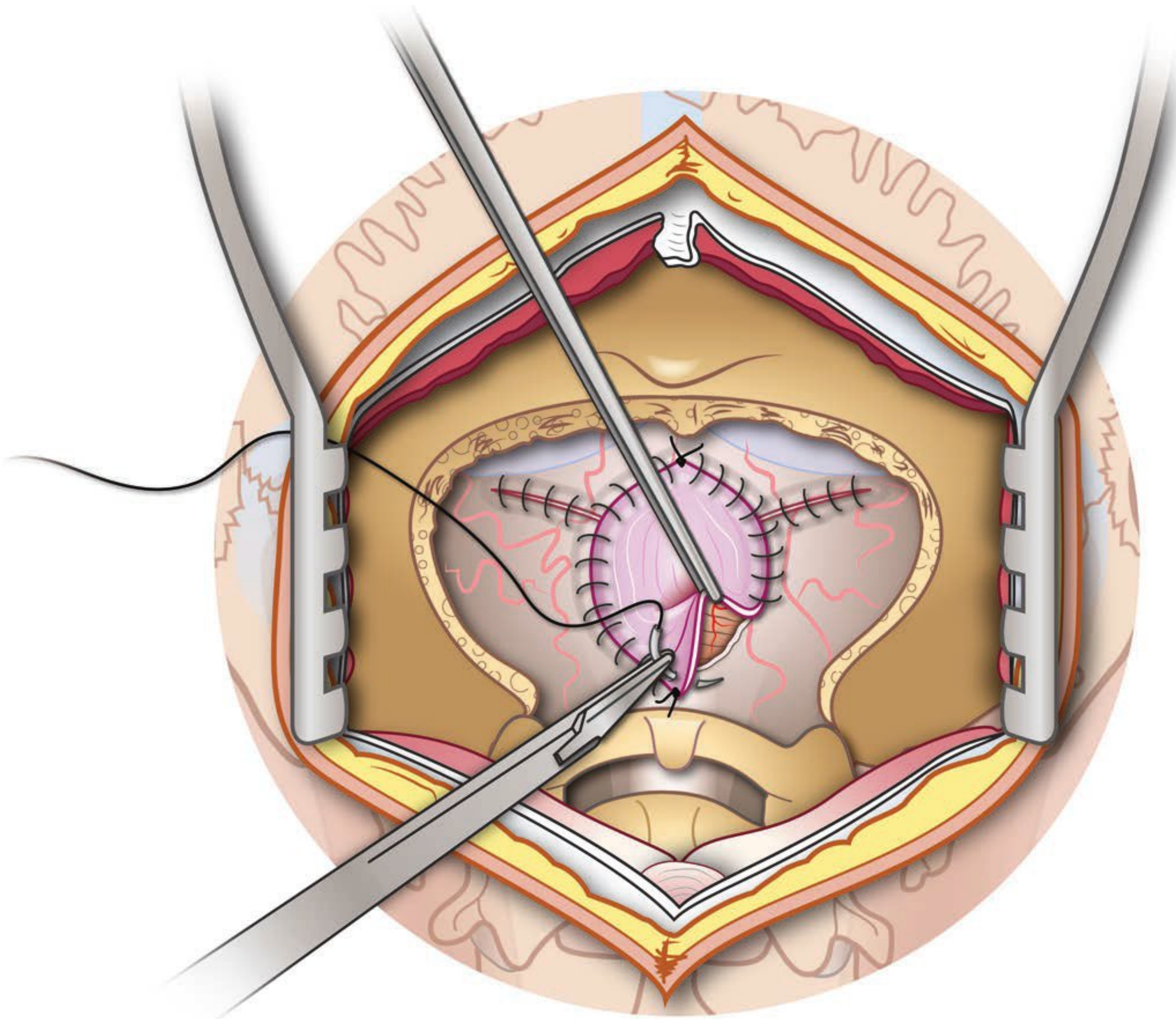

Figure	Procedural Steps	Pearls
Fig. 5.13	**Once an adequate decompression is achieved, the native dura is** not **reapproximated. Duraplasty may be performed with local pericranium, cadaveric dura, or synthetic materials. Dural substitutes may be used as an onlay or incorporated with the native dural edges using a 4-0 braided nylon suture.**	• Duraplasty, in the setting of cerebellar infarction, is mandatory to accommodate anticipated swelling.
	Epidural tacking stitches are not necessary except in the setting of epidural hematoma.	• If epidural tacking stitches are placed, care must be taken (in particular, along the superior edge) to avoid the venous sinuses.

Closing

- The craniectomy defect is not closed. Replacement of bone or mesh reconstruction of the calvarium would defeat the purpose of the procedure. Patients seldom require delayed cranioplasty for this indication.
- After achieving hemostasis and irrigating the wound with antibiotic solution, the neck muscles are approximated loosely with 2-0 braided absorbable interrupted sutures.
- The need for a subgaleal drain is assessed on a case-by-case basis.
- The fascia is closed tightly with the same suture.
- Subcutaneous tissues are approximated with 3-0 braided absorbable sutures.
- The authors prefer to approximate the skin with staples due to their inertness, minimal risk for tissue necrosis, and speed of use. Alternately, 3-0 nylon or polypropylene interrupted stitches may be used for skin closure.

Postoperative Management

Ventriculostomy

- Ventriculostomy is mandatory to preempt recurrence of obstructive hydrocephalus (secondary to hemorrhage or swelling) in the early postoperative period.
- The drain is maintained in the open position, at a height of 10 cm H_2O. If drainage is minimal (, 50 mL) in 24 hours, it is closed for 24 hours and then removed, provided a repeat CT scan shows normal ventricular size.

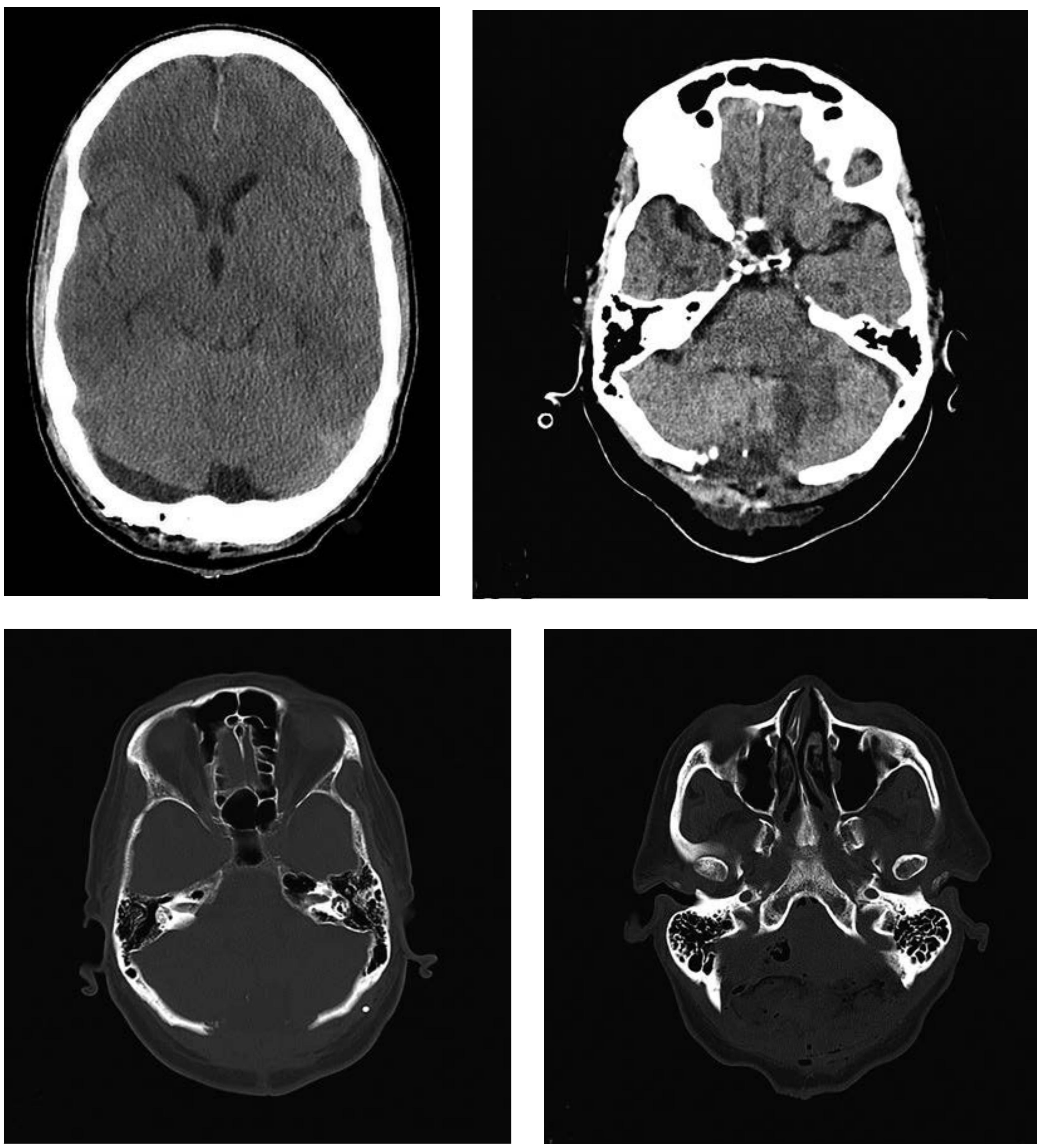

Fig. 5.14a–d (**a**) Axial CT image demonstrating resolution of hydrocephalus following evacuation of a posterior fossa epidural hematoma. (**b**) Axial CT soft tissue and (**c**) bone windows demonstrating a tailored approach for evacuation of an intracerebellar hematoma. (**d**) Axial CT bone window demonstrating the bony margins of a wide suboccipital craniectomy for decompression in the setting of ischemic stroke.

Monitoring

- The patient is observed in a monitored setting (intensive care unit), at least overnight.
- No sedation is given if the patient is extubated.

Medication

- Prophylactic antibiotics are continued for 24 hours, regardless of the presence of ventriculostomy.

Radiographic Imaging

- A noncontrast CT scan is obtained in the early postoperative period to assess the status of the hemorrhage, decompression, and ventricular size. The early postoperative study also allows screening for the development of a delayed epidural or intracerebral hemorrhage at a distant, supratentorial location—which is not uncommon.
- **Postoperative imaging (Fig 5.14).**

Further Management

- The drain (if present) is removed over the next 24 to 48 hours.
- Skin sutures or staples are removed after 1 to 2 weeks.

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6 Elevation of Depressed Skull Fractures

Anand Veeravagu, Bowen Jiang, and Odette A. Harris

Introduction

Depressed cranial skull fractures often result from high energy, blunt, traumatic impacts. Most depressed fractures are located in the frontoparietal region. Although clinical presentation is variable, approximately 25% of patients with depressed fractures present with loss of consciousness and clinical sequelae of intracranial hemorrhage.[1]

A depressed cranial fracture may be characterized further as “open” or “closed,” based on the integrity of the overlying scalp. Closed fractures, wherein the scalp is intact, may be treated nonsurgically if the depth of the depressed segment is less than the measured width of the calvarial bone adjacent to the fracture. Open fractures communicate with the external environment and, as such, are presumed contaminated. Surgical intervention is often required in these cases for debridement, repair of dural lacerations, cleansing of bone fragments, evacuation of underlying hematoma, and elevation of the depressed fracture.

Indications[2]

- Presence of an open, depressed fracture in an infant or child.
- Depression of the fracture segment greater than 5 mm below the inner table of the adjacent calvarial bone in an adult.
- Presence of gross contamination, significant extra- or intra-axial hematoma, and/or pneumocephalus suggestive of a dural tear.
- Neurologic progression in the setting of a closed fracture may be due to an associated expanding hematoma or compressive effect of the depressed bone fragment. In this case, elevation of the fracture is indicated.
- Depressed fractures crossing dural venous sinuses deserve special consideration. While compression of a dural venous sinus may induce elevated intracranial pressure and heighten the risk of venous thrombosis, the risk of hemorrhage with fracture mobilization may also be significant. Therefore, it is reasonable to observe a neurologically stable patient with a closed fracture overlying a dural venous sinus. Likewise, scalp debridement alone (without fracture elevation) is an option for a neurologically stable patient with an open fracture overlying a patent sinus. A neurologically unstable patient, however, should undergo elevation urgently.

Preprocedure Considerations

Radiographic Imaging

- Computed tomography (CT) is the standard imaging modality used to assess calvarial integrity and associated intracranial injury in the acute setting. CT venogram (CTV) may be utilized to assess sinus injury.
- Magnetic resonance imaging (MRI)/angiography (MRA) may be used to diagnose suspected vascular injury (e.g., to a dural venous sinus).
- Anteroposterior and lateral skull radiographs are used rarely to delineate bony injury and/or the presence of missile fragments.
- **Preoperative imaging (Fig. 6.1).**

Medication

- Open fractures should be treated consistent with other open lacerations. This includes administration of tetanus toxoid and broad-spectrum antimicrobial prophylaxis.
- If elevated intracranial pressure is suspected, additional management, in accordance with traumatic brain injury (TBI) guidelines, is recommended. This may include hyperosmolar therapy.
- Antiepileptic drug (AED) prophylaxis is appropriate for the prevention of early seizures in the setting of TBI, with intracranial pathology identified on CT imaging.

Operative Field Preparation

- Limited clipping of local hair is reasonable for a closed, compressed fracture. A wider approach may be necessary in the setting of an open, compound fracture with anticipated or known intracranial injury.
- Standard sterile surgical technique is used to prepare the operative site.
- Incisions are marked and infiltrated with 1% lidocaine with 1:100,000 epinephrine.
- Prophylactic antibiotics are administered.
- Availability of blood products should be dictated by the type of injury and planned surgical intervention. Rapid and significant blood loss is possible, for example, in the setting of a suspected dural venous sinus injury.

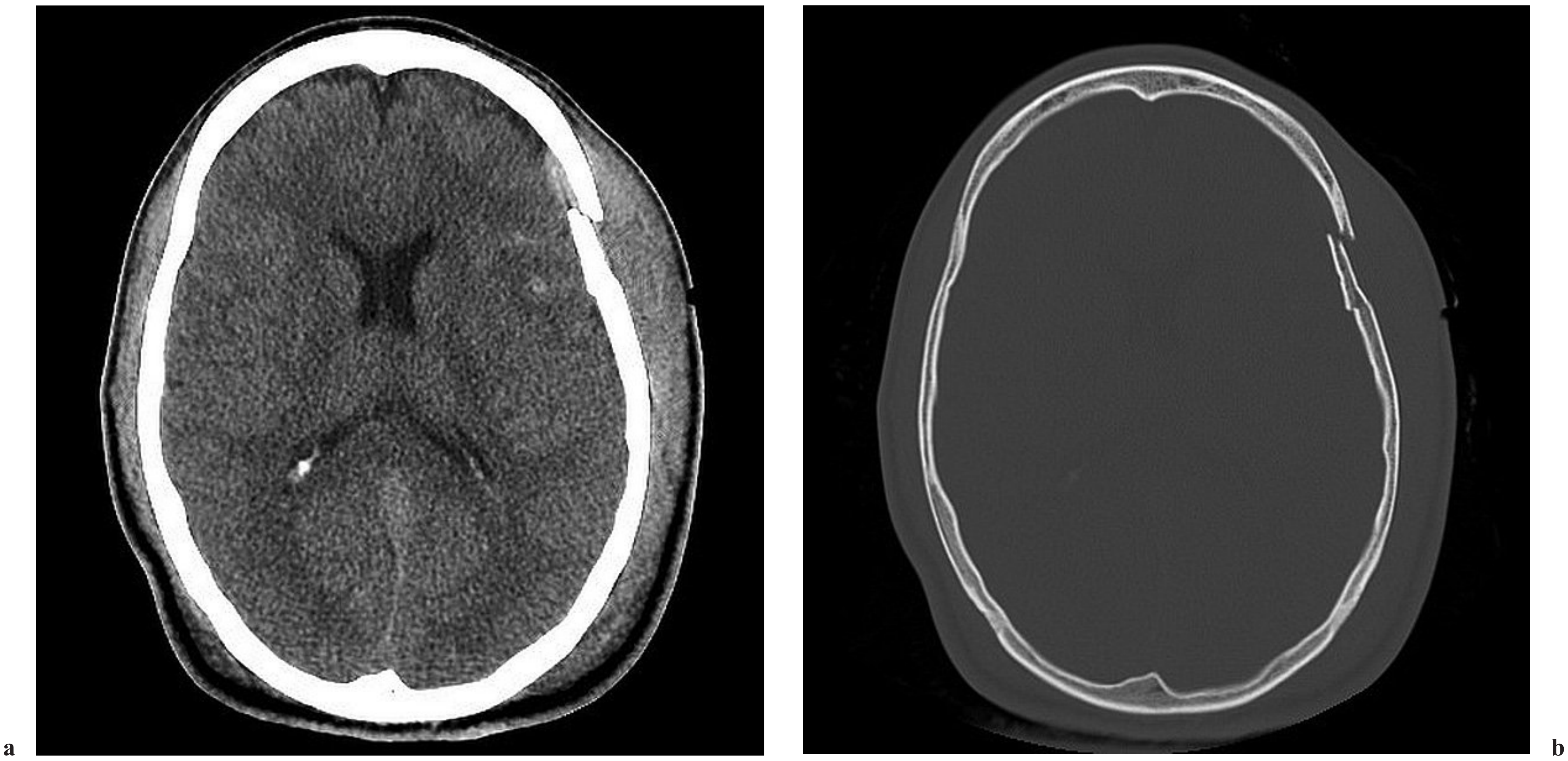


Fig. 6.1a, b Axial CT (**a**) brain and (**b**) bone windows demonstrating a focal comminuted and depressed left frontal skull fracture with associated extra-axial blood and parenchymal contusion.

Operative Procedure

Positioning (Fig. 6.2)

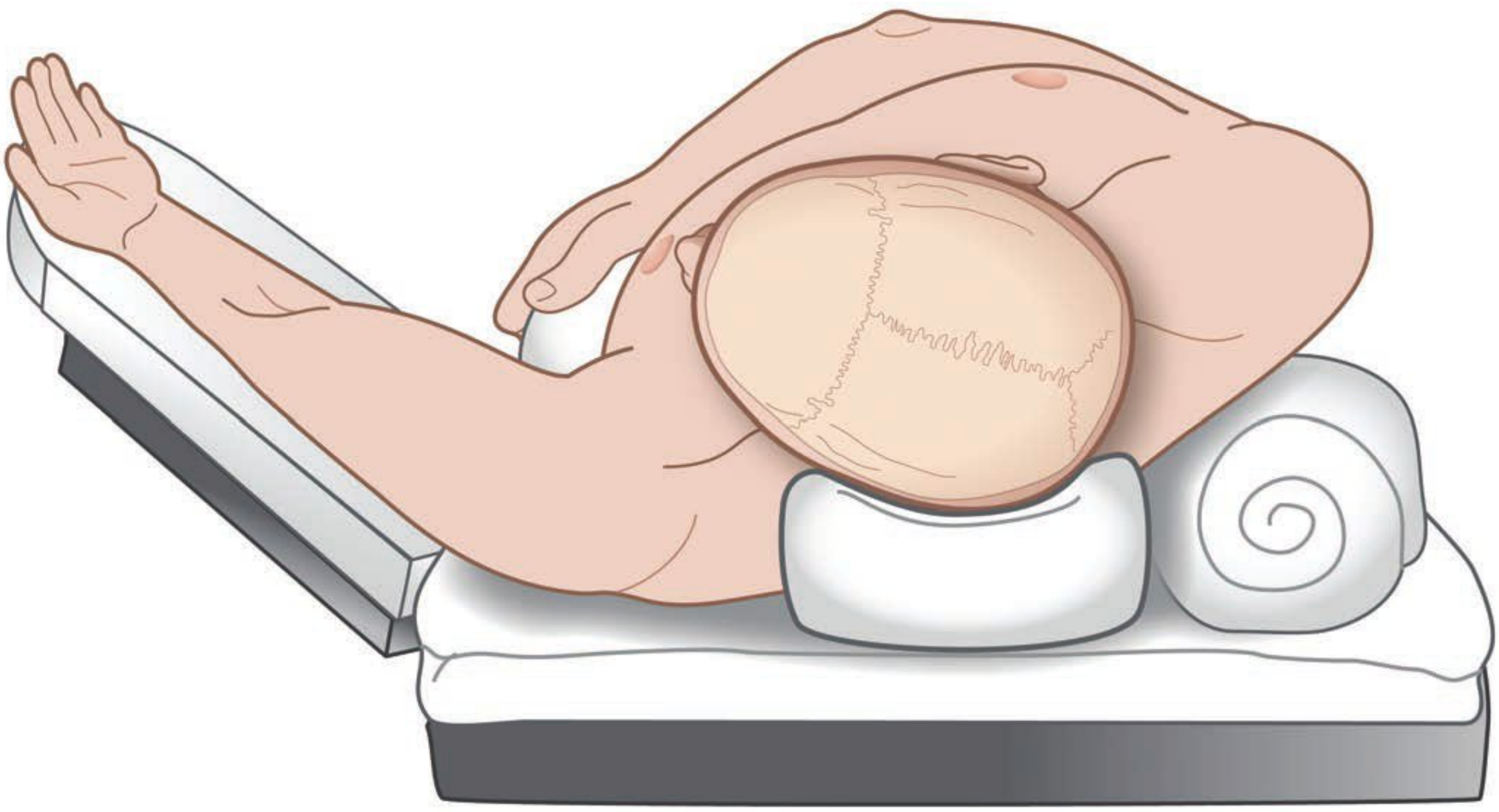


Figure	Procedural Steps	Pearls
Fig. 6.2	**Patient position is dictated by location of injury and planned surgical procedure. In the event of a standard frontotemporoparietal craniotomy, the patient may be positioned supine, with the head turned to the contralateral side. An ipsilateral shoulder roll may be placed and the head of the bed elevated slightly. A horseshoe-shaped headrest should be used.[3]**	• A slightly elevated position may improve the surgeon's view of the injury, but may also increase the risk of air embolism. Head flexion should be minimized to avoid obstruction of venous outflow and increased airway resistance.

Skin Incision (Fig. 6.3a, b)

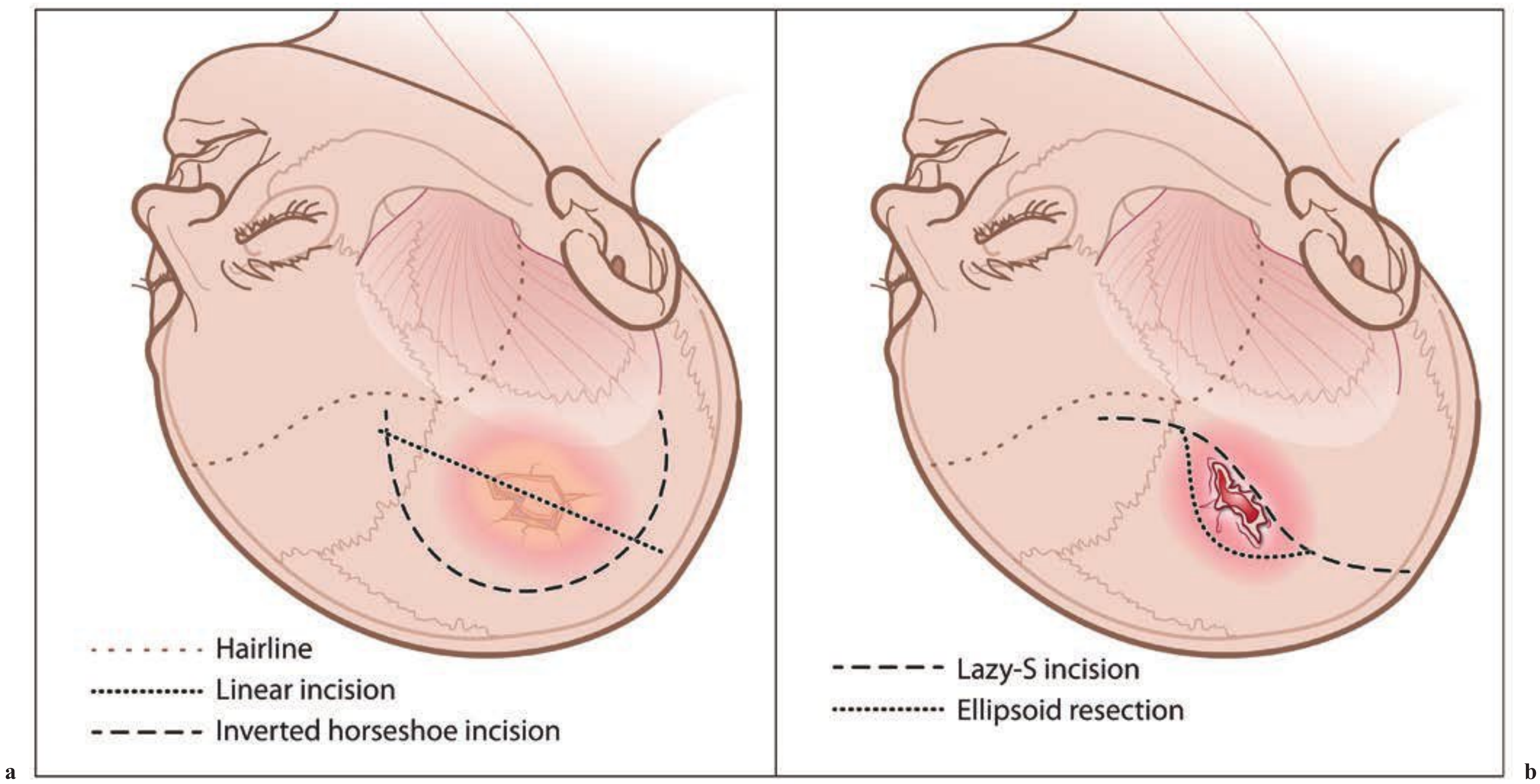


Figure	Procedural Steps	Pearls
Fig. 6.3	**Superficial debridement may be necessary at the planned incision site for open fractures. A (a) linear, (a) inverted horseshoe, or (b) lazy-S incision may be selected, based on the actual fracture location and the presence of a scalp disruption. (b) Scalp lacerations should be excised as an ellipse and incorporated into the incision if possible. A bicoronal incision is preferred for access to depressed fractures in the forehead area.**	• When feasible, the incision should be planned posterior to the hairline.

Subcutaneous Dissection (Fig. 6.4)

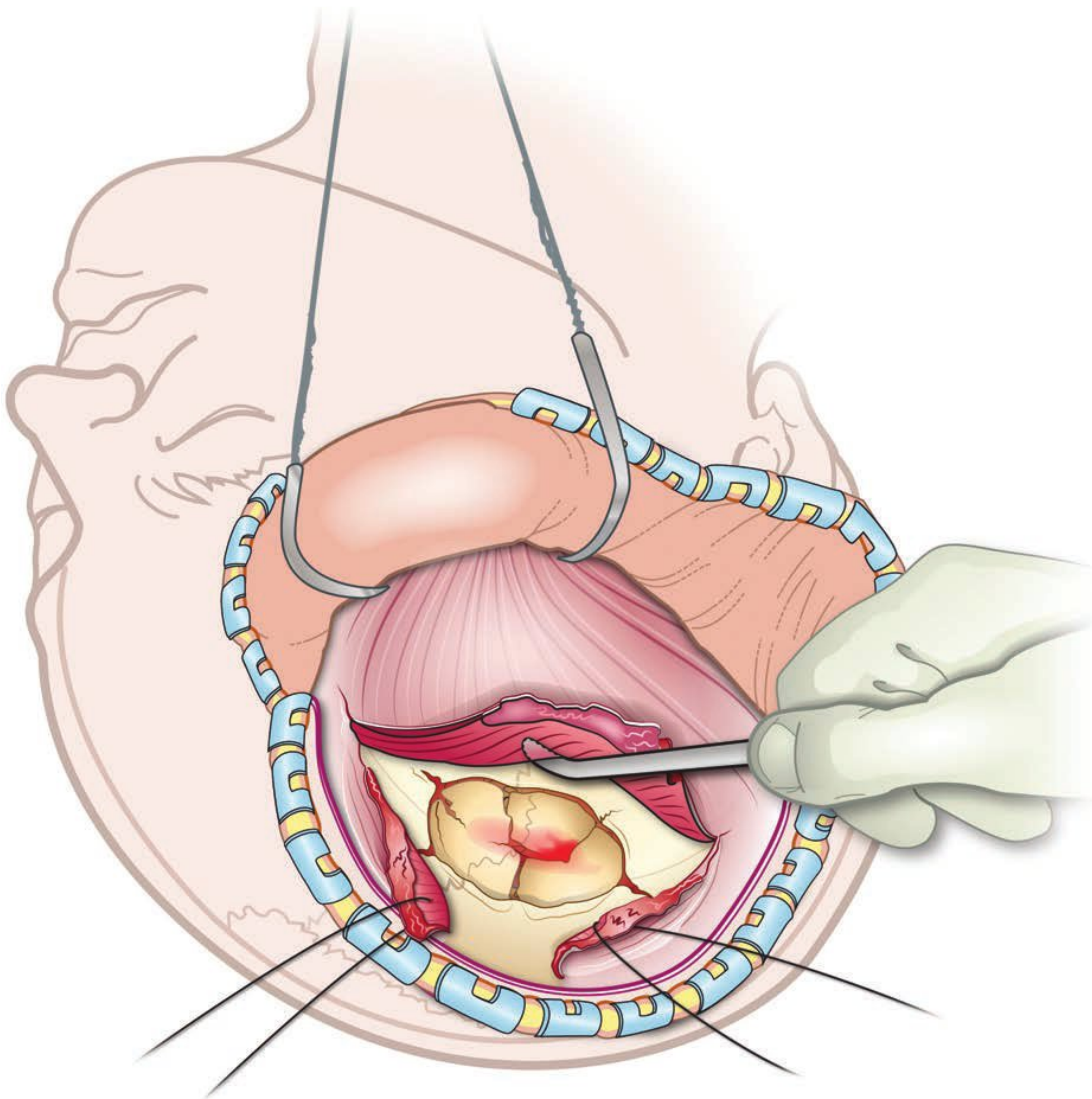


Figure	Procedural Steps	Pearls
Fig. 6.4	**Bipolar electrocautery is used for hemostasis. The scalp flap can be separated from the pericranium using a periosteal elevator. The plane between pericranium and galea may be developed with sharp dissection.** **The temporalis muscle may be exposed and the fascia incised for dissection using monopolar cautery. Well-preserved muscle can be separated from the underlying bone using sharp dissection. The muscle should be reflected inferiorly and secured with suture or hook-based retraction.** **For closed fractures, the underlying skull is inspected and loose fragments removed. Contused pericranium in an open fracture is incised, with the corresponding clean pericranium elevated to allow for inspection of the bone.**	• Where palpable and/or visible bony depression is present, the temporalis should be dissected away from the underlying bone with a periosteal elevator. Avoid the use of monopolar electrocautery in these areas. • Any impacted fragments that may be compressing or lacerating dura are not yet removed at this stage.

Craniectomy (Fig. 6.5a–c)

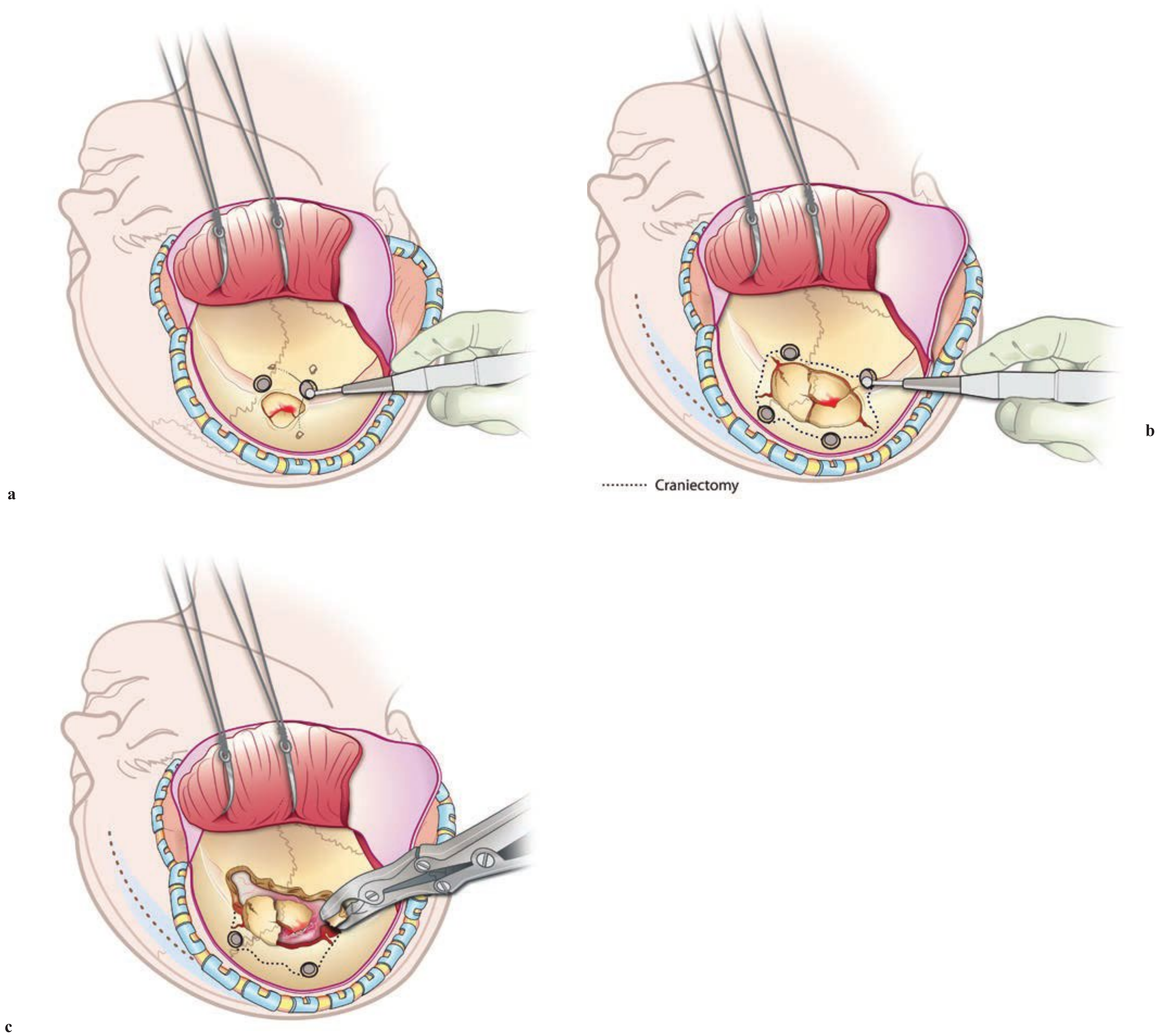


Figure	Procedural Steps	Pearls
Fig. 6.5	**(a) A standard, high-speed neurosurgical drill is used to create several points of trephination in the normal bone lateral to the rim of the depressed bone. (b) In the setting of an open fracture, a larger craniectomy that incorporates the traumatic fracture line may be planned. (c) Leksell rongeurs (or a matchstick bur) can be used to complete a circumferential craniectomy, maintaining a margin of normal bone around the area of depression. Free bone fragments are carefully removed and discarded.**	• Bone edges are waxed. Salvageable bony fragments should be soaked in antibiotic solution before being reassembled.

Depressed Fracture Elevation and Exploration of Dural Tears[4] (Fig. 6.6)

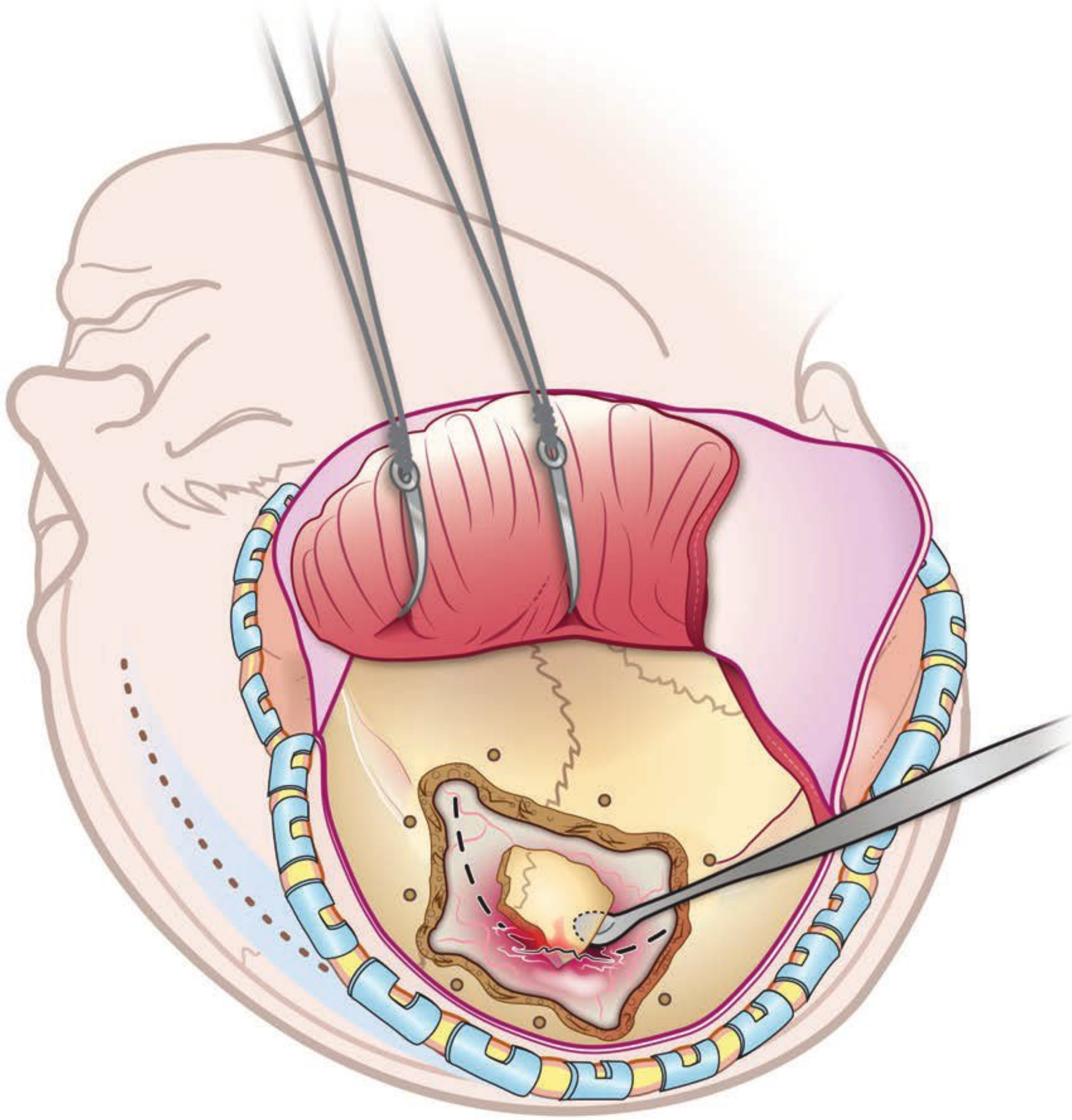
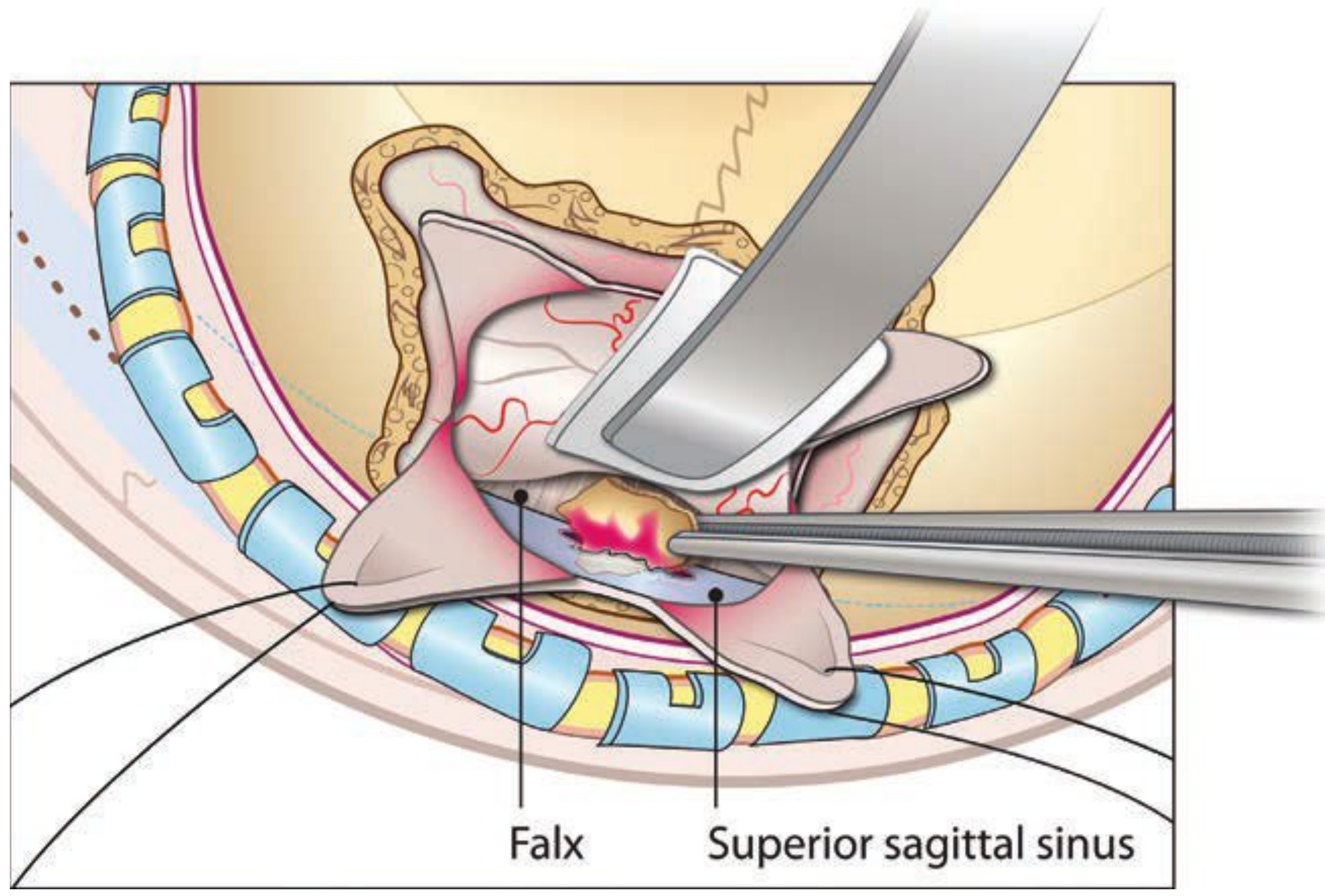


Figure	Procedural Steps	Pearls
Fig. 6.6	**The depressed bone is elevated with a no. 1 Penfield. Epidural hematoma, if present, is evacuated. Bleeding dural vessels are cauterized. Any area of dural penetration should be explored. This may require extension of the dural defect to permit adequate visualization of the subdural space and cortex. If the dural tear cannot be approximated primarily, interposition of a pericranial graft may be necessary.** **Holes are drilled circumferentially at the periphery of the craniectomy defect. Epidural tacking stitches are placed with 4-0 braided nylon sutures.**	• Autograft may be preferable to allograft for dural repair in the setting of an open fracture given presumed contamination of the wound and increased risk of infection. • “Ping pong”-type depressed skull fractures in the pediatric population can be elevated with gentle aspiration using a breast milk extractor.

Venous Sinus Repair (Fig. 6.7a, b)



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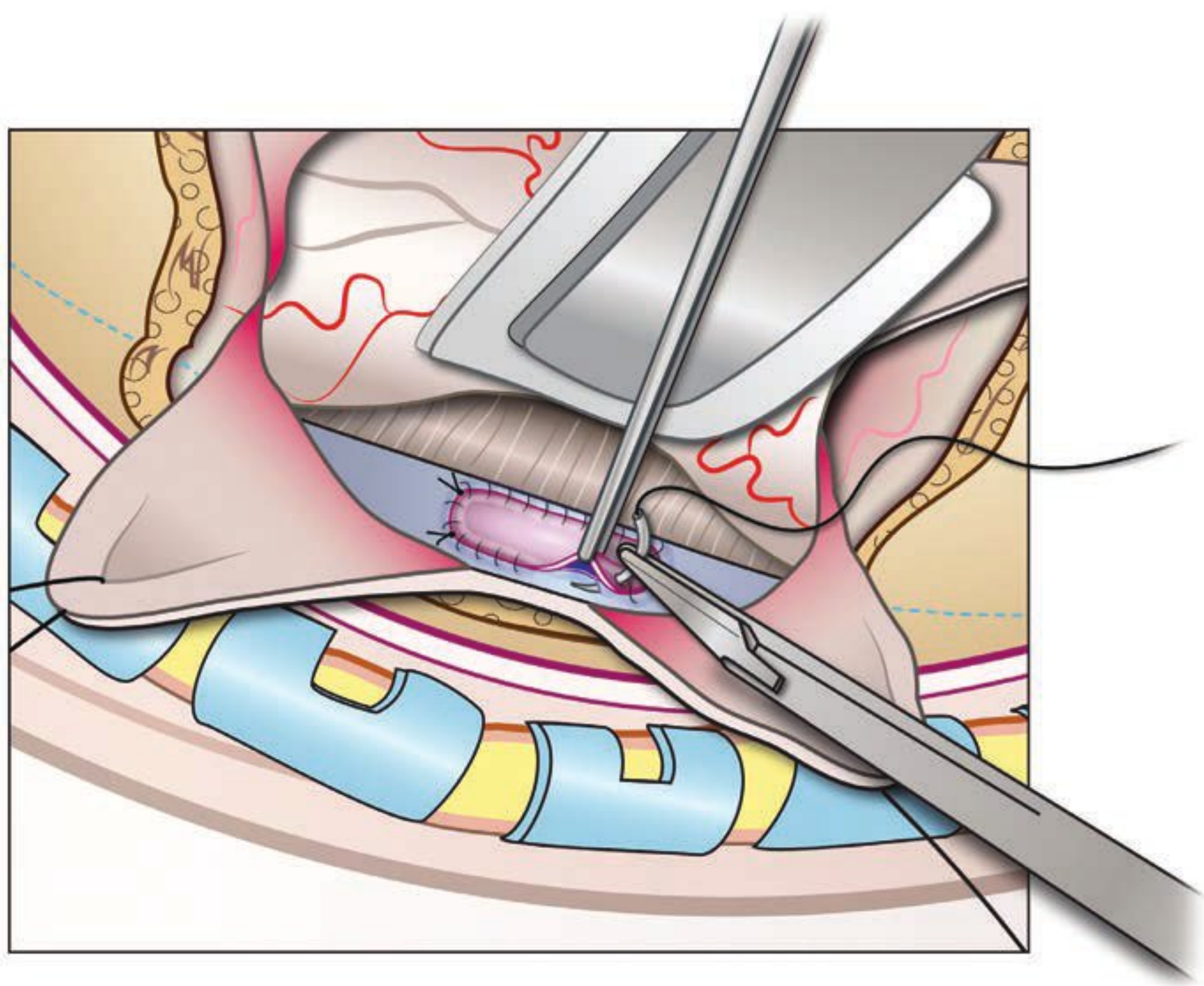


b

Figure	Procedural Steps	Pearls
Fig. 6.7	**If injury to the superior sagittal sinus is identified, management is dictated by anatomic considerations.** **(a) If initial mechanical maneuvers to achieve hemostasis fail, the anterior one-third of the sinus can be ligated without serious adverse effects. (b) However, injury involving the posterior two-thirds requires repair with a galeal or pericranial patch.**	• Depressed fractures with potential venous sinus involvement may require additional preoperative imaging to assess sinus patency and injury. • Management of venous sinus injury is discussed in Chapter 10.

Calvarial Reconstruction (Fig. 6.8)

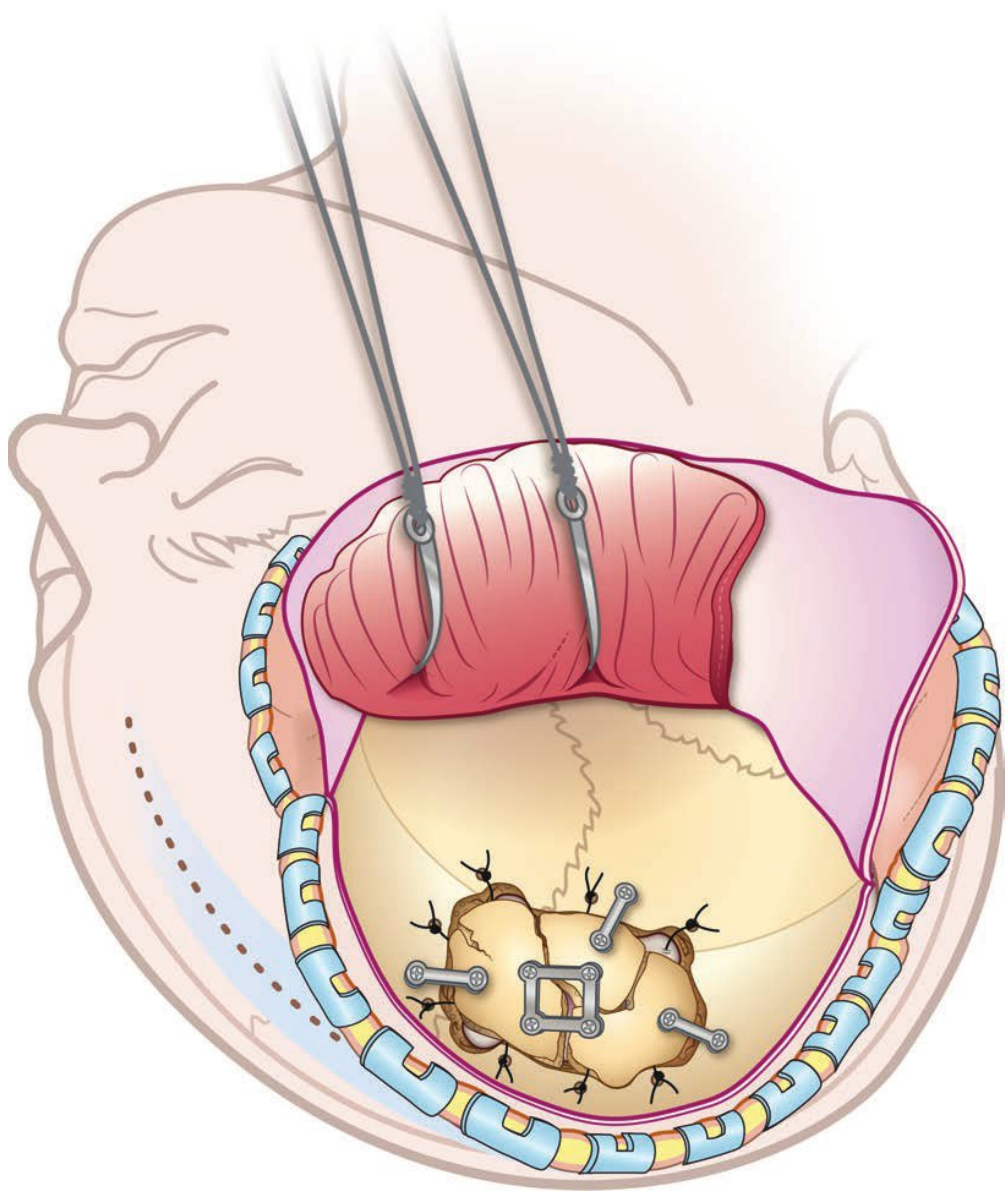


Figure	Procedural Steps	Pearls
Fig. 6.8	**If explanted bone fragments are not excessively comminuted or contaminated, they may be replaced using a mini-plate and screw fixation system.** **If the bone fragments are not salvageable, titanium mesh may be used to bridge the defect.**	• Salvageable fragments may be reassembled on the back table prior to reimplantation, so as to achieve reasonable cosmesis. Special attention (and possibly the participation of a plastic surgeon) may be required in areas of high visibility, such as the orbital rim and forehead. • Methyl methacrylate should be avoided in children but can be used as a reconstructive adjunct for adults—either to augment the reimplanted bony construct or to provide contour if mesh must be used to cover larger defects. • Absorbable bone plates and screws are recommended for pediatric patients. • A custom cranioplasty implant is an option for an adult patient with a large cranial defect. However, this does require a second surgical procedure, as well as use of a protective helmet during the interval between injury and receipt of the implant.[5]

Closing

- The wound is irrigated with copious amounts of antibiotic solution.
- Depending on type of traumatic injury, sterile drainage tubing may be implanted and secured.
- Temporalis muscle and fascia are reapproximated with 2-0 braided nylon sutures.
- The galea is closed with inverted, interrupted 3-0 braided absorbable sutures.
- The skin is closed either with staples or 3-0 nylon vertical mattress stitches.
- A sterile dressing is applied and accompanied by a compressive head wrap, if necessary.

Postoperative Management

Further Management

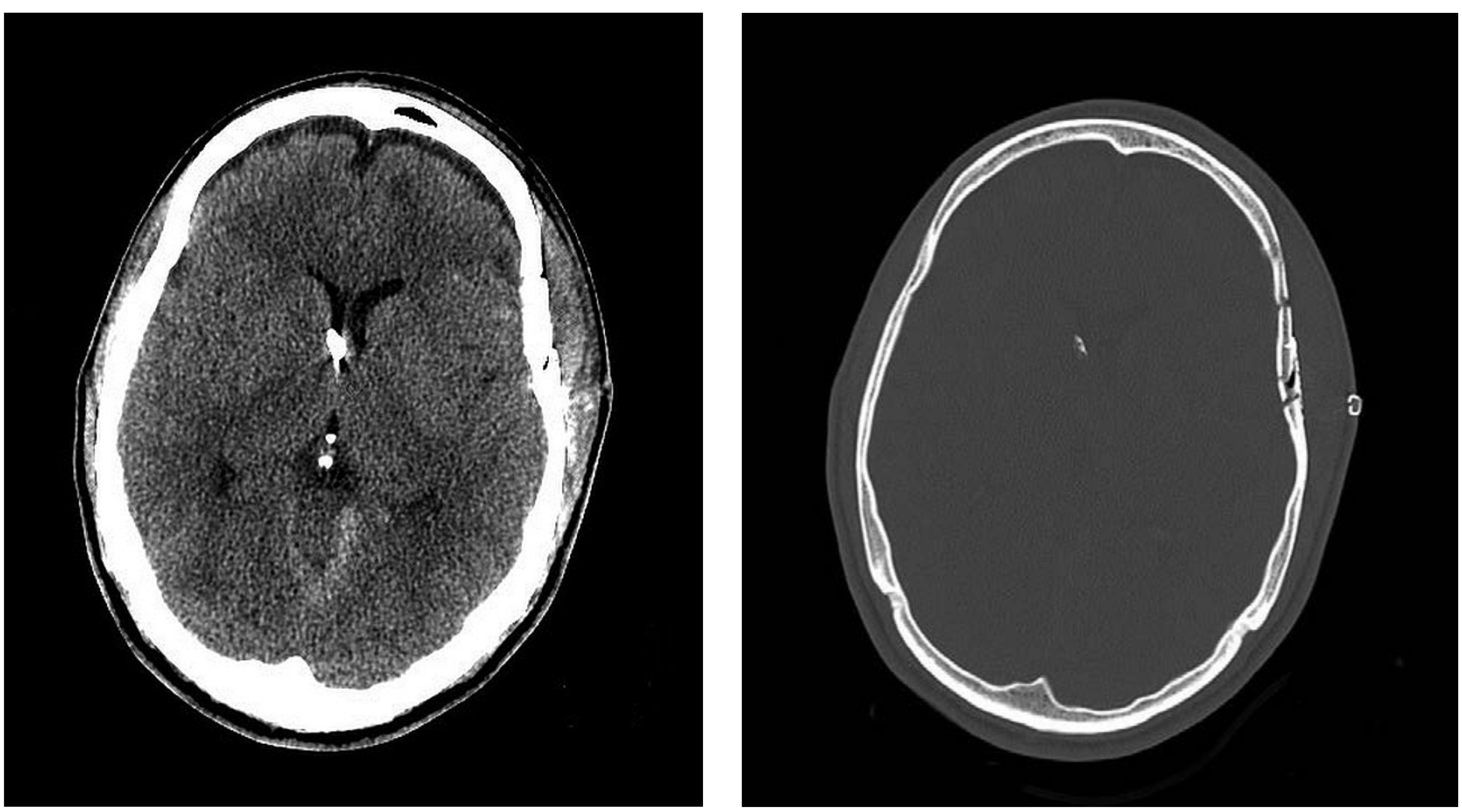
- Posttraumatic and postoperative management are performed in accordance with published TBI guidelines.
- Skin sutures or staples may be removed in 7 to 10 days, depending on type of injury and wound closure.
- Prophylactic antibiotics are given for 5 to 7 days to lessen the risk of central nervous system infection. The authors prefer intravenous cefazolin or piperacillin-tazobactam. However, there is insufficient evidence to support a specific agent or duration of therapy in this setting.
- Anticonvulsants are often given to reduce risk of seizures, although the supporting evidence is equivocal.

Radiographic Imaging

- Patients with contaminated, open depressed fractures managed surgically should be followed with CT imaging over the 2 to 3 months after initial debridement. Clinical signs/symptoms of infection, as well as wound complications and seizures, may prompt unscheduled CT investigation. Intravenous contrast infusion is indicated if a diagnosis of infection is contemplated.
- **Postoperative imaging (Fig. 6.9).**

Special Considerations

- Depressed fracture over a venous sinus poses a unique situation. A preoperative angiogram with venous flow phase, CT venogram, or MRA is recommended. The decision to operate is based on the neurologic status of the patient, the location of sinus involvement, and the degree of venous flow compromise.
- A neurologically stable patient with a closed, depressed fracture over a venous sinus can be observed. A patient with an open, depressed fracture over a patent venous sinus should undergo skin debridement without elevation of the depressed bone segment. However, if the patient is neurologically unstable, urgent elevation may be required.
- In the case of sinus thrombosis, the anterior one-third of the superior sagittal sinus usually can be ligated without consequence. However, injury to the posterior two-thirds of the sinus requires either primary repair or interposition grafting (with a galeal or pericranial patch). Alternatively, a piece of muscle or gelatin sponge can be sutured over the sinus as a bolster.
- If the native bone cannot be replaced, either titanium cranioplasty or a polyetheretherketone (PEEK) implant may be considered.



a b

Fig. 6.9a, b Axial CT (**a**) brain and (**b**) bone windows demonstrating elevation and repair of the depressed skull fracture depicted in Fig. 6.1. An external ventricular drain has been placed to facilitate monitoring of intracranial pressure and therapeutic drainage of cerebrospinal fluid.

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7 Invasive Neuromonitoring Techniques

Mathieu Laroche, Michael C. Huang, and Geof rey T. Manley

Introduction

Invasive neuromonitoring assists the diagnosis and treatment of patients presenting with—or at risk for—intracranial hypertension, defined as intracranial pressure (ICP) greater than 20 mm Hg. A variety of intracranial pathologies such as traumatic brain injury, subarachnoid hemorrhage, intracerebral hemorrhage, and ischemic stroke (associated with malignant edema) may contribute to an altered level of consciousness and, therefore, an unreliable neurologic exam. Further decline in neurologic status may be difficult to detect based on serial clinical evaluation alone. Invasive neuromonitoring can point to signs of deterioration and trigger appropriate interventions. Although ICP monitoring is most common, additional advanced modalities for the monitoring of brain tissue oxygen tension, microdialysis, cerebral blood flow, and jugular venous saturation can help the practitioner achieve a more comprehensive understanding of pathologic cerebral physiology and, in turn, provide individualized treatment with targeted therapies.

Indications

Monitoring of ICP by External Ventricular Drain or Intraparenchymal Pressure Probe[1]

- Diagnosis and treatment of intracranial hypertension
  - An external ventricular drain (EVD) is considered the gold standard for ICP measurement. Placement of an EVD allows both for diagnostic monitoring of ICP and therapeutic drainage of cerebrospinal fluid (CSF).
  - An intraparenchymal pressure monitor (fiberoptic or micro strain gauge device) allows for monitoring of ICP alone. The intraparenchymal probe may be coupled with other neuromonitoring modalities in a multiport bolt apparatus or used in isolation.
- As per published guidelines, indications for ICP monitoring in the setting of severe traumatic brain injury (TBI)[2]
  - Glasgow Coma Scale (GCS) score ≤ 8 after resuscitation, in combination with an abnormal head computed tomography (CT; hematoma, contusions, swelling, herniation, compressed basal cisterns) (Level II recommendation)
  - GCS ≤ 8 after resuscitation, with a normal head CT, and associated with two or more of the following on admission (Level III recommendation):
    - Age . 40 years
    - Unilateral or bilateral motor posturing
    - Systolic blood pressure , 90 mm Hg

Monitoring of Brain Tissue Oxygen Tension, Jugular Venous Saturation, and/or Cerebral Blood Flow[3]

- Ancillary monitoring of cerebral physiology may facilitate cerebral perfusion pressure (CPP) management in severe TBI with loss of autoregulation (Level III recommendation).
- The brain tissue oxygen tension probe usually is placed in the less injured cerebral hemisphere for more consistent measurement and early detection of secondary brain injury.

Microdialysis[4]

- Ancillary monitoring of cerebral metabolic parameters may facilitate CPP and brain-specific management in severe TBI (Level III recommendation).
- Placement of the microdialysis catheter is dictated by the specific pathology:
  - In the right frontal lobe of patients with diffuse brain injury.
  - In the pericontusional tissue (penumbra) in patients with a focal mass lesion; a second probe may be placed in uninjured or “normal” tissue for comparison.
  - In the region of the brain at risk of vasospasm following severe subarachnoid hemorrhage.[4]

Preprocedure Considerations

Radiographic Imaging

- Noncontrast head CT should be reviewed for:
  - Size of the ventricular system
  - Intraventricular hemorrhage
  - Mass effect or focal lesion
  - Skull fractures
  - Distance from the bone to the frontal horn (for EVD placement)

Coagulation Parameters

- International normalized ratio (INR), partial thromboplastin time (PTT), and platelets should be in normal range.
- In the coagulopathic patient, consider transfusion of platelets, fresh frozen plasma (FFP), and/or prothrombin complex concentrate—as appropriate—before the procedure.

Availablity of All Necessary Equipment

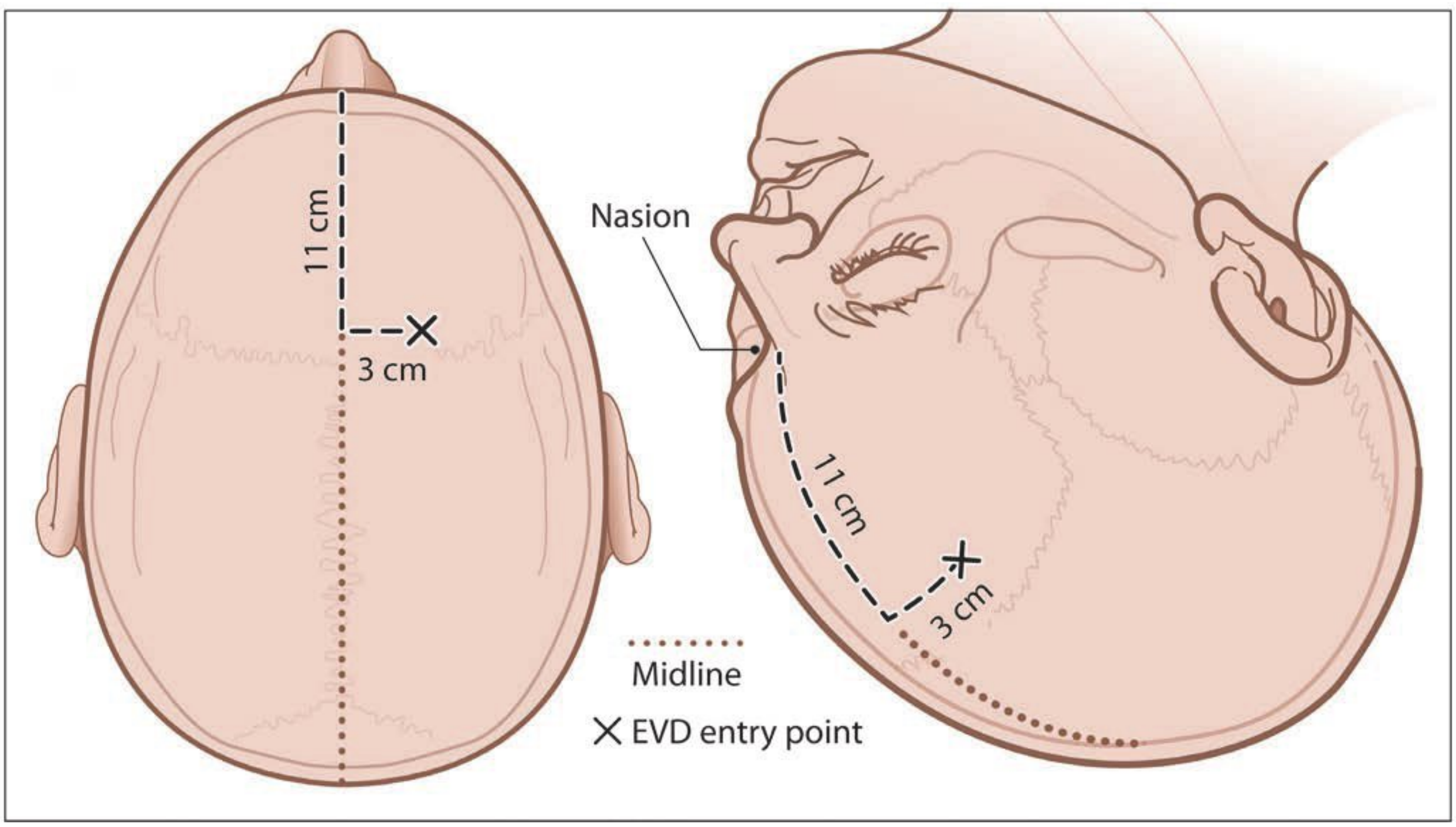
- Placement can be performed either in the operating room or at the bedside (most commonly).

Medication

- Lidocaine 1% with epinephrine 1:100,000 for local anesthesia
- Midazolam or propofol for sedation
- Fentanyl for analgesia

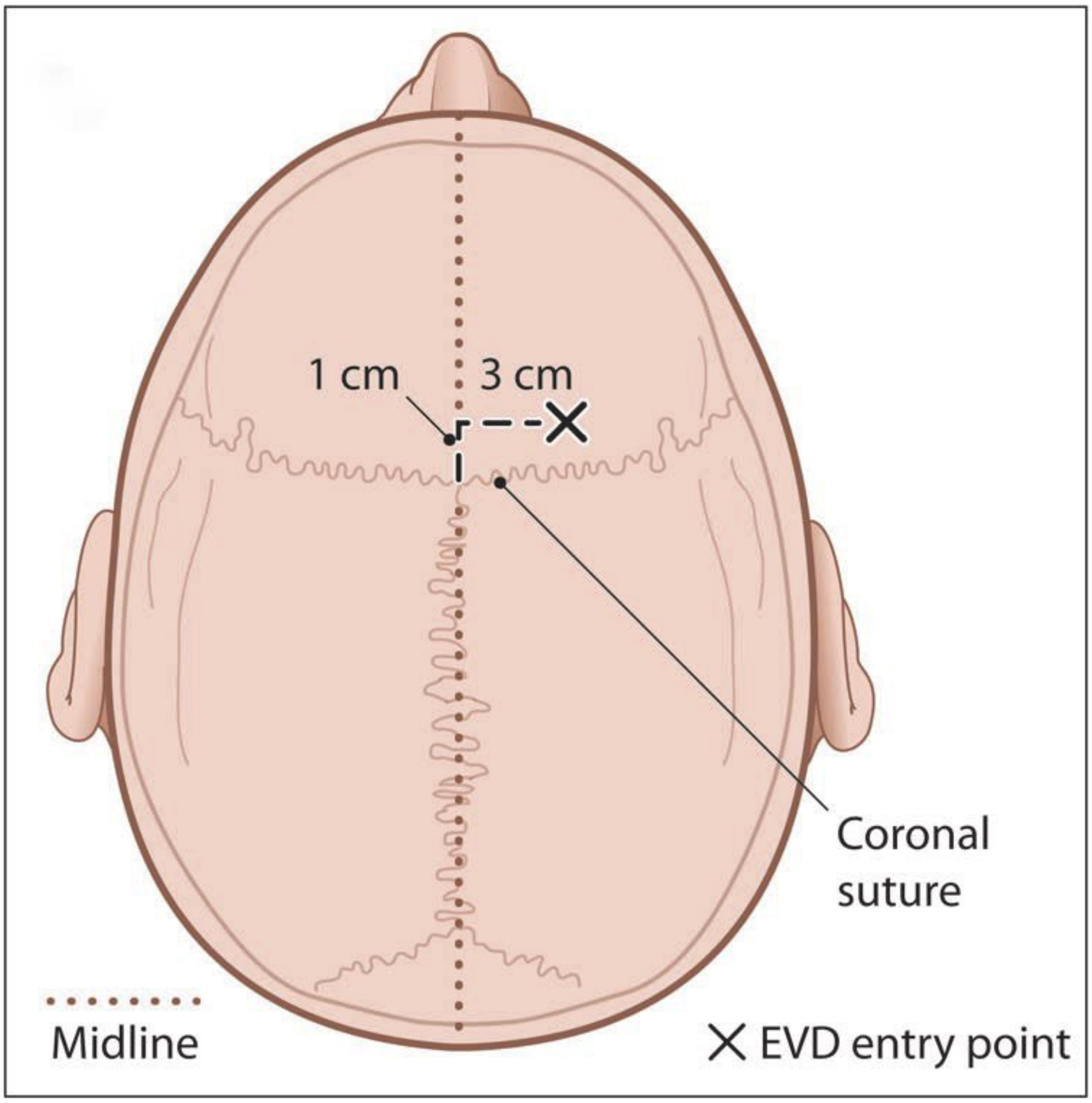
Operative Field Preparation for Intracranial Neuromonitoring

- Position the head in the neutral position (a rigid C-collar, bean bag, or fixation with tape are effective ways to achieve this at the bedside).
- Elevate the head of the bed approximately 30 degrees.
- Clip hair overlying the frontal quadrant using an electric razor.
- Identify important anatomic landmarks:
  - Midline
  - Nasion
  - Mid-pupillary line
  - External auditory canal
  - Coronal suture (by palpation)
- Identify the approximate location of Kocher's point by one of the following strategies:
  - 11 cm posterior to the nasion and 3 cm lateral to midline
  - 1 cm anterior coronal suture and 3 cm lateral to midline
  - Intersection of the midpupillary line with a perpendicular line extending from the midpoint of an imaginary line connecting the external canthus to the tragus
- Infiltrate the skin at the planned incision site with 1% lidocaine with epinephrine 1:100,000.
- Prepare the skin with alcohol before application of providine iodine or chorhexidine.
- **Anatomic landmarks for placement of EVD (Fig. 7.1).**



a

Fig. 7.1a–c Multiple measurement strategies have been proposed to determine the optimal entry point for insertion of an EVD (or comparable invasive monitor): (**a**) 11 cm posterior to the nasion and 3 cm lateral to midline, (continued)



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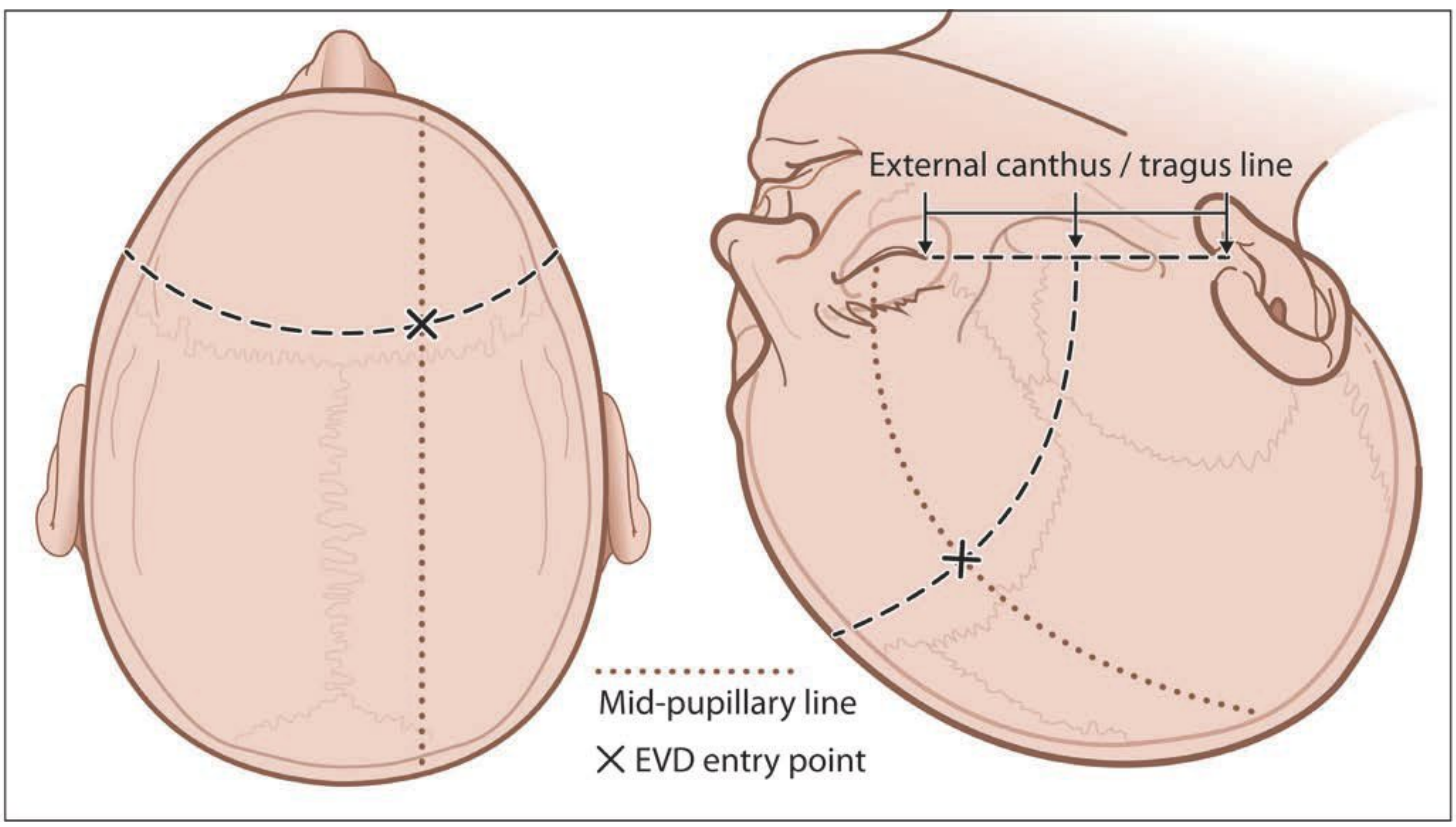


c

Fig. 7.1a–c (continued) (**b**) 1 cm anterior to coronal suture and 3 cm lateral to midline, and (**c**) intersection of the midpupillary line with a perpendicular line extending from the midpoint of an imaginary line connecting the external canthus to the tragus.

Operative Procedure

Placement of Intracranial Monitors

Positioning (Fig. 7.2)

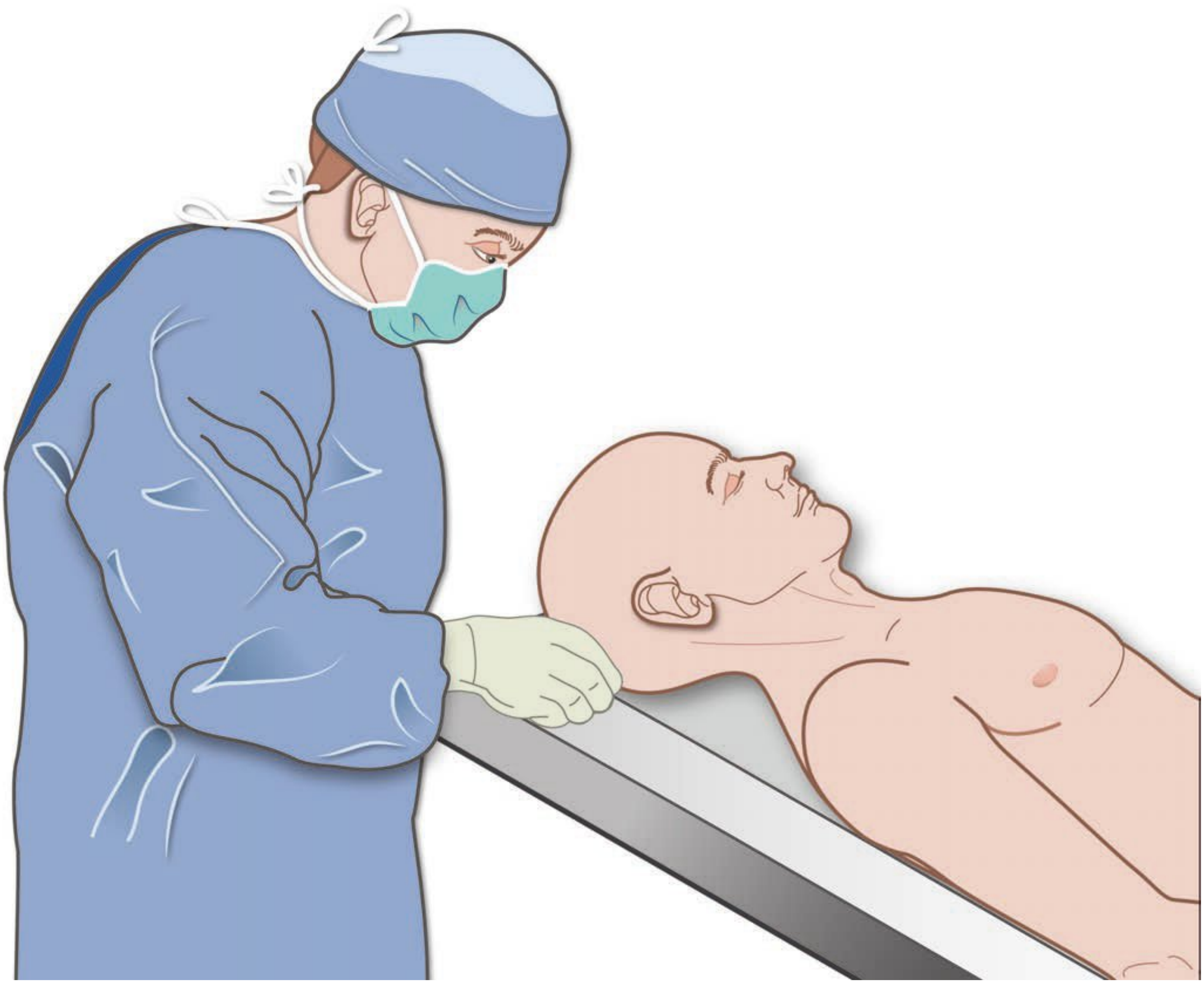


Figure	Procedural Steps	Pearls
Fig. 7.2	**The head is maintained in the neutral position with the head of bed at 30 degrees.**	• The operator stands behind the patient. • A C-collar or bean bag is useful to maintain the head in the neutral position. • EKG electrodes can be placed on the nasion and tragus for easier palpation of the landmarks after draping.

Skin Incision (Fig. 7.3)

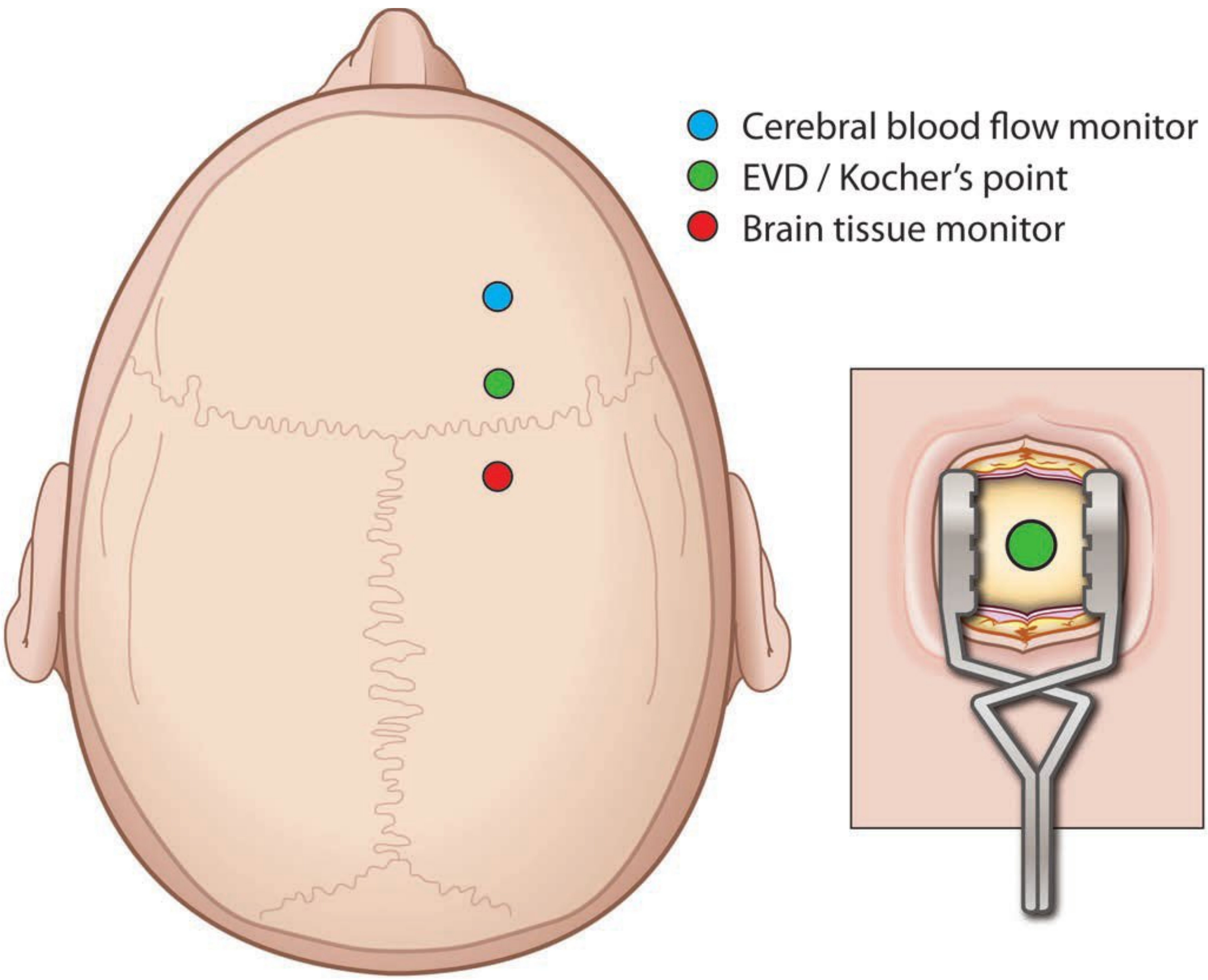


Figure	Procedural Steps	Pearls
Fig. 7.3	**A small stab incision is made at the planned entry site and extended through the scalp to the level of bone.**	• For EVD: at Kocher's point. • For brain tissue oxygen: 1 to 2 cm behind Kocher's point. • For cerebral blood flow : 1 to 2 cm in front of Kocher's point. • If advanced neuromonitoring probes are too close to the EVD, or each other, they may not provide accurate and reliable information.

Twist Drill Craniostomy (Fig. 7.4)

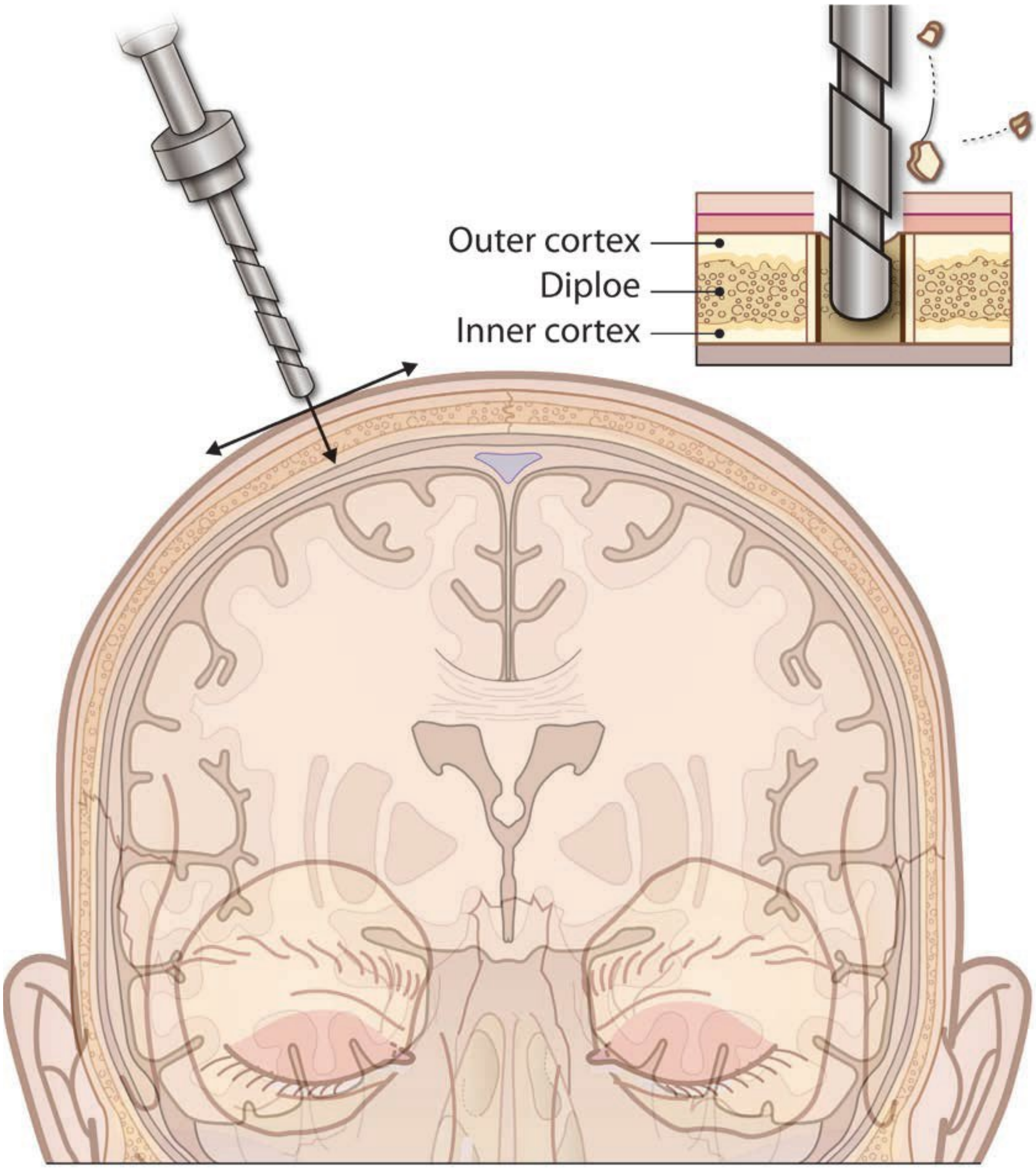


Figure	Procedural Steps	Pearls
Fig. 7.4	**Using the twist drill, a small craniostomy is performed, followed by copious irrigation to remove blood and bone debris.**	• An assistant is helpful to stabilize the head during drilling to maintain neutral positioning. As a general rule, each cannulation system comes equipped with a proprietary drill bit. For an EVD, a 5.3-mm drill bit is provided. If available, a drill safety stop should be used. • It is important to perform the craniostomy absolutely perpendicular to the plane of the skull. The trajectory may be assisted by aiming at the ipsilateral inner canthus in the coronal plane and just anterior to the tragus in the sagittal plane or with the use of a tripod device. • The operator is able to feel a change in the resistance as the drill travels through the outer cortex (hard), diploe (soft), and inner cortex (hard). The operator should slow down as more resistance is felt while the drill penetrates into the inner cortex to avoid plunging into the brain tissue. After removing the twist drill, the dura can be palpated using a spinal needle or a small blunt instrument.

Variation for Bolt-type Monitors (Fig. 7.5)

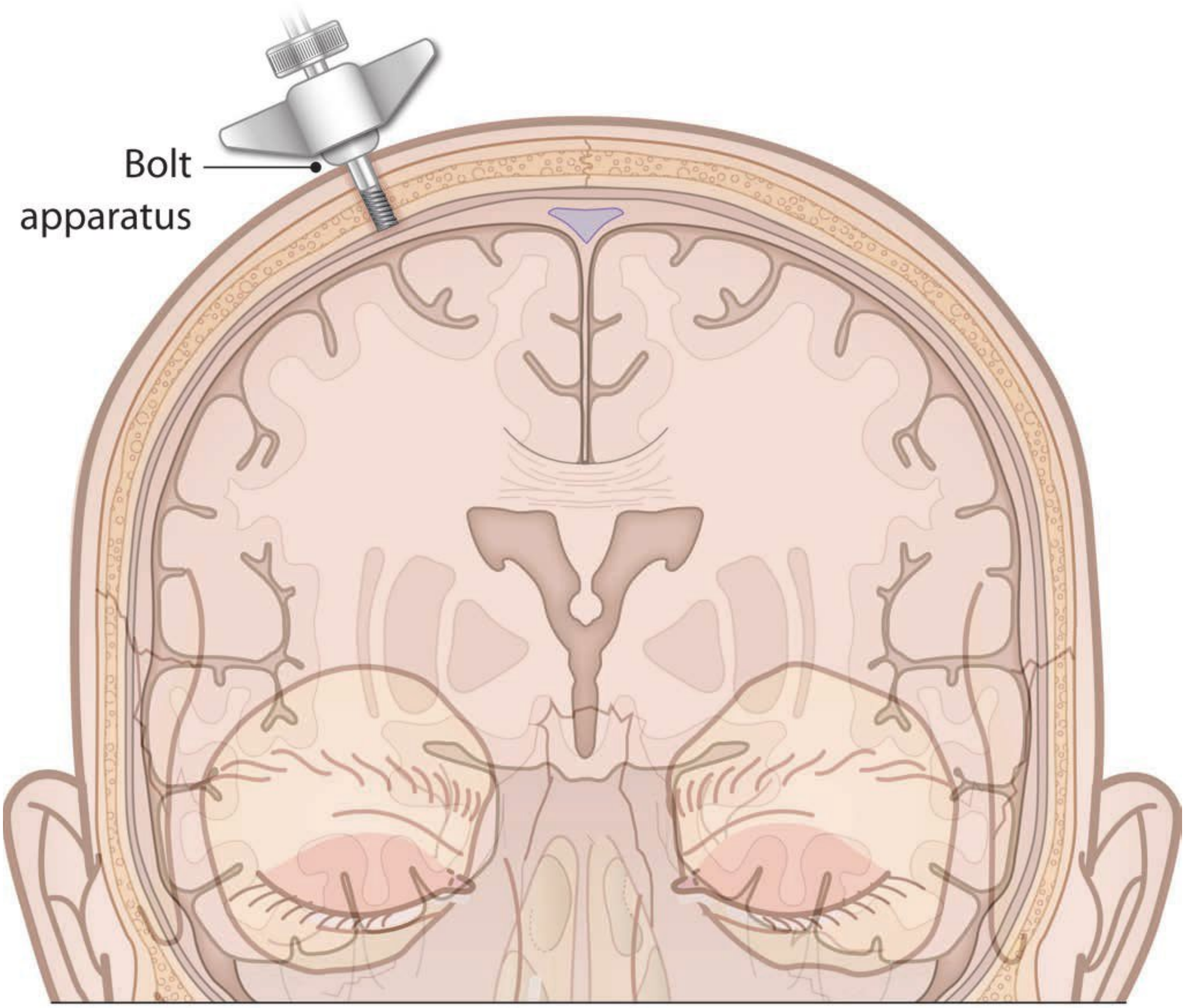


Figure	Procedural Steps	Pearls
Fig. 7.5	**If a bolt-based system is being used, the bolt should be screwed into the craniostomy site to finger tightness.**	• The dura then is punctured by passage of the central stylet. The fiberoptic pressure monitor or EVD catheter is threaded through the central opening in the bolt to the desired depth. The cuff is tightened and the locking sheath pulled over top to secure the system.

Opening of Dura and Leptomeninges (Fig. 7.6)

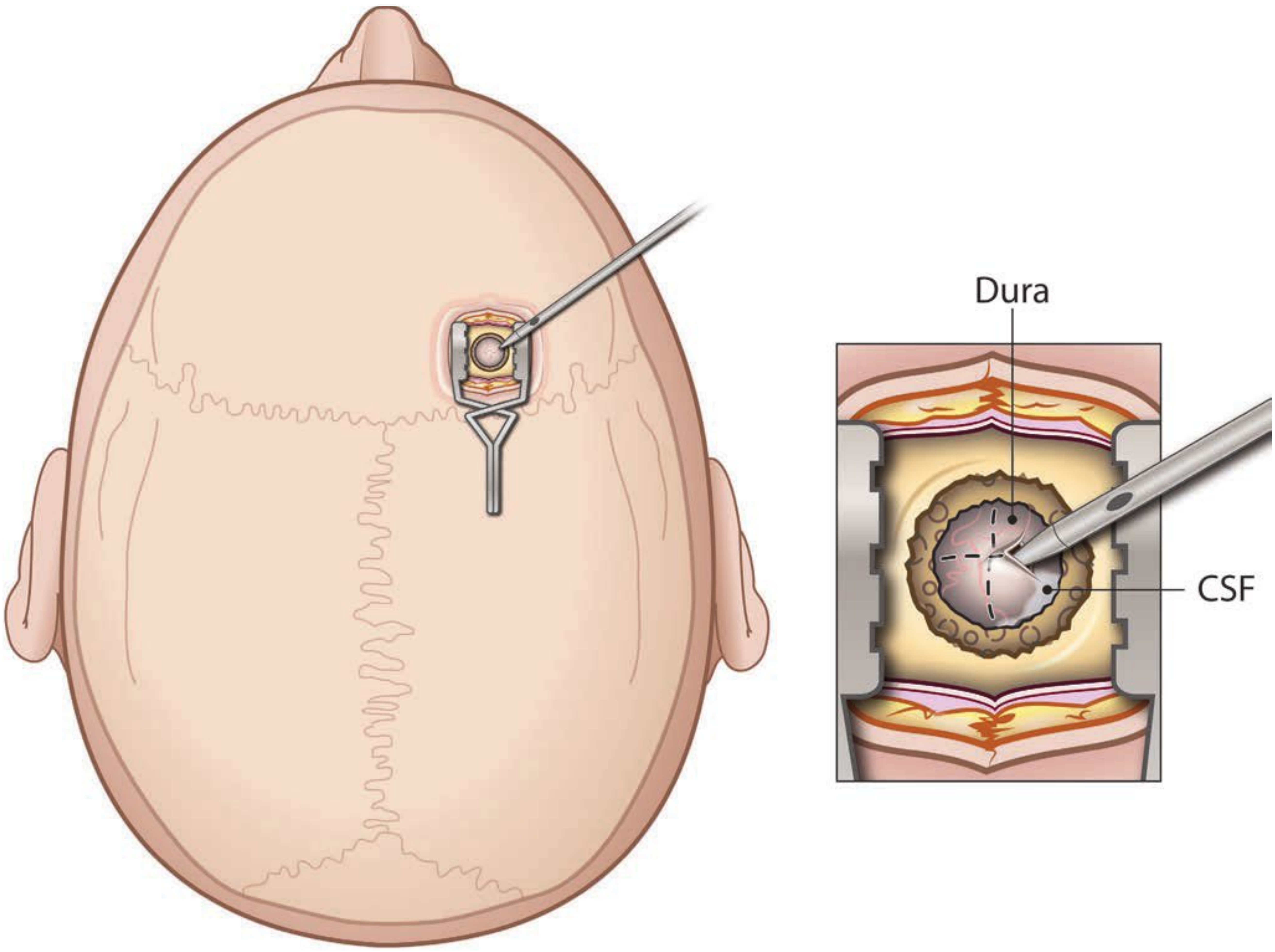


Figure	Procedural Steps	Pearls
Fig. 7.6	**The dura is punctured using a 18-gauge spinal needle or a 14-gauge needle.**	• A loss of resistance will be felt when the dura is perforated using the needle. Multiple punctures might be necessary to open the dura completely. • For brain tissue oxygen monitors: The dura must be opened completely beneath the craniostomy to avoid damaging the electrode tip. To achieve a better result, a no. 11 blade is used to open the dura in a cruciate manner, under direct visualization. A slighty larger skin incision may be necessary.
	The pia is perforated using the spinal needle or a no. 11 blade.	• A good pial opening is essential to minimize the risk of subdural placement of neuromonitors.

Variation for External Ventricular Drain (Fig. 7.7)

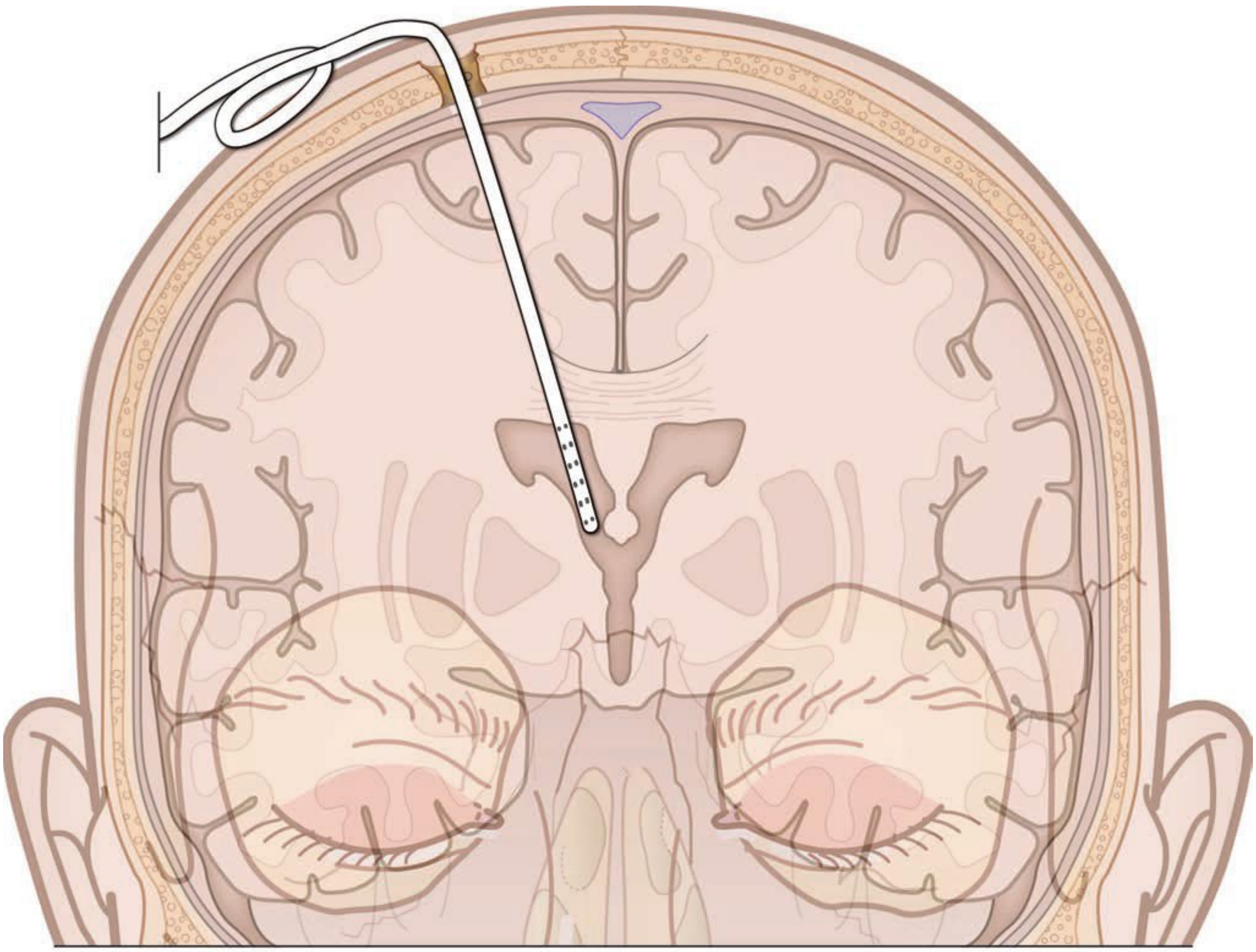
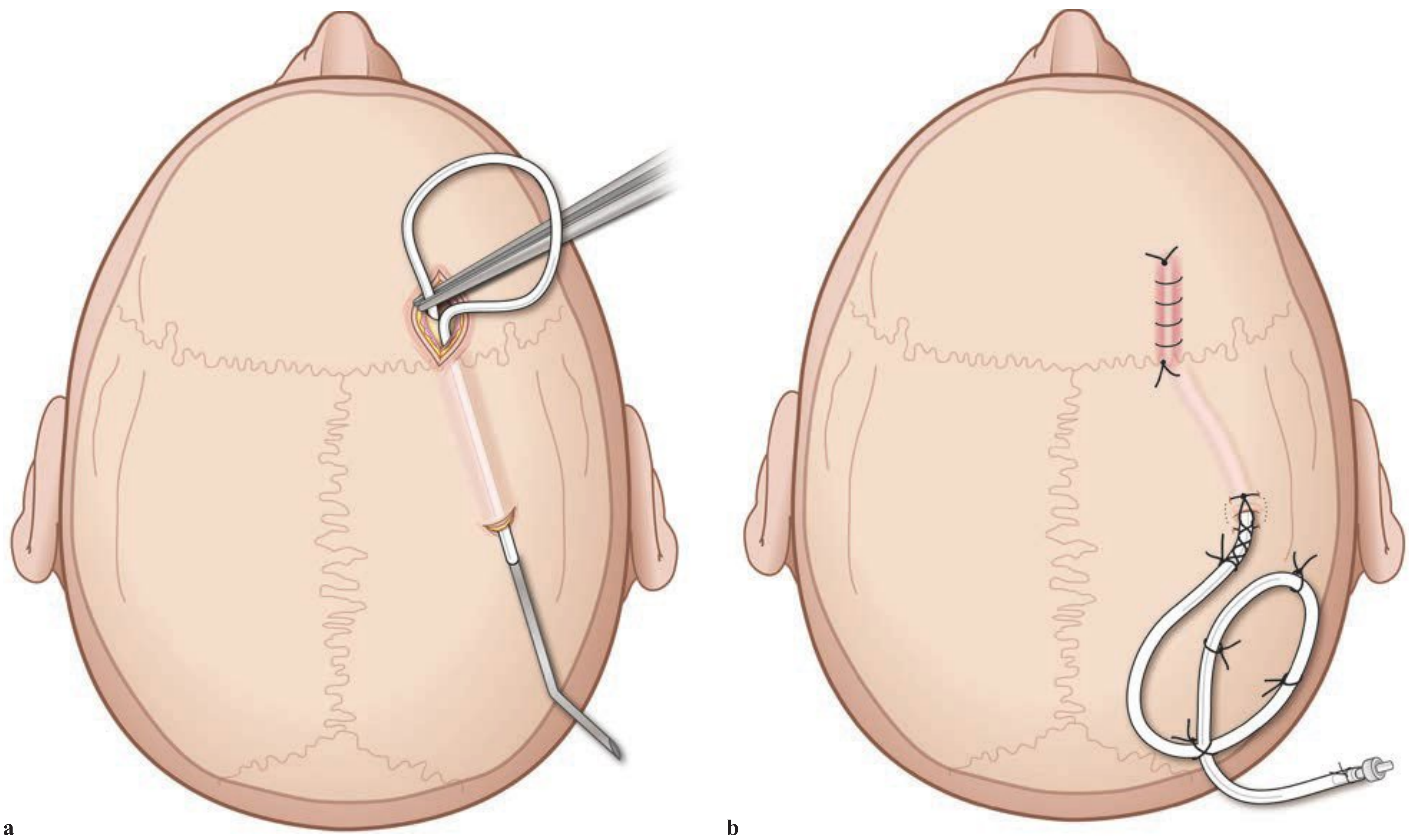


Figure	Procedural Steps	Pearls
Fig. 7.7	**The ventricular catheter—with stylet—is inserted slowly to a maximal depth of 6 cm from the outer table of the bone. When the frontal horn is cannulated, a slight increase in resistance, followed by a loss of resistance (a "pop"), is classically felt. The stylet then is removed. There should be clear CSF drainage from the ventricular catheter.**	• The ipsilateral frontal horn should be punctured at a depth of 3 to 5 cm from the inner table of the bone with the catheter oriented perpendicular to the bone and targeted at the inner canthus of the ipsilateral eye in the coronal plane and just in front of the tragus in the sagittal plane.[5,6] • If the ventricle is not cannulated after three attempts, the ventricular catheter should be left in place and its position verified with a head CT. • EVD placement is more difficult in patients with small ventricles. In this situation, adjuncts such as a tripod (a small device that ensures that the catheter is perpendicular to bone),[7] neuronavigation, and ultrasound may be considered to assist accurate catheter positioning.

Tunneling and Securing the Cathether (Fig. 7.8a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 7.8	**(a) Using a trocar, the ventricular catheter is tunneled about 5 cm from the incision.**	• Secure the Luer lock connection with a 2-0 silk tie.
	(b) After removing the trocar, a Luer lock and cap are applied. The EVD is secured to the skin at multiple points with 3-0 nylon stitches.	• A gentle loop of the external portion of the catheter permits stay sutures at 3, 6, 9, and 12 o'clock. Failure to secure the EVD adequately to the patient may leave the system vulnerable to unintended, traumatic explantation.

Variations for Monitor Placement (Fig. 7.9)

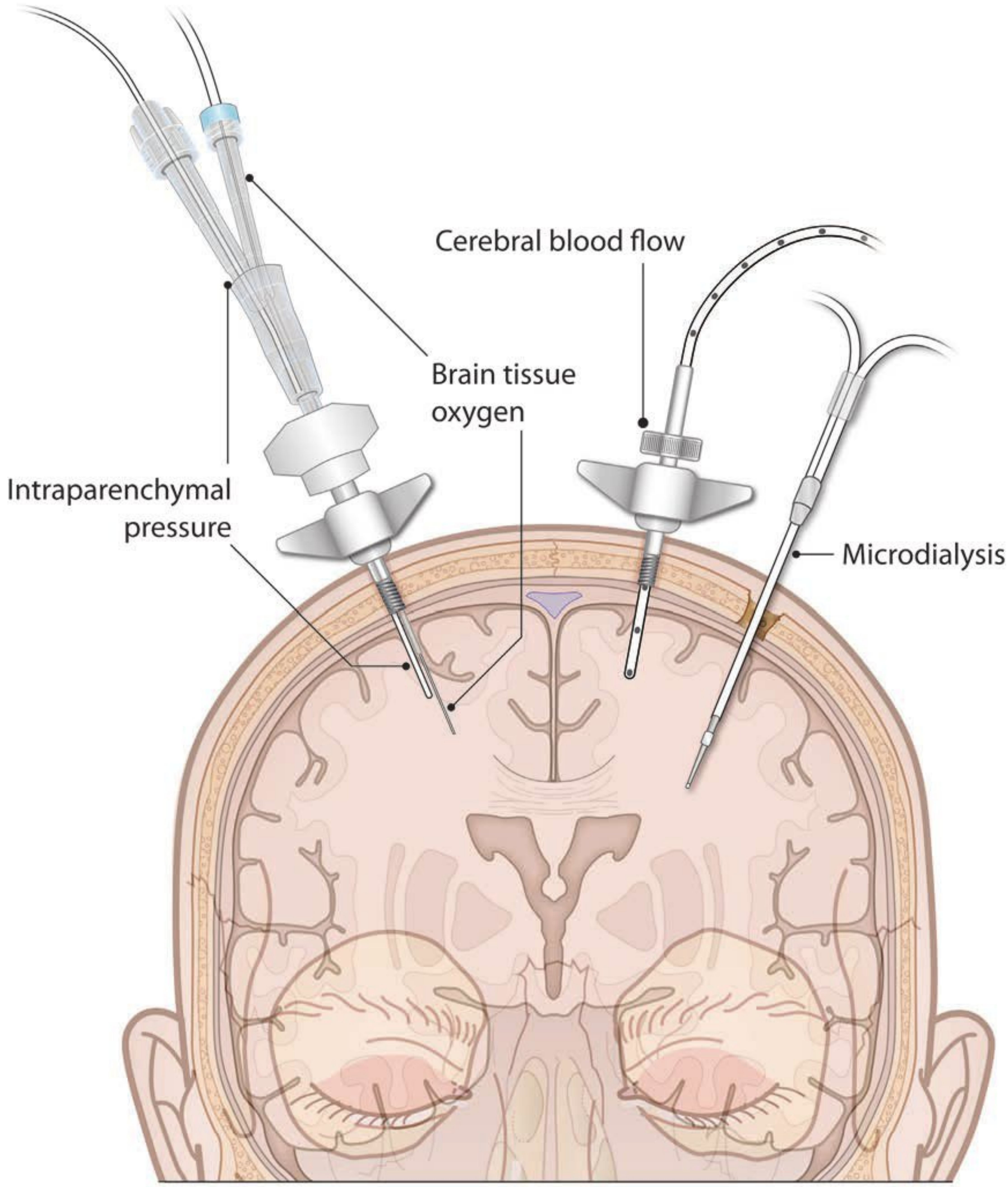


Figure	Procedural Steps	Pearls
Fig. 7.9	**The fiberoptic ICP probe is zeroed with respect to air.**	• To zero the probe, follow the individual manufacturer's instructions.
	Intraparenchymal Monitor **The probe then is introduced into the central opening of the bolt apparatus and advanced into the brain parenchyma—deep enough to obtain a reliable ICP measurement (no more than 2.5 cm). The pressure probe then is secured to the bolt system or tunneled and secured to the skin depending on the system.**	• Visualization of the ICP waveform during insertion can assist in the placement. If no waveform or an unexpectedly high pressure is observed, remove the probe temporarily, reassess the patency of the dural opening, and consider irrigation with a small amount of sterile saline. • The ICP monitor can be tested after insertion with brief bilateral manual compression of the jugular veins (Queckenstedt maneuver). This maneuver reduces venous outflow and, thereby, increases ICP.
	Variation for Brain Tissue Oxygen Monitor **After ensuring that the dura and the pia are opened, the inner sleeve is inserted into the bolt. The brain tissue oxygen probe, in turn, is inserted through the inner sleeve into its predetermined port. The inner sleeve then is secured to the bolt by a screw.**	• There should be no resistance when the inner sleeve and the brain tissue oxygen probe are inserted if the dura is widely open and the pia has been pierced. Any significant resistance during placement of the inner sleeve indicates a need for wider dural opening. Resistance during probe placement could mean that the probe is migrating in the epidural space or sliding over the brain. An FiO2 challenge (rapid increase in inspired oxygen to 100%) should be used to verify that the probe is functioning.
	Variation for Cerebral Blood Flow Monitor **After connecting to the monitor, the cerebral blood flow probe is inserted into the white matter (2 to 2.5 cm deep to the dura, into the centrum semiovale). The probe is secured to a bolt or tunneled and secured to the skin.**	
	Variation for Microdialysis Cathether **The microdialysis probe is inserted into the parenchyma to a depth of about 2 cm, depending on the region of interest. It is secured to the skin after tunneling, or it can be secured through a bolt system.[8]**	

Placement of Jugular Venous Saturation ($SjVO_2$) Monitor

Positioning (Fig. 7.10)

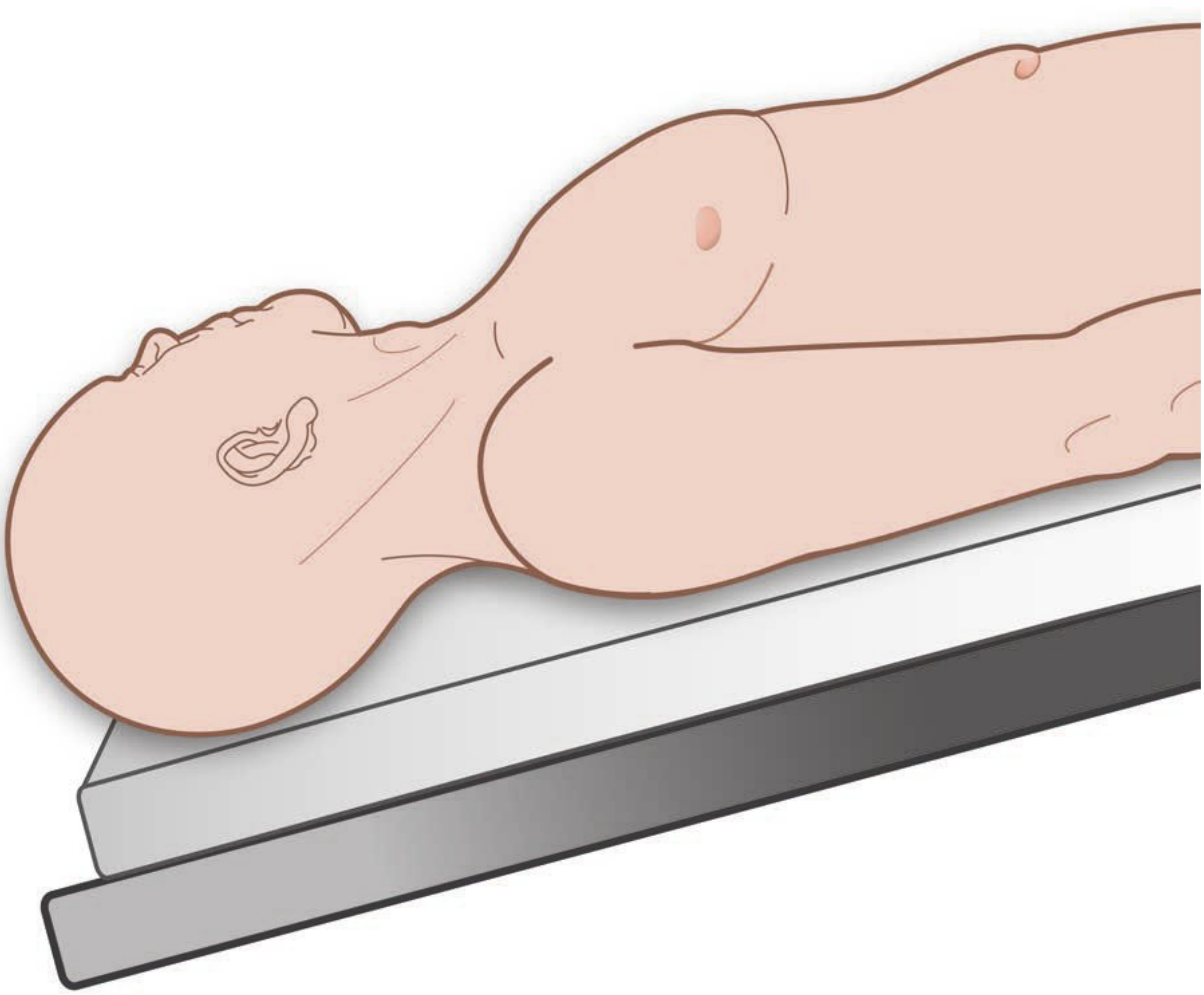


Figure	Procedural Steps	Pearls
Fig. 7.10	**The patient is positioned in a slight Trendelenburg position to distend the jugular vein. The entire neck and the upper thorax are prepped and draped.**	• Retrograde catheterization of the internal jugular vein is accomplished using the same Seldinger technique as for the placement of central venous catheters.

Skin Incision and Insertion (Fig. 7.11)

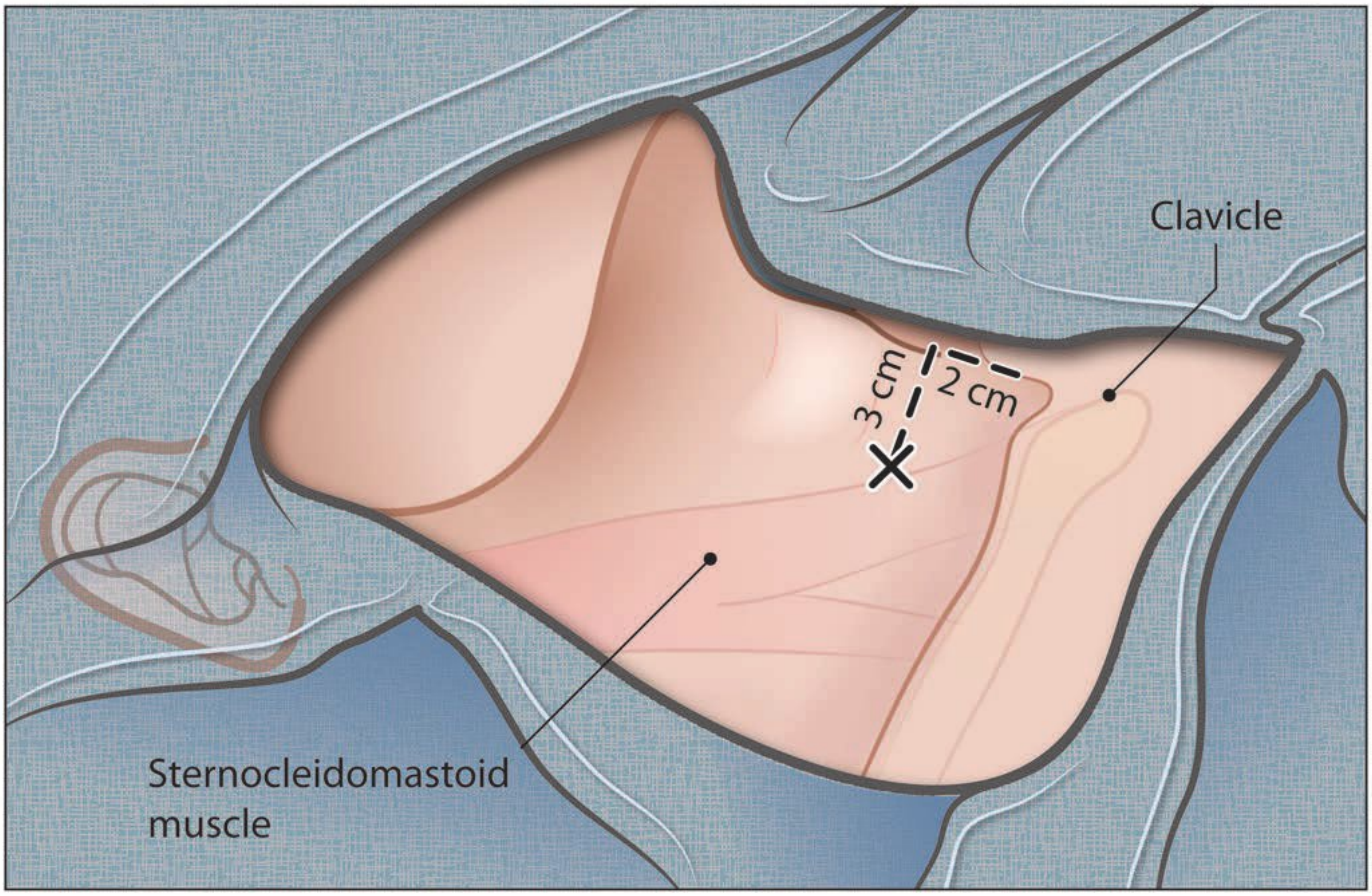


Figure	Procedural Steps	Pearls
Fig. 7.11	**The puncture site is medial to the sternocleidomastoid muscle, about 3 cm lateral and 2 cm above the medial border of the clavicle. After the internal jugular vein is cannulated, the Seldinger technique is used to advance the introducer sheath. The medial and distal port of the fiberoptic catheter are flushed with a heparinized solution and the catheter is advanced to a depth of 16 to 18 cm.**	• The needle must be advanced from the insertion point toward the external auditory meatus under constant aspiration with a 30-degree angle in the sagittal plane. When the internal jugular vein is cannulated, there will be a blush of dark blood and a loss of resistance. • The guidewire should not be introduced more than the intended length of the fiberoptic catheter (16 to 18 cm). • An ultrasound device can be helpful in identification and cannulation of the vessels.

Verification of Position (Fig. 7.12)

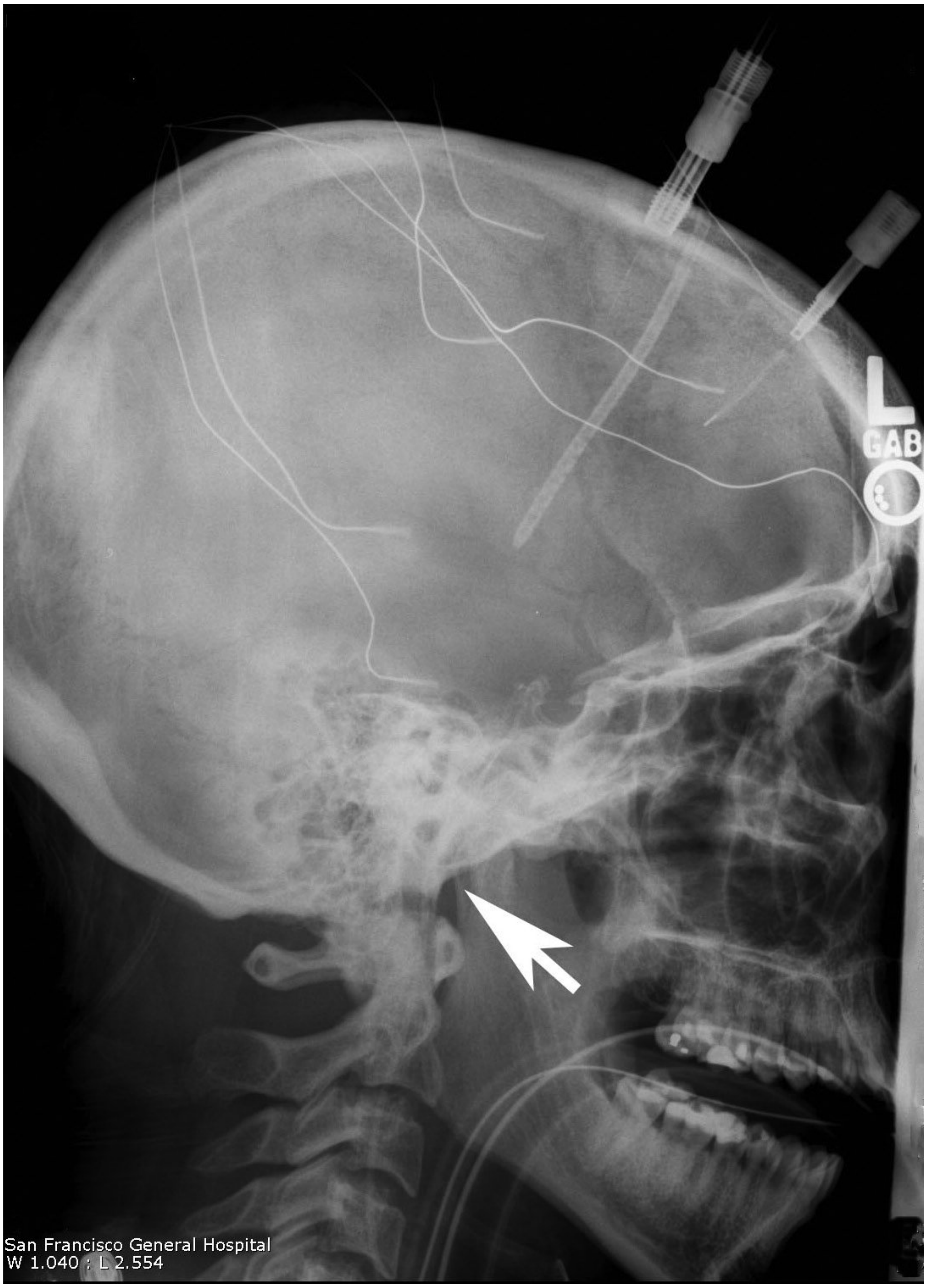


Figure	Procedural Steps	Pearls
Fig. 7.12	**Anteroposterior (AP) and lateral skull X-rays are obtained to verify position. In this representative lateral X-ray, the tip of the catheter is denoted by the arrow.**	• The tip of the fiberoptic catheter should be high in the jugular bulb to maximize the likelihood of measuring the venous blood draining from the brain and to minimize contamination from extracranial blood. X-ray verification is recommended to ensure that the tip of the catheter is just medial to the base of the mastoid bone in the AP plane and at the lower portion of C1 in the lateral plane. The position of the catheter can also be verified with a head CT, where it should be seen in the jugular foramen at the base of the skull.

Closing

- The incision site is irrigated. The skin incision is closed with 3.0 nylon sutures.
- A sterile transparent dressing is placed over the incision site (or around the bolt apparatus).
- Calibration
  - **EVD:** after catheter placement, the drain height is selected (in cm H_2O). The drainage system is set with the zero point level to the top of the patient's ear. This corresponds to the approximate level of the foramen of Monro—the midpoint of the ventricular system. The pressure waveform may be recorded by attachment to an external strain gauge or by insertion of a fiberoptic pressure probe or micro strain gauge device into the EVD lumen (and connection to a stand-alone monitor box).
  - **Parenchymal ICP monitor:** the fiberoptic pressure probe is attached to a stand-alone monitor box and zeroed with respect to air prior to insertion into the seated bolt apparatus.
  - **Brain tissue oxygen monitor:** Calibration is achieved through the use of a smartcard.
  - **Cerebral blood f ow monitor:** To ensure that the probe is optimally placed, the K value on the monitor should be between 4.8 and 5.6 and the probe position assistant (PPA) below 2. The K value varies depending on the conductivity of the tissue. The K value of white matter is between 4.8 and 5.9. PPA indicates the artifact created by the pulsation of the brain tissue (if the probe is close to a vessel). A value of 0 indicates no artifact.
  - **Jugular venous saturation monitor:** Once correct probe position has been verified, light intensity calibration of the oximetry system can be performed. A blood sample from the tip of the catheter is also sent for analysis to confirm the value on the oximetry system. Frequent recalibration is required and should be prompted by any sudden change in the jugular venous saturation—prior to any alteration of medical management.

Postoperative Management

Monitoring

- Patients for whom invasive neuromonitoring is indicated generally will be housed in the intensive care unit setting. The majority will be intubated. Intensive adjunctive monitoring with a combination of frequent neurologic checks, an arterial line, a central venous catheter, telemetry, pulse oximetry, and, in some cases, end-tidal CO_2 capnography is routine in this population.

Medication

- Sedation with propofol or dexmedetomidine is preferred because the short-acting nature of these agents permits serial assessment of neurologic status.
- A prophylactic dose of antibiotics (cefazolin, or clindamycin in the setting of allergy to penicillin) should be administered within the hour prior to skin incision for monitor placement.

Radiographic Imaging

- It is common practice to perform a post-procedure noncontrast head CT in order to verify the position of the probe(s) and to exclude iatrogenic hemorrhage.
- Most invasive intracranial monitors, with the exception of the external ventricular drain, are not MRI-compatible. For further information, refer to the manufacturer guidelines for the specific device.
- **Postprocedure CT imaging (Fig. 7.13).**

Further Management

- Advances in the fields of neurointensive care and multimodal neuromonitoring have significantly changed the management of severe traumatic brain injury (TBI) in the last two decades. Since 1995, the Brain Trauma Foundation has published management guidelines for the treatment and prevention of intracranial hypertension (ICP . 20 mm Hg) and the maintenance of adequate CPP (50 to 70 mm Hg) in order to minimize secondary injuries. The use of advanced neuromonitoring modalities such as the brain tissue oxygen, cerebral blood flow, and microdialysis probes should be considered in cases where cerebral autoregulation is compromised. When used appropriately, these additional monitors may provide a more comprehensive understanding of the altered physiology and enable individualized, targeted therapy.
- **Cerebral tissue oxygen ($PbtO_2$)** is measured by a small, polarographic, Clarke-type intraparenchymal probe that records the partial pressure of brain tissue oxygen tension. It is usually inserted in noninjured white matter, away from any contusion, to permit an estimate of "global" cerebral physiology and serve as an early detection system for secondary brain injury. Accurate, real-time measurements can be obtained 1 to 2 hours after insertion. The frequency and duration of cerebral desaturation episodes—defined as $PbtO_2$ less than 15 mm Hg—correlate with outcome. Although there seems to be a trend toward better outcome with $PbtO_2$-targeted therapy to prevent and agressively treat episodes of subthreshold $PbtO_2$, it is unclear whether a higher $PbtO_2$ offers any beneficial effect for the patient.[3,9–11] Monitoring of $PbtO_2$ also highlights the interdependence of brain tissue oxygen tension and pulmonary function. Before attributing a low $PbtO_2$ to a reduction in cerebral blood flow, it is necessary to exclude any extracranial conditions that could negatively impact blood oxygenation, such as lung contusions, acute respiratory distress syndrome, pneumonia, atelectasis, or anemia. Adjunctive diagnostic modalities—arterial blood gas (ABG), complete blood count (CBC), chest X-ray, and FiO_2 challenges—may help to elucidate the underlying cause of an observed desaturation. Moreover, the position of the probe should be assessed before initiating more aggressive treatments. Improper probe positioning in the epidural space, in a sulcus, in the cortex, or adjacent to contused brain can cause erroneous readings.
- **Jugular venous saturation monitor ($SjVO_2$):** Retrograde cannulation of the distal portion of the internal jugular vein permits a "global" measurement of the oxygen delivery to the brain. Normal $SjVO_2$ ranges between 55 and 70% A low

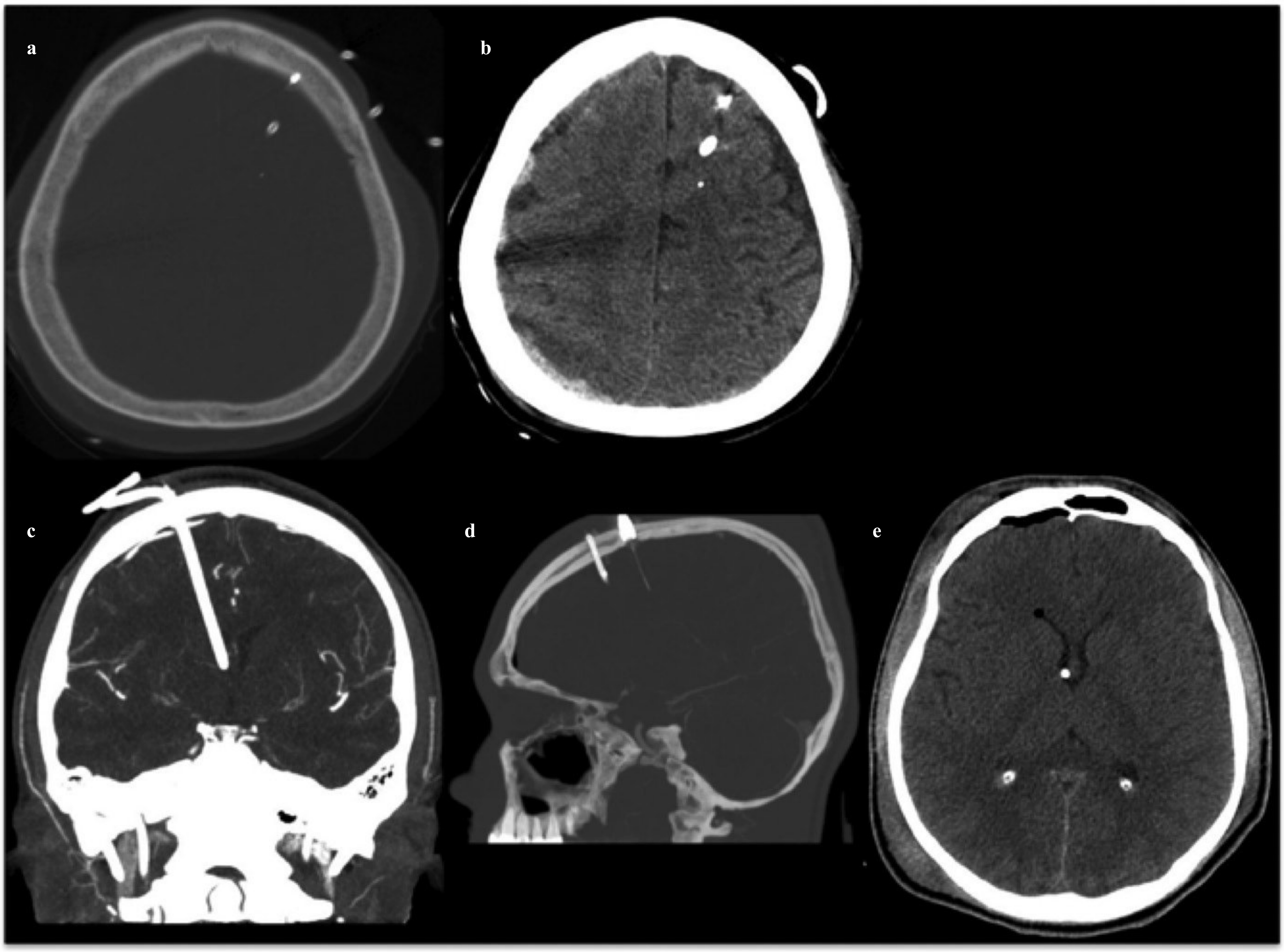


Fig. 7.13a–e Normal appearance of the indwelling blood flow and cerebral tissue oxygen probes, as well as the EVD catheter, at the level of the left frontal lobe (**a**, bone window; **b**, brain window). From anterior to posterior: cerebral blood flow, EVD, and cerebral tissue oxygen. (**c, e**) Optimal positioning of the EVD catheter in the right anterior horn, near the foramen of Monro, and (**d**) the cerebral brain tissue oxygen probe in the white matter of the right frontal lobe.

saturation (, 50%) has been correlated with ischemia and worse outcome after severe TBI, whereas a high value (. 80%) may correlate either with hyperemia (where increased flow reduces the saturation difference) or with brain death (where impaired metabolism and tissue death reduce the saturation difference). The observed value is sensitive to the position of the catheter. Contamination by extracerebral venous blood, for example, will lead to a lower value.[12,13] As with brain tissue oxygen monitoring, potential systemic causes (hypoxia, hypotension, hypocarbia, anemia) must be ruled out when a low value is observed. Although much controversy exists regarding the optimal side for placement of the $SjVO_2$ probe, it is typically inserted on the right side because the right transverse sinus is the most frequently the dominant site for the venous drainage of the brain. The jugular venous saturation monitor, when used in combination with the $PbtO_2$ probe, provides both a global ($SjVO_2$) and a focal ($PbtO_2$) assessment of brain tissue oxygenation. This combination allows for the distinction between hyperemia and hardware failure if a value seems to be out of range. Moreover, the tandem use of $SjVO_2$ and $PbtO_2$ may facilitate modification of therapy to optimize CPP in the setting of impaired autoregulation. The practitioner should be aware that the measurement of $SjVO_2$ is extremely labor intensive because of the frequent need to assess the position of the probe and to compare blood samples obtained from the tip of the cathether to the values obtained by oximetry.

- **Cerebral blood f ow (CBF) monitoring:** An intraparenchymal probe measures the local blood flow using a thermal diffusion technique. The probe is inserted in the white matter (normal CBF 20–35 mL/100 g/min). A value of less then 9 mL/100 g/min indicates a degree of ischemia that will lead to irreversible cellular damage. It is important to note that the measured value reflects the status of only the small, spherical volume of brain tissue (27 mm^3) around the catheter tip and that the measurement is extremely probe position-dependent.[14–16] Proximity of the probe to injured tissue will produce a lower CBF value as compared with that measured by a probe positioned within normal-appearing cortex.
- **Microdialysis:** A microdialysis probe allows for the study of the brain tissue chemistry through measurements of cerebral metabolism. Glucose, pyruvate, and lactate are markers of energy metabolism. Glutamate and glycerol are markers for neuronal injury. The ratio of lactate to pyruvate correlates

with the severity of clinical symptoms and outcome after brain injury. Microdialysis has been used in the setting of severe TBI and subarachnoid hemorrhage to predict ischemia and vasospasm.[4] The use of microdialysis is labor intensive and necessitates a highly trained team. Results will differ depending on whether the probe is positioned within normal or contused tissue.[17]

Special Considerations

ICP remains the cornerstone of invasive brain monitoring. Advanced neuromonitoring techniques provide an opportunity for better understanding of cerebral pathophysiology; however, effective use of this technology requires an understanding of how to both properly place the probe and interpret the data. Data derived from these modalities are extremely dependent on the position of each probe. Therefore, verification of probe position is essential prior initiating significant changes in clinical management. Furthermore, patients requiring such monitoring typically are complex and may present with a variety of cerebral pathophysiologic abnormalities. The practitioner must possess a deep and clear understanding of cerebral physiology and metabolism in order to use the information effectively in the patient-specific treatment of TBI. In summary, while there does exist a role for the use of advanced neuromonitoring techniques, the results must be interpreted and applied critically.

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8 Surgical Debridement of Penetrating Injuries

Roland A. Torres and P.B. Raksin

Introduction

Although open head injuries are commonly referred to as *penetrating*, not all such injuries are alike. The term *penetrating* injury technically describes the situation in which a projectile enters the skull but does not exit. A *perforating* injury occurs when the projectile passes entirely though the head, leaving both an entrance and an exit wound. This distinction has prognostic implications. In a series of projectile-related head injuries during the Iran-Iraq War, patients treated for perforating wounds had a poorer postsurgical outcome (50% greater morbidity and mortality) than those treated for penetrating wounds.[1]

Penetrating head injuries may result from intentional or unintentional events, including shootings, stabbings, blast injuries, and motor vehicle or occupational accidents (e.g., nails). Stab wounds are characterized by a smaller impact area and lower velocity than missile wounds. For the purposes of this chapter, we limit our discussion to missile wounds.

Historically, the management of civilian missile injuries has been informed by and evolved in concert with military practice. Since World War II, military neurosurgeons have uniformly advocated thorough debridement and watertight dural closure to prevent cerebrospinal fluid (CSF) leak and possible infection. During the Vietnam War era, craniectomy or craniotomy was accompanied by aggressive debridement of the in-driven bone, projectile fragments, and associated debris. The pursuit of debris into areas of potentially viable brain tissue was believed to be responsible for additional neurologic deficits and impairment.[2,3] Partially in response to this finding and as the result of experience gleaned from multiple military conflicts over the past 40 years, a new management paradigm has emerged. Initial treatment of projectile wounds of the brain is now designed to preserve the maximum cerebral tissue and function either by limiting the wound debridement performed through a craniectomy or by care of scalp wounds only.[4–6] Branvold et al found no relationship between the presence of retained fragments and the development of either a seizure disorder or an infection of the central nervous system.[7] Findings such as this one support the growing consensus that routine reoperation for removal of retained fragments is unnecessary. The net result of this strategy has been improved outcomes with significantly decreased morbidity and mortality.

Indications

- The totality of the observed injury reflects a combination of forces: (1) direct crush injury inflicted by the projectile along its path; (2) cavitation produced by the centrifugal effects of the projectile on the parenchyma; and (3) stretch injury resulting from the shock wave generated by the projectile in transit. Each must be factored into the decision-making process.
- Two fundamental decisions drive management: (1) whether or not to operate and, if so, (2) the extent of the intervention to be undertaken.
- The decision of *whether or not to operate* is dictated both by clinical status and the observed radiographic pathology.
  - Supportive, expectant (nonoperative) management may be appropriate for a patient presenting with a Glasgow Coma Scale (GCS) score ≤ 5 and bilateral fixed, dilated pupils post-resuscitation.
    - If such a patient presents with a potentially reversible mass lesion and is deemed otherwise medically viable, consideration may be given to emergent operative intervention.
    - If no extra-axial mass lesion is present, consideration may be given to a trial of hyperosmolar therapy (20% mannitol bolus 1 g/kg); if a significant improvement in motor exam and/or pupillary response is noted, the patient may be considered a potential candidate for surgery.
  - Hemodynamic instability and/or profound coagulopathy may influence the decision to forego operative intervention.
  - Certain ominous radiographic findings portend a poor prognosis: anteroposterior or bilateral hemispheric through-and-through trajectory; or trajectory through the brainstem, hypothalamus, posterior fossa, and/or venous sinuses. These factors should be taken into account when determining candidacy for operative intervention.
  - On the other hand, a patient presenting with a GCS score of 14 or 15 and minimal radiographic injury may require only local wound care and close observation.
- Clinical exam and radiographic features guide the *extent of operative intervention*.[5,8]
  - Limited surgery may be appropriate for a patient presenting with a small entrance wound, coupled with minimally depressed bone fragments and little or no mass effect and/or hematoma on head computed tomography (CT). Such a patient may benefit from superficial debridement.[9]

- Craniotomy/craniectomy with targeted, limited debridement may be appropriate for a patient presenting with limited mass effect, some in-driven bone fragments, some projectile fragments, and mild to moderate cerebral edema. Only the easily accessible bone and projectile fragments should be retrieved. Aggressive adjacent brain debridement should be avoided. These patients do very well with a combination of copious intraoperative antibiotic irrigation, formal dural closure, good scalp closure, and periprocedural broad-spectrum antibiotics.
- Craniotomy/craniectomy with more extensive debridement is appropriate in the presence of significant mass effect. Space-occupying lesions should be evacuated. Debridement of necrotic brain tissue, along with safely accessible bone and missile fragments, is recommended.[5,10,11] Deep-seated bone and missile fragments—especially in eloquent areas—should not be retrieved because this has been shown to correlate with worse outcomes. When the projectile's trajectory traverses an air sinus, operative intervention is recommended to achieve water-tight closure of the damaged dura.[1,9] This may decrease the risk of CSF fistula and abscess formation.[1,12]

- No evidence-based recommendations address the timing of intervention. Here, pragmatism applies.
  - If a significant space-occupying lesion is present, emergent surgical intervention is warranted for relief of mass effect as a life-saving measure—with the recognition that it may not change outcome.
  - If findings suggesting mass effect are less compelling, it would be reasonable to monitor intracranial pressure (ICP) and manage expectantly.
  - If the goal is simple wound care, it would follow that expedient intervention may diminish the risk of infection and CSF complications.[9,10]

Preprocedure Considerations

General

- Attend to the ABCs of resuscitation (airway, breathing, circulation).
- Control brisk bleeding from the scalp and associated wounds with hemostats or temporary staple closure, as well as a pressure dressing. Large, isolated scalp wounds may lead to fatal blood loss.
- Document entrance and exit (if present) wounds, as well as the presence of powder burns, CSF leak, and brain herniation.
- Early invasive ICP monitoring is an option when unable to follow a serial neurologic exam, when the need to evacuate an observed mass lesion is uncertain, and/or when imaging suggests increased intracranial pressure.[9] Brain tissue oxygen monitoring may be considered as well.

Radiographic Imaging

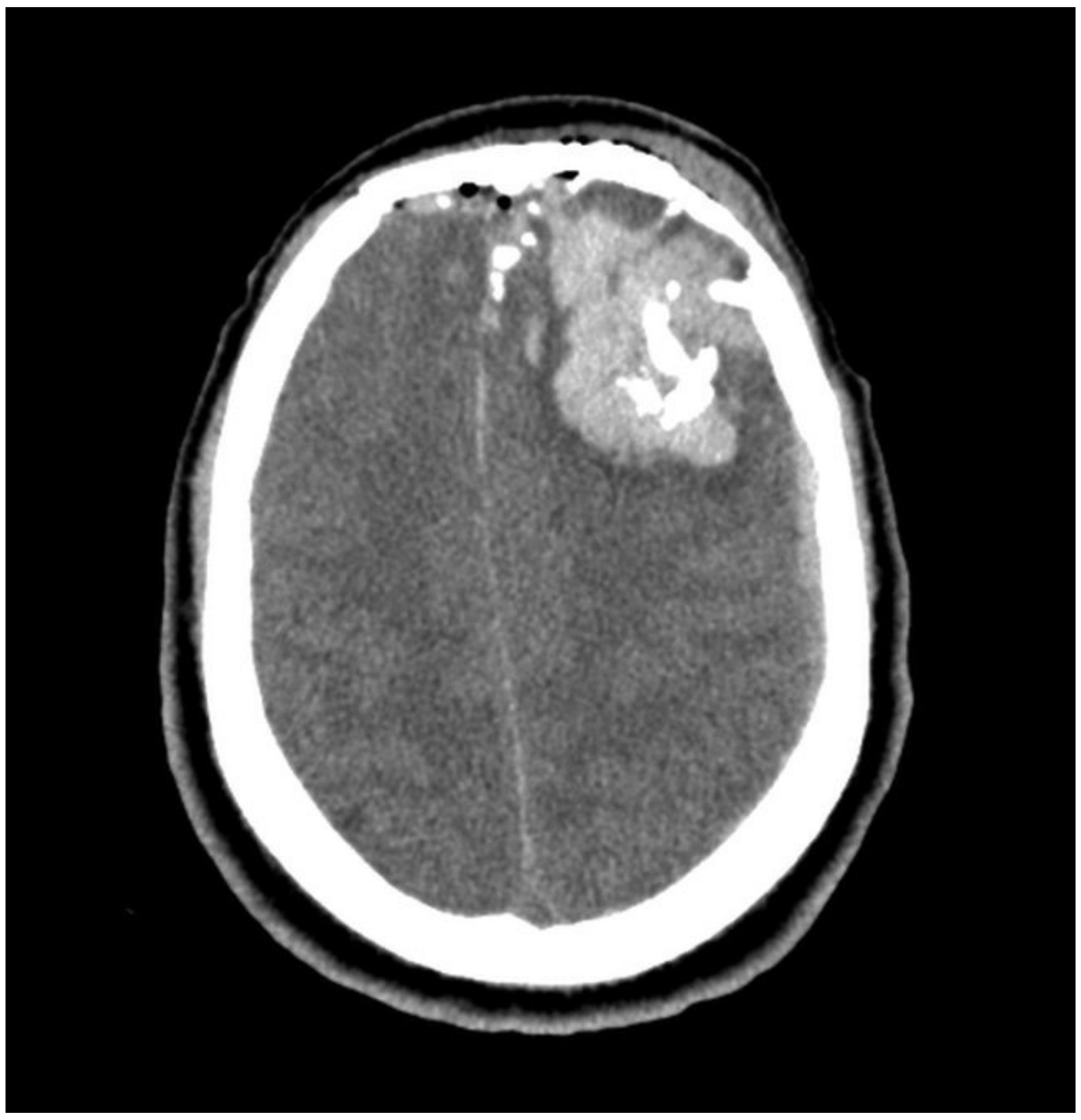
- Anteroposterior and lateral skull X-rays may provide general information regarding the presence of radiopaque foreign bodies as well as entrance and exit sites. The ease with which multiplanar CT can be obtained in most settings has largely obviated the need for this diagnostic modality.
- Noncontrast CT provides the most comprehensive source of anatomic information. CT will reveal the presence of hematoma and foreign bodies—both bony and metallic—as well as information regarding the likely missile trajectory. The CT should be studied for potential violation of vascular structures.
- If direct vascular injury is suspected, emergency vascular imaging may be appropriate.
  - Imaging findings arousing suspicion may include: orbitofacial or pterional location; trajectory through a venous sinus or the Sylvian fissure; the presence of fragments crossing dural compartments; or the presence of a large hematoma proximate to a named vessel.
  - Formal cerebral angiography not only permits diagnostic assessment but also offers the potential for intervention.
  - In recognition of expediency, CT angiography may be another option in this setting.[9]
  - A single negative study does not definitively rule out injury. The development of unexplained subarachnoid hemorrhage or hematoma in the days following the initial injury may provide an indication for delayed or repeat imaging.
- Magnetic resonance imaging (MRI) is generally contraindicated in the setting of a penetrating injury with metallic foreign body. However, it should be noted that most civilian ammunition—particularly pistol ammunition—is actually nonferromagnetic and, hypothetically, should not preclude MRI evaluation. Caution must be exercised with shotgun wounds as many shotgun shells now deliver steel shot (due to Environmental Protection Agency legislation regarding lead pollution). MRI may play a role in the diagnostic evaluation of penetrating injuries from wooden or nonmagnetic objects. Keep in mind that MRI is not practical in the acute setting, given the time necessary to perform the study as well as potential risks associated with transporting a critically ill patient to an often "remote" area of the hospital.
- **Preoperative imaging (Fig. 8.1).**

Medication

- Antimicrobial prophylaxis is administered. Broad-spectrum coverage, perhaps skewed toward skin flora, is appropriate in the setting of gross contamination of the wound.
- Antiepileptic drug prophylaxis is initiated.
- A loading dose of mannitol 20%(1 g/kg) may be given.
- A type and cross-match should be performed. Coagulopathy often develops in the setting of penetrating injury due to increased tissue thromboplastin activity. Ensure availability of a range of blood products (red blood cells, fresh frozen plasma, and platelets), as well as adjunctive agents (aprotinin, desmopressin, recombinant factor VII, tranexamic acid, vitamin K, and prothrombin complex concentrates) that might become necessary perioperatively.

Operative Field Preparation

- If vascular injury is suspected, ensure that appropriate supplies (microscope, aneurysm clips, microsurgical instruments, blood products) are available prior to skin incision.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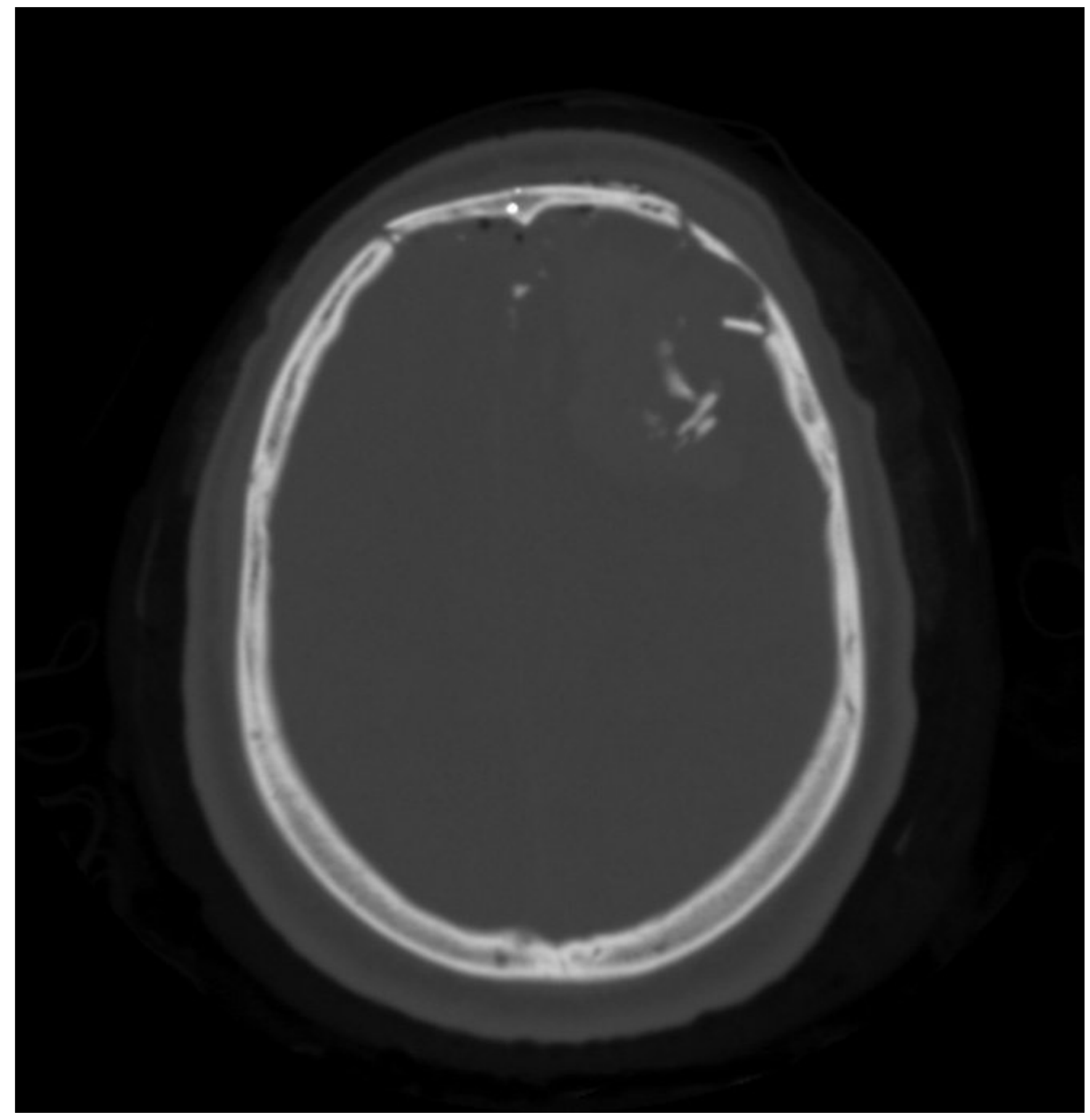

b


c

Fig. 8.1a–c Axial CT (**a**) brain and (**b**) bone windows demonstrating a comminuted bilateral frontal bone fracture, associated with a large left frontal intraparenchymal hematoma, in-driven bone, and pneumocephalus. (**c**) Three-dimensional reconstructed image demonstrates the full extent of the bony injury; note that the missile is actually lodged in the extracranial space, just posterior and lateral to the depressed fracture.

- Control bleeding from scalp and associated wounds. Temporary staple or suture closure may be necessary to permit preparation of the field.
- Foreign bodies protruding from the head are left in place during preparation of the surgical site.
- A wide area of scalp is shaved to ensure identification of entrance and exit sites, to clear superficial scalp debris, and to allow for a large cranial opening.
- The surgical site is prepared with alcohol, followed by a povidone-iodine or chlorhexidine solution in the usual sterile fashion. Avoid the latter if exposed brain is present. A diluted povidone-iodine solution may be used for the preparation of large contaminated wounds.
- The incision is marked and infiltrated with 1% lidocaine with 1:100,000 epinephrine. Avoid areas of exposed brain tissue.

Operative Procedure

Positioning (Fig. 8.2)

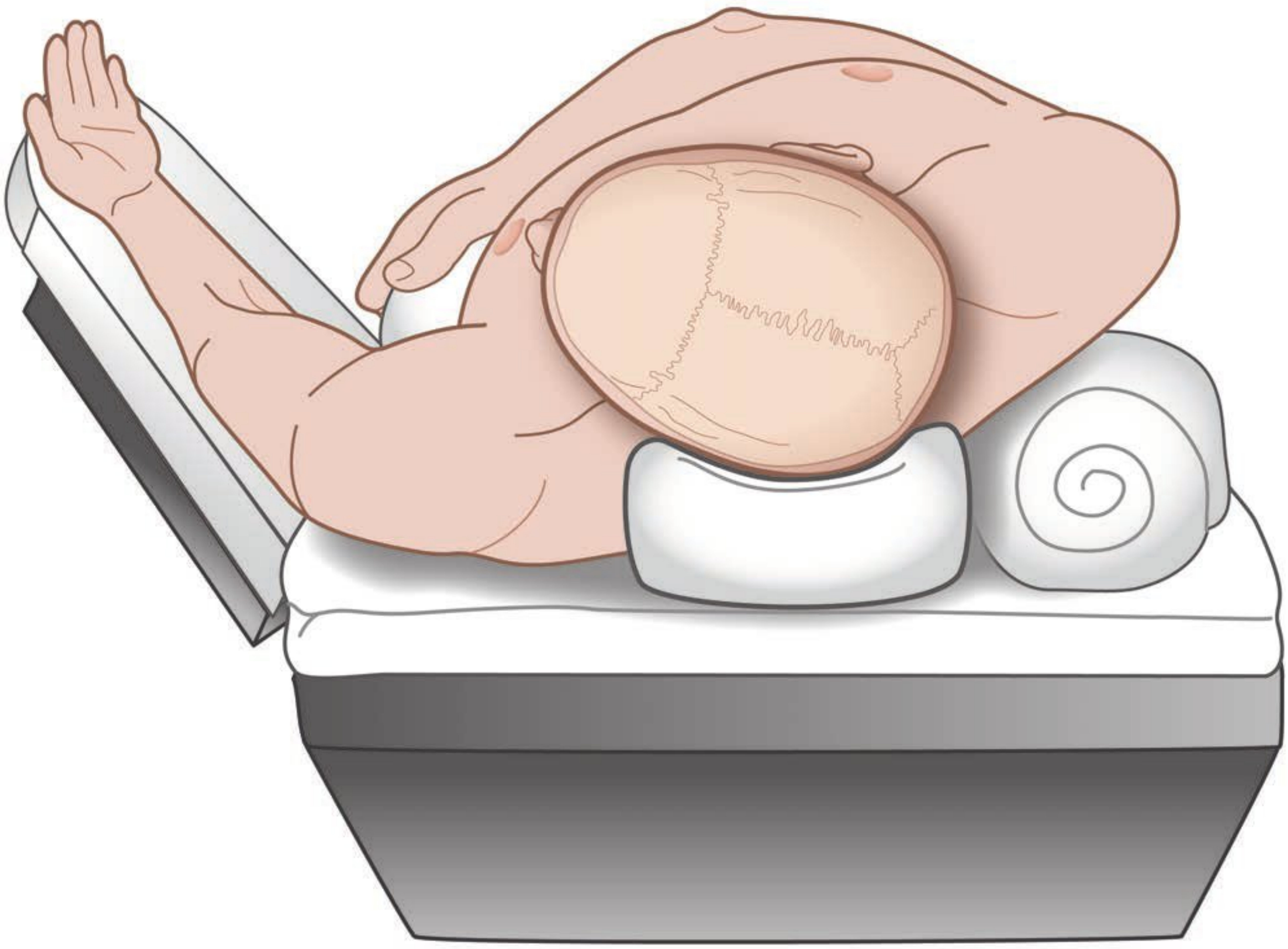


Figure	Procedural Steps	Pearls
Fig. 8.2	**The patient position will be dictated by the localization of the pathology. A donut or horseshoe head holder is used to expedite the procedure.** **If a unilateral procedure is planned, the patient is positioned supine, with the head turned contralateral to the side of the approach. A shoulder roll is placed longitudinally beneath the ipsilateral shoulder.** **If a bilateral procedure is planned, the patient's head is positioned in a neutral, upright position.** **The back of the bed is raised slightly.**	• If the cervical spine has not been cleared, the cervical collar should be maintained and the patient rotated in-line to expose the side of the approach.

Incision Planning (Fig. 8.3)

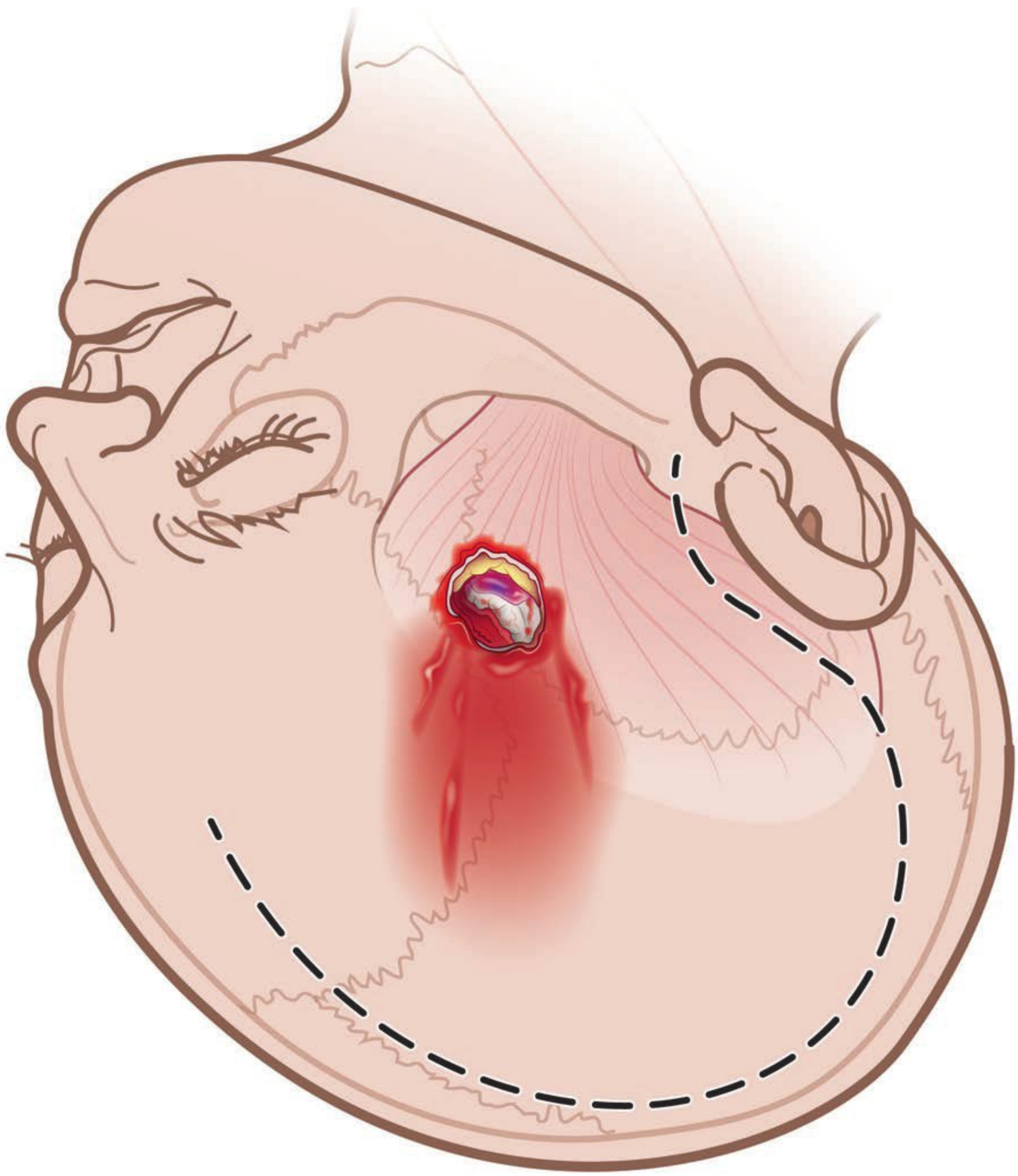


Figure	Procedural Steps	Pearls
Fig. 8.3	**A reverse question mark–type incision is traced on the scalp for a unilateral approach. A bicoronal incision—positioned posterior to the hairline—is marked for a bilateral procedure.** **A no. 10 blade is used to incise the skin along the previously marked line. The incision is carried down to the level of pericranium superiorly and temporalis fascia inferiorly. Scalp clips are applied to the skin edges to facilitate hemostasis.**	• Avoid incorporating the entrance/exit wound into the incision, given the high likelihood of devitalized local soft tissue. By the same token, be sensitive to the position of the wound(s) with respect to the planned incision and scalp blood supply.

Subcutaneous Dissection (Fig. 8.4)

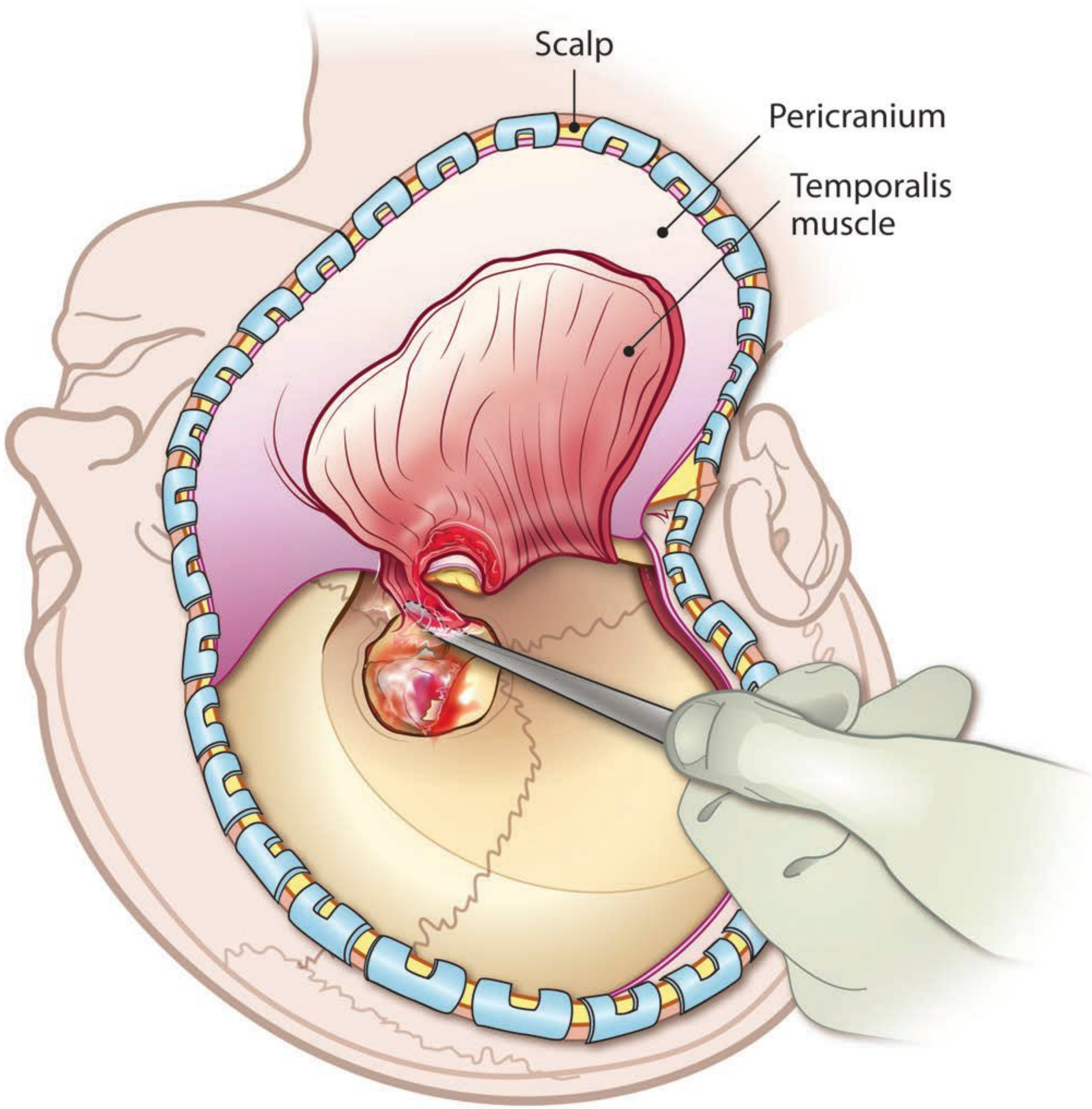


Figure	Procedural Steps	Pearls
Fig. 8.4	**The pericranium is opened with monopolar electrocautery, in-line with the scalp incision. The temporalis fascia and muscle are also opened with monopolar electrocautery. The resultant myocutaneous flap is reflected forward until the keyhole and root of zygoma are visible. The flap is secured with the surgeon's retraction system of choice.**	• Dissection of soft tissue away from areas of known bony defect (i.e., entrance and exit sites) should be accomplished with a periosteal elevator rather than electrocautery. • In the setting of a bicoronal approach, the pericranium may be elevated in a separate layer to provide vascularized grafting material later in the procedure.

Bur Hole Placement (Fig. 8.5)

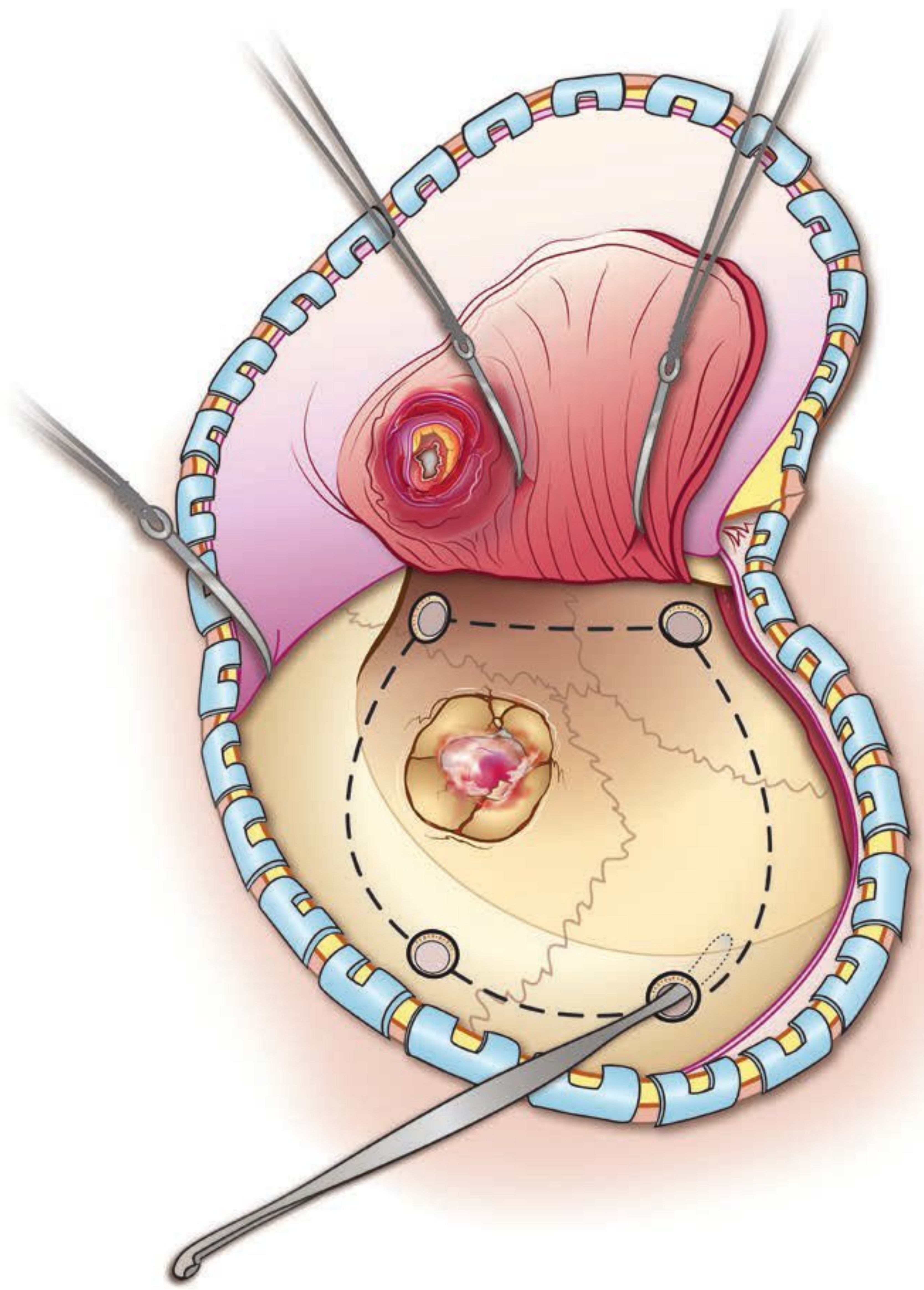


Figure	Procedural Steps	Pearls
Fig. 8.5	**For a unilateral approach, bur holes are placed at the key hole, just above the root of zygoma, over the parietal eminence, and at a point that is just anterior to coronal suture and ~1 cm lateral to midline.** **For a bilateral approach, bur holes are placed bilaterally at the keyhole; just above the root of zygoma; at the junction of superior temporal line and coronal suture; and at one or two points straddling the midline, anterior to coronal suture.** **Bone wax is applied to the bony edges. A no. 3 Penfield is used to strip the dural attachments from the undersurface of the calvarium between each set of holes.**	• If substantial bony injury is present, it may be feasible to remove portions of the involved calvarium without the use of power tools. In such cases, bur holes should be positioned to facilitate creation of a bone flap that allows access to adequate surface area to permit control of vascular structures, judicious debridement, and dural closure. • Take particular care when adequate access requires crossing the midline. If the path is not readily cleared, remember that bur holes are cheap relative to a sinus injury.

Craniotomy (Fig. 8.6)

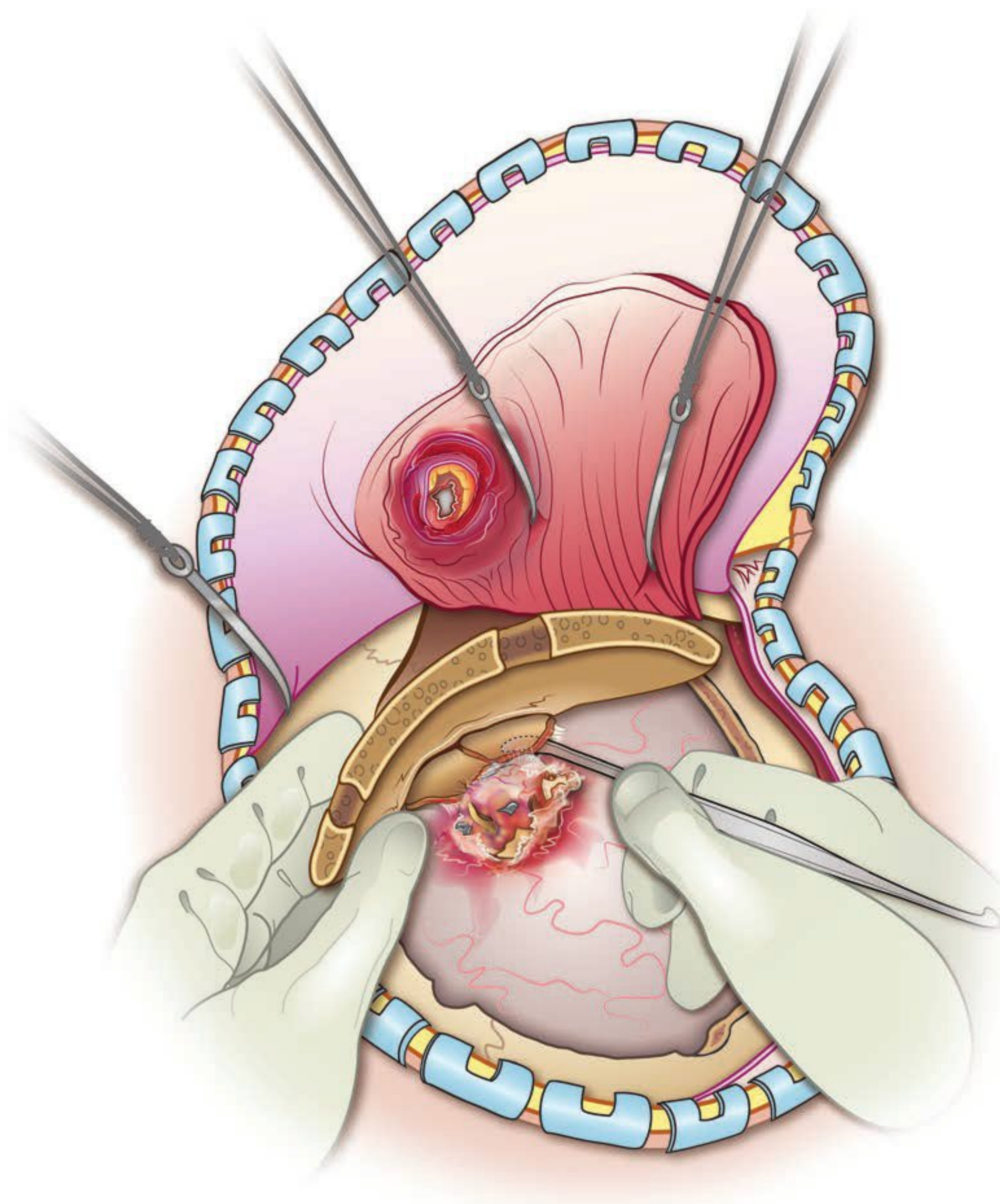


Figure	Procedural Steps	Pearls
Fig. 8.6	**The craniotome is used to create a path that circumnavigates the previously placed bur holes. The resulting bone flap is carefully elevated away from the underlying dura and set aside in antibiotic solution.** **For a bilateral approach, it may be easier to create two separate unilateral flaps, temporarily leaving a strip of bone along the midline. Craniotome cuts then can be made across the midline and the bony isthmus removed.** **Venous sinus bleeding is controlled with a combination of gentle pressure and hemostatic agents.** **Epidural hematoma, if present, may be evacuated at this time.**	• Direct visualization of the dural surface during elevation of the bone flap is key, as the craniotomy site likely includes an area of known bony and dural defect. • If direct injury to the sinus is suspected, it may be necessary to proceed with repair and/or ligation (anterior one-third only). Preoperative imaging should prompt appropriate forethought and preparation.

Dural Opening (Fig. 8.7)

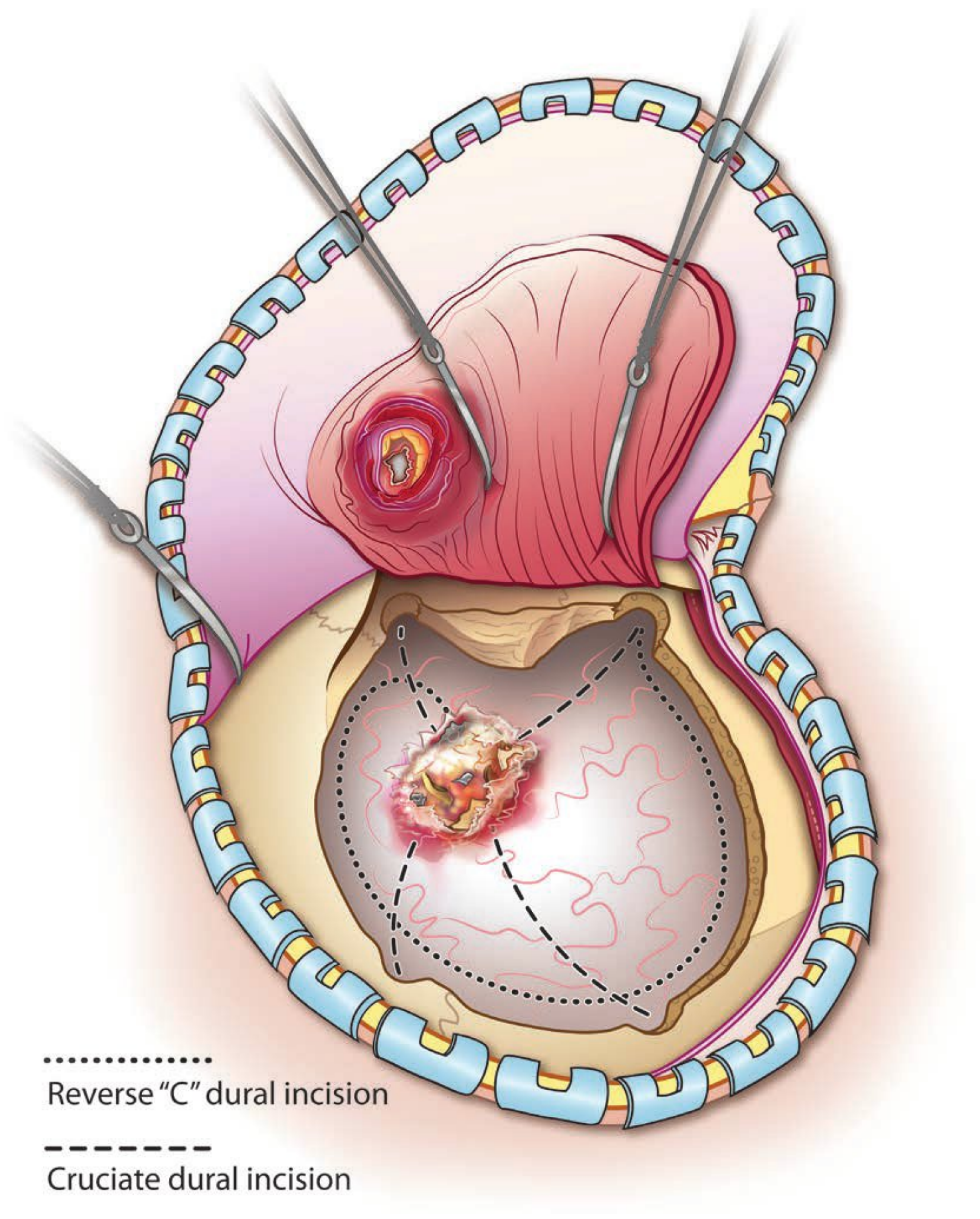
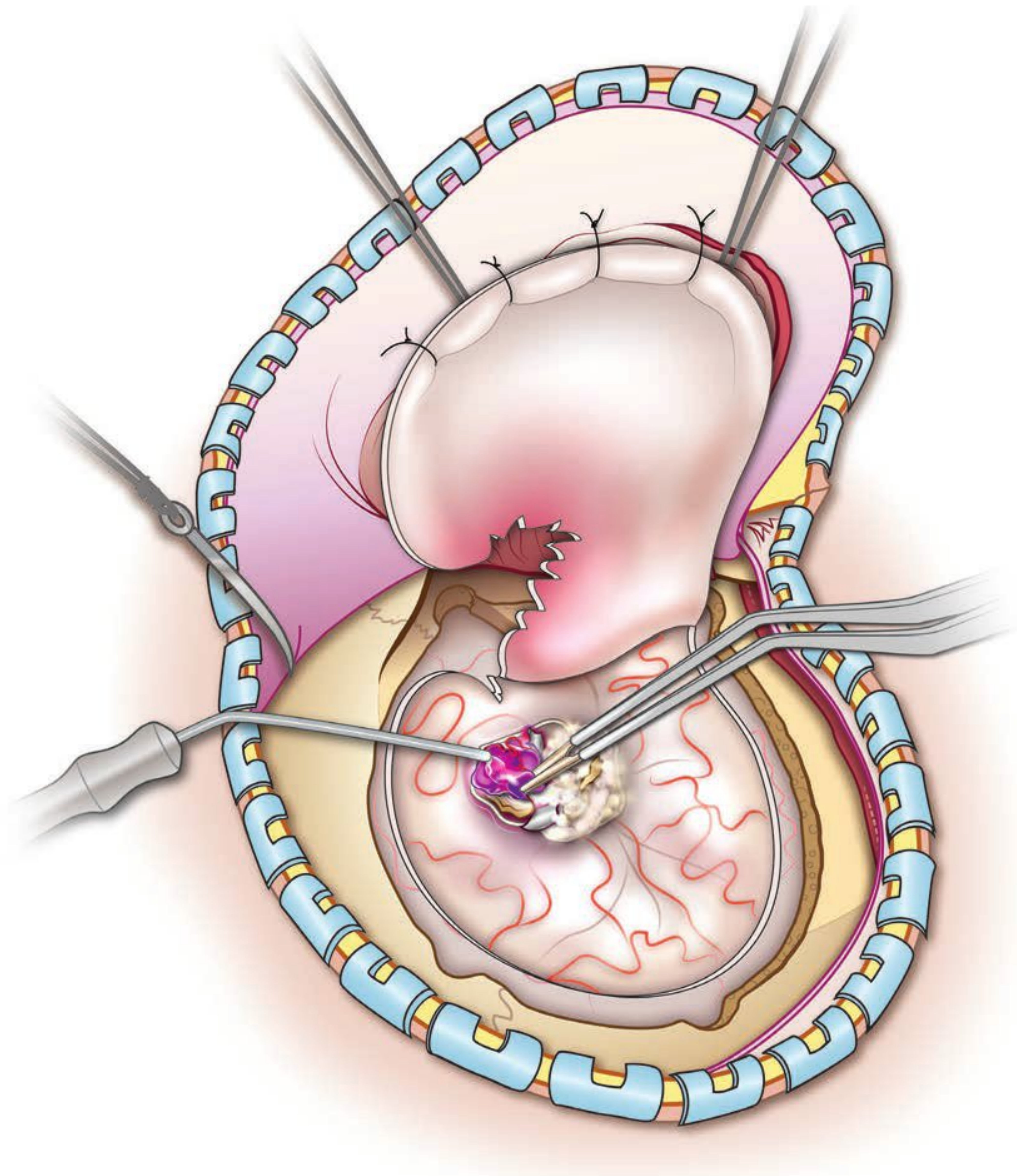
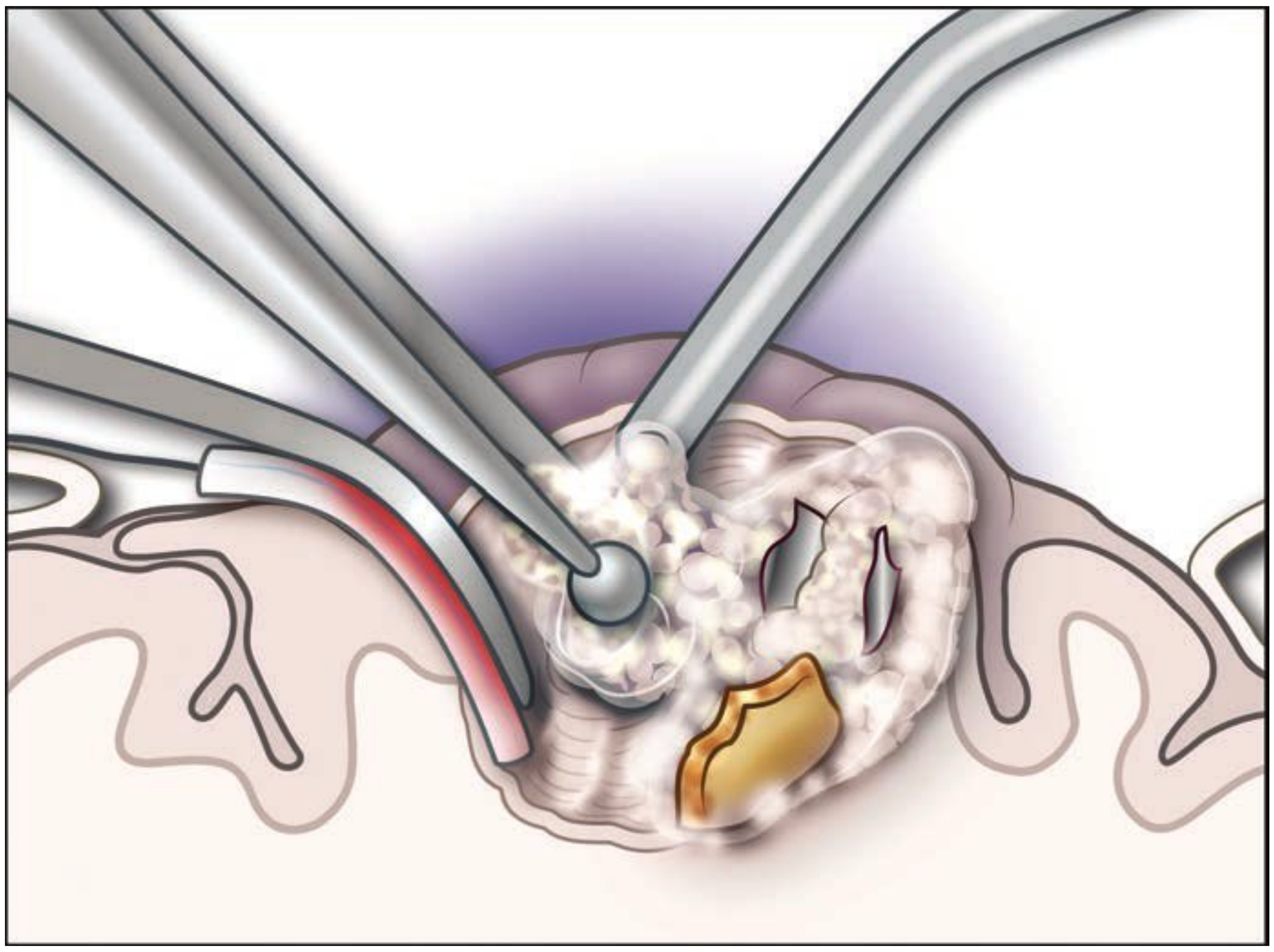


Figure	Procedural Steps
Fig. 8.7	**By definition, the dura is already "open." In certain cases, it may be appropriate simply to enlarge the existing dural opening to permit the necessary exposure for local debridement.** **If a need for broad exposure is anticipated, a cruciate or reverse C-shaped dural opening should be considered.** **In the setting of a bicoronal approach, trap-door dural flaps can be reflected toward the midline sagittal sinus.**

Approach to Parenchymal Injury (Fig. 8.8a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 8.8	**Subdural hematoma, if present, should be evacuated with a combination of gentle suction and saline irrigation. (a) Inspect the cortical surface. Address obvious points of arterial or venous bleeding. There is likely obvious cortical disruption. This should be the portal of entry for debridement. Associated large intraparenchymal hematoma should be approached with a combination of gentle suction and bipolar electrocautery. Upon entry to the hematoma cavity, suction out any liquid clot. Remove solid clot in a piecemeal fashion. (b) If no significant hematoma is present, superficial, necrotic brain tissue should be debrided with gentle suction and irrigation. Readily accessible missile and bone fragments should be retrieved. Continue until gliotic brain is visible on all sides. Hemostasis should be achieved with a combination of bipolar electrocautery and hemostatic agents.**	• Principles of debridement for penetrating injuries encompass techniques previously discussed for evacuation of subdural hematoma (Chapter 1) and cerebral contusions (Chapter 3). Management of venous sinus injury is discussed in Chapter 10. Techniques for frontal sinus reconstruction are discussed in Chapter 27. Please refer to these sections for more detailed nuances of management. • A hand-held malleable retractor, introduced over a saline-moistened 1 3 3 cm cotton pattie may assist visualization. • No attempt should be made to follow missile trajectory to deep subcortical structures. • Always maintain awareness of position relative to the lateral ventricles. Avoid entry to the ventricle, if feasible.

Duraplasty (Fig. 8.9)

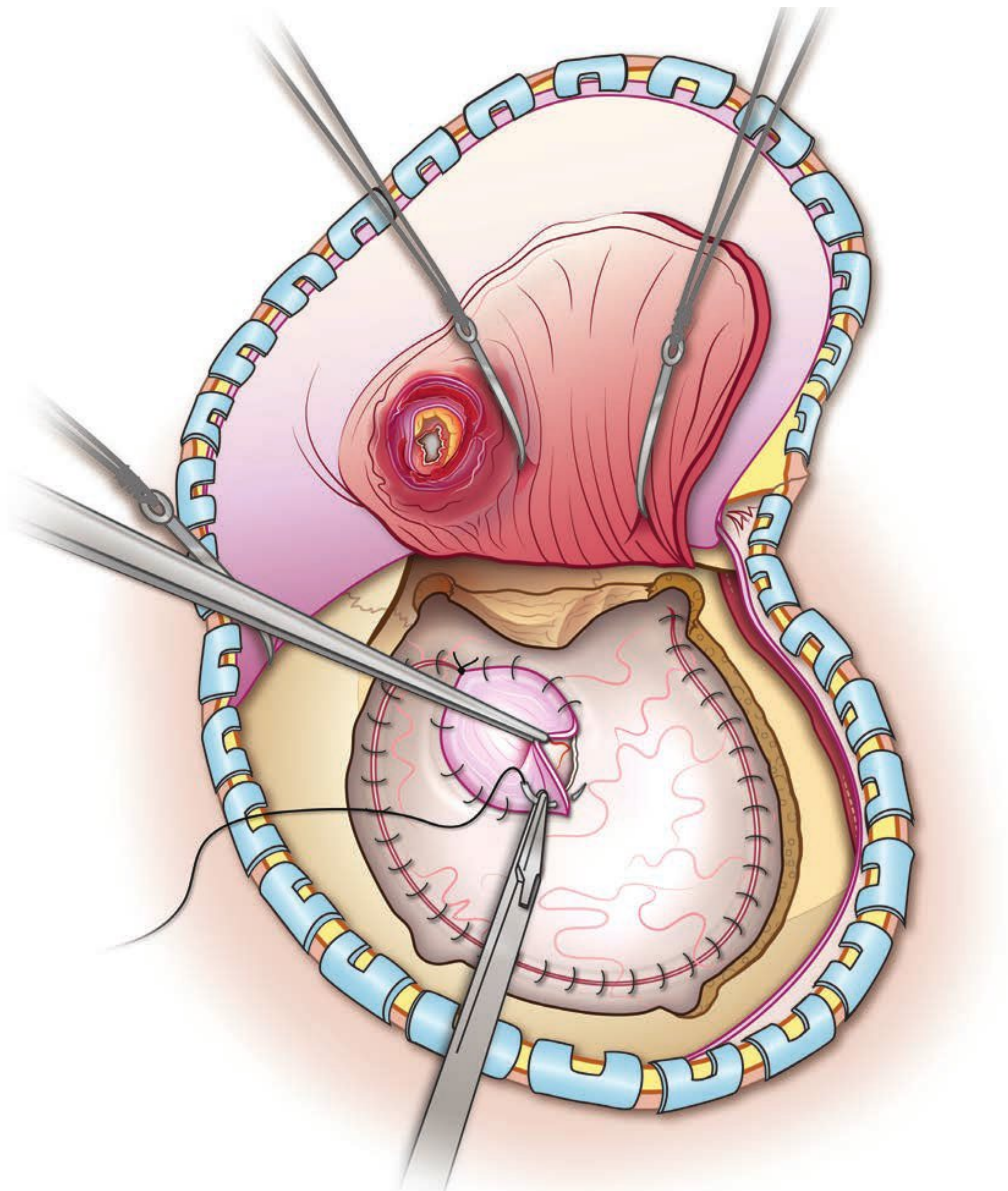


Figure	Procedural Steps	Pearls
Fig. 8.9	**Once debridement of devitalized brain tissue is complete, assess the extent of the dural defect.** **For a unilateral approach, a piece of pericranium may be harvested to bridge the defect. The graft is incorporated circumferentially with 4-0 braided nylon sutures.** **For a bicoronal approach, the previously harvested vascularized pericranial graft may be flapped over the exenterated frontal sinus and secured with 4-0 braided nylon suture, augmented by fibrin glue.**	• It is important to determine the relationship of the defect to adjacent air sinuses. • If no viable pericranium is available, temporalis fascia, fascia lata, or synthetic dural substitute may be prepared for this purpose.

Closing

- The surgical site is irrigated with antibiotic solution.
- The decision of whether to replace the bone flap at the conclusion of the procedure is based both on the degree of brain swelling present and whether the bone flap can be salvaged. In some cases, the bone flap is too comminuted or too grossly contaminated to permit re-implantation.
- The soft tissue elements (muscle and scalp) must be inspected at sites of entry and exit. Sharp local debridement back to viable tissue may be necessary. Irrigate with copious amounts of antibiotic solution prior to single-layer reapproximation with 3-0 nylon interrupted stitches. The participation of a plastic surgery colleague may be appropriate if extensive soft tissue injury is present and challenges to achieving sufficient surface area coverage are anticipated.
- A Jackson-Pratt drain is laid in the subgaleal space prior to closure.
- The temporalis muscle and fascia are re-approximated with 0 braided absorbable sutures.
- The galea and subcutaneous tissue are reapproximated with 2-0 braided absorbable sutures.
- The skin is closed with staples. A running-locking 3-0 nylon stitch may assist hemostasis if coagulopathy is present or bolster the closure if substantial swelling is present.

Postoperative Management

Monitoring

- Patients should be monitored in the intensive care unit setting following operative intervention.
- The use of invasive neurologic monitors (intraparenchymal or intraventricular) is appropriate for patients in whom serial neurologic exam is not feasible and/or whose GCS remains ≤ 8.
- The output of subgaleal and/or subdural drains—if present—should be monitored. Drain removal may be considered when outputs become minimal and/or serial imaging demonstrates resolution of the targeted collection.
- Monitor for clinical evidence of CSF otorrhea or rhinorrhea.

Medication

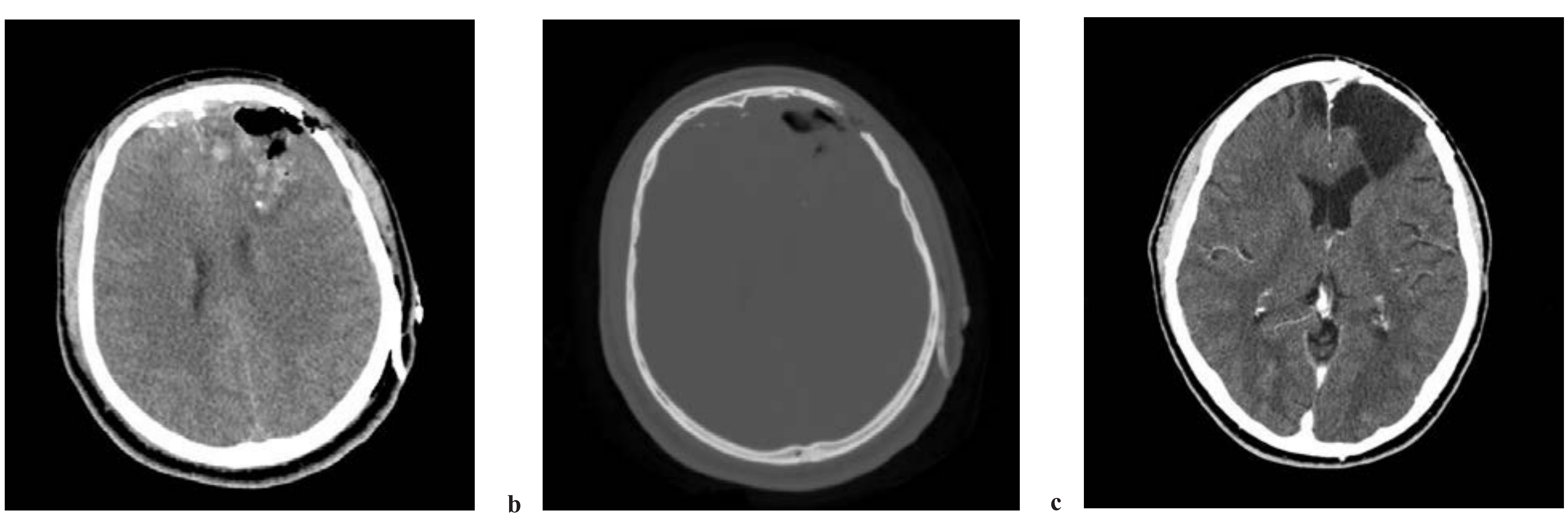
- The optimal prophylactic antimicrobial regimen and duration of therapy remain a matter of debate. There is the suggestion that broad-spectrum coverage should probably continue for a period that is somewhat longer than standard prophylaxis for a clean, elective procedure. The authors continue broad-spectrum coverage for 3 to 5 days post-injury.[9]
- Antiepileptic drug prophylaxis is continued for a total of 7 days post-injury.

Radiographic Imaging

- Immediate postoperative CT allows for assessment of residual or new hematoma, extent of foreign body debridement, and edema pattern. Once stability of any evolving hematoma has been established, CT imaging should be repeated only for significant changes in neurologic status.
- The persistence or delayed development of pneumocephalus beyond the immediate postoperative period—in the absence of an overt CSF leak—should prompt a search for an occult point of egress.
- The presence of new subarachnoid hemorrhage or hematoma in the area of a named vessel should prompt vascular imaging. Likewise, repeat vascular imaging at an interval of several days is appropriate for any patient who underwent such imaging at presentation—with a negative result—on the basis of suspicious CT findings.
- **Postoperative imaging (Fig. 8.10).**

Further Management

- Invasive neuromonitoring devices are removed when neurologic status dictates.
- Skin sutures or staples are removed at an interval of 10 to 14 days.



a b c

Fig. 8.10a–c Axial CT (**a**) brain and (**b**) bone windows demonstrating evacuation of the frontal hematoma and accessible foreign body fragments. A bony defect remains. (**c**) CT obtained approximately 3 months later (at the time of cranioplasty) demonstrates expected frontal encephalomalacia.

Special Considerations

- CSF leak
  - The incidence of CSF leak following missile injury approached 28% in one large series.[13]
  - This complication results from direct violation of the dura—by projectile or bony fragments—along with failure to seal the defect by normal tissue healing processes.
  - CSF drainage occurs along the path of least resistance—from entrance or exit wounds or from the ear or nose in the setting of air sinus violation.
  - The most feared complication of CSF leak is infection—meningitis and/or abscess.[1,12,14]
  - Every effort should be made to attain a water-tight closure of the dura at the time of initial surgical debridement.[1,9] Primary suture closure may be feasible. Sometimes, augmentation with a pericranial graft or synthetic material is necessary. In other cases, the leak occurs along the skull base, where "closure" is not necessarily feasible. A multi-layer wound closure will bolster the repair.
  - CSF leak may be a delayed phenomenon. Initial brain swelling may tamponade a site of potential egress. The leak may only become evident as swelling subsides several days after the injury.
  - If a CSF leak develops, initial management may consist of temporary diversion via ventriculostomy or lumbar drain (if not contraindicated). The head of the bed should be elevated. Many leaks will resolve spontaneously with conservative measures. If the leak is refractory to CSF diversion, surgical repair is recommended.[9]
  - If the point of egress is not obvious by imaging, a CT sinus metrizamide study may assist localization. Low-dose intrathecal fluorescein (less than or equal to 50 mg) may provide an adjunct at the time of endoscopic exploration.
- Infectious complications
  - The rate of infection following penetrating brain injury is lower in the civilian than military population and appears to vary directly with the use of broad-spectrum antibiotics in the early management of these patients.[9]
  - Risk factors for infection include CSF leak, wound dehiscence, violation of an air sinus, transventricular trajectory, and/or injury crossing midline.[15] Retained missile and bone fragments demonstrate a less conclusive relationship to the development of infection.
  - Most infections occur relatively early in the post-injury period. In one study, 55% occurred within 3 weeks and 90% with 6 weeks; rarely, a delay in onset of several years may be observed.[16]
  - There exists great variability in practice around the issue of antimicrobial prophylaxis in the setting of penetrating injury. The current Penetrating Brain Injury guidelines make the argument that if extensive Class I and Class II data support the use of prophylaxis in the setting of clean procedures, it would be reasonable to provide broader coverage of longer duration in the setting of a known open, contaminated wound. However, no data conclusively support a specific regimen or duration.[9]
  - *Staphylococcus* is isolated most commonly; however, a wide range of gram-negative and anaerobic organisms have also been implicated as causative agents—bolstering the argument for broad-spectrum coverage at the outset. Once an infectious process has been identified, antibiotic therapy must be tailored to culture and susceptibility data. Surgical debridement may be indicated in the setting of brain abscess or empyema. Please see Chapter 20 for further discussion regarding the surgical management of intracranial infection.

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9 Management of Traumatic Neurovascular Injuries

Boyd F. Richards and Mark R. Harrigan

Introduction

All traumatic cerebrovascular injuries (TCVI) involve either partial or complete disruption of the vessel wall. Traumatic arterial cerebrovascular injuries constitute a continuous spectrum of disease, ranging from minimal disruption of the intima to occlusion or transection of the artery. TCVI can also lead to the formation of arteriovenous fistulas and aneurysms. These injuries can be classified according to location (extracranial or intracranial) and by mechanism (blunt or penetrating).

This chapter is divided into four categories based on location and mechanism. The authors present algorithms based on our preferred treatment strategy for most cases at our institution.

Indications

Extracranial Blunt Injury

- TCVI occurs in about 1% of all blunt trauma patients.[1] Carotid injury occurs in 0.1 to 1.55% of blunt trauma patients. Vertebral injury occurs in 0.2 to 0.77% of trauma patients.
- Motor vehicle collisions account for 41 to 70% of cases.[2] Other mechanisms of injury include assault, pedestrian versus vehicle, and hanging.
- The injury may result from a direct vascular blow, extreme hyperextension/rotation, or laceration by bony fragments.
  - Independent risk factors for carotid artery injury include: closed head injury (with Glasgow Coma Scale [GCS] score ≤ 6), petrous bone fracture, diffuse axonal injury, and LeFort II or III fracture.
  - Cervical spine injury—C1, 2, or 3 fracture; transverse foramen fracture; or subluxation—is an independent risk factor for vertebral artery injury.
- The most commonly used classification system divides TCVI into five types (**Table 9.1**).[3,4]
- Arterial dissection (type I and II injuries)
  - Results from rapid deceleration of the body with subsequent stretching of the involved vessel.
  - Two mechanisms have been proposed (**Figs. 9.1** and **9.2**): (1) intramural hematoma formation between layers of the artery wall; and (2) an intimal tear leading to exposed subendothelial collagen, initiating platelet aggregation and leading to thrombus formation.
  - Specific segments of the carotid and vertebral arteries are more vulnerable to dissection than others:
    - Carotid: the distal cervical internal carotid artery (ICA), where the ICA is stretched over the lateral masses of the cervical spine, is at risk. Injury typically results from hyperextension and rotation to the contralateral side.
    - Vertebral: the V2 and V3 segments, as the vessel travels through the transverse foramina of C6 to C2 and around the lateral mass of C1, are at risk. V2 segment injuries typically have an associated cervical spine injury, whereas injury to V3 or V4 segments may occur in isolation.
- Traumatic aneurysm (type III injuries)
  - This results from disruption of the internal elastic lamina, which weakens the vessel wall and leads to expansion of the adventitia.
  - The term *pseudoaneurysm* implies a complete disruption of all layers. However, dissecting aneurysms may contain a complete artery wall. So, the term *traumatic aneurysm* is more appropriate.
  - Traumatic aneurysms of the carotid artery typically occur in the mid- or upper cervical ICA and account for 15 to 44% of TCVIs. A portion (7.6%) of carotid injuries that initially consist only of luminal irregularity later develop into traumatic aneurysms.[5]
  - Traumatic aneurysm accounts for only 4.8% of vertebral artery TCVIs.
  - Unlike spontaneous dissecting aneurysms, traumatic aneurysms tend to persist and often enlarge over time.[6]
- Occlusion (type IV injuries)
  - Traumatic vascular occlusion may occur at the time of the injury or may arise in a delayed fashion as the result of thrombus formation at the site of an arterial dissection.

Table 9.1 Classification of blunt traumatic cerebrovascular injury

Type	Description
I	Luminal irregularity or dissection; , 25% stenosis
II	Raised intimal flap or dissection; . 25% stenosis
III	Traumatic aneurysm
IV	Complete occlusion
V	Transection and/or development of arteriovenous fistula

Source: Biffl WL, Moore EE, Offner PJ, et al. Blunt carotid arterial injuries: implications of a new grading scale. J Trauma 1999;47(5):845–853; Biffl WL, Moore EE, Elliott JP, et al. The devastating potential of blunt vertebral arterial injuries. Ann Surg 2000;231(5):672–681.

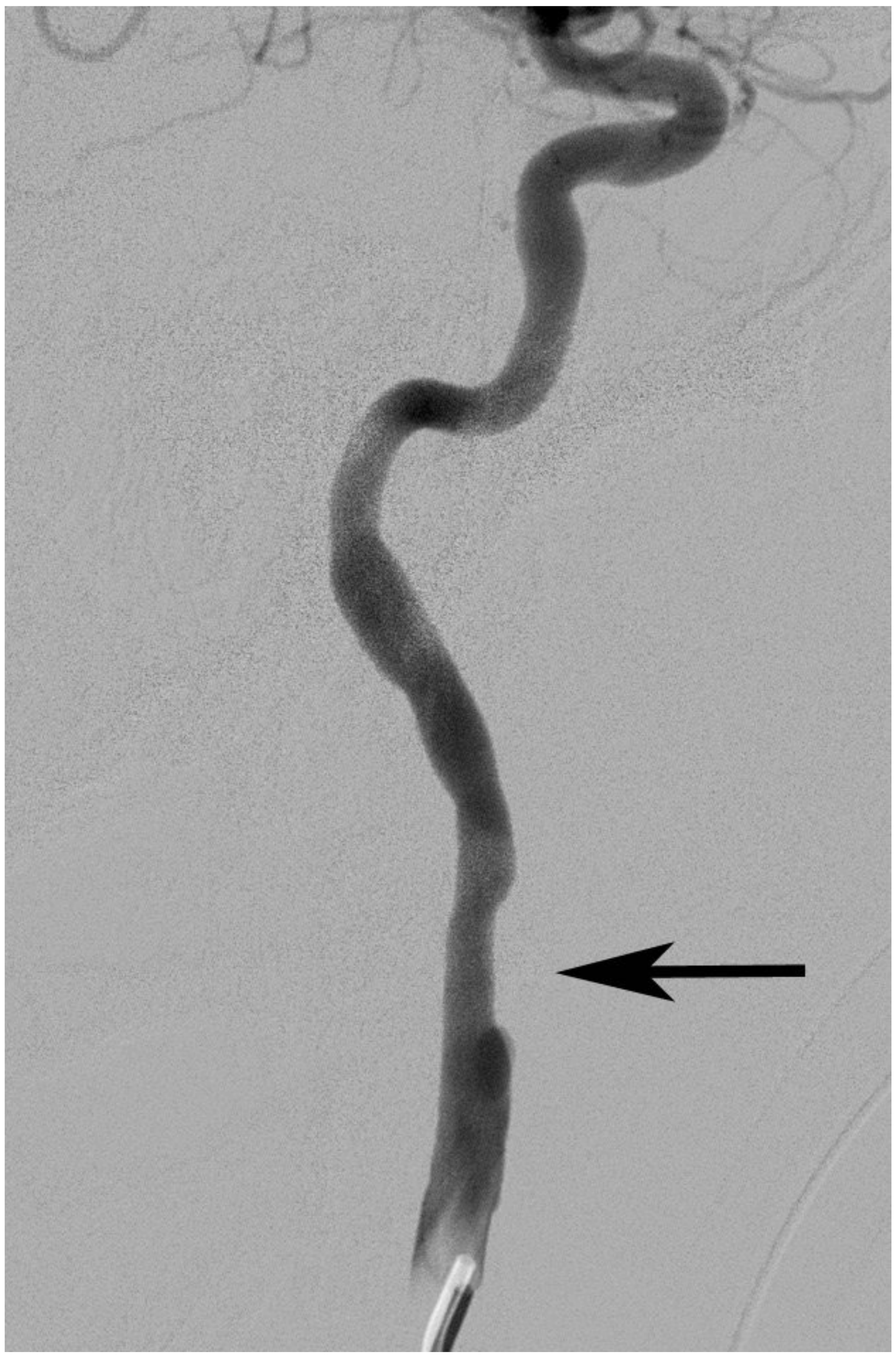


Fig 9.1 Type I traumatic cerebrovascular injury. A mid-cervical internal carotid artery intramural hematoma (arrow) causing , 25% reduction in luminal diameter.

- Occlusion is much less common than arterial dissection.
- Patients may present with symptoms of ischemic stroke or remain asymptomatic if good collateral circulation exists.

- Arteriovenous f stulas (type V injuries)
  - Present with tinnitus, cervical radiculopathy, heart failure, hemorrhage, steal, intracranial venous hypertension, or embolic stroke.
- **Type I traumatic cerebrovascular injury (Fig. 9.1).**
- **Type II traumatic cerebrovascular injury (Fig. 9.2).**

Extracranial Penetrating Injury

- Penetrating neck trauma is accompanied by vascular injury in 20% of patients.[7]
- Seventy-five percent of these vascular injuries are attributable to stabbing. Gunshot wounds account for the remainder.[8]
- The venous system is more commonly affected but less likely to require treatment.
- Carotid artery injury due to penetrating neck trauma results in vessel occlusion in 36% of cases and traumatic aneurysm formation in 33% of cases.[9] As compared with blunt extracranial carotid injury, the rate of ischemic stroke with a penetrating injury is lower, but the mortality rate is higher.[10]
- Penetrating extracranial injuries can be classified by type:
  - Arterial laceration
  - Dissection
  - Occlusion
  - Aneurysm
  - Arteriovenous f stula. Fistulas may be either carotid-cavernous (discussed in the blunt intracranial injury section) or vertebral-venous in nature. The latter may present as tinnitus, cervical radiculopathy, heart failure, hemorrhage, steal, intracranial venous hypertension, or embolic stroke. Slow-flow fistulas may be followed expectantly with serial angiography every 12 months in asymptomatic and otherwise clinically stable patients. High-flow fistulas may cause brainstem or spinal cord symptoms due to pressure from arterialization of the cervical venous plexus. Posterior circulation ischemia may result from diversion of flow.
- Physical examination is the most important part of the diagnostic evaluation for penetrating cervical vascular injury (see box below).
  - If physical signs of vascular injury are present, there is a 90% chance of a major arterial or venous injury.[11]
  - In the absence of physical signs, the risk of major vascular injury falls to 0.9%[11]

Physical Findings

Physical findings of penetrating, extracranial cerebrovascular injury

- Active bleeding
- Hematoma
- Thrill or bruit
- Absence of carotid pulse
- Neurologic deficit

Intracranial Blunt Injury

- Data regarding the overall incidence of blunt intracranial TCVIs is lacking. Such injuries are substantially less common than blunt extracranial injuries.
- GCS score , 8 and the presence of facial fractures are independent risk factors for blunt intracranial arterial injury.[12]
- Blunt intracranial injuries may be classified by type:
  - Dissection
    - May be associated with trivial trauma or blunt injury in closed head trauma, as well as penetrating injury.
    - The most common affected sites are the supraclinoid ICA and the intradural portion of the vertebral artery.
    - Intracranial dissection may be associated with underlying vascular abnormality of the cerebral arteries, including fibroelastic thickening and congenital deficiency with disruption of the internal elastic lamina. Associated conditions that may predispose one to dissection in the

Fig. 9.2a, b **Type II traumatic cerebrovascular injury,** two examples: **(a)** focal dissection, likely an intimal flap, with thrombus (arrow) and **(b)** diffuse injury, likely an intramural hematoma (arrows).

setting of blunt injury include fibromuscular hyperplasia, cystic medial degeneration, Marfan syndrome, homocystinuria, and syphilis.

- Patients may present with unilateral headache, cranial nerve palsy (from mechanical compression or neurapraxia from the expanded artery or transient impairment of blood supply), Horner's syndrome, and/or focal cerebral ischemia.

◦ Aneurysm
- Traumatic aneurysms account for , 1% of all intracranial aneurysms in adults, but comprise about one-third of pediatric aneurysms.[13]
- Aneurysms in this setting result from rapid deceleration, which causes sudden brain movement and arterial wall injury from stationary structures such as the skull base or falx cerebri.
- Pericallosal branch (anterior communicating artery [ACA]) aneurysms, resulting from collision between the artery and the edge of the falx, are most common.
- Basilar artery and petrocavernous segment aneurysms often are associated with skull base fractures.

◦ Arteriovenous f stula
- Arteriovenous fistulas—arising from either the carotid or vertebral circulation—are present in 4% of all patients with blunt TCVI.[14]
- The most common intracranial traumatic fistula is a direct carotid-cavernous fistula (CCF).
- Seventy-five percent of direct CCFs occur secondary to trauma.
  - Most are associated with facial or skull base fractures.
  - Iatrogenic injury—due to transsphenoidal surgery, skull base surgery, or percutaneous lesioning of the trigeminal ganglion—also accounts for a significant number of traumatic fistulas.
- Patients typically present with cavernous sinus syndrome (see box on next page).
- Indications for urgent treatment include:
  - Increased intracranial pressure or the presence of cerebral cortical venous hypertension
  - Progressive visual deficit
  - Increased intraocular pressure
  - Worsening proptosis

Traumatic Cavernous Fistula
Traumatic cavernous fistula symptoms and physical findings
- Painful exophthalmia
- Pulsating conjunctival hyperemia
- Ophthalmoplegia
- Vascular murmur
- Elevated intraocular pressure
- Loss of vision (due to venous congestion)

Intracranial Penetrating Injury

- Penetrating intracranial injury may result in dissection, occlusion, traumatic aneurysm, or arteriovenous fistula. All have been discussed previously. However, the formation of traumatic intracranial aneurysms secondary to penetrating injury warrants further consideration.
- Traumatic intracranial aneurysms can result from direct injury by missile, bullet, or bone fragments. Aneurysms are present in:
  - 2.7% of patients with missile injuries to the head.[16]
  - 12% of patients with stab wounds to the head.[17]
- Aneurysms may appear as soon as 2 hours after the injury and are most commonly found along branches of the middle cerebral artery (MCA) (as opposed to intracranial aneurysms due to blunt trauma, which are most often identified on branches of the ACA).
- Factors that should raise suspicion for a traumatic aneurysm include:
  - Missile or bone fragments close to the skull base
  - Large hematoma at the missile entrance wound
- Though aneurysms occurring secondary to trauma are believed to carry a high risk of rupture, one study found that 19.4% of these lesions healed spontaneously and shrank or disappeared altogether on subsequent angiograms.[18]

Preprocedure Considerations

Radiographic Imaging

Extracranial Blunt Injury

- A screening computed tomography angiogram (CTA) or magnetic resonance angiogram (MRA) should be performed for any patient with risk factors for TCVI and/or any unexplained neurologic deficit (**Fig. 9.3**). In the setting of TCVI, CTA may reveal:
  - Eccentric vessel lumen combined with mural thickening
  - Stenosis

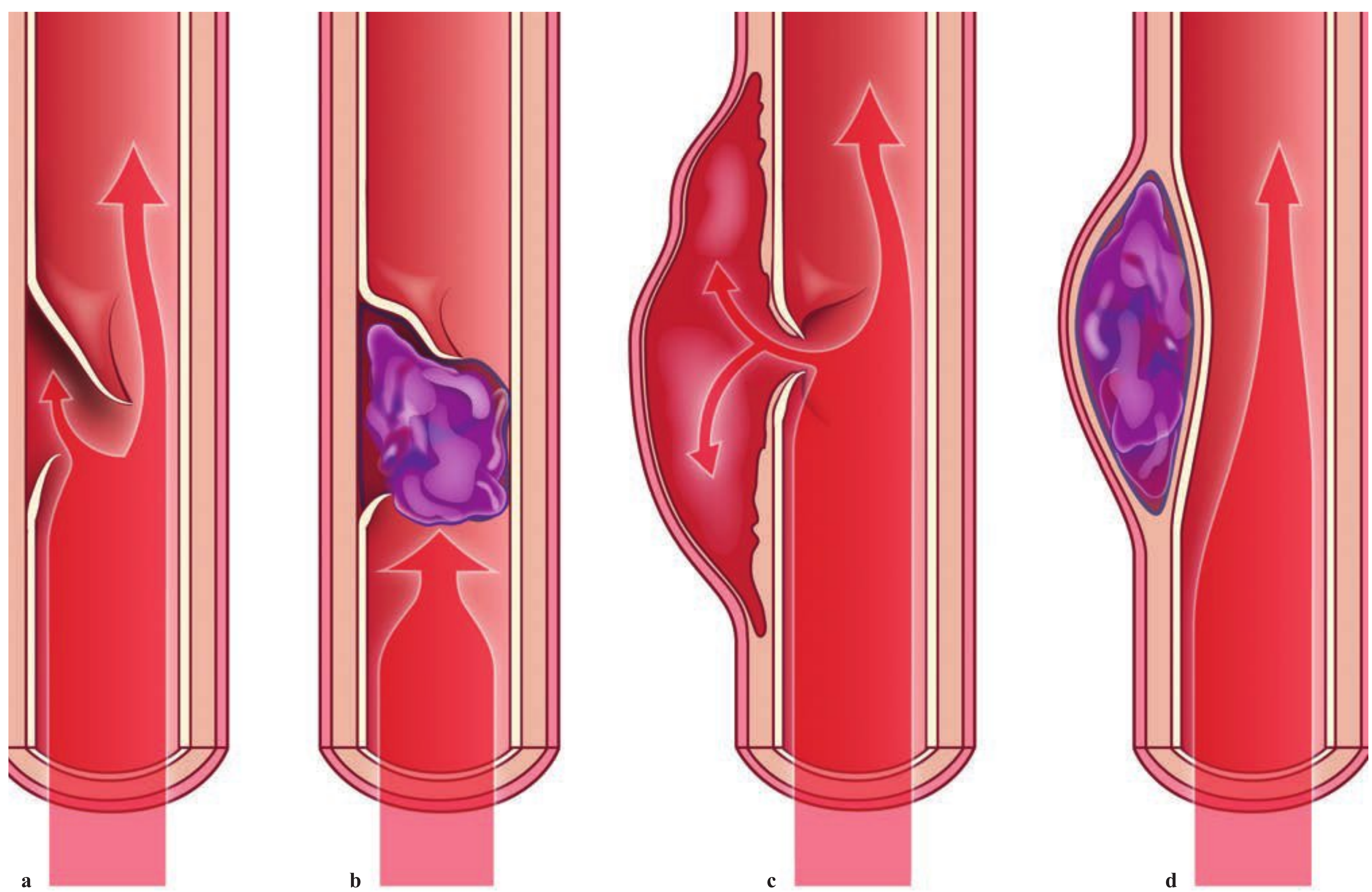


Fig. 9.3a–d Patterns of injury in blunt, extracranial traumatic cerebrovascular injury. Common types of injury include: (**a**) intimal tear, (**b**) intimal tear with associated thrombosis, (**c**) dissecting aneurysm formation due to disruption of the internal elastic lamina and bulging of the adventitia, and (**d**) intramural hematoma.

  - Occlusion
  - Dissecting aneurysm
  - Mural thickening
- Cerebral angiography is indicated when necessary for clarification of the diagnosis or when endovascular treatment is planned. In the setting of TCVI, angiography may reveal:
  - Eccentric, smooth, or tapered stenosis
  - Intimal flap and associated false lumen
  - Tapered stenosis proximal to a dissecting aneurysm ("string and pearl" sign)
  - Flame-shaped occlusion
  - Dissecting aneurysm
  - Intraluminal thrombus

Extracranial Penetrating Injury

- CTA or MRA is the first-line imaging modality at our institution.
- Angiography is reserved for cases in which the CTA results are equivocal or when endovascular treatment is anticipated.
- Angiography is also indicated if there is a retained metallic foreign object that might obscure interpretation of CTA or MRA due to artifact.

Intracranial Blunt Injury

- Dissection
  - All patients suspected of having an intracranial dissection should undergo a CTA or MRA as a first-line imaging modality. However, if a dissection is strongly suspected, conventional angiography remains the gold standard.
- Aneurysm
  - CTA is the recommended screening modality. However, traumatic aneurysms are often located distally and can be dangerous even when , 3 mm. These two features render CTA less reliable.
  - Angiography is recommended for all patients in whom a traumatic aneurysm is suspected.
- Arteriovenous f stula
  - Angiography is the gold standard to image arteriovenous fistulas.
    - An early-filling vein may be a pathognomonic sign.
    - Assess for access to the lesion by looking at the direction of flow within each of the venous structures.
    - For CCFs, assess the presence of the superior ophthalmic vein as a possible access point for treatment.
  - CTA and MRA are static studies. Early venous filling often is not visualized as the timing of the contrast bolus may affect timing of the filling of the veins.

Intracranial Penetrating Injury

- A screening CTA or MRA (unless contraindicated) should be performed for any patient presenting with penetrating head injury.
- Metallic foreign bodies may compromise CT images secondary to scatter artifact. They may also render an MRA impossible. In this case, an angiogram may be necessary prior to removal of the foreign object.
- MRI and MRA are useful in cases of a wooden foreign body injury, as it is difficult to visualize wooden material on a CT.
- Repeat, delayed angiography should be performed 3 to 6 months later for patients in whom an arteriovenous fistula is suspected.

Management

Extracranial Blunt Injury (Fig. 9.4)

- The cornerstones of management for extracranial blunt TCVI are antithrombotic therapy (to minimize thromboembolic complications), follow-up imaging, and selective use of endovascular techniques.
- Medical management
  - Anticoagulation with intravenous heparin, followed by warfarin, has been common practice. However, hemorrhagic complication rates range from 8 to 16%[19] and a significant proportion (30–36%) of patients with this type of injury are not candidates for systemic anticoagulation due to concomitant injuries.
  - Antiplatelet therapy offers a more favorable risk profile and may be equivalent to or superior to anticoagulation with respect to neurologic outcomes.[20] The authors prefer single agent antiplatelet therapy in the form of aspirin 325 mg per day.
  - Repeat noninvasive imaging, preferably CTA, should be undertaken in 6 months.
- Endovascular management
  - Dissection
    - Dissections require treatment (usually stenting) if there are new neurologic deficits or other symptoms despite antiplatelet therapy.
    - Stenting requires dual antiplatelet therapy for a period of approximately 1 month; this may prove problematic for polytrauma patients.
  - Traumatic aneurysm
    - Endovascular treatment is indicated if the patient is symptomatic despite antiplatelet therapy or if the aneurysm is found to enlarge significantly on follow-up imaging. Follow-up imaging should be performed after 6 months (see Fig. 9.5).
    - A covered stent may be appropriate if the traumatic aneurysm occurs in a portion of the vessel devoid of important branches.
    - Coil embolization of traumatic aneurysms should be avoided whenever possible as the wall of the aneurysm maybe either extremely fragile or consist entirely of thrombo-fibrous tissue. Coils within traumatic aneurysms may be prone to migrate through the wall of the aneurysm.
  - Occlusion
    - Vessel occlusion should be approached in a similar manner to acute ischemic stroke. Symptomatic arterial occlusions should undergo recanalization when feasible and appropriate. Patients with asymptomatic occlusions may do well with conservative management (see Fig. 9.6).

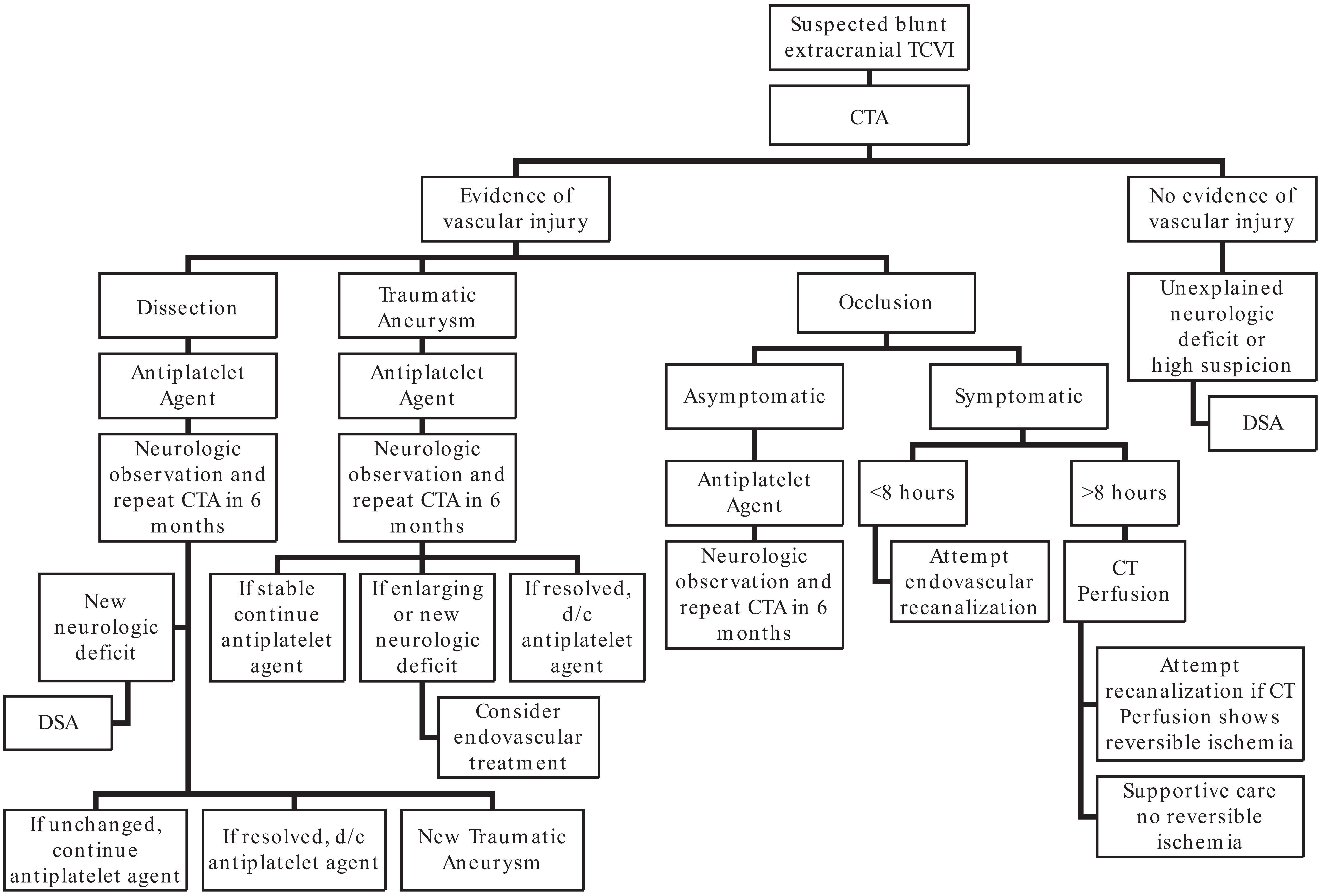


Fig. 9.4 Algorithm for the management of blunt, extracranial traumatic cerebrovascular injury. DSA, digital subtraction angiography; CTA, CT angiography; d/c, discontinue.

- Reperfusion techniques, including mechanical thrombectomy and attempted recanalization, should be considered if the time from symptom onset is less than 8 hours and noninvasive imaging modalities (such as CT perfusion or MR perfusion) suggest a reversible ischemic penumbra. Reperfusion techniques in such cases may include emergent stent placement or thrombectomy.
- Stenting in the acute setting requires loading with two antiplatelet agents (e.g., aspirin and clopidogrel) at least 3 hours prior to the procedure. An alternative would be to treat the patient with an intravenous GPIIB/IIIA inhibitor—to permit stenting immediately—and proceed with antiplatelet agent loading later. The use of these agents in any patient with polytrauma should be considered carefully because of bleeding risks and the potential need for other invasive interventions.

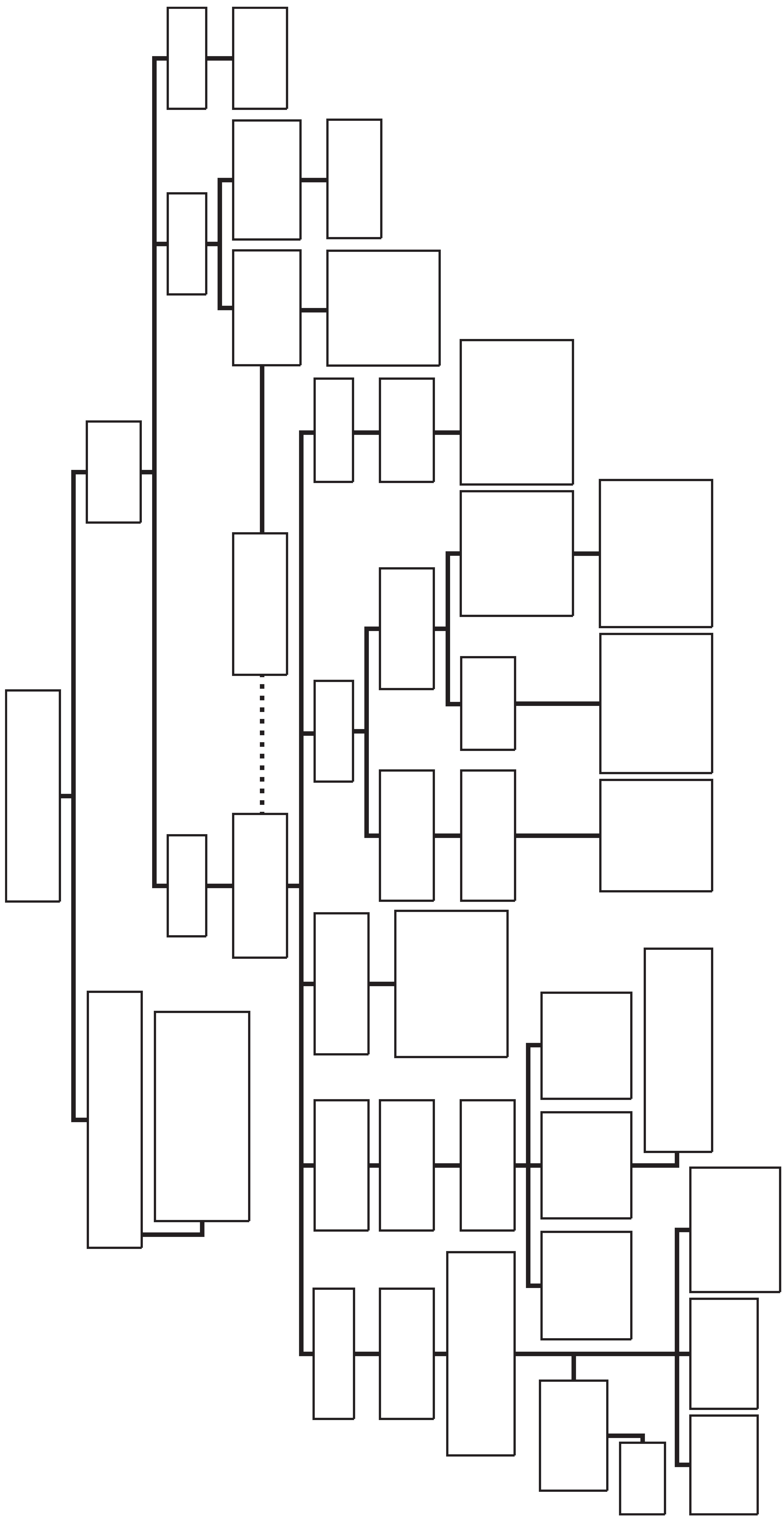
Extracranial Penetrating Injury (Fig. 9.7)

- The choice of an open surgical or endovascular approach for the management of penetrating neck injuries is based on the location of the injury (see Fig. 9.8). The surgical approach for penetrating vascular injuries will be described in more detail (see Operative Procedure, p. 145).
- A few elements of management are common to all such injuries:
  - Assertive manual compression should be used to control bleeding initially.
  - The airway must be secured, preferably by endotracheal intubation. If endotracheal intubation is not feasible, cricothyrotomy is the next best option for airway control. Nasotracheal intubation should be avoided when possible because of the possibility of cranial or nasopharyngeal injury due to the penetrating injury.
  - Endovascular Treatment
    - Endovascular treatment may be preferable for patients with Zone I and III injuries due to the difficulty of surgical access to these areas (see Fig. 9.9).
    - Covered stent placement may be effective for carotid lacerations, provided the lesion can be crossed.
    - Endovascular arterial occlusion may be indicated. Selective occlusion of external carotid branches is usually straightforward. In some situations, occlusion of the internal carotid or vertebral artery may be necessary to control bleeding. Angiographic assessment of collateral circulation to the affected brain territory can help determine the risk of resultant cerebral ischemia. Sacrifice of an artery should include occlusion of the vessel both proximal and distal to the injury, if possible, to minimize the chance of retrograde bleeding through the distal segment of the affected artery.

a b

Fig. 9.5a, b Traumatic dissecting aneurysm (type III traumatic cerebrovascular injury). Patient with an asymptomatic cervical ICA dissecting aneurysm identified on screening CTA. Because significant enlargement was noted on follow-up surveillance imaging, it was treated with a covered stent. Angiograms (**a**) pre- and (**b**) post-stenting.

Fig. 9.6 Arterial occlusion (type IV traumatic cerebrovascular injury). Patient with asymptomatic complete occlusion of the ICA secondary to blunt trauma. The patient was managed conservatively and did not experience neurologic problems attributable to the occlusion.



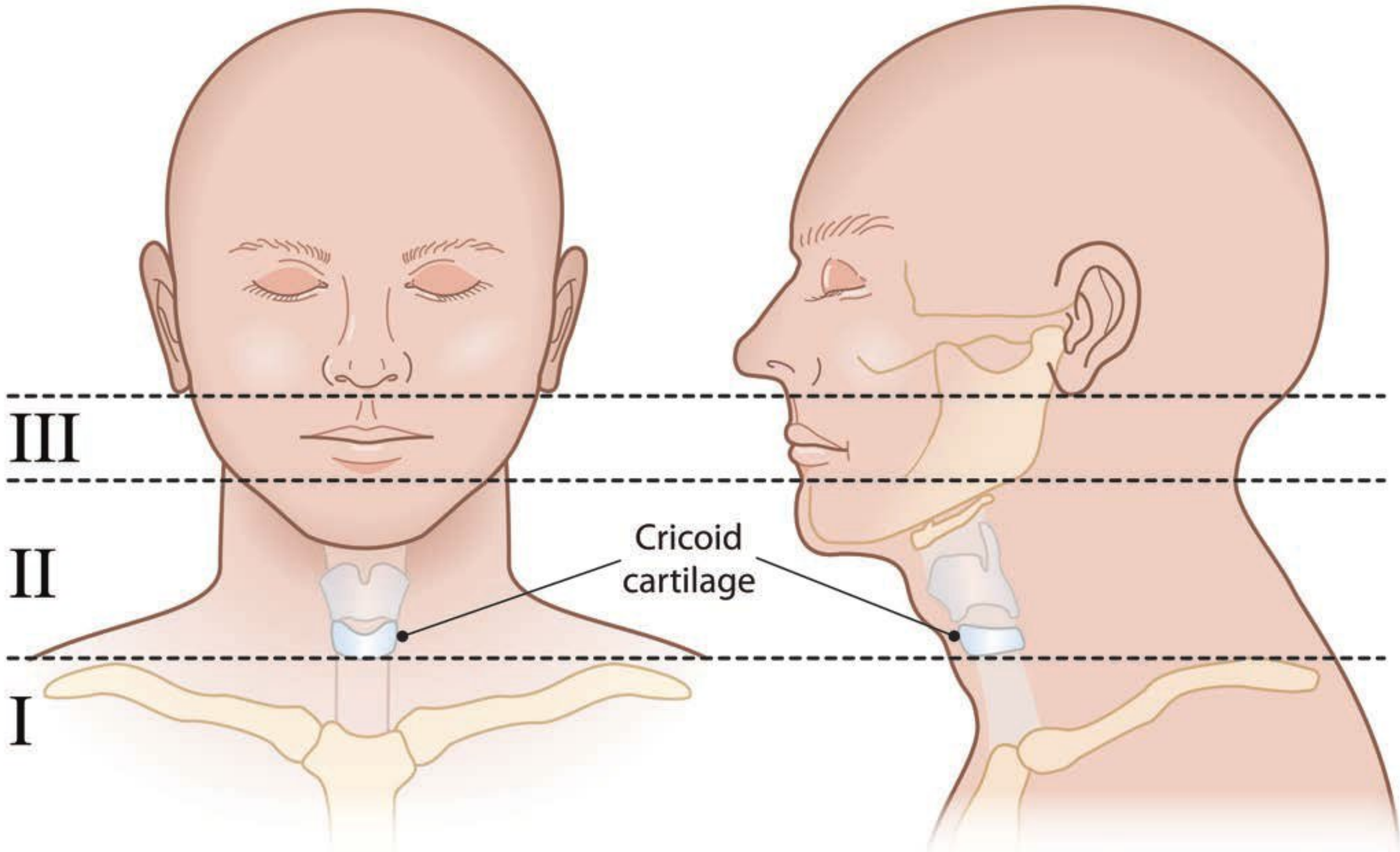


Fig. 9.8 Zones of the neck. Anatomic zones of the neck. Zone I: clavicle to the cricoid cartilage. Zone II: cricoid cartilage to the angle of the mandible. Zone III: angle of the mandible to the base of skull.

a b

Fig. 9.9a, b Arterial dissection due to penetrating neck trauma. Patient with a knife wound to the distal cervical ICA (Zone III). The injury was initially controlled by placement of a Foley balloon catheter in the wound to stop the bleeding. Angiography showed complete transection of the vessel (**a**, arrow). The patient was treated with endovascular sacrifice of the ICA (**b**).

Intracranial Blunt Injury (Fig. 9.10)

- Injury type dictates the management of blunt intracranial TCVIs.
- Dissection
  - Hemorrhagic and symptomatic flow-limiting dissections can be treated with endovascular occlusion and/or stenting.
  - Clinically silent intracranial dissections should be monitored with surveillance imaging every 6 months to assess for the delayed development of dissecting aneurysms.
- Aneurysm
  - Conservative management (i.e., no intervention) is associated with a mortality rate as high as 50%[14] Therefore, all traumatic intracranial aneurysms should be treated when possible.
  - Open surgical clipping with evacuation of associated hematoma often involves sacrifice of the parent vessel.
  - Coil embolization of traumatic aneurysms may be performed in a similar manner to the treatment of spontaneous aneurysms; however, the former often involves sacrifice of the parent vessel.
- Arteriovenous f stula
  - Open surgical packing of the cavernous sinus is an option for patients who require craniotomy for other reasons related to the trauma.
  - Endovascular treatment depends on the flow state of the fistula. A four-vessel cerebral angiogram (to assess collateral circulation) and balloon test occlusion are prudent in case therapeutic occlusion of the affected carotid artery becomes necessary.
    - Low-flow traumatic fistulas may be treated with coil or liquid embolic embolization.
    - High-flow lesions may require a covered stent plus coiling and liquid embolic embolization, or carotid occlusion. A pitfall of using coil embolization alone to treat high-flow fistulas is that the coils may migrate around the cavernous sinus, resulting in recurrence of the fistula (Fig. 9.11).

Intracranial Penetrating Injury (Fig. 9.12)

- Conventional treatment of intracranial aneurysms due to penetrating trauma is by craniotomy and clipping or trapping. Endovascular treatment is an option, though global experience, to date, is limited.

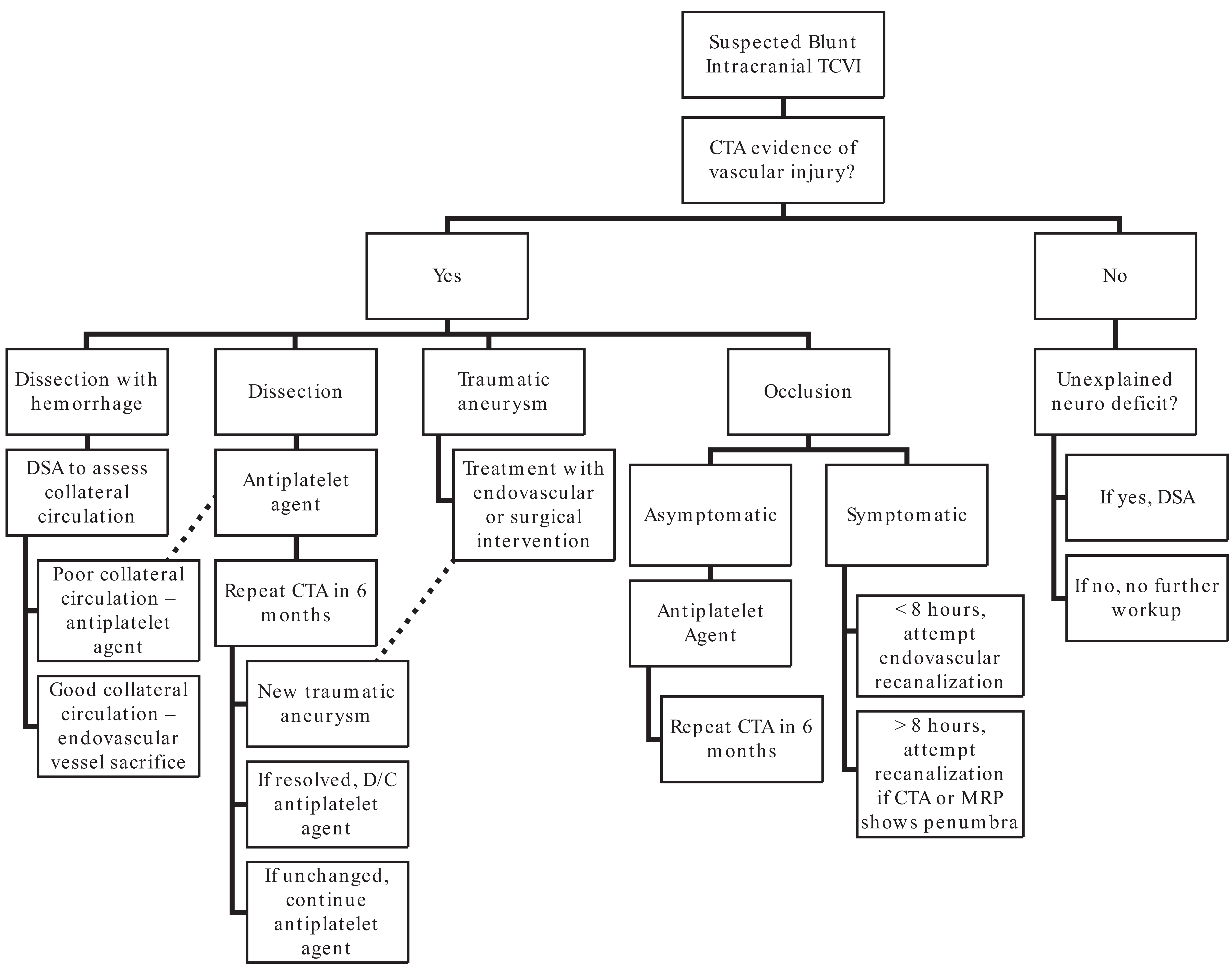


Fig. 9.10 Algorithm for the management of blunt intracranial cerebrovascular injury. MRP, magnetic resonance perfusion.

a b

Fig. 9.11a, b Intracranial blunt injury, dissection. (**a**) Patient with an intradural vertebral artery dissection (arrow) due to blunt trauma. The dissection caused a cerebellar hemorrhage. (**b**) The lesion was treated with endovascular occlusion.

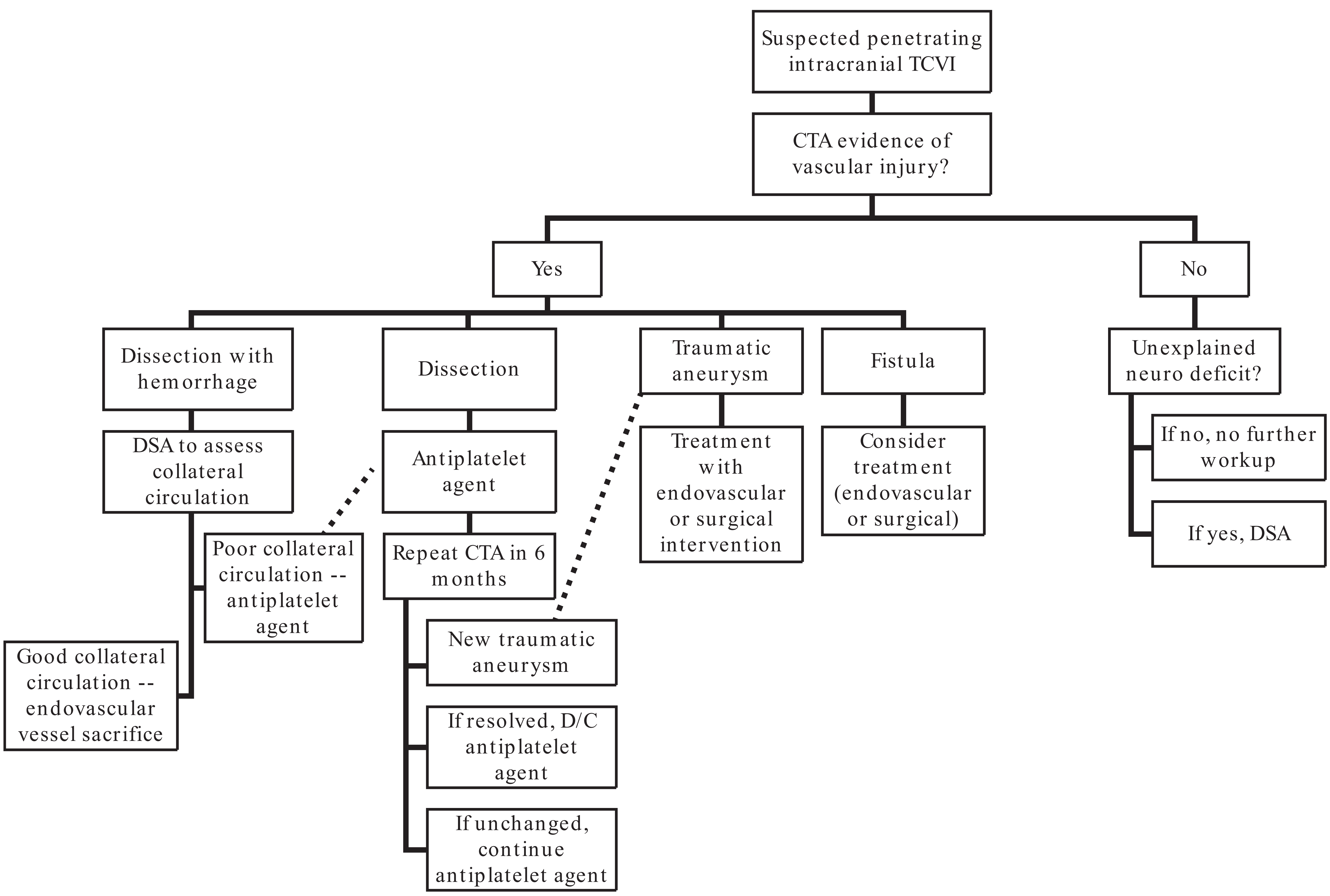
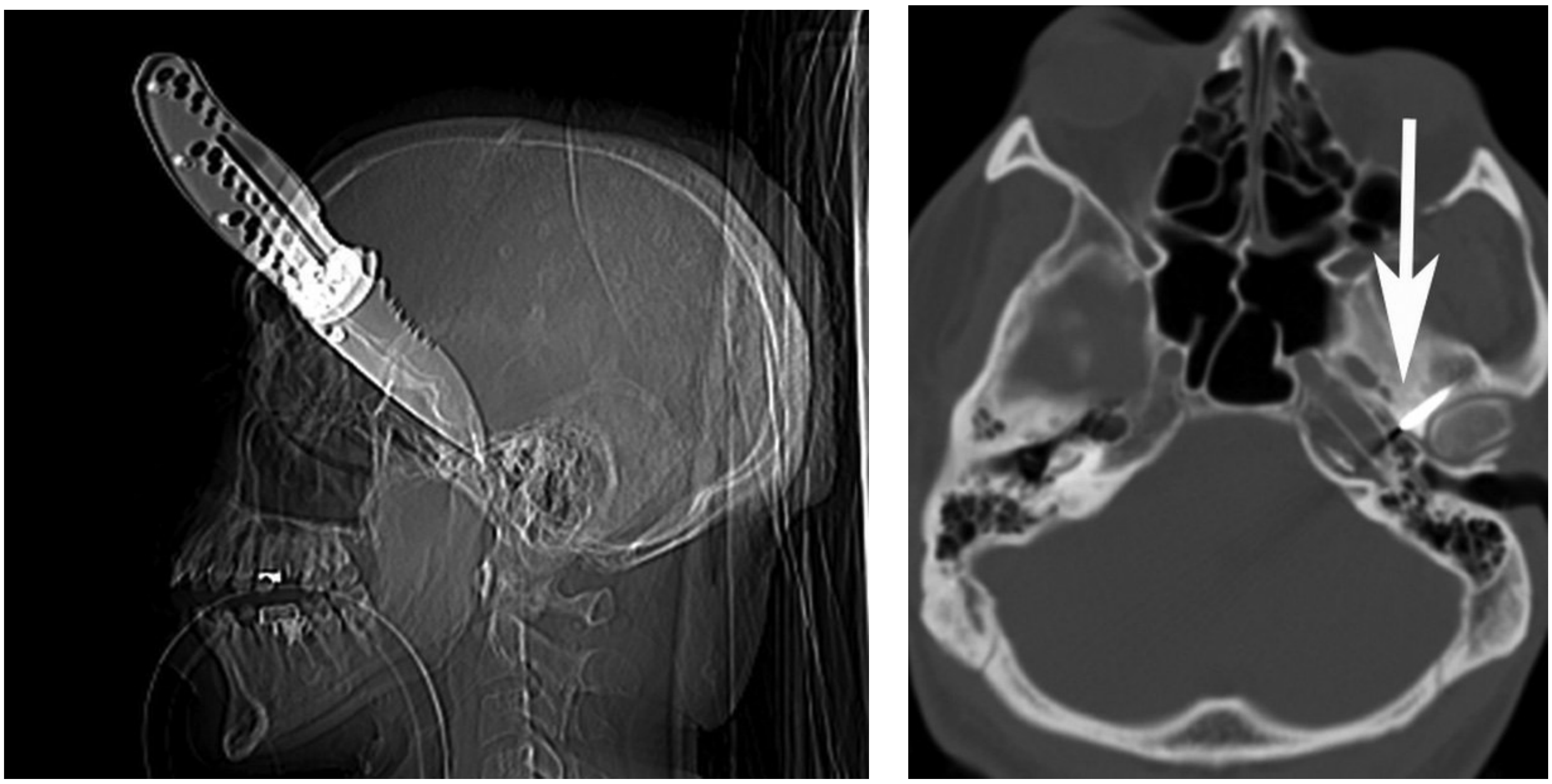


Fig. 9.12 Algorithm for the management of penetrating intracranial cerebrovascular injury.

- Removal of foreign bodies should be deferred until radiographic evaluation has been completed.
  - In patients with no evidence of intracranial hemorrhage or cerebrovascular injury, the penetrating object can be removed under general anesthesia.
  - If the foreign body appears to be proximate to or providing tamponade for a potential vascular injury, the foreign body should be removed in the operating room under direct vision.
- Penetrating intracranial injury **(Fig. 9.13).**



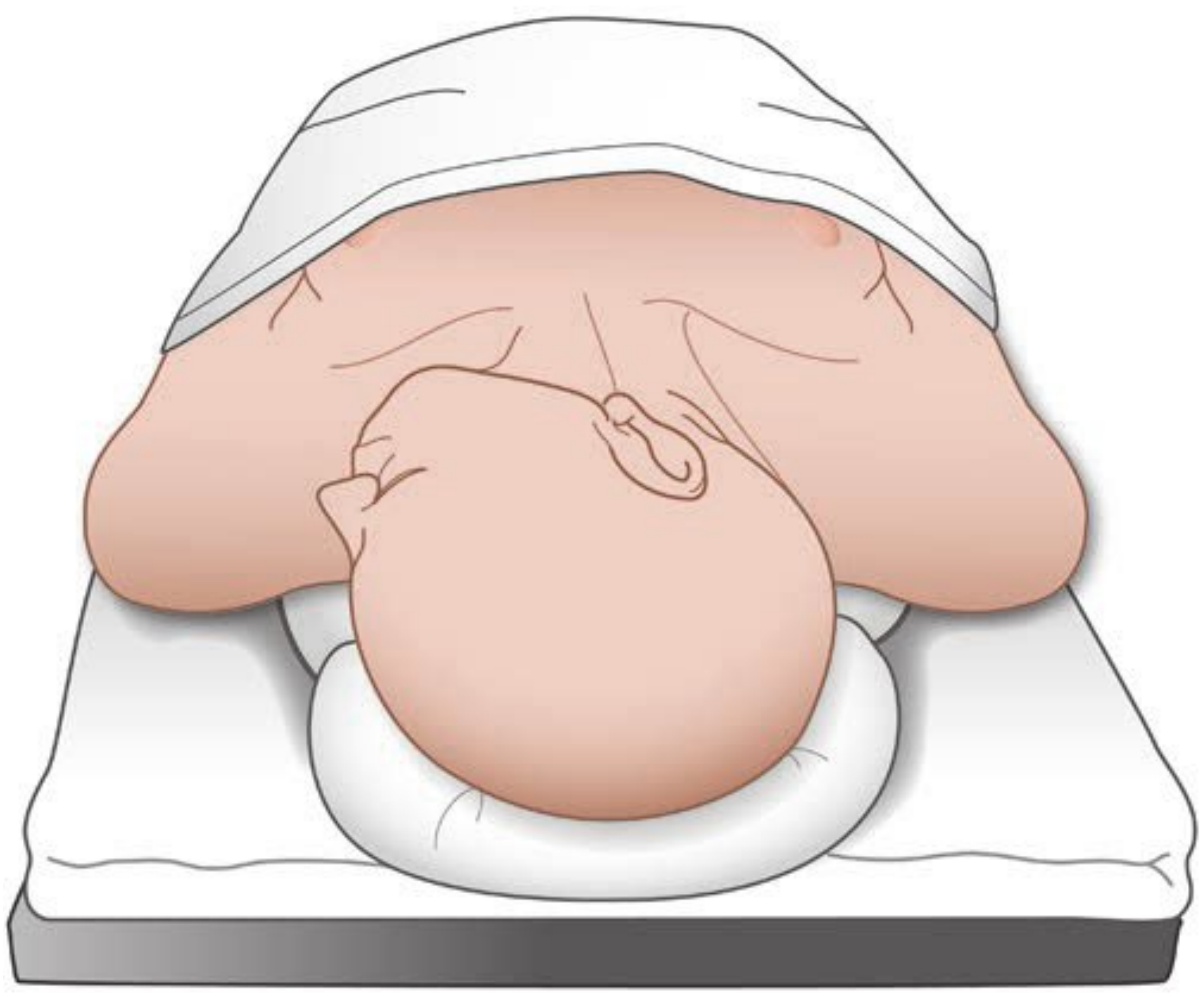
a b

Fig. 9.13a, b Penetrating intracranial injury. (**a**) Patient with a knife wound to the left temporal area. (**b**) The blade penetrated the squamous portion of the temporal bone. The tip was buried in the petrous bone (arrow), adjacent to the carotid canal and temporomandibular joint. Once it was established by imaging that the injury did not involve any arterial structures, the patient underwent craniotomy and removal of the knife blade.

Operative Procedure

Surgical Management of Extracranial Penetrating Arterial Injuries – Zone II

Positioning (Fig. 9.14a, b)


a

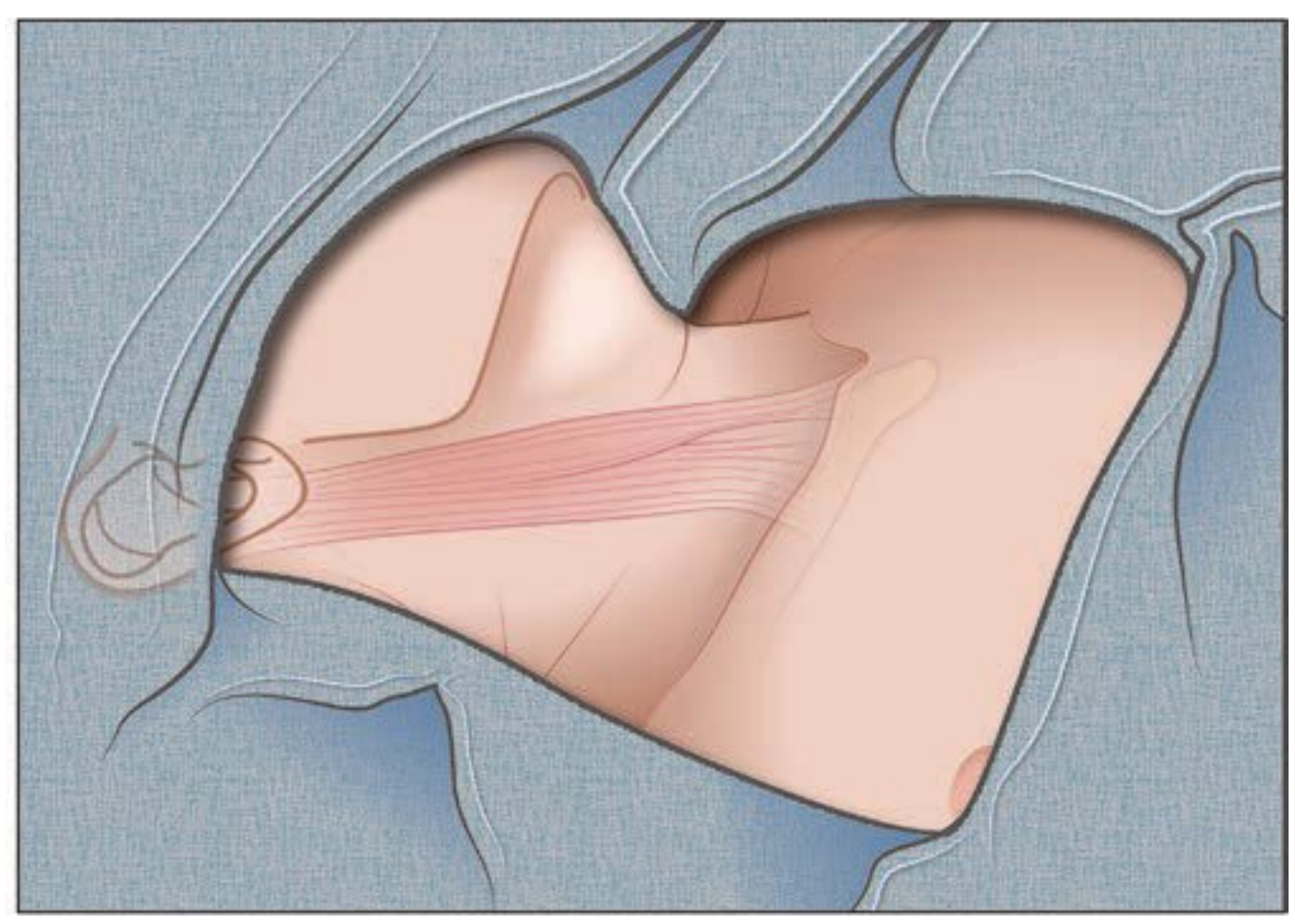

b

Figure	Procedural Steps	Pearls
Fig. 9.14	**(a) Place a roll between the shoulder blades to extend the patient's neck, and rotate the patient's head away from the side of injury. (b) Prep and drape the entire neck, upper chest, and lower face.**	• Remove the cervical collar if the patient is wearing one.

Incision (Fig. 9.15)

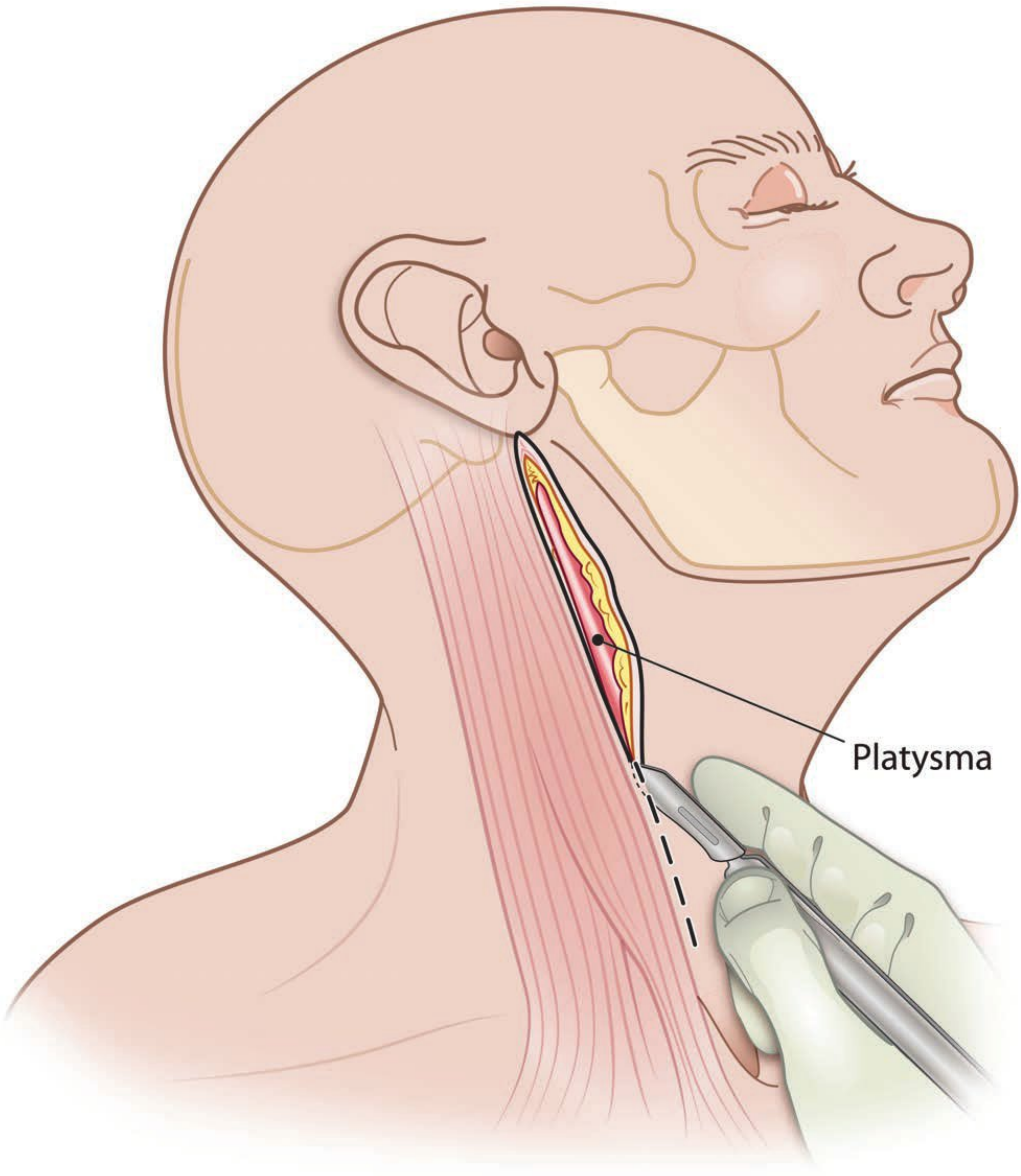


Figure	Procedural Steps	Pearls
Fig. 9.15	**Make a longitudinal incision along the anterior border of the sternocleidomastoid muscle (SCM).**	• Err on making the incision too long rather than too short; it may extend from the ear lobe to the sternal notch if necessary.

Initial Dissection (Fig. 9.16)

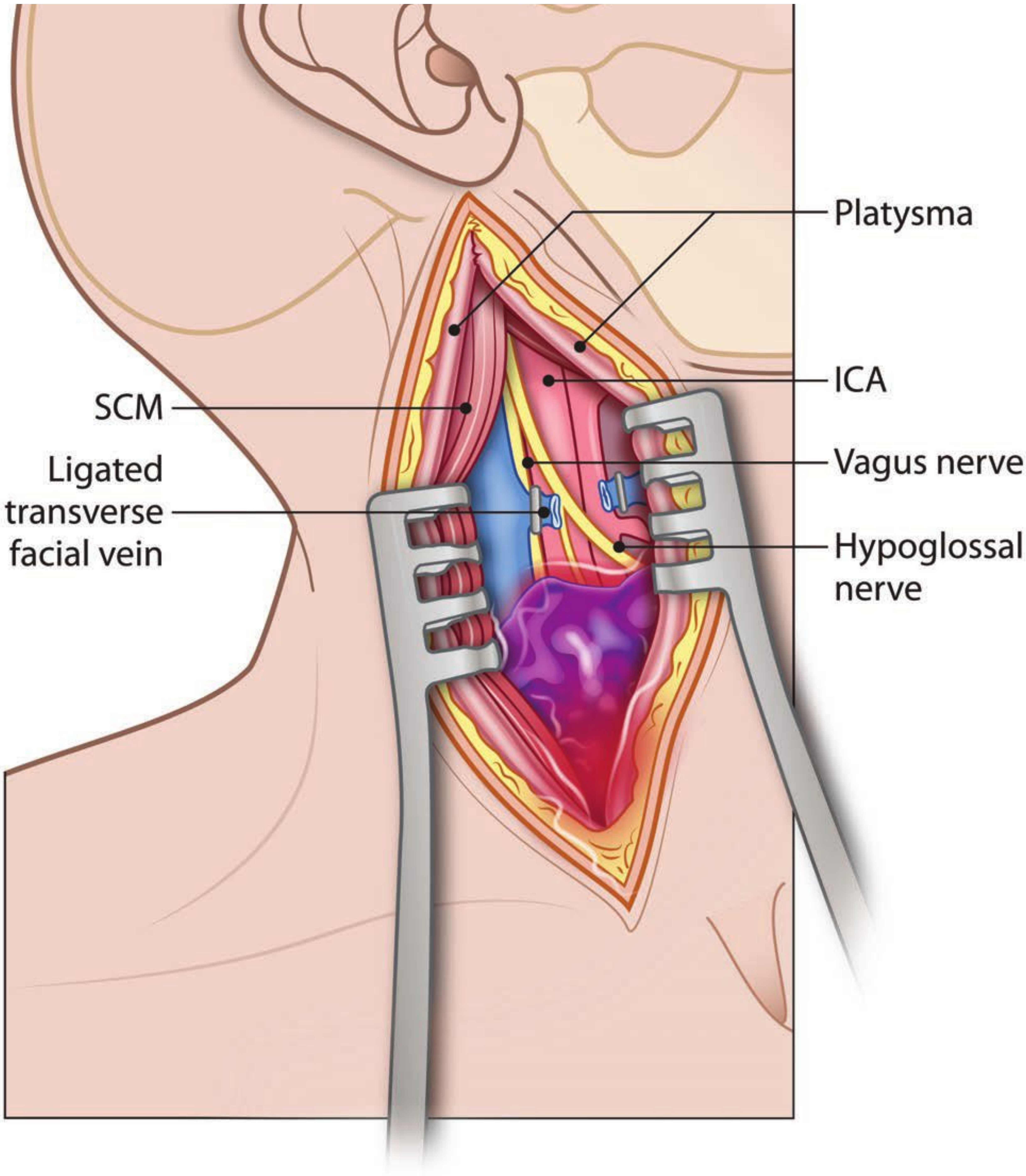


Figure	Procedural Steps
Fig. 9.16	**Use monopolar cautery to divide the platysma muscle. Mobilize and retract the sternocleidomastoid muscle laterally. Ligate and divide the transverse facial vein.**

Carotid Artery Dissection (Fig. 9.17)

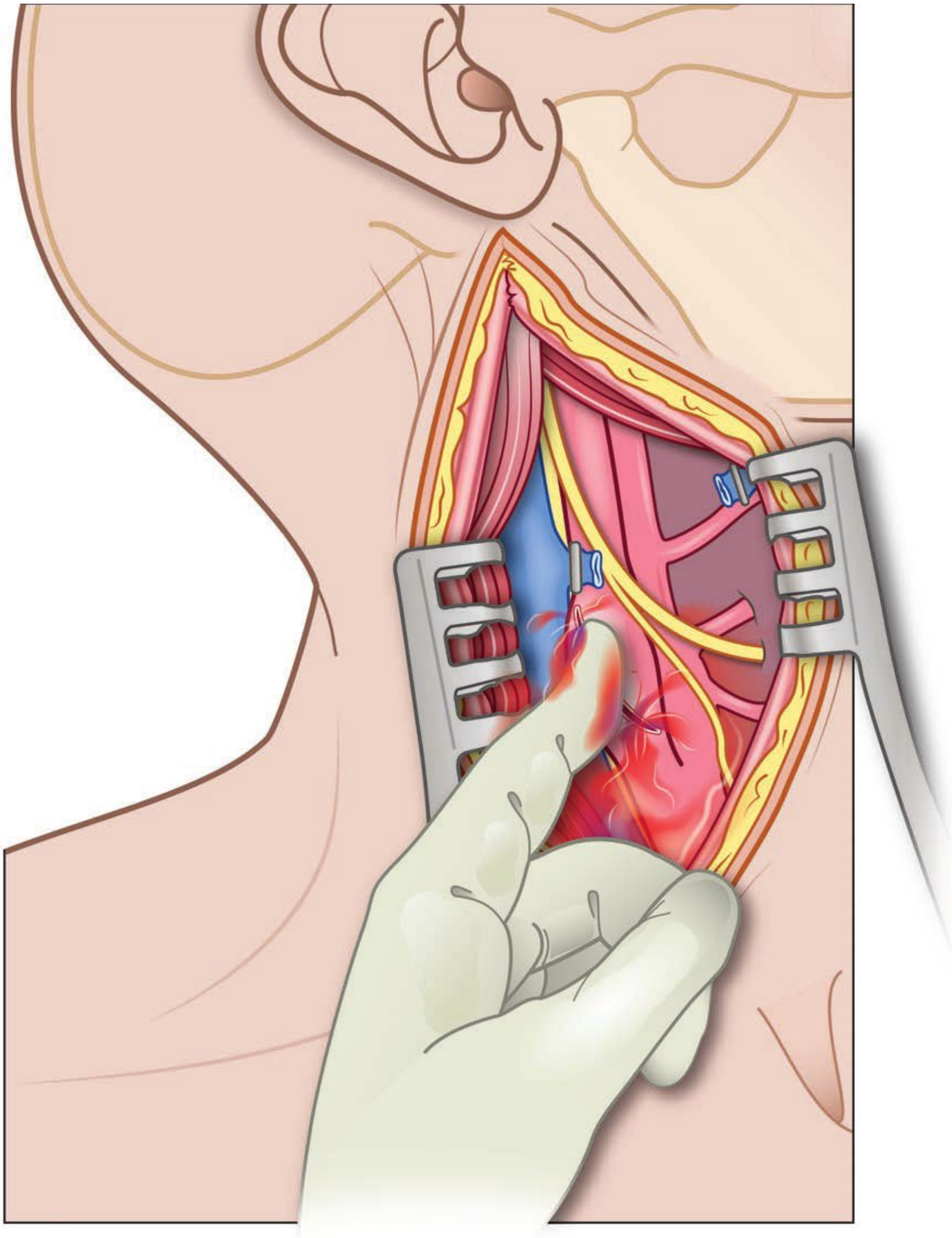


Figure	Procedural Steps	Pearls
Fig. 9.17	**Use both blunt and sharp dissection to expose the carotid sheath.**	• Avoid the area of injury by working around the hematoma. All veins (including the internal jugular vein) may be ligated and divided if necessary. If both internal jugular veins are involved, one should be preserved. Use judicious and selective compression of bleeding arterial branches and veins as they are encountered.

Proximal and Distal Control (Fig. 9.18)

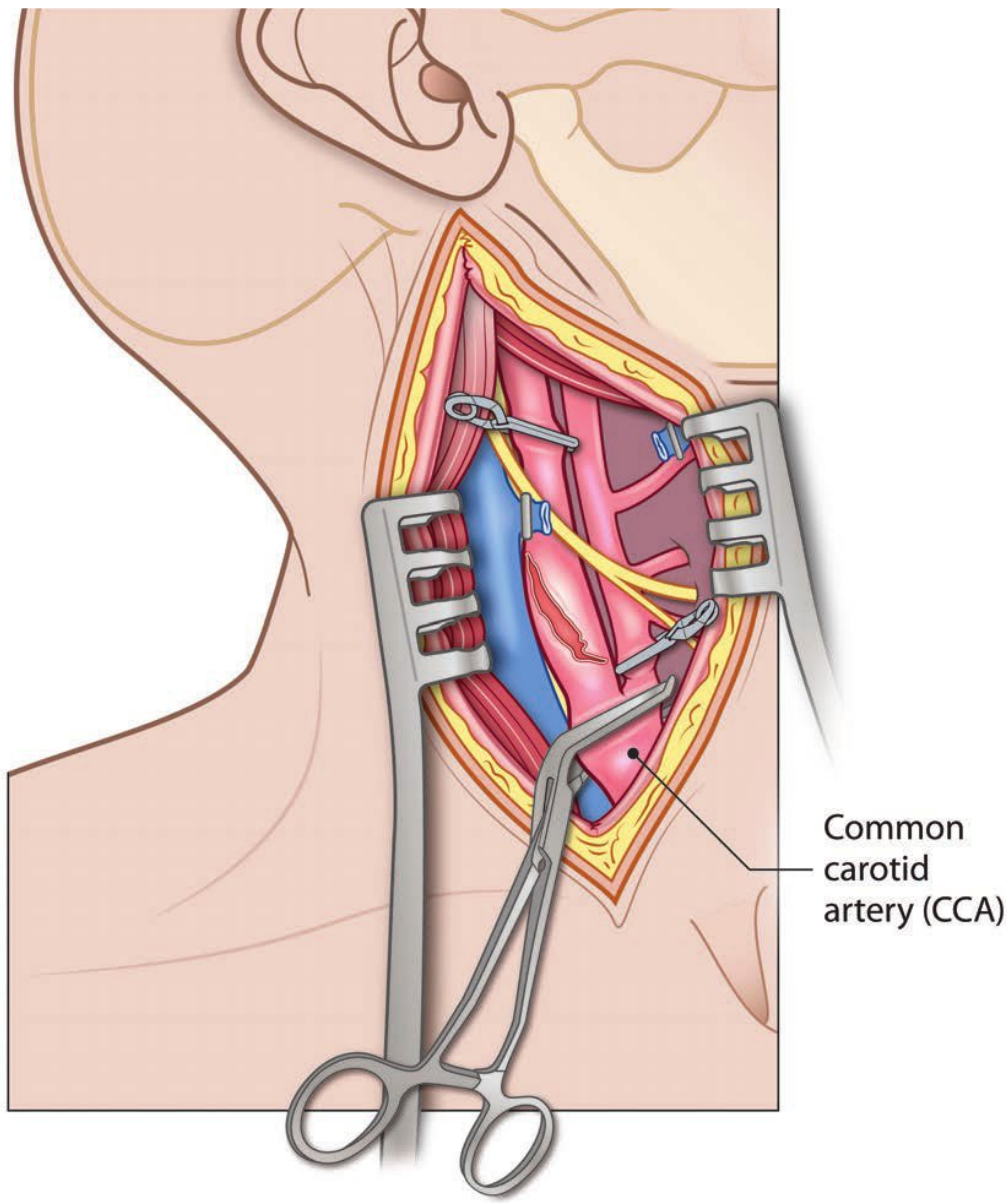
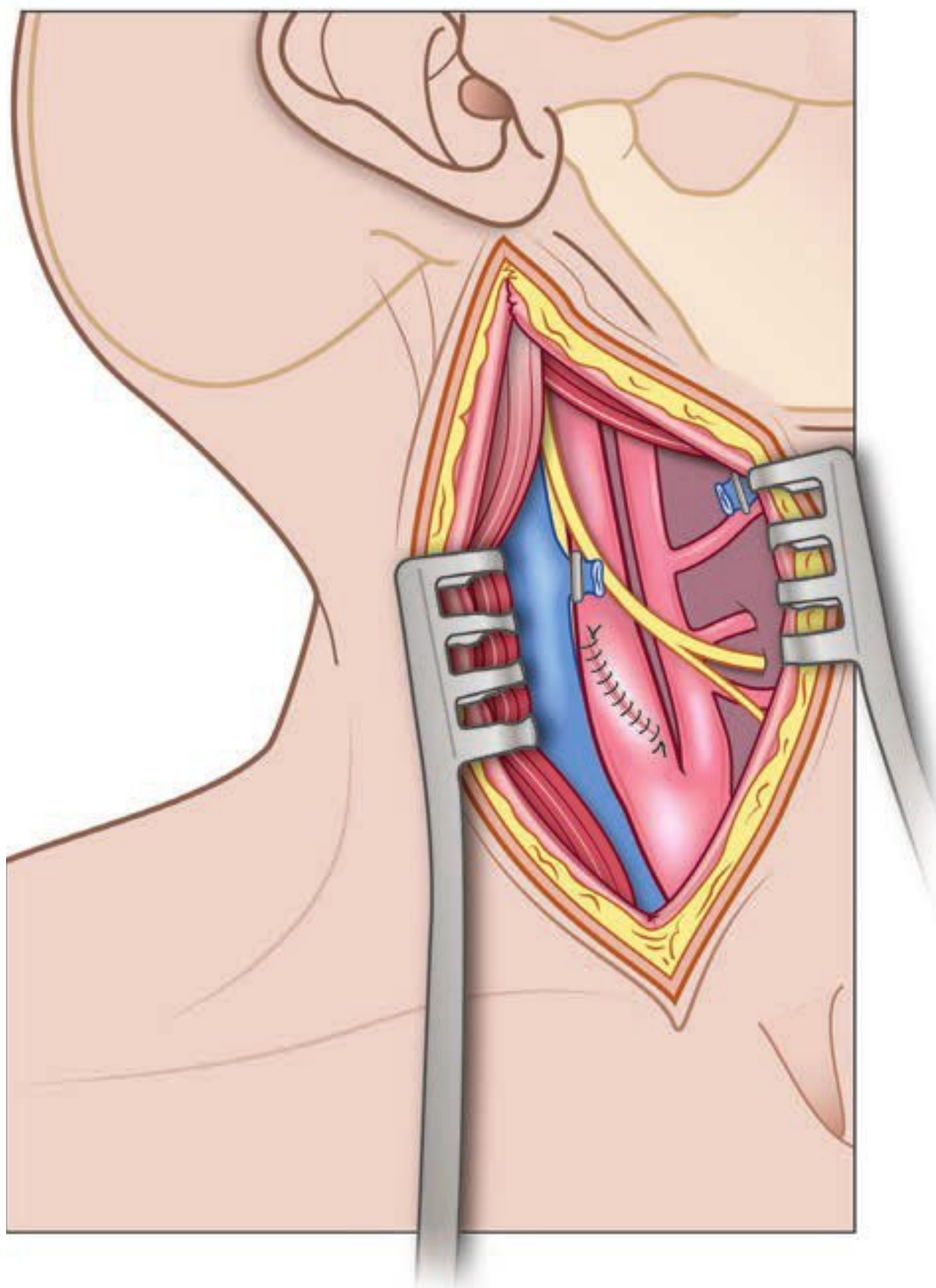


Figure	Procedural Steps	Pearls
Fig. 9.18	**Once the ICA distal to the injury and the CCA or ICA proximal to the injury have been exposed, place either a clamp or an aneurysm clip on the artery in each location.**	• Large permanent aneurysm clips are usually sufficient for the ICA, and a Fogarty clamp is usually necessary for the common carotid artery. Large aneurysm clips may also be used for temporary occlusion of external carotid artery (ECA) branches.

Repair of Arterial Injury (Fig. 9.19a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 9.19	**(a) Repair the arterial injury primarily, when possible, with a running 6-0 nonabsorbable polypropylene monofilament stitch.** **(b) When primary repair is not possible, place a tubular polytetrafluoroethylene (PTFE) interposition graft and secure with simple interrupted 6-0 polypropylene monofilament sutures.** **Remove the arterial clamps in the following order: ECA, CCA, and ICA.**	• Ligation and sacrifice of the ICA should be avoided; repair of the artery versus ligation results in an 8% versus 50% ischemia stroke rate.[10]

Closing

- Leave a drain in place. Close the wound with absorbable braided stitches in the platysma muscle and staples or stitches in the skin.

Postoperative Management

Monitoring

- All patients with cerebrovascular injuries should be monitored in a neurologic intensive care unit during the acute phase, with frequent neurologic examinations, vital sign monitoring, and daily laboratory studies.
- Blood pressure monitoring with an arterial line is preferable for patients with labile blood pressure or for those requiring continuous medication infusions for blood pressure control. Maintenance of systolic blood pressure between 90 and 180 mm Hg is adequate for most patients.
- The need for invasive intracranial monitoring is dictated by standard neurosurgical criteria (e.g., for patients with elevated intracranial pressure due to head injury).

Medication

- Antithrombotic therapy with aspirin (325 mg daily) is indicated for most patients with traumatic cerebrovascular injury.
- More aggressive antithrombotic therapy, with systemic anticoagulation, may be necessary for patients with significant intraluminal arterial or venous thrombosis.
- Dual antiplatelet therapy (e.g., aspirin and clopidogrel) is necessary for all patients receiving a vascular stent.
- In most cases, antithrombotic therapy for 3 months is appropriate.

Radiographic Imaging

- Follow-up imaging of traumatic cerebrovascular lesions with CTA at a 3- to 6-month interval is useful to monitor dissections and to check for the development or progression of traumatic aneurysms.

Further Management

- An outpatient clinic follow-up evaluation should be completed 3 to 6 months after discharge.

Special Considerations

Antithrombotic Therapy

- The use of antithrombotic medication is a reasonable option in patients with cerebrovascular injuries as a measure to prevent thromboembolic ischemic stroke. However, all antithrombotic medications, including antiplatelet agents and anticoagulation, carry a risk of hemorrhagic complications, particularly in patients with intracranial hemorrhage or polytrauma. Although level III clinical evidence and guidelines about the use of antithrombotic medications in trauma patients are lacking, the authors of this chapter recommend the use of aspirin in most patients with cerebrovascular injuries. For patients with traumatic intracranial mass lesions (e.g., subdural hematomas or clinically significant intracerebral hemorrhage), and/or for whom cranial surgery is anticipated or has been done, avoiding antithrombotic medications seems prudent.

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10 Management of Venous Sinus Injuries

Laurence Davidson and Rocco A. Armonda

Introduction

Major dural venous sinuses form at the dural reflections where the superficial and deep layers of the dura split and the deep layer fuses to form the falx cerebri and the tentorium cerebelli. Injury to the dural venous sinuses may be encountered in penetrating and nonpenetrating head trauma or can result from planned or accidental disruption during a craniotomy.[1–3] The dural venous sinus has a three-sided lumen that is tethered laterally by the adjacent dura mater and deeply by the falx cerebri or tentorium cerebelli. Hemorrhage can arise from the sinus roof, lateral walls, venous lakes, arachnoid granulations, emissary veins, or cortical vein tributaries.

The decision to repair versus sacrifice the sinus is dependent on the location of injury. When repair is indicated, the type and extent of injury will largely dictate the optimal repair technique, which ranges from direct repair to segmental replacement.

Indications

- Traumatic injury resulting in significant hemorrhage or thrombosis
- Resection of an infiltrating neoplasm
- Three areas require repair to maintain patency[1,4]
  - Posterior two-thirds of the superior sagittal sinus
  - Torcular herophili
  - Dominant transverse sinus
- All other areas may be ligated with minimal risk[1,4]

Preprocedure Considerations

Radiographic Imaging

- Computed tomography (CT)
  - Dural venous sinus injury should be suspected if imaging shows an epidural hematoma in the region of a major venous sinus.[5] In one study, 89% of epidural hematomas arising from a dural venous sinus had an associated fracture that crossed the sinus.[1] Posterior fossa epidural hematomas involve the dural venous sinuses in 42.5% of cases.[6]
  - CT venography (CTV), which requires the administration of intravenous contrast and is taken during the venous phase, can be diagnostic of sinus thrombosis. The empty delta sign may be seen in the area of sinus thrombosis.[7] CTV is indicated when there is a depressed skull fracture over a dural venous sinus, which can cause sinus stenosis and thrombosis.[8,9]
- Cerebral angiography
  - Although angiography remains the gold standard for imaging the dural venous sinuses, it is invasive and time consuming, which renders it impractical in the setting of acute trauma.
- **Preoperative imaging (Fig. 10.1).**

Medication

- Antimicrobial prophylaxis is initiated.
- Antiseizure prophylaxis is initiated.

Operative Field Preparation

- General patient positioning
  - Secure the patient to the table, as up to 60 degrees of reverse Trendelenburg may be needed to minimize intracranial venous pressure if bleeding is profuse.
  - The injured dural venous sinus segment should be at the highest point of the operative field.
  - Avoid excessive neck rotation or flexion.
  - A bilateral craniotomy exposure is indicated to address injury to the superior sagittal sinus. A supra- and infratentorial approach is necessary to address injury to the transverse sinus.
- Measures to maximize cranial venous outflow
  - Avoid compressive airway tape.
  - Minimize jugular compression from a rigid cervical collar.
  - Avoid excessive neck rotation or flexion.
  - Internal jugular central venous lines are contraindicated due to the possibility of iatrogenic thrombosis and impairment of cranial venous outflow.
- Blood loss
  - Large volume hemorrhage may occur from the injured venous sinus. Significant losses may also occur—both preoperatively and intraoperatively—from scalp, bone, and brain.
  - Packed red blood cells, platelets, and fresh frozen plasma must be available in the operating room.
- Venous air embolism
  - Venous air embolism may occur when the head is elevated above the heart, resulting in negative pressure in the dural venous sinus—allowing air to enter and become trapped in the right atrium.
  - A fall in the end tidal pCO_2 and hypotension may ensue. Strong consideration should be given to the use of capnography, a precordial Doppler probe, and an arterial line. Air embolism produces "washing machine" sounds by Doppler.
  - Removal of air from the right atrium is possible if a right atrial catheter—placed via the brachial or subclavian route—is in place.

Fig. 10.1 CT sagittal reconstruction demonstrating extensive, supra- and infratentorial epidural hematoma suggestive of a transverse sinus injury.

- Segmental sinus replacement
  - If substantial sinus disruption is anticipated, vascular reconstruction equipment should be available, including a properly sized temporary vascular shunt, Fogarty balloon catheters, nonabsorbable vascular suture, and a vein allograft.

Operative Management

Treatment is discussed separately for the following parts of the venous sinus system: anterior one-third of the superior sagittal sinus, posterior two-thirds of the superior sagittal sinus, torcular herophili, and dominant transverse sinus.

General Considerations by Anatomic Location

- Superior sagittal sinus—anterior one-third
  - The majority of injuries in this area can be managed with tamponade techniques or direct suture repair if the laceration is small.
  - Lacerations that are too large to suture directly often can be treated with a sutured, bolstered patch.
  - Lesions that cannot be repaired can be treated relatively safely with sinus ligation via an encircling suture or vascular clips.
- Superior sagittal sinus—posterior two-thirds
  - This portion of the sinus should be repaired or replaced in virtually all cases, but especially when major cortical venous drainage is involved.
  - Avoid primary suture closure that compromises greater than 50% of the sinus lumen, as this may be more likely to result in compromised flow and eventual sinus occlusion.
  - If stenosis is likely to result from primary suture repair, a patch should be placed.
  - Replacement of segments of the superior sagittal sinus is the most extreme of interventions, reserved only for those cases involving either the majority of the dorsal wall or both lateral walls, in which a sutured patch cannot reconstruct a lumen at least 50% of the original size.
  - Kapp et al developed an internal shunt for use during sinus reconstruction.[3,4] This was made of a pediatric endotracheal tube with a pediatric tracheostomy cuff placed at each end. Sindou and Alvernia avoided the balloon shunt and Fogarty balloon catheter due to risk of injury to the sinus endothelium, advocating, instead, for direct packing of the lumen with hemostatic material.[2] Both emphasize the need for sinus thrombectomy of the proximal and distal ends of the sinus repair to ensure patency.
- Torcular herophili
  - Injuries that substantially disrupt the torcular herophili are rarely survivable and, in most cases, the clinical grade of the patient is such that expectant management—without surgical intervention—may be appropriate.
  - The techniques for tamponade, primary repair, and patching described for injuries to the superior sagittal sinus also apply to the torcular herophili.[1]
- Dominant transverse sinus
  - The techniques for tamponade, primary repair, and patching described for injuries to the superior sagittal sinus also apply to the superior sagittal sinus.
  - Sindou et al described a bypass of the transverse sinus to the external jugular vein using a saphenous vein graft in a patient with bilateral transverse sinus thrombosis.[10] Meticulous wound closure is necessary to prevent compression and subsequent thrombosis of the subcutaneous vein graft.

Operative Procedure

Surgical Approach to Injuries of the Anterior Third of the Superior Sagittal Sinus

Positioning (Fig. 10.2)

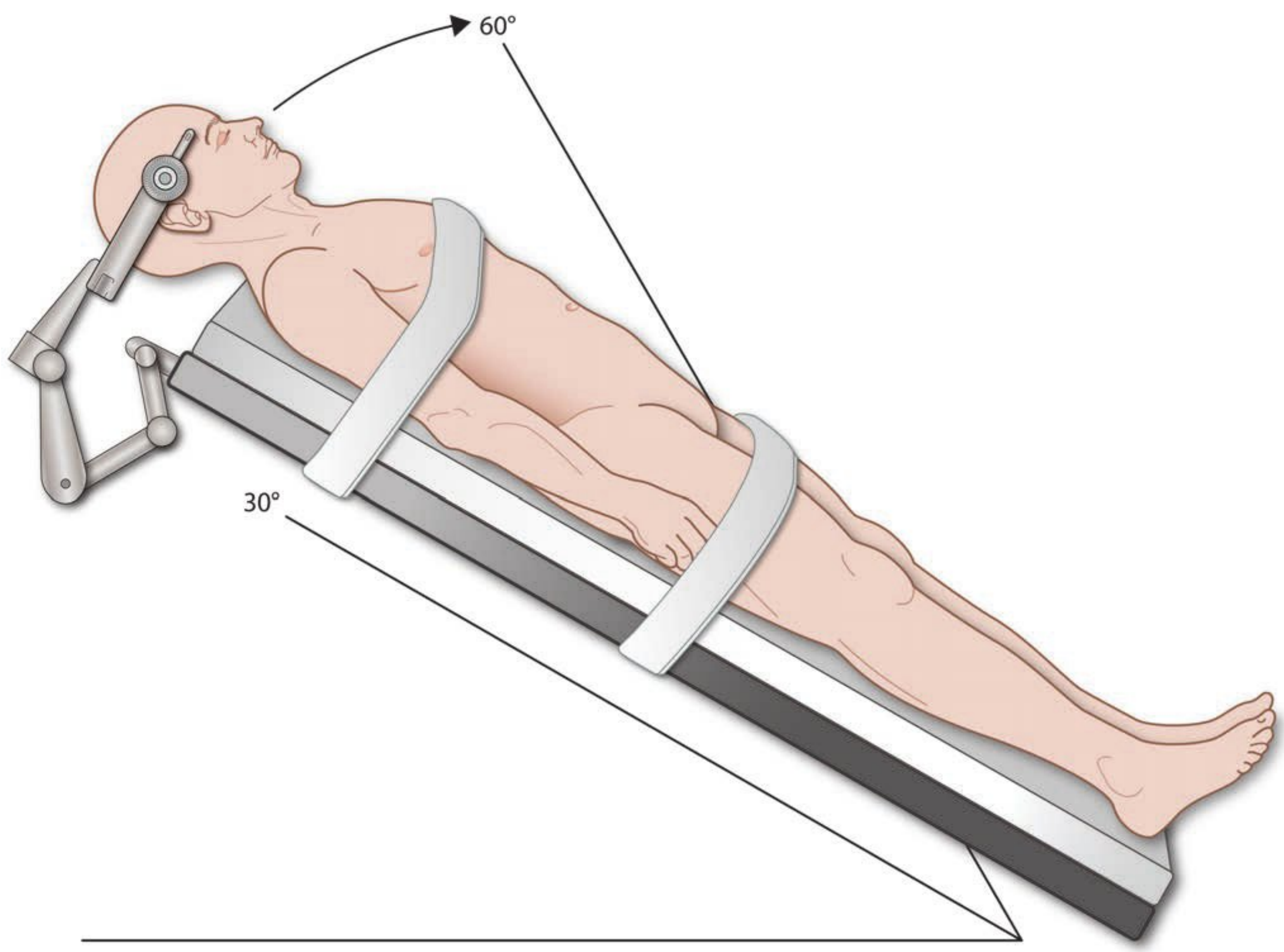


Figure	Procedural Steps	Pearls
Fig. 10.2	**The patient is positioned supine, with the head elevated above the heart. The patient should be secured to the table so as to allow an angle of elevation up to 60 degrees, if necessary.**	• Anesthesia monitoring for venous air emboli (VAE) should include precordial Doppler, end-tidal pCO_2, and placement of a right atrial catheter (to permit VAE retrieval). • In severe cases, consider preparation for greater saphenous vein harvest.

Incision (Fig. 10.3)

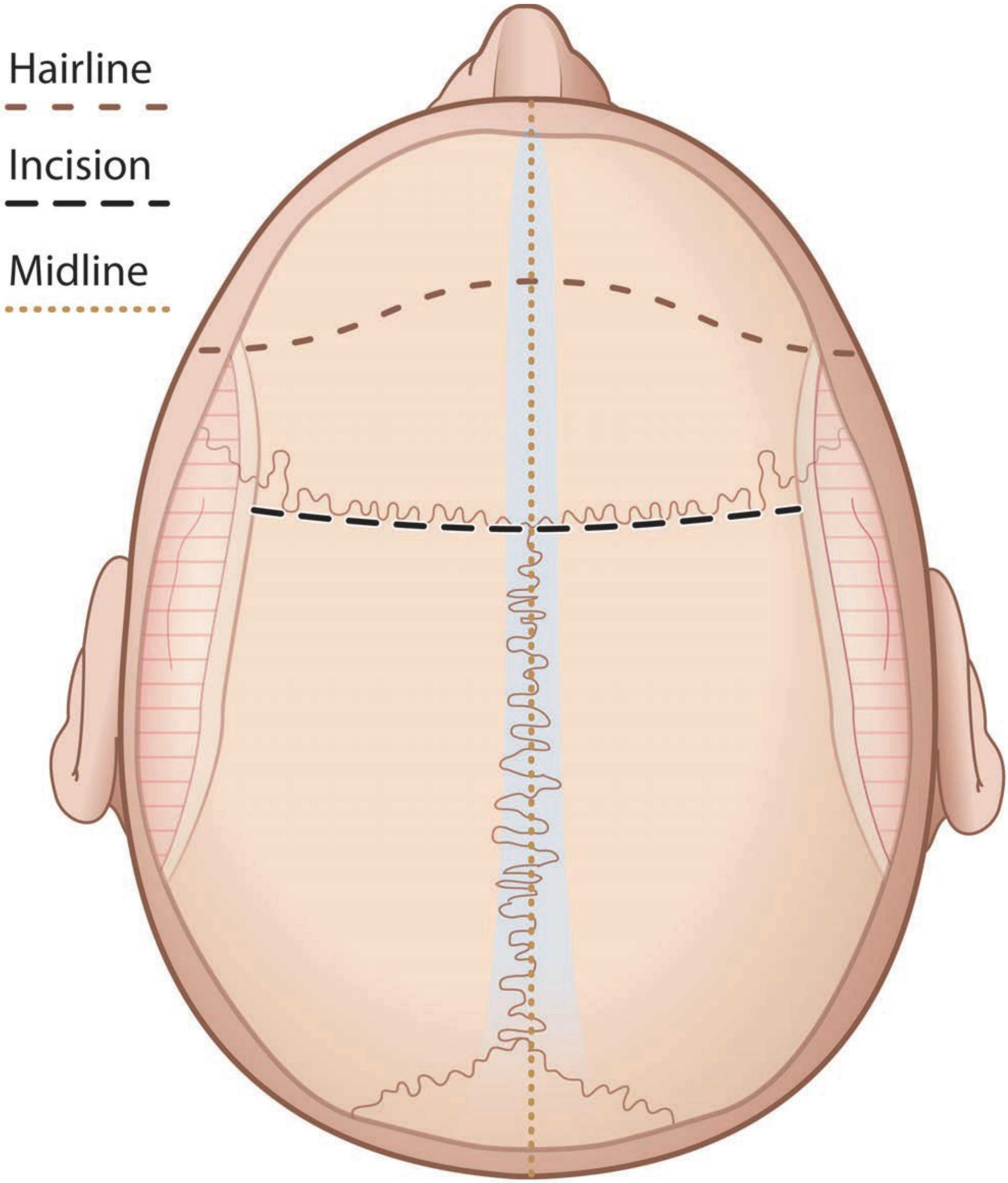
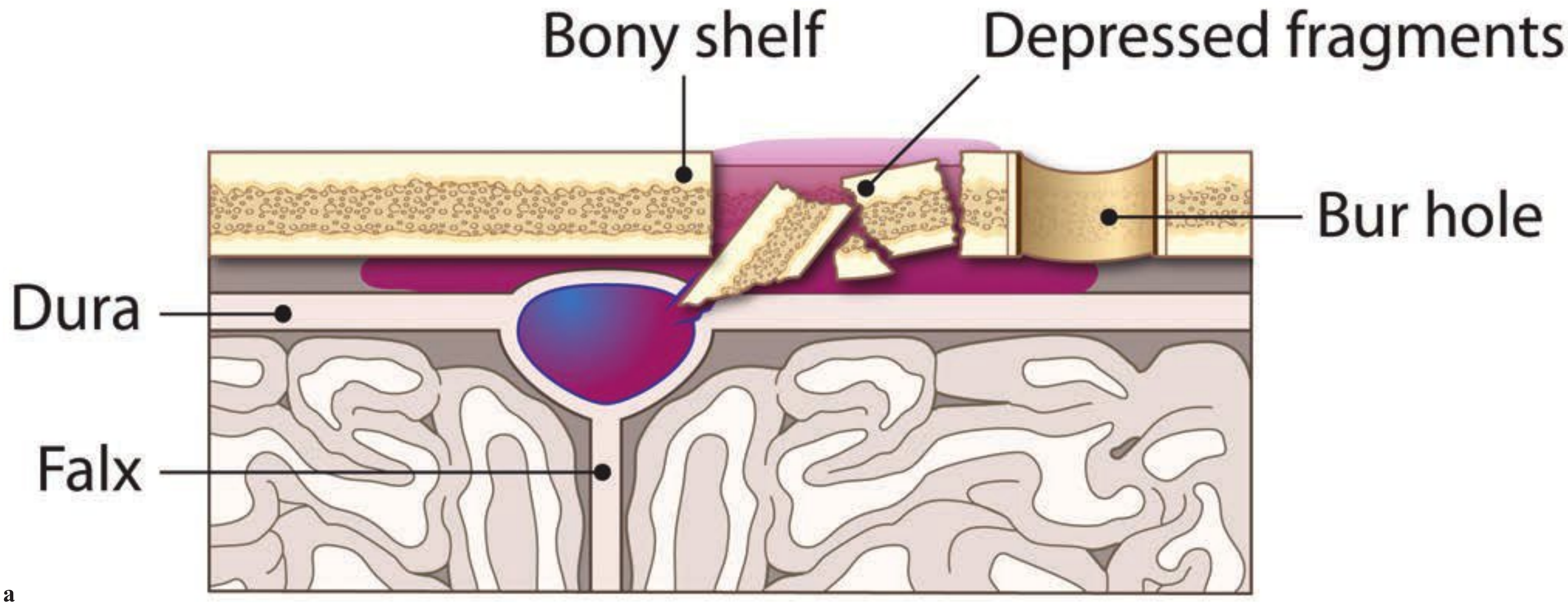


Figure	Procedural Steps	Pearls
Fig. 10.3	**The orientation of the incision will be dictated by the specific location of the injury.**	• In general, an incision allowing exposure of both sides of the superior sagittal sinus or providing access to the supra- and infratentorial compartments—in the case of a transverse/sigmoid injury—is advised.

Craniotomy (Fig. 10.4a, b)



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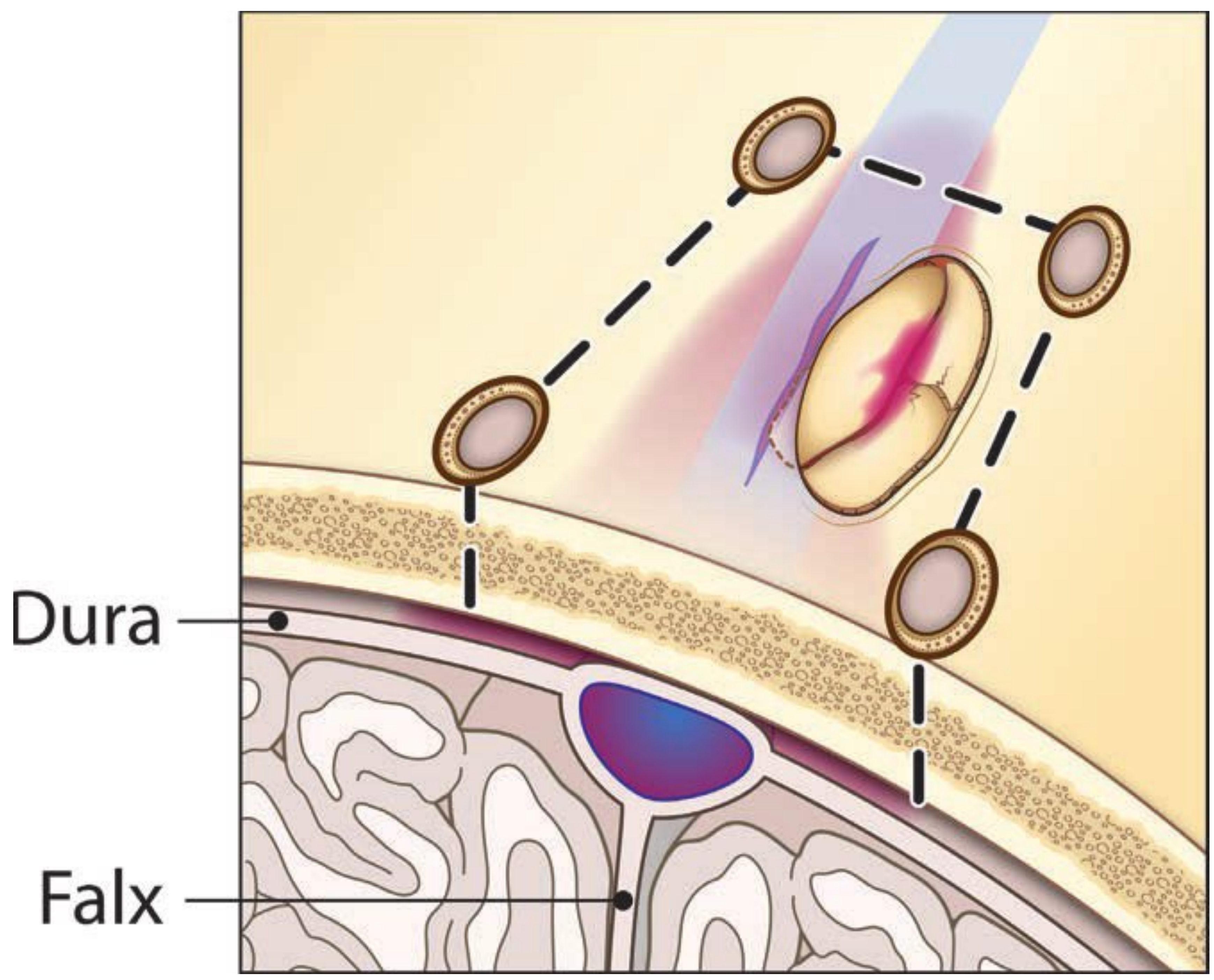
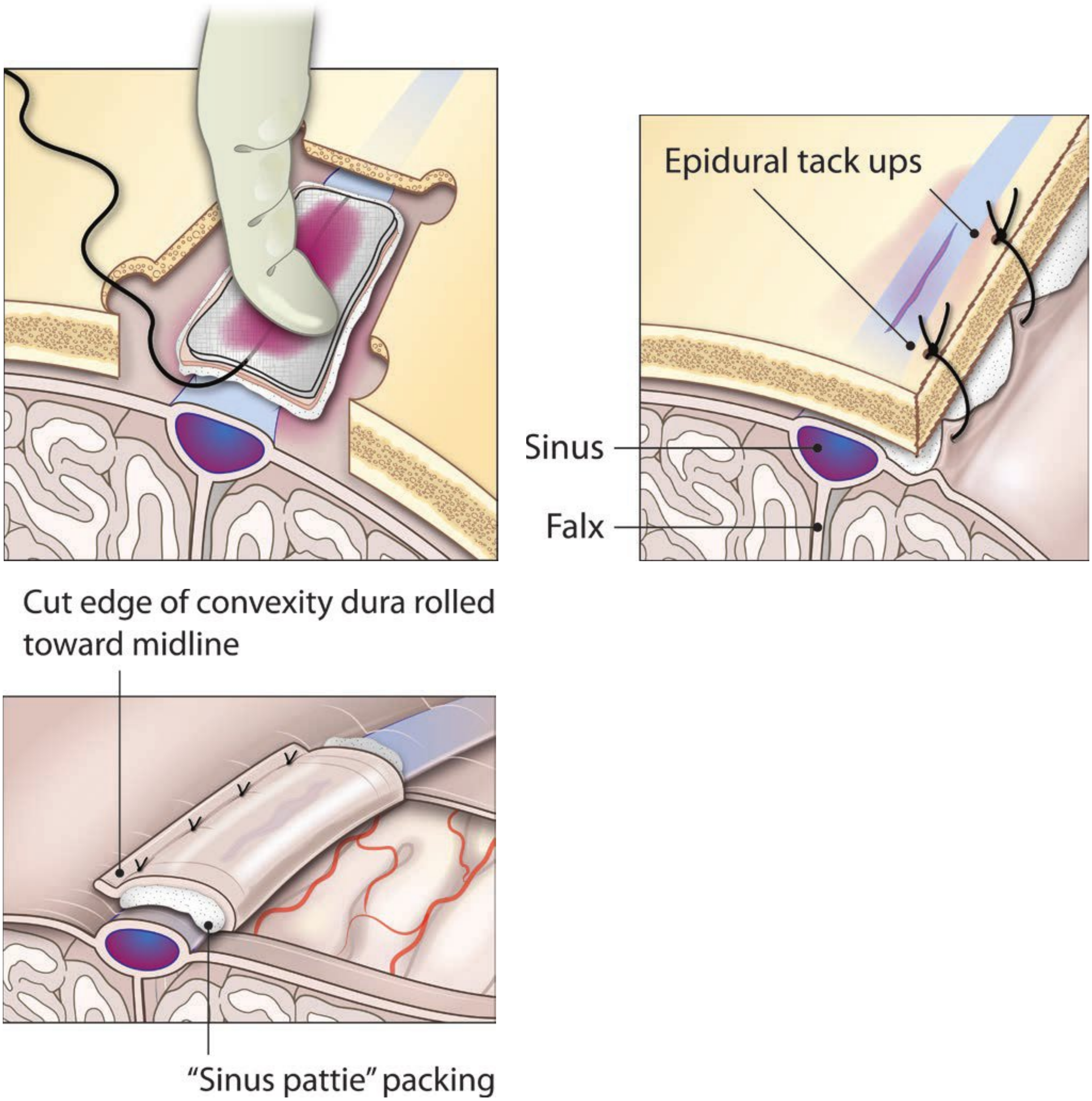


b

Figure	Procedural Steps	Pearls
Fig. 10.4	**The position of bur holes depends upon the anatomy of the specific fracture.** **(a) If a nondepressed, linear fracture with suspected dural sinus laceration is present, consider leaving a bony shelf adjacent to the sinus in order to permit the use of epidural tacking stitches that might tamponade the lacerated sinus.** **(b) If fracture fragments appear depressed into the sinus, bur holes should be placed at the outer rim of the depressed segment—allowing access to normal structures at the periphery.** **If the sinus is transected, bilateral bony exposure—both proximal and distal to the sinus injury—is necessary.**	• Fracture fragments should be elevated in stages; defer removal of any fragment directly over the sinus until last.

Tamponade (Fig. 10.5a–c)



a b c

Figure	Procedural Steps	Pearls
Fig. 10.5	**(a) Apply digital pressure, supplemented with "sinus patties" (a combination of 1 3 3 in cotton patties, hemostatic absorbable gelatin compressed sponge, and strips of hemostatic oxidized cellulose polymer).** **(b) Place epidural tack-up stitches with 4-0 braided nylon suture when usable bone is adjacent to the injury.** **(c) In some cases, the lateral convexity dura may be rolled toward the midline—over top the injured sinus segment and packing—and secured to form a "burrito."**	• Sinus patties should be prepared prior to exposure. • This combination may be supplemented with strips of hemostatic oxidized cellulose polymer and absorbable hemostatic matrix paste or comparable hemostatic agents. Also, cotton balls and muscle may be employed to bolster the tamponade.

Sinus Ligation (Fig. 10.6)

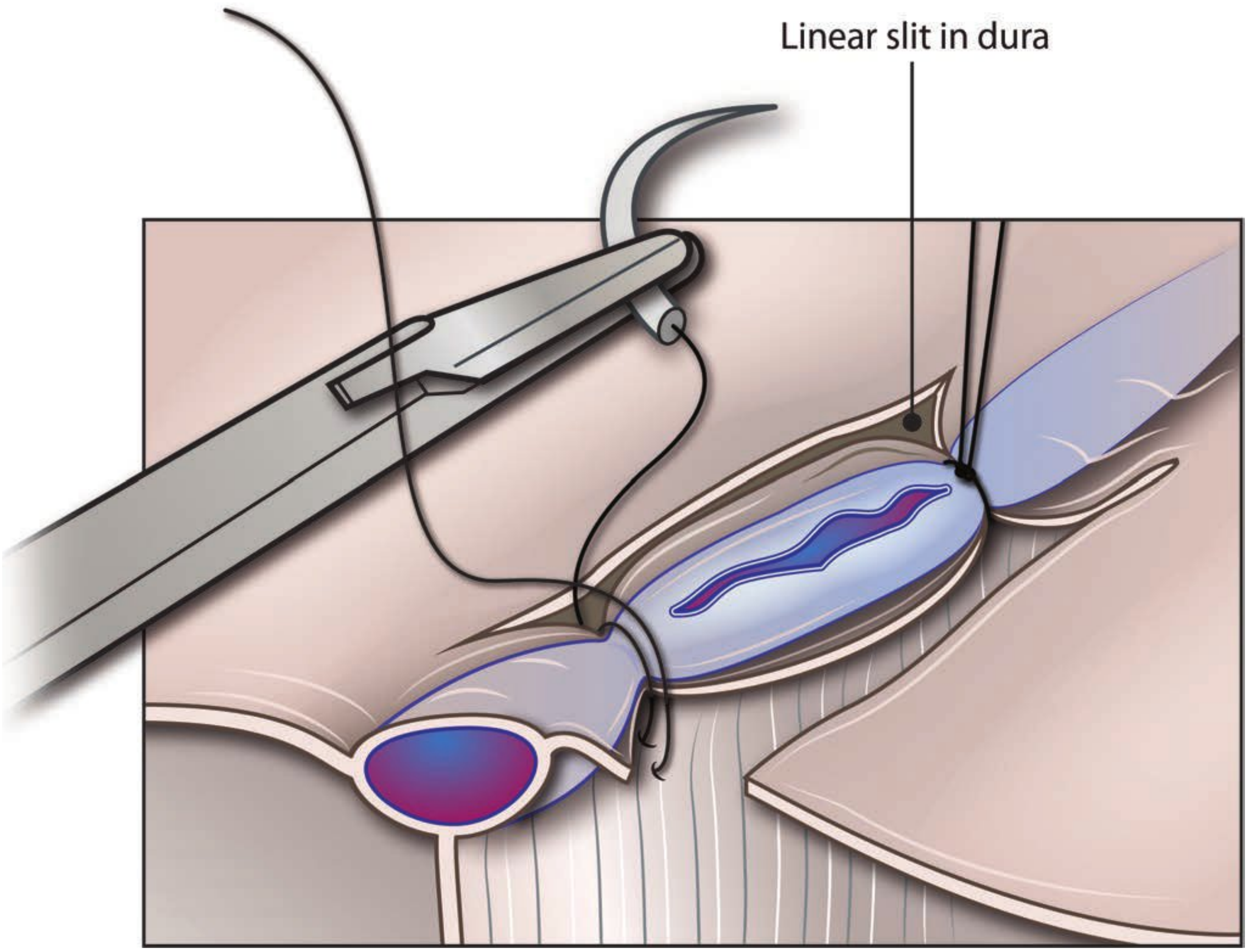


Figure	Procedural Steps	Pearls
Fig. 10.6	**Injuries involving the** anterior third **of the superior sagittal sinus (in front of the coronal suture) may be amenable to ligation.** **The sinus—anchored by the falx and convexity dura—first must be released.** **Following release of the sinus, ligation may be performed by a double ligature technique, using 2-0 nonabsorbable polypropylene suture or nylon. Make a double circular course beneath the sinus, into the falx and then more superficially, to be ligated and divided.**	• Tamponade sinus bleeding during dissection through the use of hemostatic agents and cotton patties, augmented with head of bed elevation (while monitoring for VAEs). • Alternatively, ligation may be performed with a surgical hemostatic double clip at the inferior insertion of the sinus into the falx, near the crista galli. Attention must be paid to ensure that the clips cross the sinus completely.

Sinus Patch (Fig. 10.7)

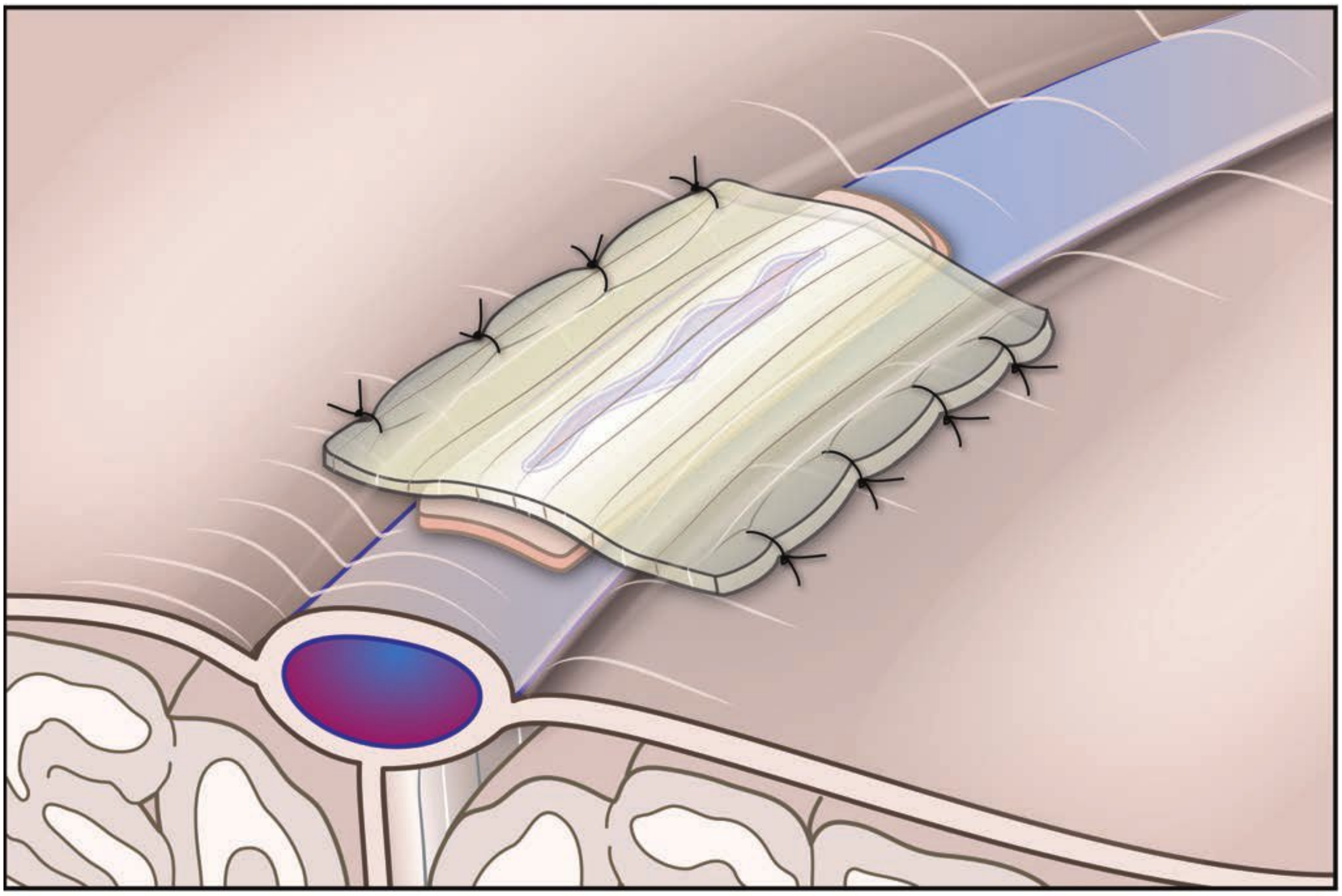
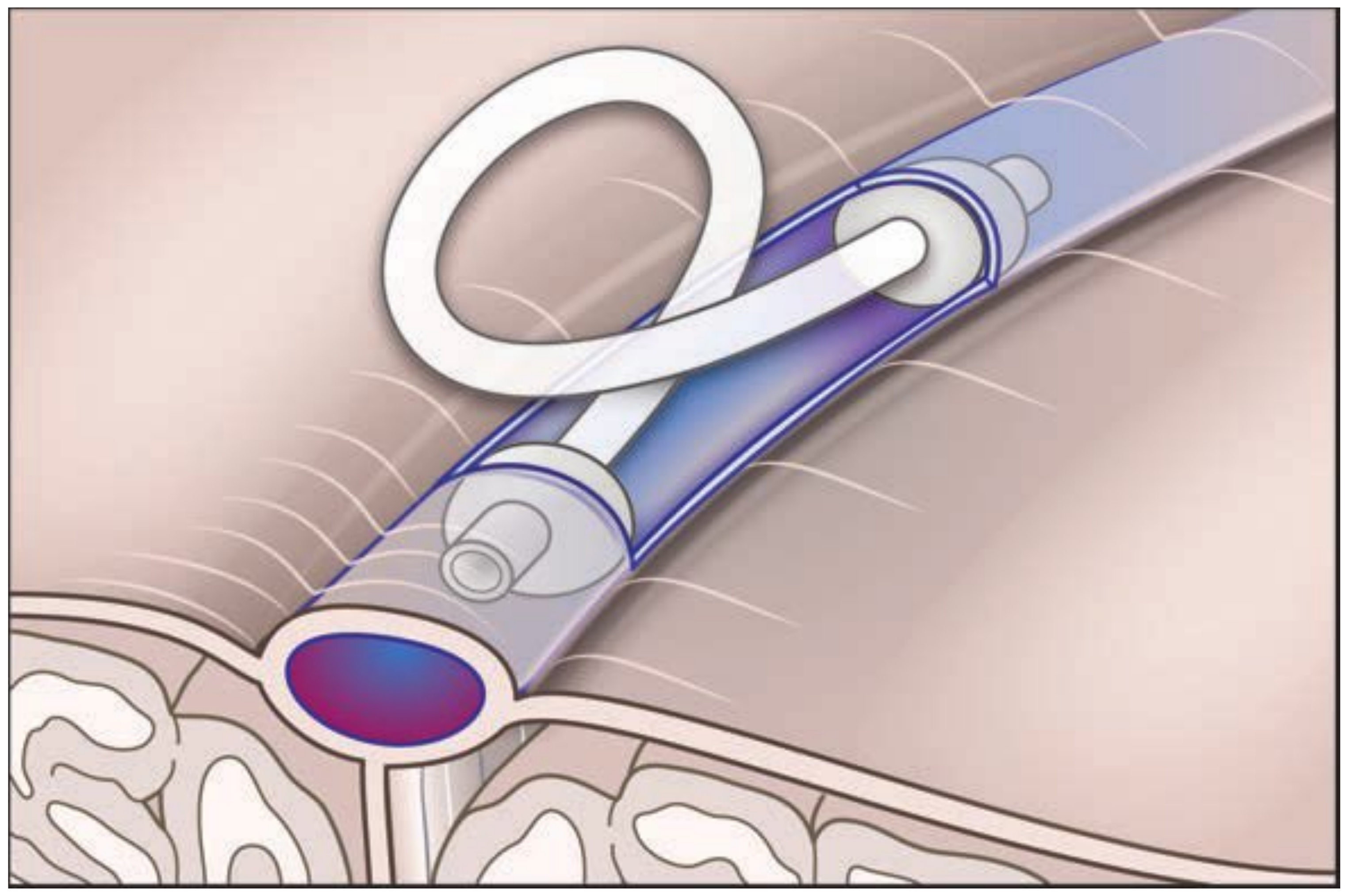
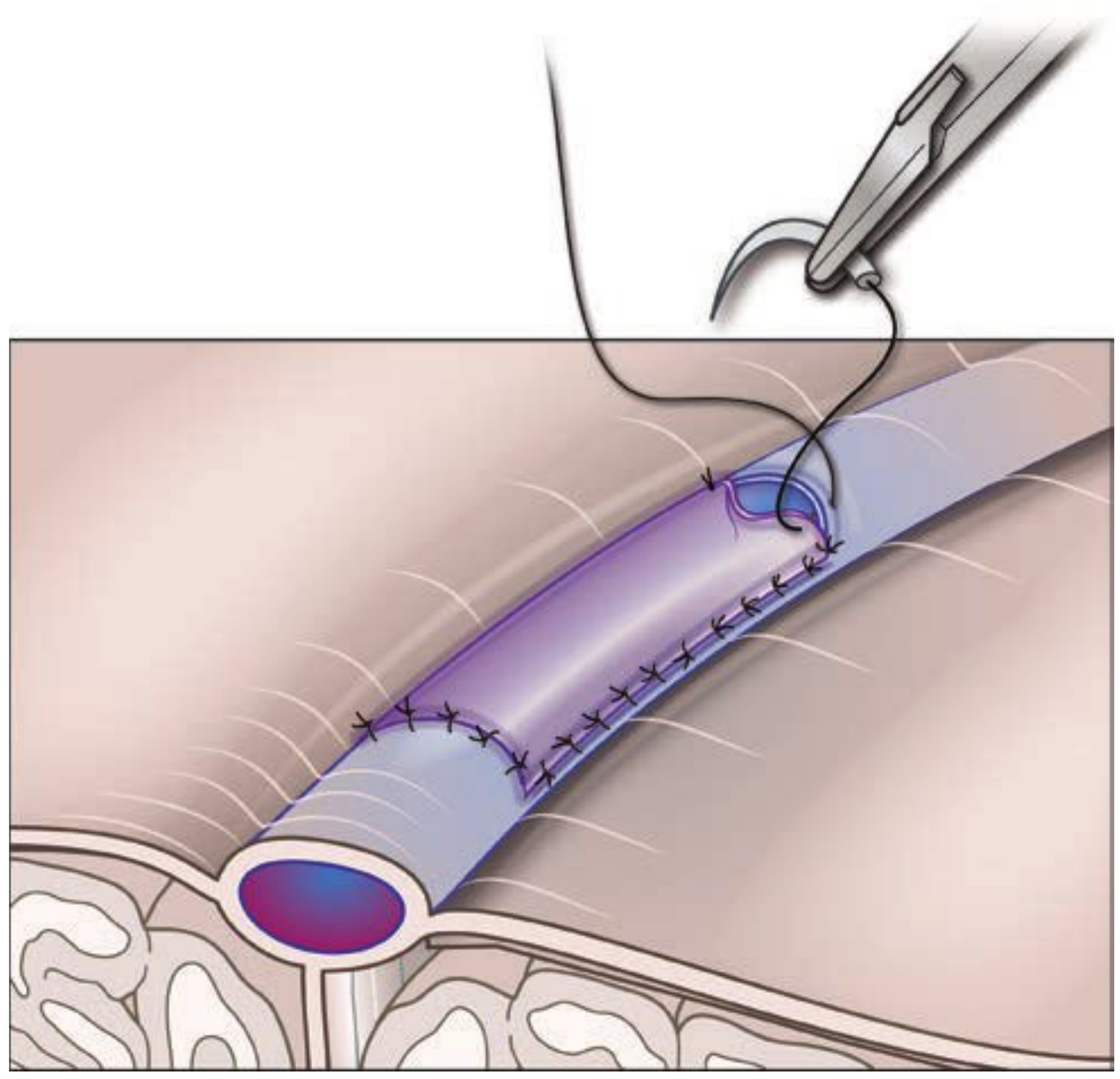


Figure	Procedural Steps	Pearls
Fig. 10.7	**Lacerations that are too large to suture directly may be treated with a sutured, bolstered patch.**	• This technique does not work well on the lateral sinus walls.
	Options for patch material include adjacent dura (curled over the sinus), temporalis fascia, fascia lata, and synthetic dura or vascular substitutes.	• Avoid direct suturing of the patch to the double layers of the sinus.
	A layer of muscle or hemostatic absorbable gelatin sponge should be interposed between the patch and underlying sinus laceration.	
	Secure the patch—with a series of interrupted, peripherally placed 4-0 braided nylon or nonabsorbable polypropylene stitches—to the adjacent dura.	
	Replace the overlying bone to bolster the sinus repair.	• Take care to avoid occluding the sinus or major cortical veins in the area.

Sinus Interposition Graft (Fig. 10.8a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 10.8	**Interposition grafting may be appropriate in cases of complete sinus disruption (posterior to the coronal suture), in patients deemed to be salvageable.** **The greater saphenous vein must be harvested in advance from the upper portion of the thigh. The graft should be reversed to prevent the valves from obstructing flow.** **(a) A temporary shunt should be placed, with heparin fluid irrigation of the shunt tubing as well as the proximal and distal ends of the sinus. (b) The vein graft is placed around the shunt and incorporated with multiple, interrupted, end-to-end 6-0 nonabsorbable polypropylene stitches, leaving a small dorsal region to remove the shunt and tie the final stitches.**	• Typical synthetic vascular graft material is prone to thrombosis in this location and should be avoided, if possible. Likewise, arterial grafts may progressively occlude from extensive arterial wall thrombosis. Cadaveric vein may be an option in rare cases. • Historically, the vascular shunt featured a double balloon confguration that allowed venous flow without bleeding around the shunt. More recently, other authors have described the use of a Rumell vessel loop around the shunt proximally and distally to avoid endothelial sinus injury and delayed thrombosis.

Variation for Injuries of the Posterior Two-thirds of the Superior Sagittal Sinus, Torcular Herophili, and Dominant Transverse Sinus

Positioning (Fig. 10.9)

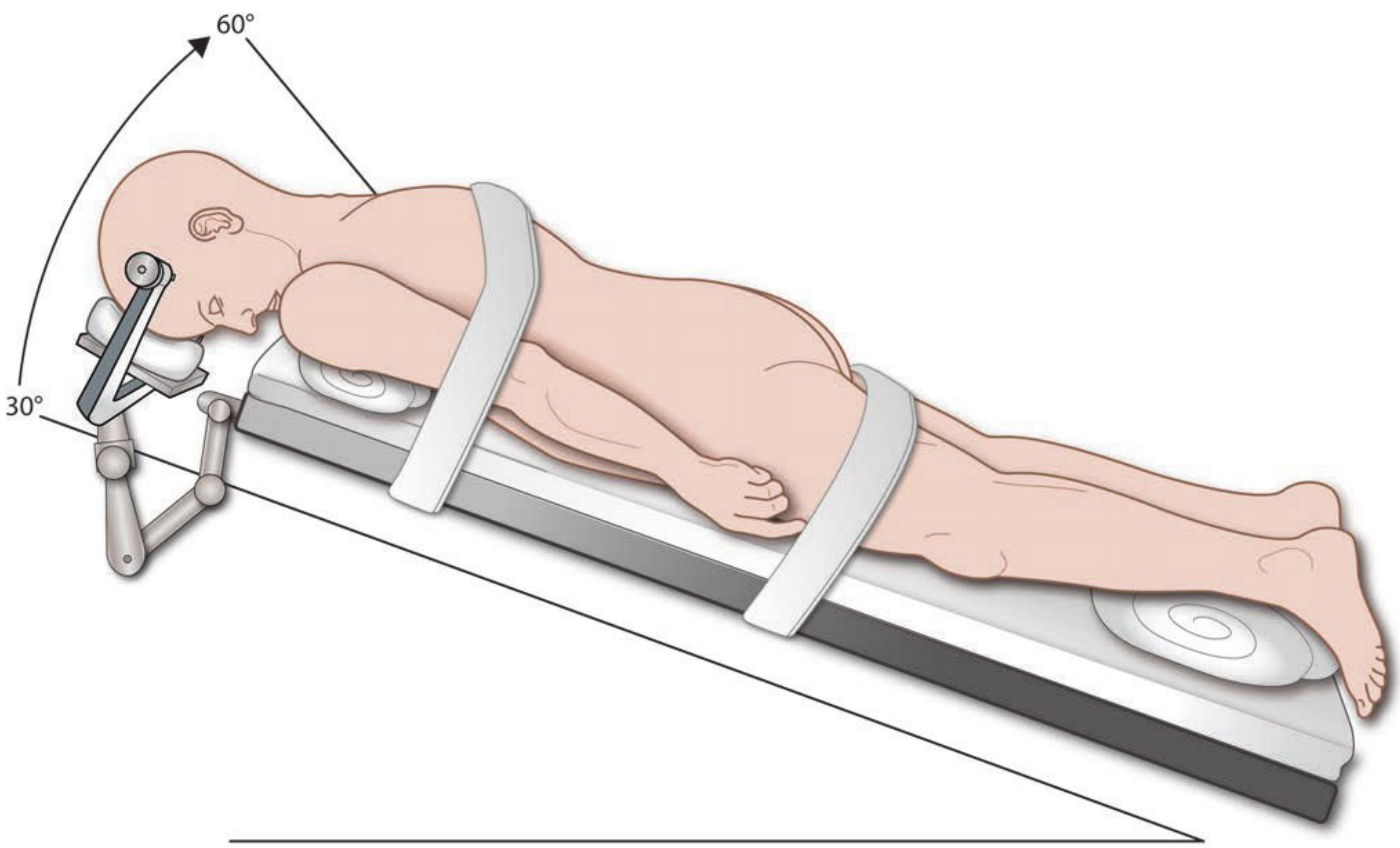


Figure	Procedural Steps	Pearls
Fig. 10.9	**The approach to these sinus segments is best accomplished with the patient in prone position.** **Injuries involving the middle third of the sinus may be approached in the supine position. Alternately, the patient may be in lateral position, with the falx cerebri parallel to horizontal and the head tilted up 45 degrees.**	• Refer to Fig. 10.2 for details regarding anesthetic adjuncts in this setting.

Incision (Fig. 10.10)

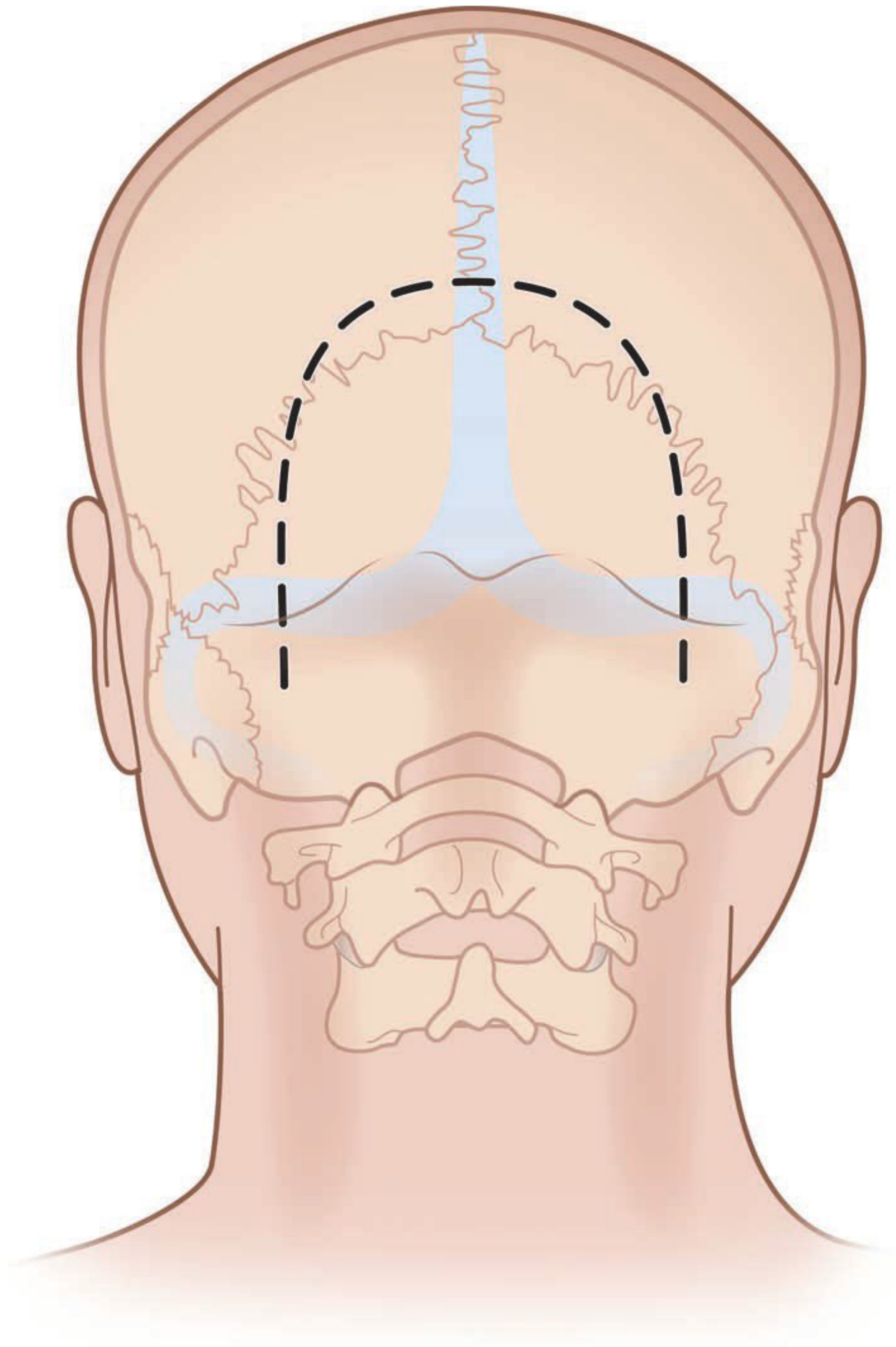


Figure	Procedural Steps
Fig. 10.10	**An inverted U-shaped incision permits access to the supratentorial and infratentorial compartments.** **A transverse, linear incision providing access to the bilateral hemispheres may be used to approach injuries to the middle third segment of the sagittal sinus.**

Craniotomy (Fig. 10.11)

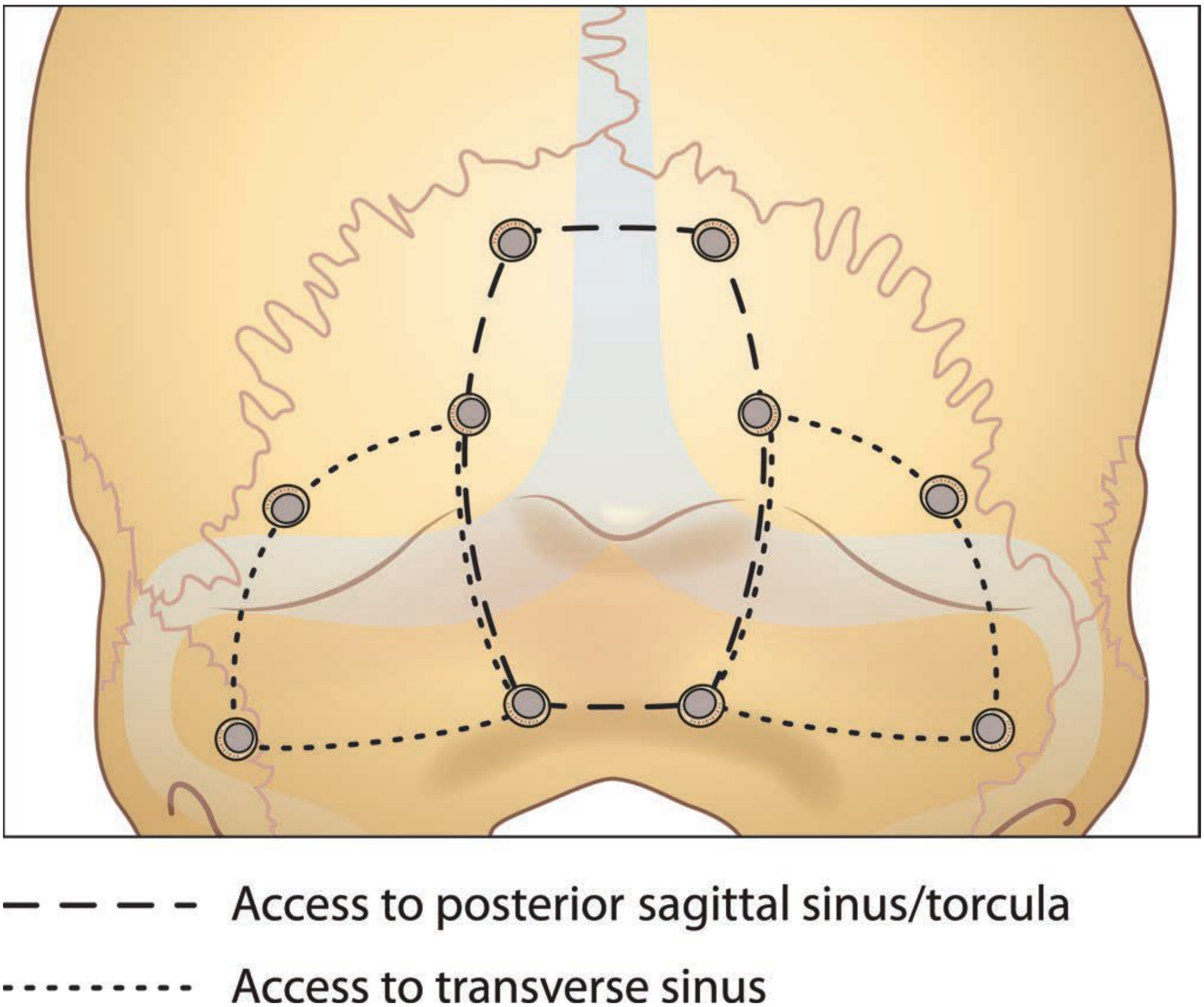


Figure	Procedural Steps	Pearls
Fig. 10.11	**The position of bur holes depends on the anatomy of the specific fracture.**	• The bony opening should permit access to both sides of the sinus in question.

Direct Repair (Fig. 10.12)

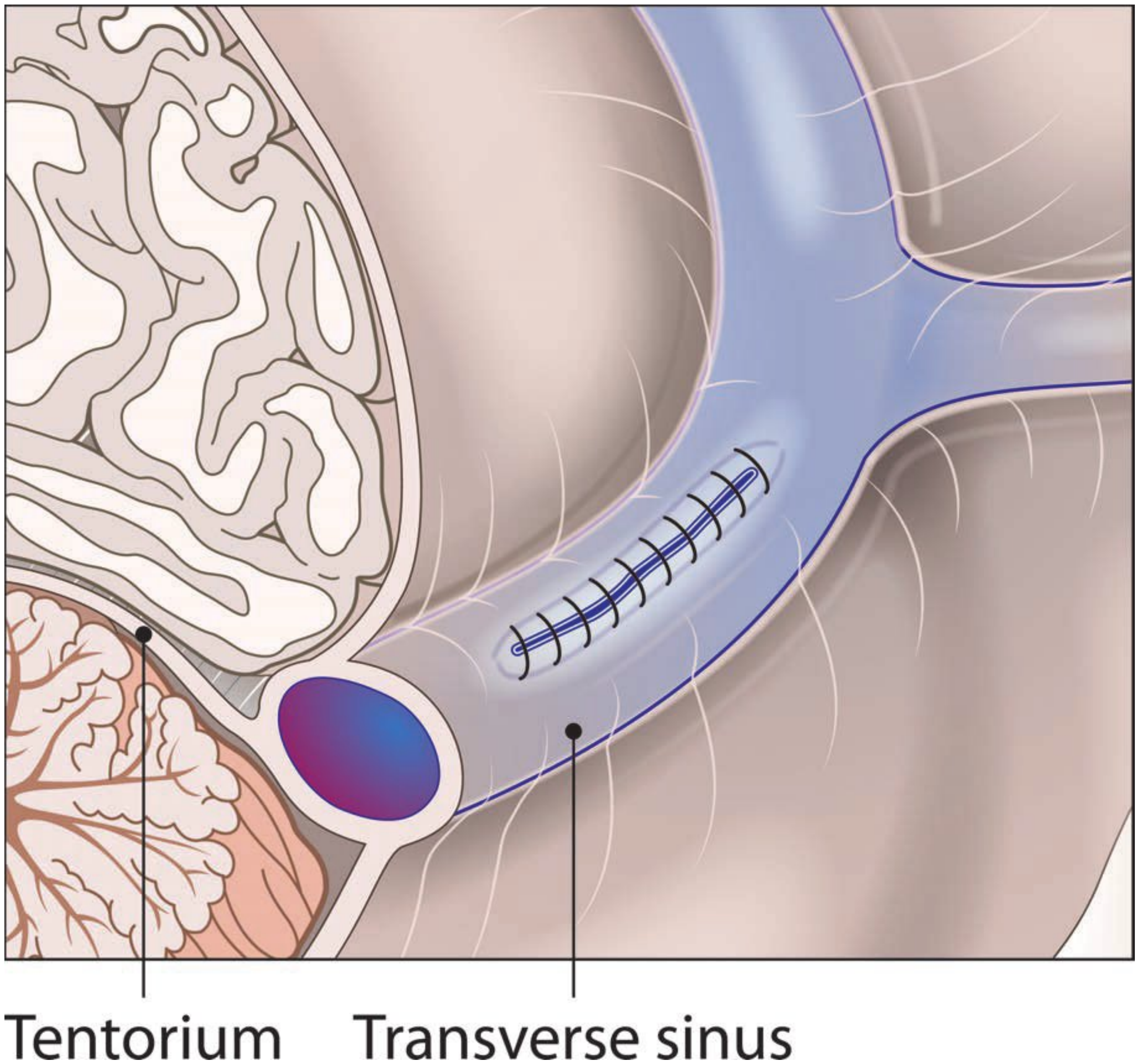


Figure	Procedural Steps	Pearls
Fig. 10.12	**The use of adjuncts discussed in Fig. 10.5 for tamponade may be effective, but must be tempered by the risk of sinus and/or cortical vein occlusion.**	• Tamponade is particularly poorly tolerated in the region of the central sulcus when the vein of Trolard is involved.
	Primary suture repair of lacerations may be attempted with 6-0 nonabsorbable polypropylene suture.	• Injury involving a single lateral wall at the junction of a venous lake, which does not respond to tamponade, may be isolated and treated with suturing parallel to the sagittal plane along the sinus edge. • Avoid primary suture closure that compromises . 50% of the sinus lumen. • If stenosis is likely to result from primary suture repair, a patch should be considered.

Sinus Patch (Fig. 10.13)

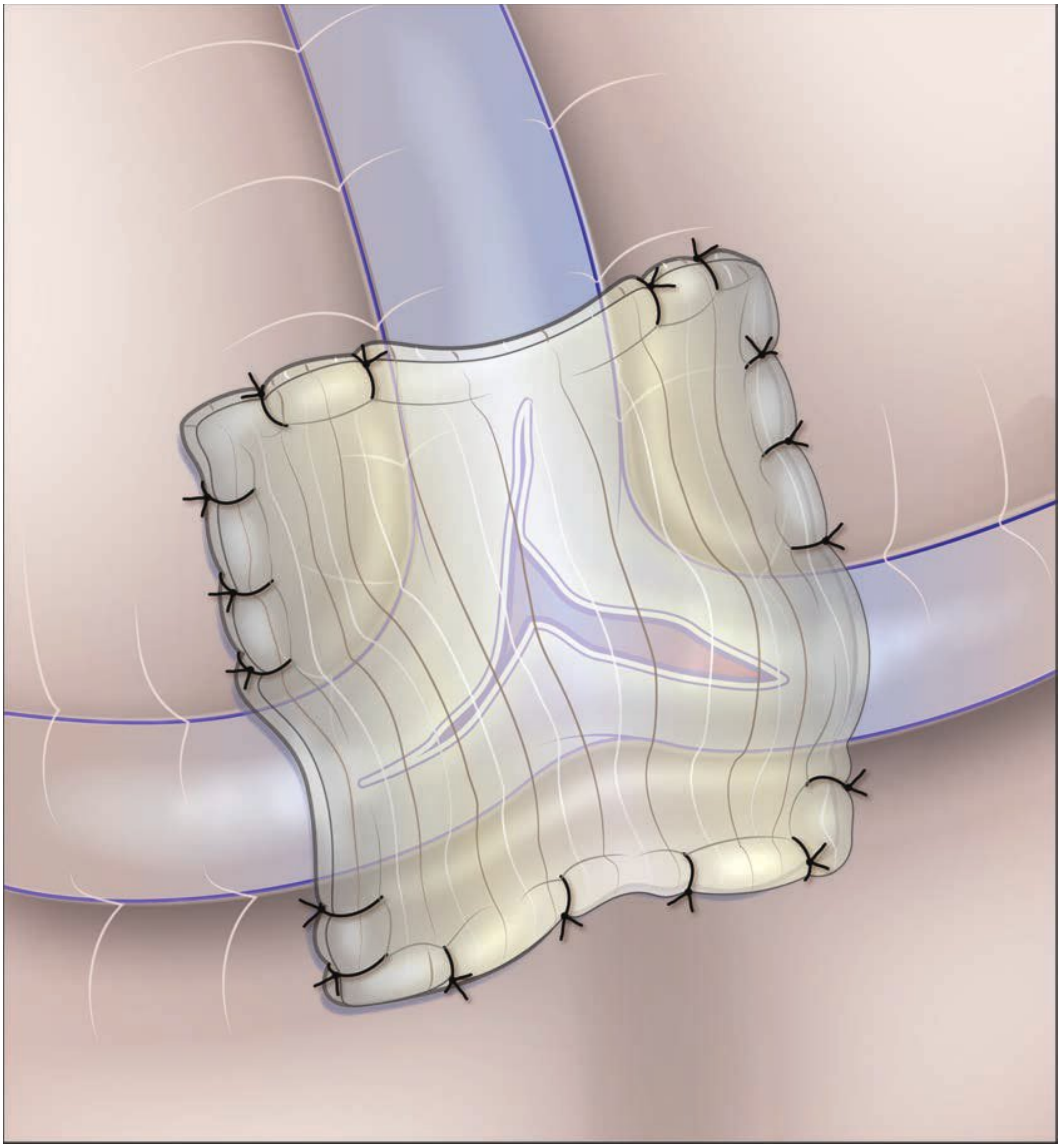


Figure	Procedural Steps	Pearls
Fig. 10.13	**Lacerations that are too large to suture directly may be treated with a sutured, bolstered patch.** **Interposition grafting is a daunting proposition in this area.** **The vein graft must be oriented such that the valves allow flow from the anterior to posterior portions of the sinus in a nonlimiting fashion.**	• Refer to Fig. 10.7 for details regarding patching of the venous sinus. • Replacement of a superior sagittal sinus segment is reserved only for cases that involve both lateral walls or the majority of the dorsal wall, where a sutured patch cannot reconstruct a lumen at least 50% of the original size. • Refer to Fig. 10.8 for details regarding interposition grafting.

Closing

- Dural closure is performed with 4-0 braided nylon suture.
- The bone flap is reapproximated—if feasible—with an intracranial plating system.
- The surgical site is irrigated with antibiotic solution.
- Meticulous hemostasis is attained along the skin edges. A subgaleal drain may be left in place if necessary.
- The galea and subcutaneous tissue are reapproximated with 2-0 braided absorbable suture inverted stitches.
- The skin is closed either with staples or 3-0 nylon suture.

Postoperative Management

Monitoring

- The patient is monitored in the intensive care unit setting to permit frequent neurologic checks and continuous hemodynamic monitoring.
- Invasive blood pressure monitoring and a central venous catheter are employed to provide continuous monitoring of blood pressure and volume status. Blood pressure is maintained in a normal range. The goal of intravenous fluid therapy is euvolemia.
- The head of the bed is maintained at 30 degrees.
- Invasive neurologic monitors are placed if indicated by the patient's overall neurologic status (Glasgow Coma Scale score ≤ 8).

Medication

- Antimicrobial prophylaxis is continued for 24 hours.
- Antiepileptic prophylaxis is continued for 7 days.

Radiographic Imaging

- A CT scan is performed early in the postoperative period to rule out hemorrhage and/or ischemia. Imaging is repeated for any significant change in neurologic status.
- Dedicated vascular imaging (CTV, magnetic resonance venography, or angiography) may be appropriate if thrombosis is suspected.
- **Postoperative imaging (Fig. 10.14).**

Special Considerations

Late Complications

- Post-repair venous sinus stenosis or sinus compression (e.g., from a depressed skull fracture) increases the risk of delayed sinus thrombosis. Venous sinus thrombosis may lead to progressive bilateral encephalopathy, increased intracranial pressure, cerebral edema, intraparenchymal hemorrhage, and venous infarction. Deep venous hemorrhage and infarction involving the thalamus can occur with injury to the straight sinus at the level of the tentorium.

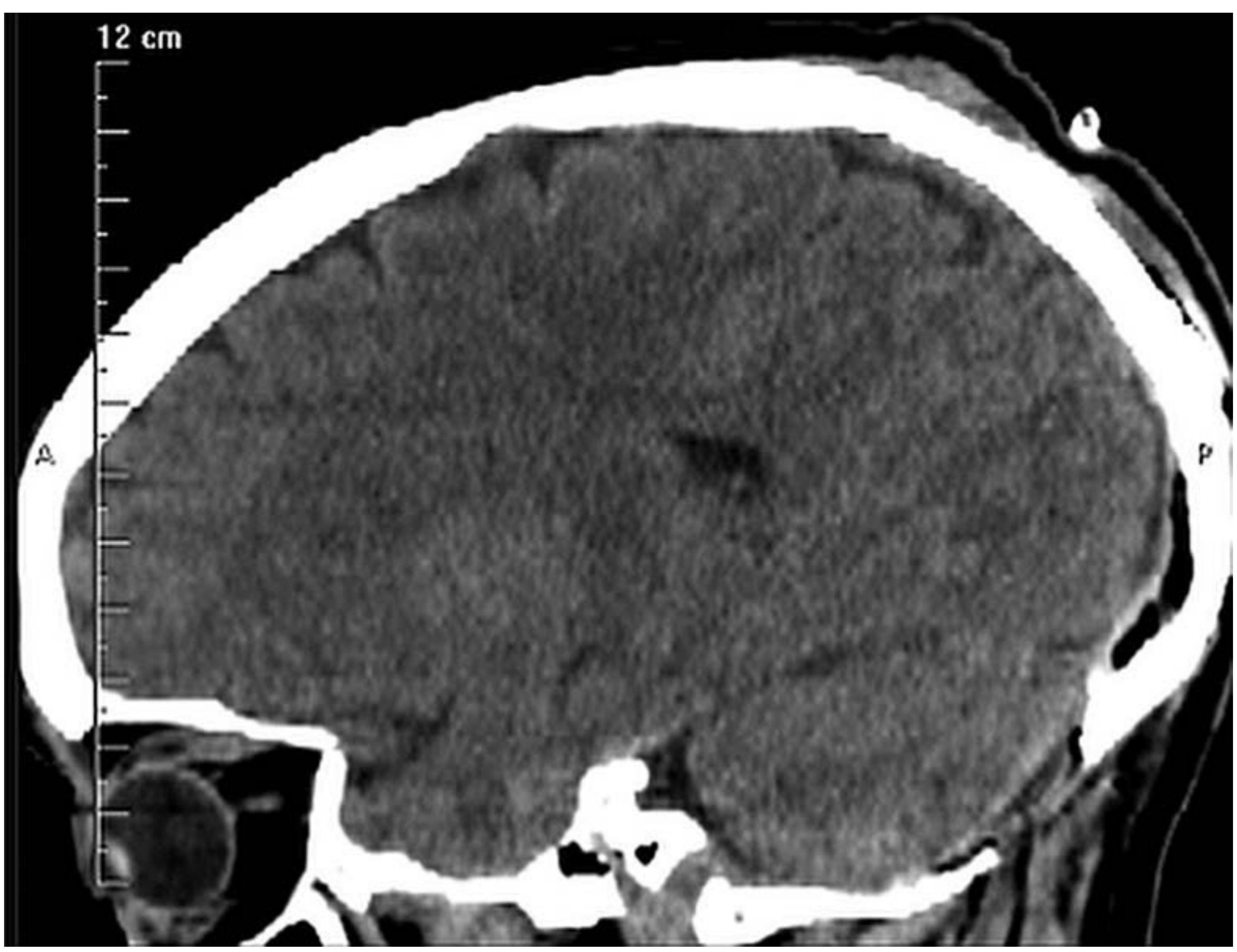


Fig. 10.14 Sagittal CT reconstruction demonstrating resolution of extra-axial hematoma following repair of a transverse sinus injury.

- The indications for delayed craniotomy or decompressive craniectomy include:
  - Elevated intracranial pressure not responsive to maximal medical therapy
  - Severe cerebral edema or the presence of an intracranial hematoma with impending brain herniation
  - Elevation of a depressed skull fracture or removal of a foreign body when dural sinus patency is compromised

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II Spinal Emergency Procedures

11 Application of Closed Spinal Traction

Nirit Weiss

Introduction

Emergency closed spinal traction may be performed for patients who present with cervical spinal misalignment and/or instability secondary to trauma. Use of lighter weight (5–10 lb) can maintain alignment and immobilize an unstable spine, if closed traction reduction is not deemed appropriate at the time. Reduction of fracture dislocation and realignment with increased weight (10–80 lb) can decompress the spinal cord and nerve roots. After successful application of traction, bracing or surgery may be deemed appropriate. If traction is unsuccessful, surgery likely follows. Manipulation under anesthesia (MUA) may be helpful in patients who fail awake inline traction reduction.[1] Weighted inline halo ring traction can be converted to long-term halo-vest immobilization if needed. Most commonly used traction options are Gardner-Wells (G-W) tongs and Halo rings.

Indications

- Cervical spinal misalignment due to traumatic fracture/dislocation
- Spinal cord/nerve root compression due to misalignment
- Cervical spinal instability due to traumatic fracture or ligamentous instability requiring immobilization that cannot be adequately achieved with external orthoses alone
- Awake, cooperative patient
- Availability of radiographic/clinical monitoring during reduction
- Absence of skull fracture or prior bur hole at proposed pin sites
- Absence of occipitoatlantal or atlantoaxial dissociation or complete ligamentous injury at any level
- Absence of fracture/instability at level rostral to intended level of treatment
- Absence of known significant associate traumatic cervical disk herniation, which can worsen neurologic deficit under traction

Preprocedure Considerations

Radiographic Imaging

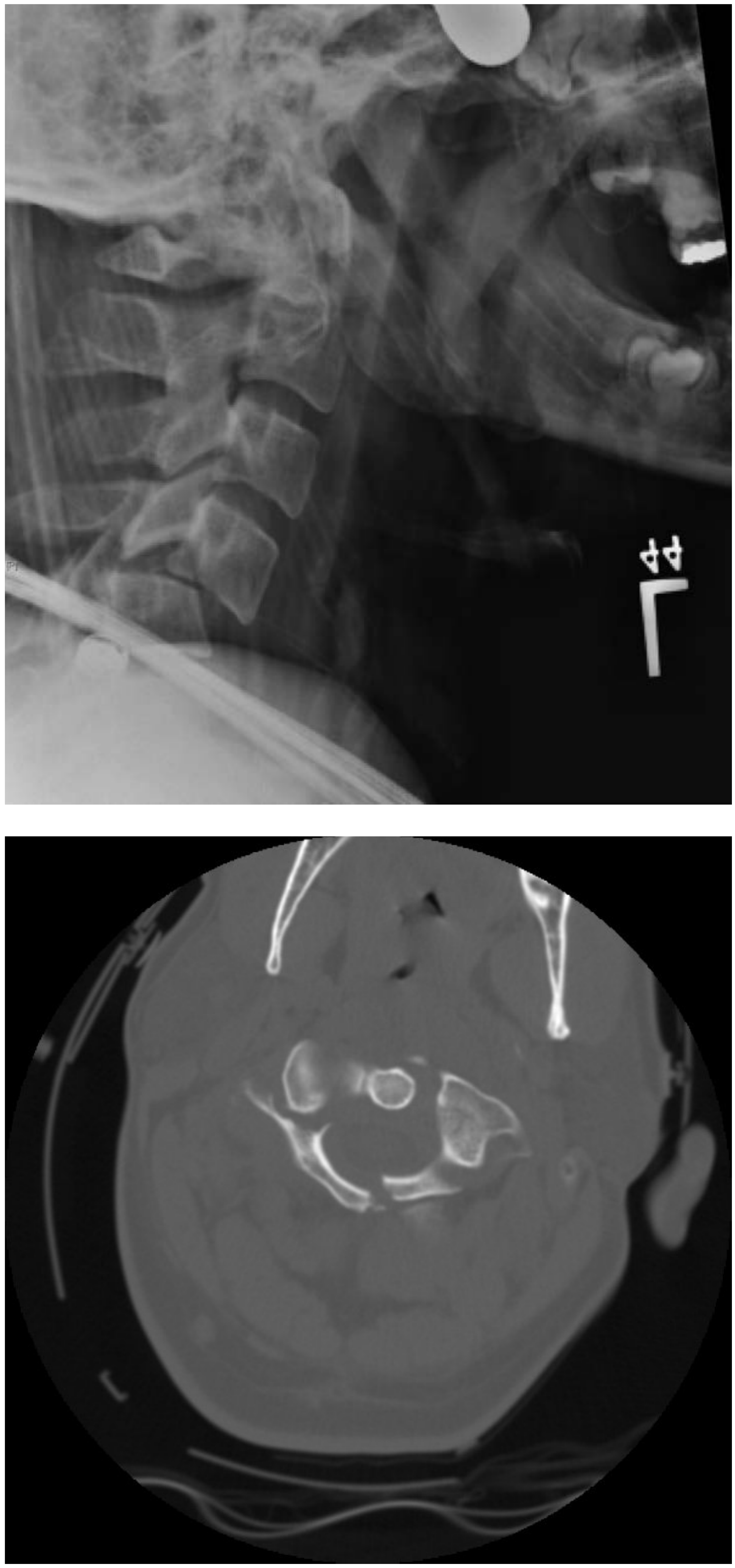
- X-ray and/or computed tomography (CT) evidence of fracture, subluxation, misalignment, instability (**Fig. 11.1**).
- Role of pretraction magnetic resonance imaging (MRI) remains controversial[2]: One-third to one-half of patients with facet subluxation have evidence of disk herniation or disruption on MRI. Inline traction in the presence of ventral cord compression may lead to neurologic injury. However, less than 1% of patients have been found in studies to have permanent neurologic deterioration resulting from application of cervical traction—despite the presence of herniated ventral disks. Depending on the time needed to obtain the MRI, the benefits of early reduction should be weighed against the risk of reduction in the face of potential unidentified ventral compression from disk herniation. In awake, cooperative patients, physical exam can be monitored while increasing traction weight, and pretraction MRI may have lower utility. In unconscious patients, significant efforts to obtain pretraction MRI should be made. Patients with incomplete injuries have greatest risk of neurologic deterioration.

Medication

- Systemic: Nonsedating pain medication (morphine, fentanyl) and muscle relaxant (diazepam) intravenously (IV) as needed to allow for patient cooperation and successful reduction.
- Local: 1% lidocaine or 1% lidocaine/0.5% bupivacaine (1:1 mixture) applied to scalp and pericranium of planned pin site locations.

Operative Field Preparation

- Alcohol prep followed by povidone/iodine to planned pin sites.
- Antibacterial (bacitracin) ointment to pins prior to placement.



a

b

Fig. 11.1 Lateral radiograph in patient with high-grade spondylolithesis at C4-5 due to bilateral facet dislocation after traction tongs placement and prior to weight application.

Operative Procedure

Positioning (Fig. 11.2)

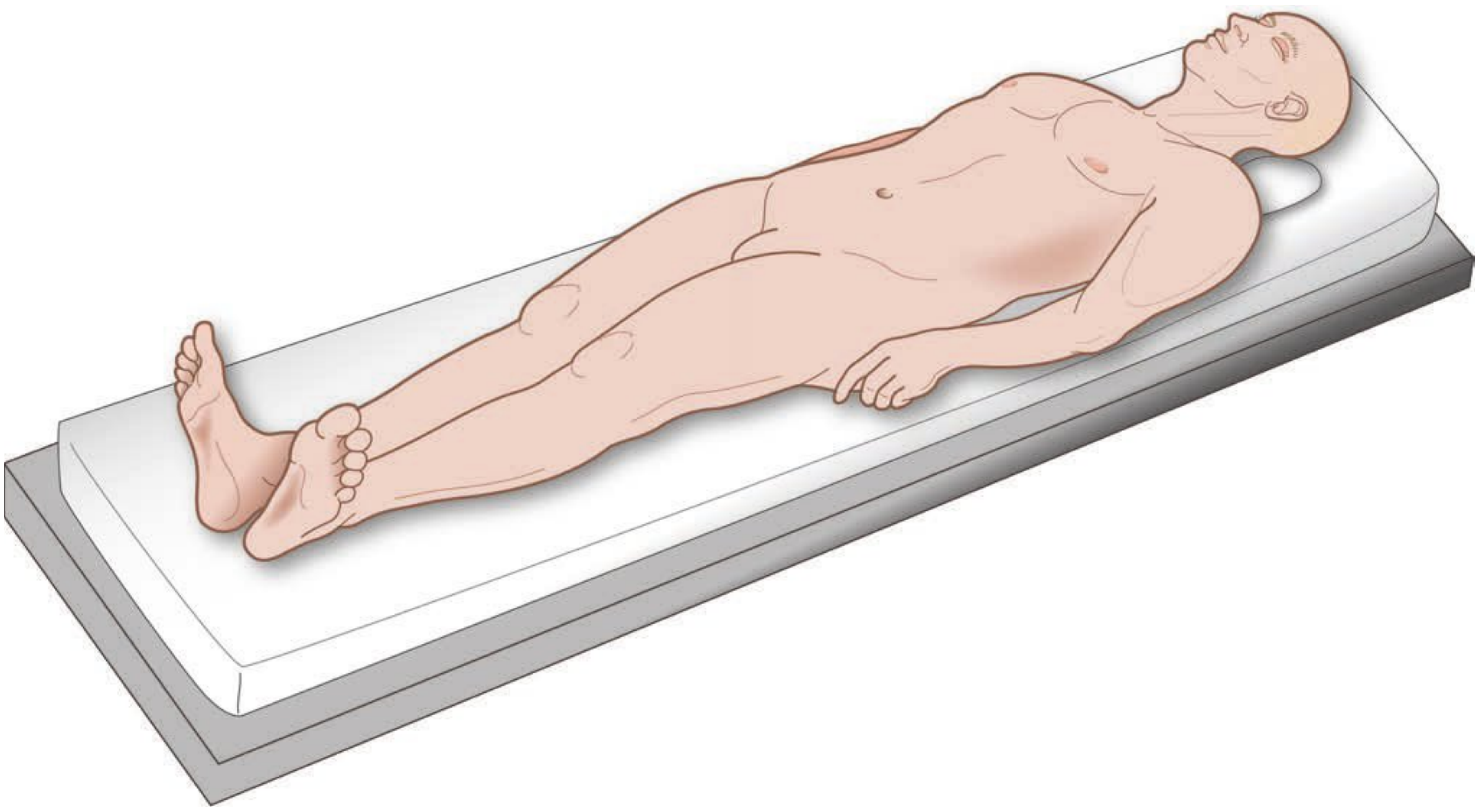
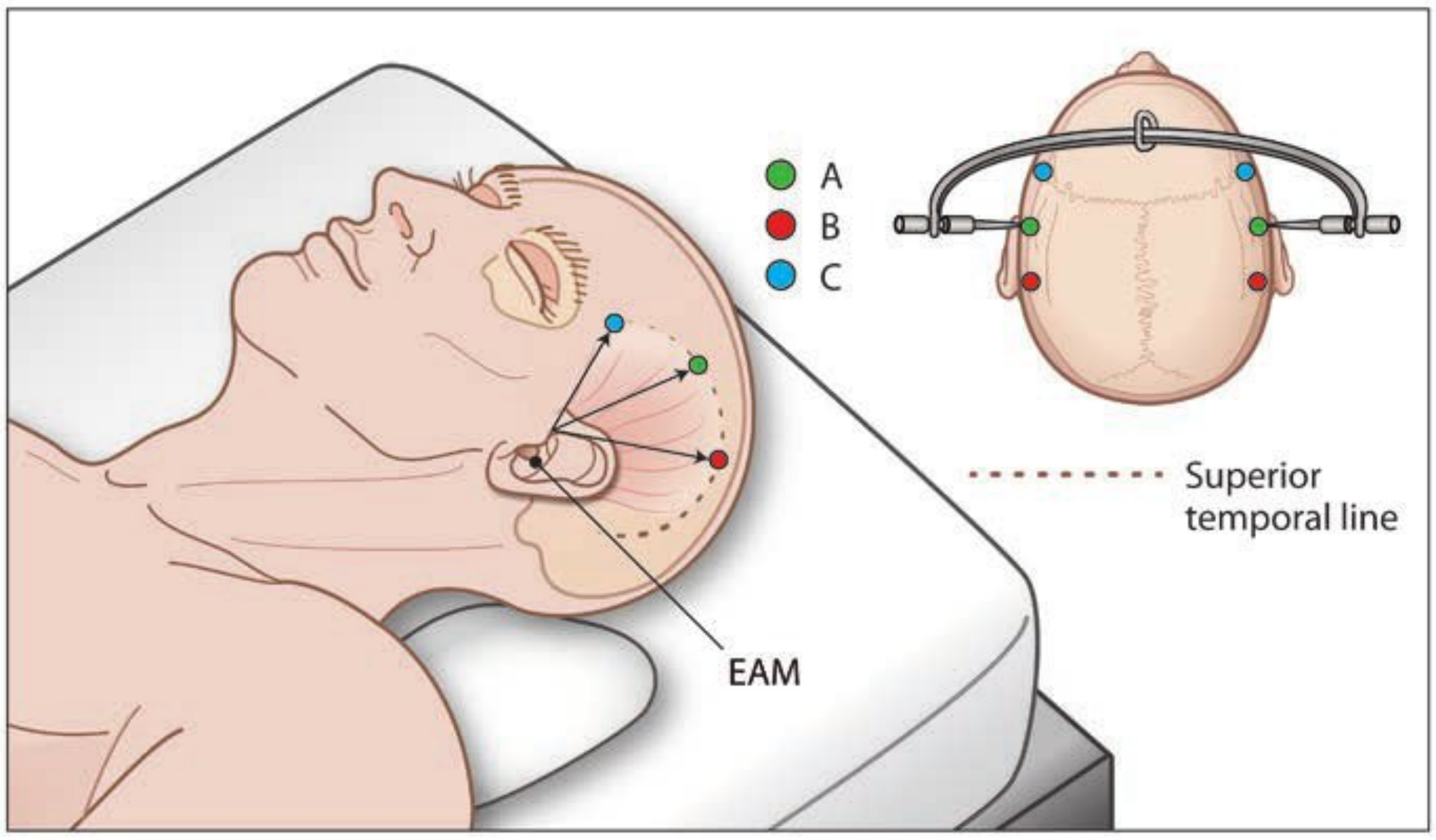


Figure	Procedural Steps	Pearls
Fig. 11.2	**Patient is positioned for application of traction, typically supine, head in neutral position.**	• It is easier to place an "open" halo ring than a closed ring while supine. Check lateral X-ray in position prior to proceeding. If one needs to reduce kyphosis, a shoulder roll can be placed. If the plan is to eventually place in halo vest, one can "preplace" the back of the halo vest for the patient to lie on.[3]

Selection of Pin Sites (Fig. 11.3a, b)



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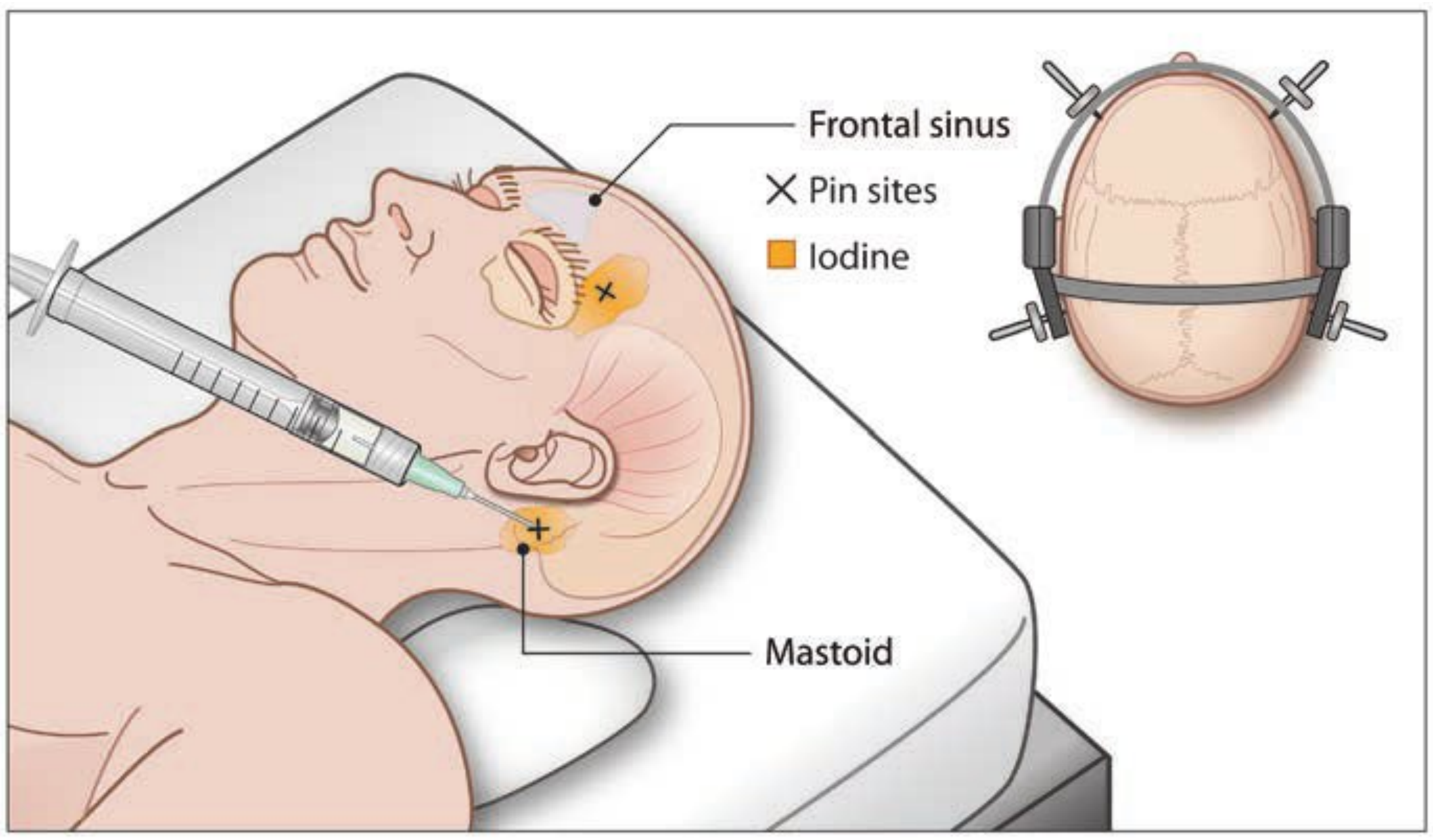

b

Figure	Procedural Steps	Pearls
Fig. 11.3	**(a) Gardner-Wells tongs. Two pin sites are required.** (A, green) **The ideal pin site placement is along the superior temporal line, above the temporalis muscle belly (mark as transparency below skin), approximately 3 to 4 cm above pinna. For neutral traction, pin directly in line above external auditory meatus (EAM). To induce a flexion correction (e.g., of jumped facets),** (B, red) **place 3 cm posterior to EAM; to induce an extension (e.g., for subluxation),** (C, blue) **place 3 cm anterior to EAM, along the superior temporal line. After preparation with alcohol and povidone iodine, local anesthetic is injected. (b) Halo ring. Select four pin sites, each marked with a pen: two anterior, two posterior. The two anterior sites should be 1 cm above orbital rim, above lateral half of the orbit (to avoid the supraorbital and supratrochlear nerves and the frontal sinus). Posterior pins should be in region of mastoid. After preparation with alcohol and povidone iodine, local anesthetic is injected.**	• Halo rings are available in MRI compatible models which can facilitate later imaging. Weights are typically not MRI-compatible and must be removed for MRI imaging. • Ensure there are no skull fractures or bur holes in region of proposed pin sites. Do not place pins into thin squamous temporal bone. • Select pin sites while assistant holds the halo ring in place, or use "suction cup" stabilizing posts to hold ring while selecting appropriate sites. Pin sites should be selected to allow for the ring to sit symmetrically around the head. • Pin sites should be selected to allow for a 1- to 2-cm space circumferentially between the scalp and the halo ring. Pins should be placed in holes that allow for most perpendicular entry into skull.[4] • Prep with alcohol followed by povidone iodine. Inject lidocaine or lidocaine/bupivacaine mixture as above into proposed pin sites, into scalp and pericranium. May incise scalp prior to pinning to avoid contamination with skin flora.

Placement of Pins (Fig. 11.4a, b)

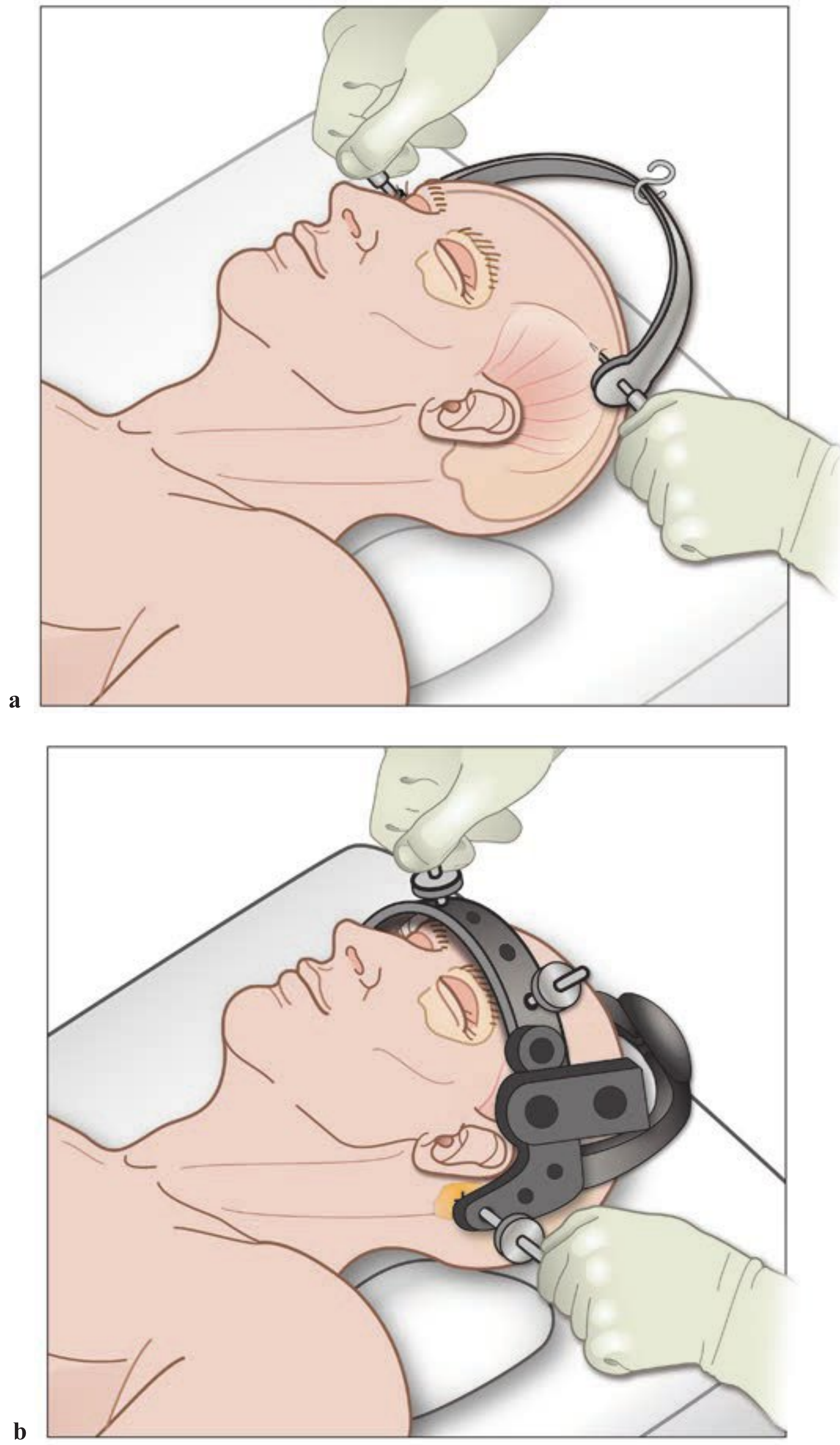

Figure	Procedural Steps	Pearls
Fig. 11.4	**(a) Gardner-Wells tongs. Place pins through the tongs into scalp and pericranium. Tighten both pins simultaneously, until torque indicator on one pin protrudes approximately 1 to 2 mm, indicating adequately tightened screws.** **(b) Halo ring. Tighten two diametrically opposed screws simultaneously until "finger tight." Then tighten the other two screws simultaneously until "finger tight." At this point, use torque wrench to adequately and safely secure pin tightness to preset maximal torque (8 in-lb for adults).**	• Pay attention to eyes and eyebrows to avoid pinning eyes open or closed. • For children: Use lower final torque for tightening (4–8 in-lb for children age 3–10, 2–4 in-lb for children under age 3).[5] Use multiple (6–10) pins in order to distribute pressure evenly circumferentially and avoid fracture or excessive skull penetration. Also, use specially supplied pediatric pins with short tips and wide flange, if available.[6]

Placement of Traction Weights and Counter-Traction (Fig. 11.5)

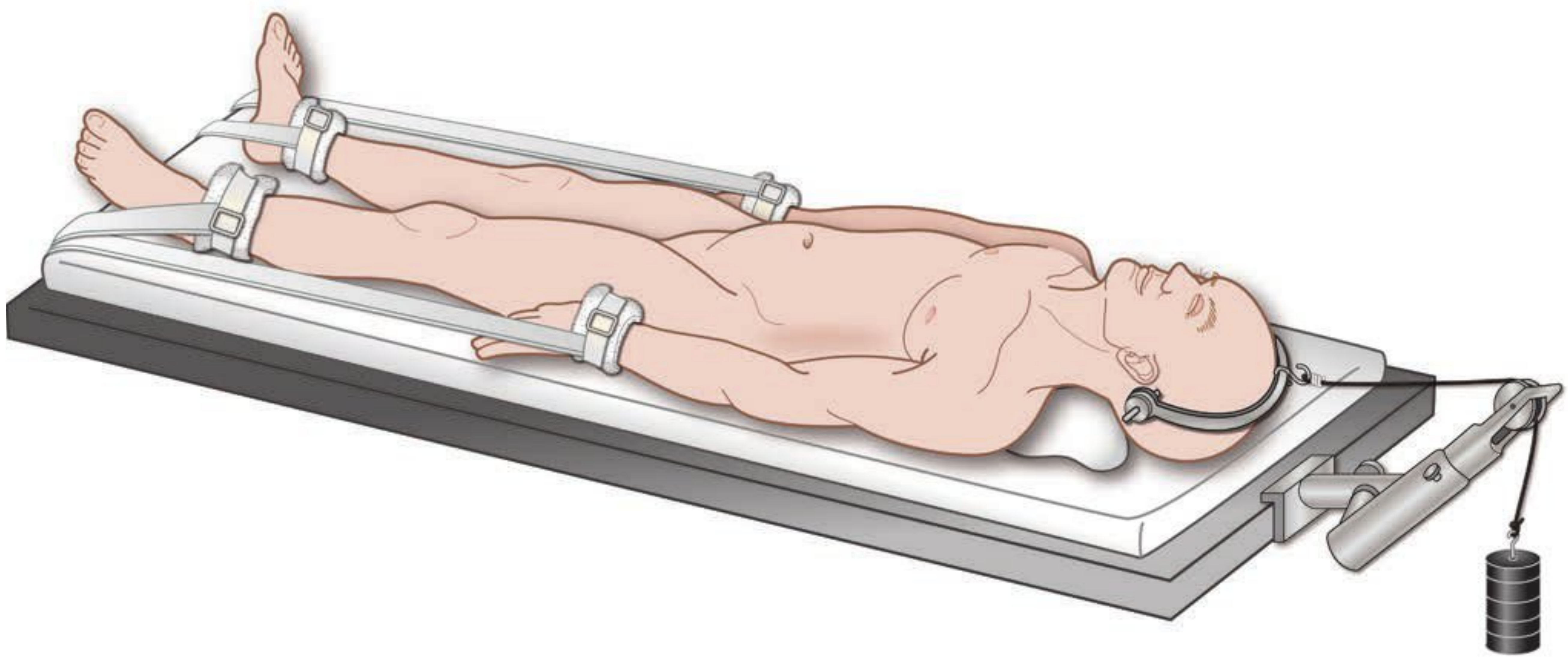

Figure	Procedural Steps	Pearls
Fig. 11.5	**Secure a knotted rope to tongs or halo ring, through a pulley at head of bed, and hang weights from there.** **Secure ankles, wrists, and shoulders with padded roped restraints to foot of bed to prevent patient from sliding up on bed when placed in traction.**	• If stabilizing an unstable fracture between occiput and C2, begin with 5 lb, and advance to 10 lb if radiographs show no change. • Below C2, begin with 10 lb to overcome weight of head through C2, and then 5 lb per level below C2 (e.g., 20 lb for C4 fracture). • Cervical traction is best performed under fluoroscopy, or obtain serial X-rays immediately after weight change, and in 30-min intervals to gauge progress. Follow the neurologic exam every 10 minutes. One may add weights in 5-lb intervals and recheck radiograph. Stop when observe: (1) successful spinal realignment radiographically, (2) neurologic deterioration, (3) undesired radiographic changes (worsening misalignment, distraction at more rostral disk level with widened disk space or splayed spinous processes or facet joints), and/or (d) patient complains of severe discomfort.

Placement of Vest (Fig. 11.6)

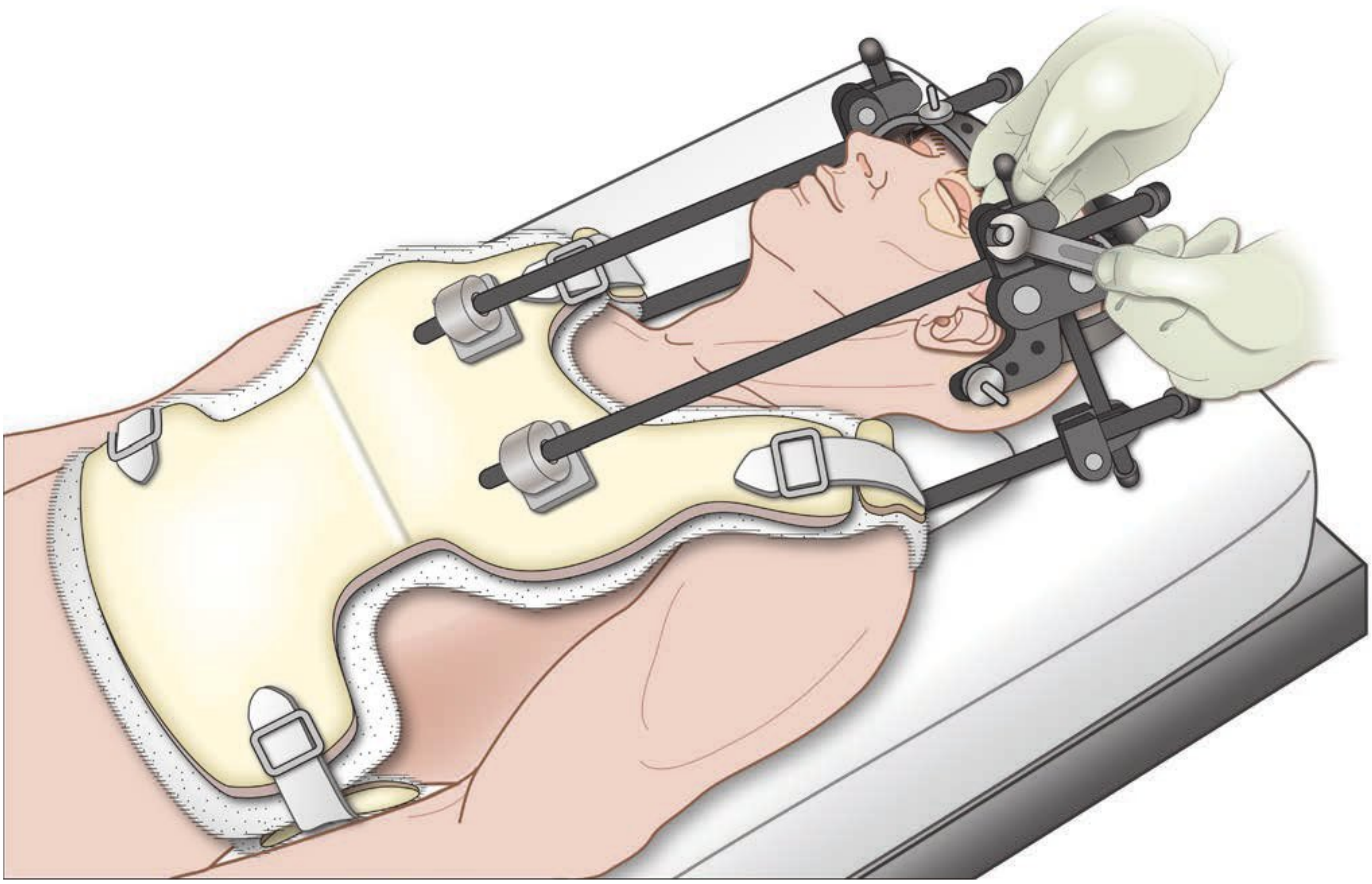

Figure	Procedural Steps	Pearls
Fig. 11.6	**Select correct vest size for the patient. Connect posterior ring to posterior vest with upright post.** **Connect anterior ring to anterior vest with upright posts. Connect anterior/posterior halves of vest to each other. Once in place, secure the ring to the posts at each point with torque wrench, maintaining head in correct alignment. Check post-placement X-rays immediately after placement and when upright day 1 and day 3.**	• Important note: Every brand and style of halo vest and head ring comes with a detailed set of instructions for application. It is recommended to review these instructions carefully prior to applying the apparatus • Incorrect sizing of vest can lead to loss of alignment. • If posterior vest has not be "preplaced," patient can be logrolled, or elevated 30 degrees while head held in gentle manual traction. • Tape wrench to anterior vest for easy access in emergency. • Watch for pressure ulcers at sites of excess pressure on shoulders, back, and chest.

Postoperative Imaging (Fig. 11.7)

Figure	Procedural Steps
Fig. 11.7	**Lateral radiograph of cervical spine after tongs traction in patient depicted in Fig. 11.1. Spinal alignment at C4-5 has improved after serial weights were applied, but the patient required open reduction and fixation.** **It is important to obtain imaging after halo or traction placement to verify alignment of the injured segment.**

Postoperative Management

Monitoring

- Monitor neurologic status and vital signs every 2 hours.
- Monitor for skin breakdown/decubitis ulcers.

Medication

- Pain management and muscle relaxation can be administered.

Radiographic Imaging

- Obtain lateral X-ray with any weight change, with any bed transfer, and once daily as routine.

Pin Site Management

- Gardner-Wells pins are checked at 24 and 48 hours to ensure that the spring-loaded force indicator is protruding. Halo pins are re-torqued to 8 in-lb once at 24 hours, and again at 48 hours. Additional tightening beyond this point can lead to skull penetration, skull fracture, pin loosening, and/or infection.
- Maintain twice-daily pin site cleaning with hydrogen peroxide or povidone iodine ointment.

Further Management

- After successful realignment, decide to brace, place in halo vest (see Fig. 11.6), or operate.
- After failed realignment, a decision to operate is usually made.

Special Considerations

Pediatric patients have special concerns regarding number of pins and pin torque pressures (see above). In patients with ankylosing spondylitis,[7,8] light cervical traction (, 5 or 10 lb) is advised. Prolonged traction with light weights may lead to desired correction with the goal of reducing the spine to the prefracture sagittal curvature. Over-distraction or correction with heavier weights quickly leads to uncontrolled re- or misalignment and neurologic injury.

For traction in patients with locked facets, apply gentle flexion force for bilateral locked facets, or flexion plus gentle rotation toward side of locked facet for unilateral locked facets. Incremental increases in weight can be applied until locked facets become perched. Once perched, slowly reducing weights to 5 to 10 lb while gently extending (by sliding in a shoulder roll) reduces the dislocation. Once reduced, maintain 5 to 10 lb weights for stabilization until definitive treatment (i.e., surgery) is accomplished.

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12 Emergency Management of Odontoid Fractures

Sanjay Yadla, Benjamin M. Zussman, and James S. Harrop

Introduction

The odontoid process, or dens, is the bony conical projection of the axis (C2), around which the ring-shaped atlas (C1) enables rotational movement of the head. Fractures of the odontoid process constitute approximately 15% of all cervical fractures. They are primarily caused by high-velocity trauma in the young and by falls in the elderly. Odontoid fractures may cause atlantoaxial instability, placing the spinal cord at risk for compressive injury. Fractures may result in progressive neurologic damage or fatality. The goal of treatment is to stabilize or immobilize the atlantoaxial joint and achieve solid fusion of the fractured dens.[1] Patients with acute odontoid fracture rarely present with severe neurologic injury but commonly complain of axial neck pain subsequent to trauma.

Although evidence-based management recommendations for odontoid fractures are lacking, patient outcomes for the most common conservative and surgical treatments have been reported.[1] This chapter discusses the emergency management of odontoid fractures with a specific focus on the most commonly performed treatments, including: (1) anterior fusion techniques (odontoid screw) and (2) posterior fusion techniques (C1-C2 transarticular screws; C1 lateral mass/C2 pars/C2 pedicle screws). Contraindications for odontoid screw placement include odontoid fractures with an anteriorly angled tip fragment, osteoporosis, transverse ligament disruption, or accompanying atlantoaxial fractures. Body build or inability to reduce the fracture can be prohibitive with this technique. In these cases, posterior atlantoaxial fusion may be warranted.

Indications

- Disruption of the transverse ligament causing atlantoaxial instability.
- Type II odontoid fractures with evidence of instability (i.e., greater than 6 mm of displacement).
- Movement at the fracture site in halo vest demonstrated on supine and upright X-rays.

Preprocedure Considerations

Radiographic Imaging

- Radiological studies—initial films should include anteroposterior, lateral, and open-mouth odontoid views.
- Computed tomography (CT) scans with reformatted images may be used to determine the type of odontoid fracture and may provide more detail of bony anatomy than plain films.
- Careful preoperative review of CT images with identification of fracture sites, bony anatomy, and vertebral artery course is necessary to determine whether instrumentation can be placed safely.
- The Anderson and D'Alonzo classification system, which classifies fracture types I, II, and III, is commonly applied (**Figs. 12.1** and **12.2**; **Table 12.1**).[2]

Medication

- Perioperative antibiotics are initiated and maintained for 24 hours after incision.

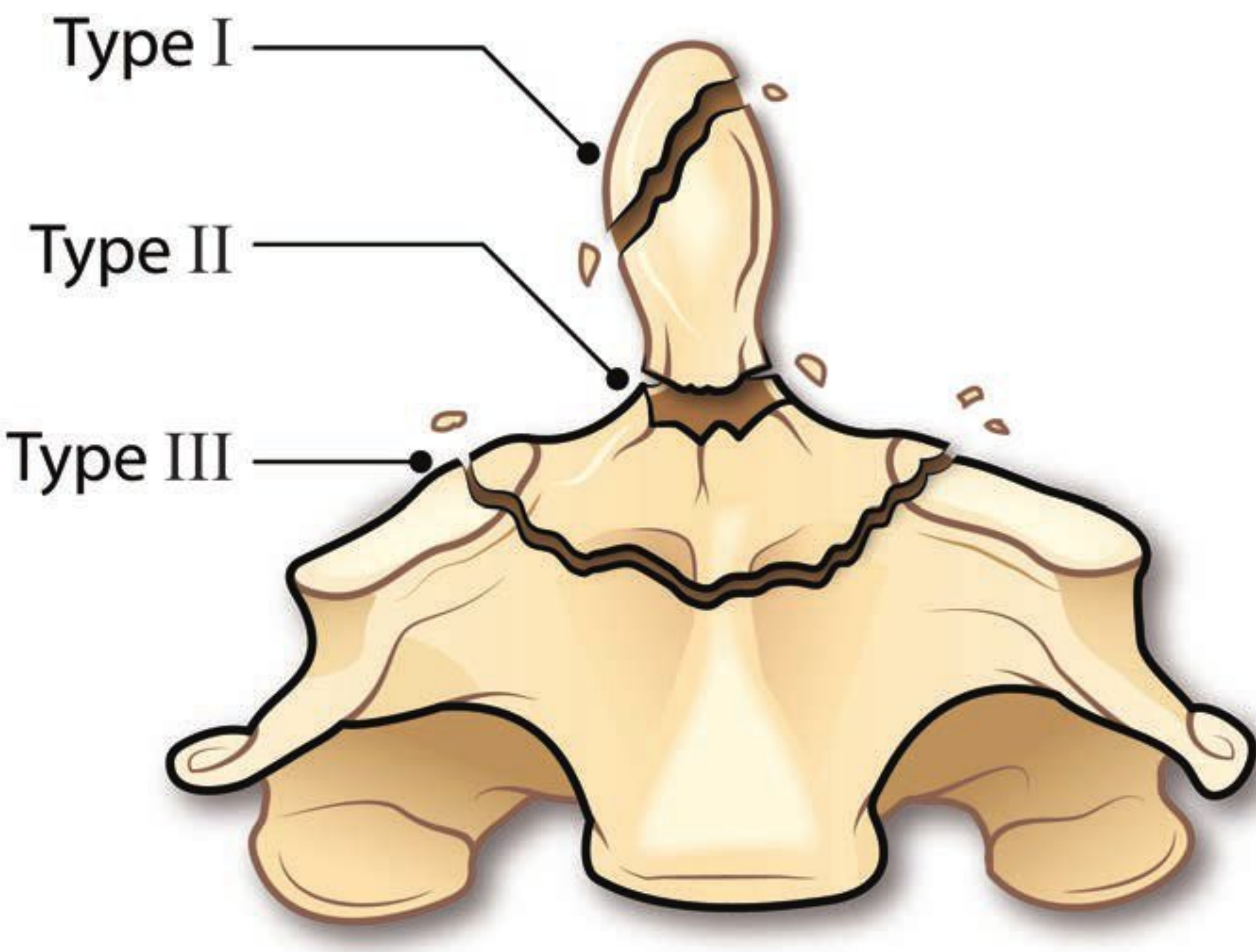
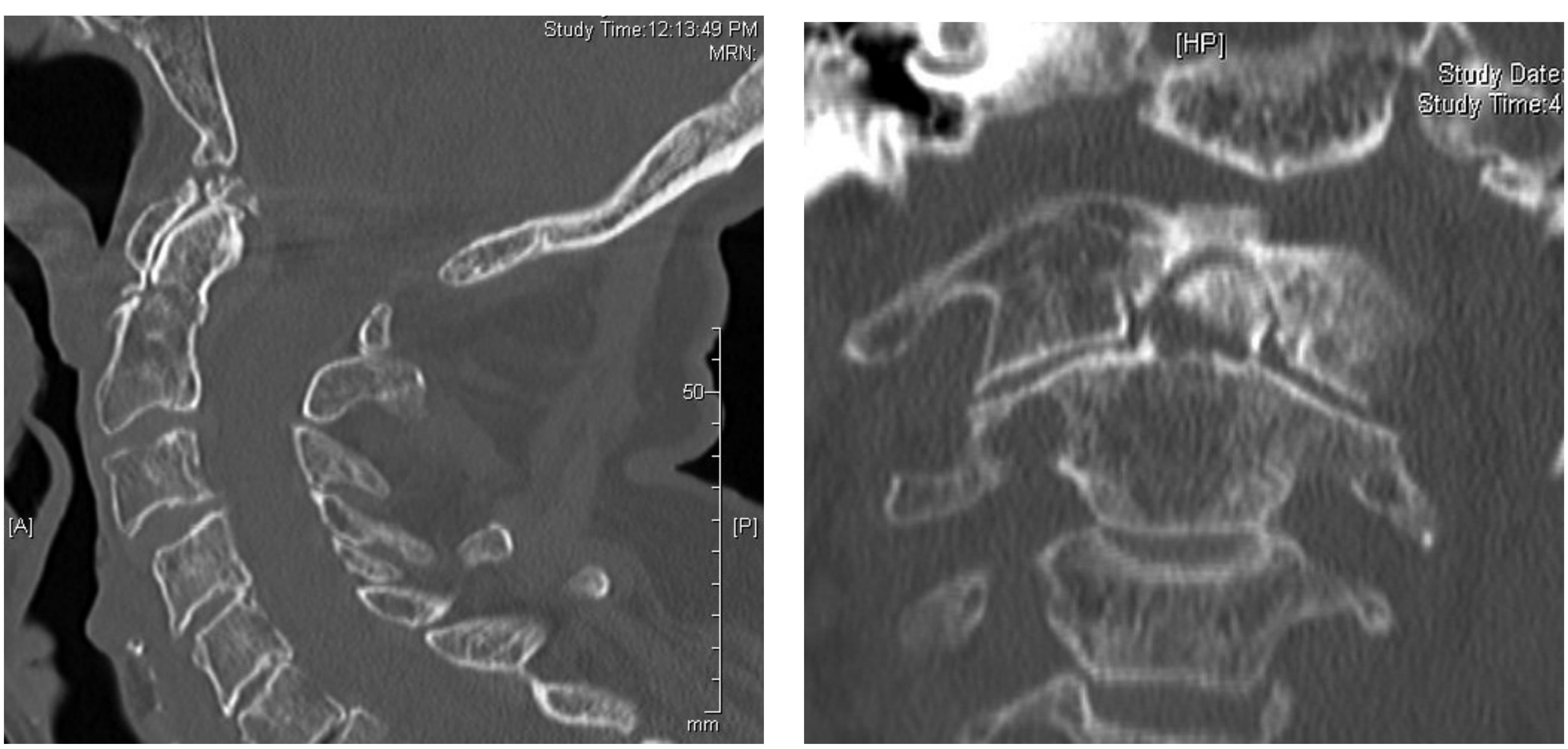


Fig. 12.1 Commonly applied classification of odontoid fractures.

Table 12.1 Documented treatment options for odontoid fractures

Type of odontoid fracture	Management		Reported fusion rates
Type 1	Conservative	External immobilization	100%
Type II	Conservative	External immobilization	55-65%
	Surgical	Anterior approach, odontoid screw	90%
		Posterior approach, atlantoaxial fusion or trans-articular screws	74-87%
Type III	Conservative	External immobilization	50-84%
	Surgical	Posterior approach, atlantoaxial fusion	100%



a b

Fig. 12.2a, b (**a**) Sagittal and (**b**) coronal preoperative CT images demonstrating a type II odontoid fracture.

Operative Procedure

Odontoid Screw

Positioning (Fig. 12.3)

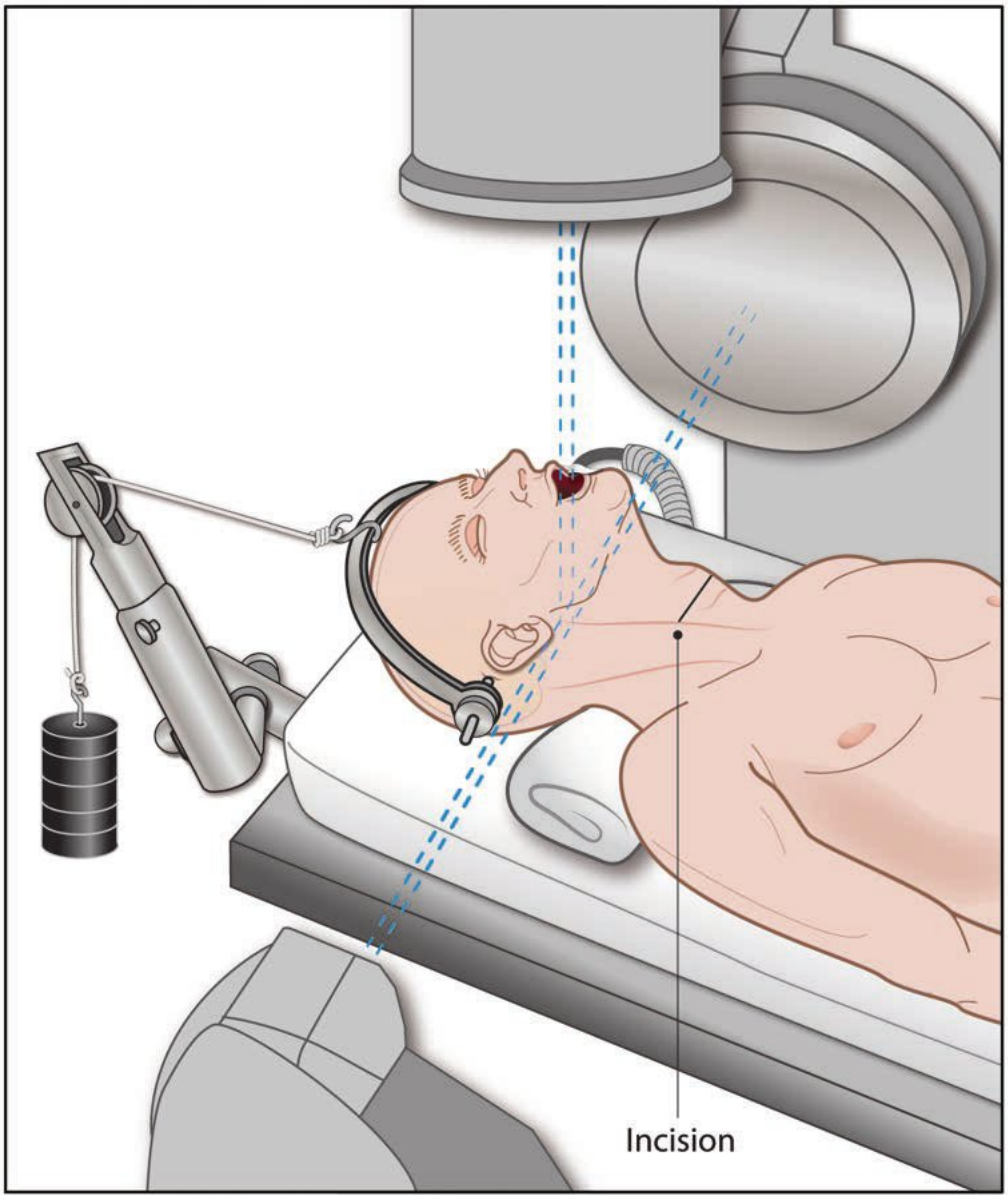
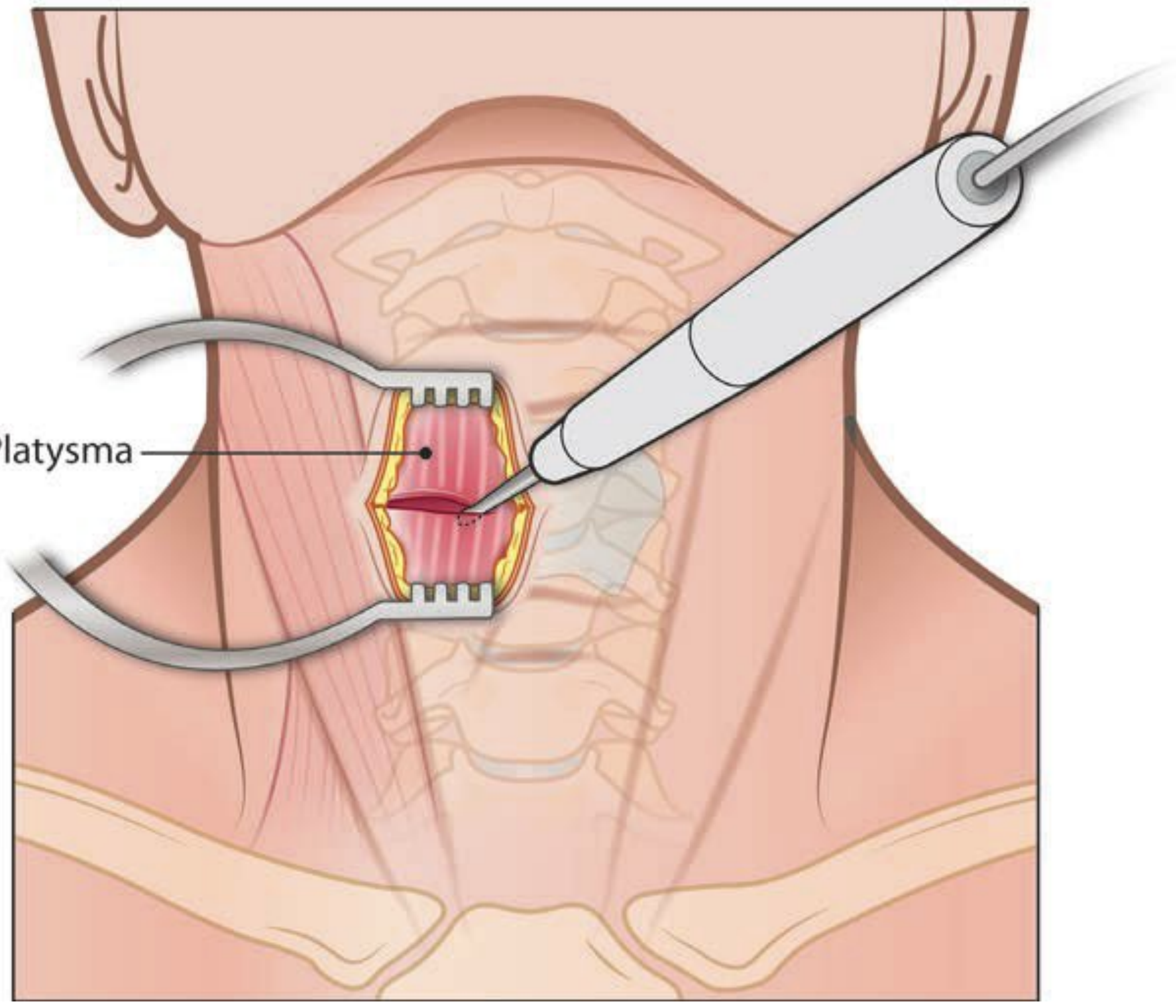
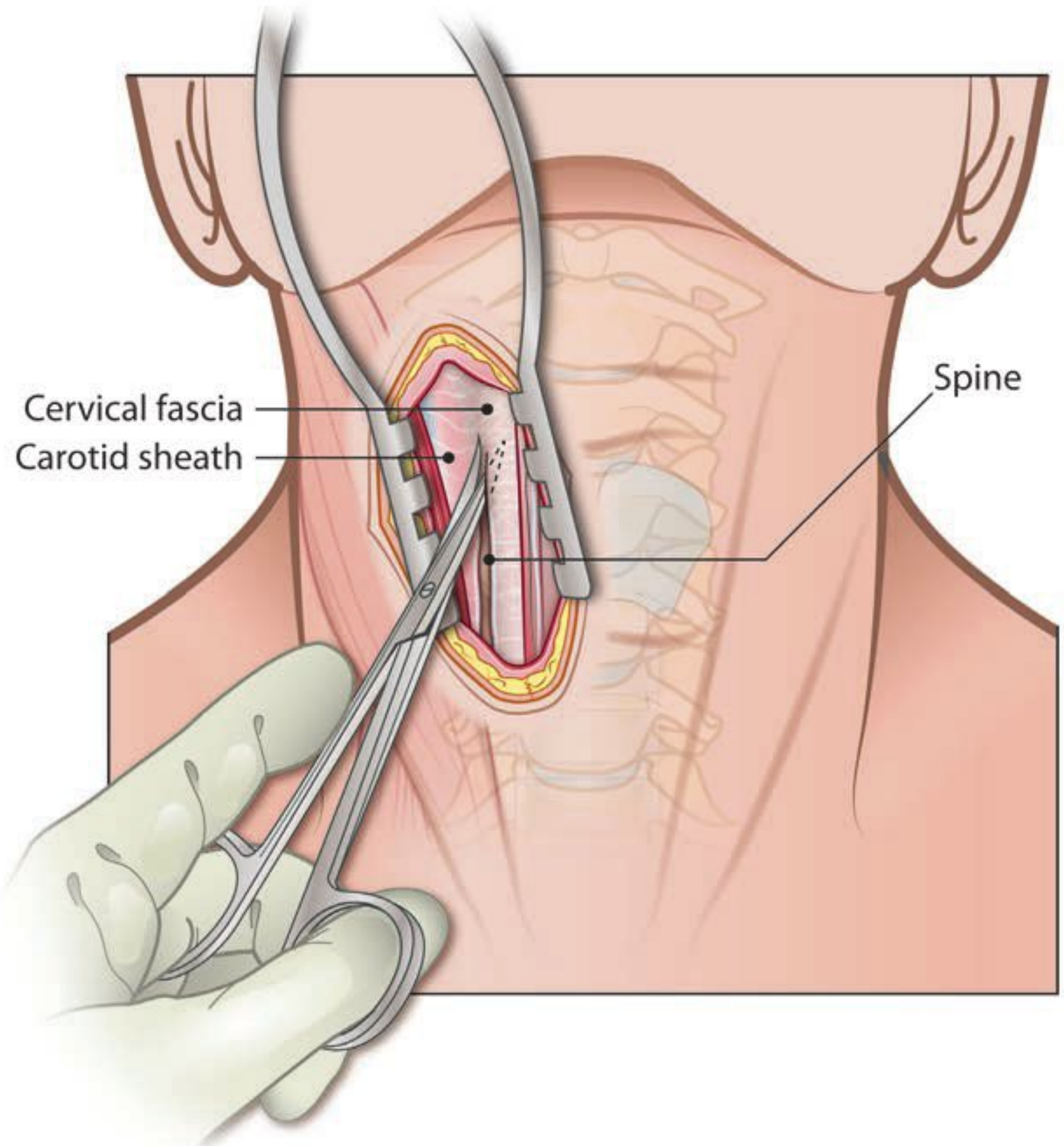


Figure	Procedural Steps	Pearls
Fig. 12.3	**The patient is positioned supine on the operating table with the head extended in traction. The patient is intubated. Biplanar fluoroscopy is used to monitor the head and dens during the procedure.**	• The anteroposterior (AP) view is obtained transorally using a C-arm fluoroscope, and a radiolucent prop may be used to open the mouth to improve AP visualization. The lateral view is obtained by a second C-arm fluoroscope, oriented horizontally. Using fluoroscopy as a guide, the head and neck are positioned to align the fracture edges. Finally, because blockage of screw insertion due to body obstruction (e.g., barrel chest) or body positioning (e.g., fixed cervical kyphosis) may limit this procedure, a Kirschner wire (K-wire) may be used to estimate screw/instrument trajectory and ensure that the patient's body will permit clearance during screw placement prior to incision.

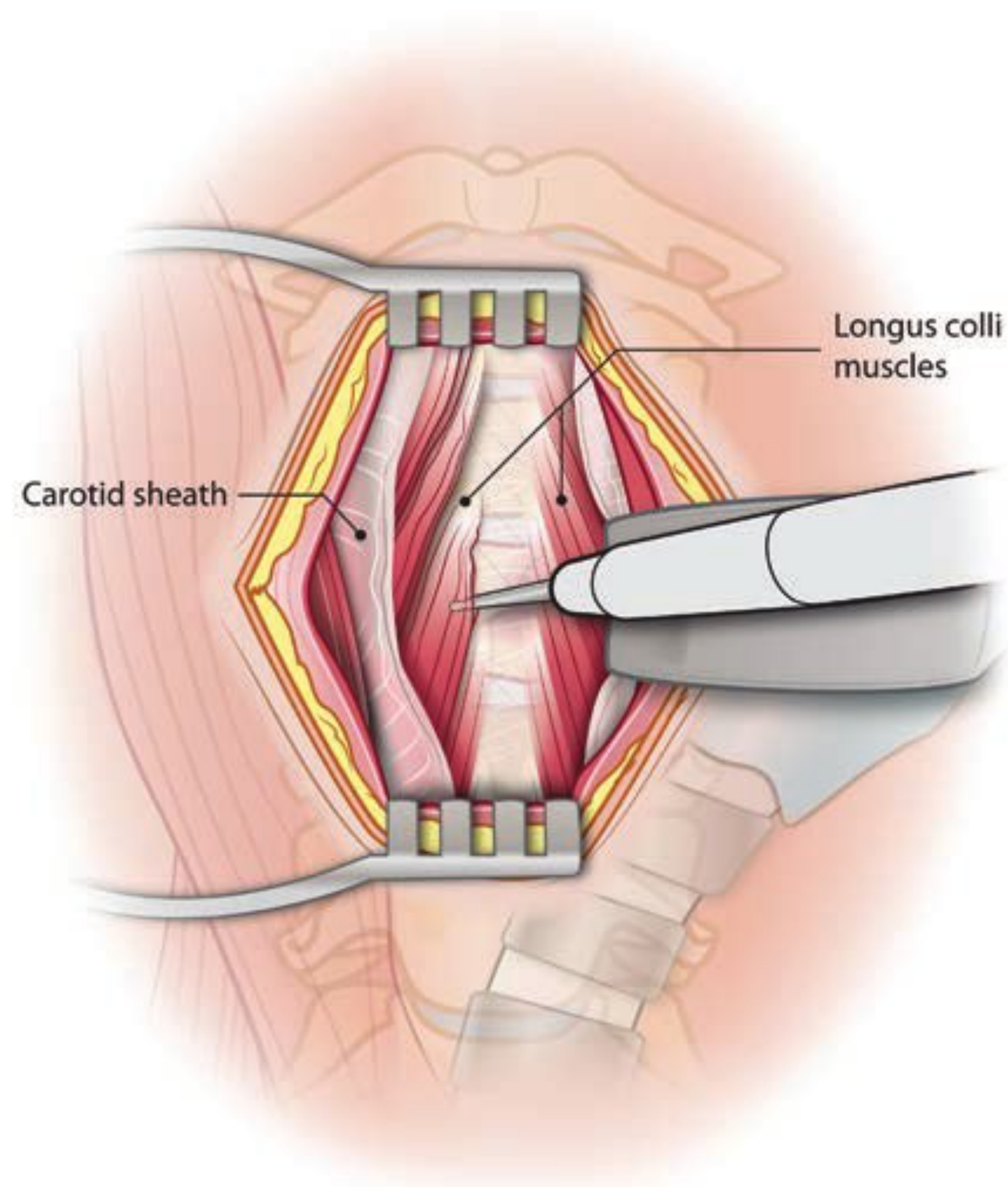
Cervical Dissection and Entry Site Preparation (Fig. 12.4a–e)



a



b



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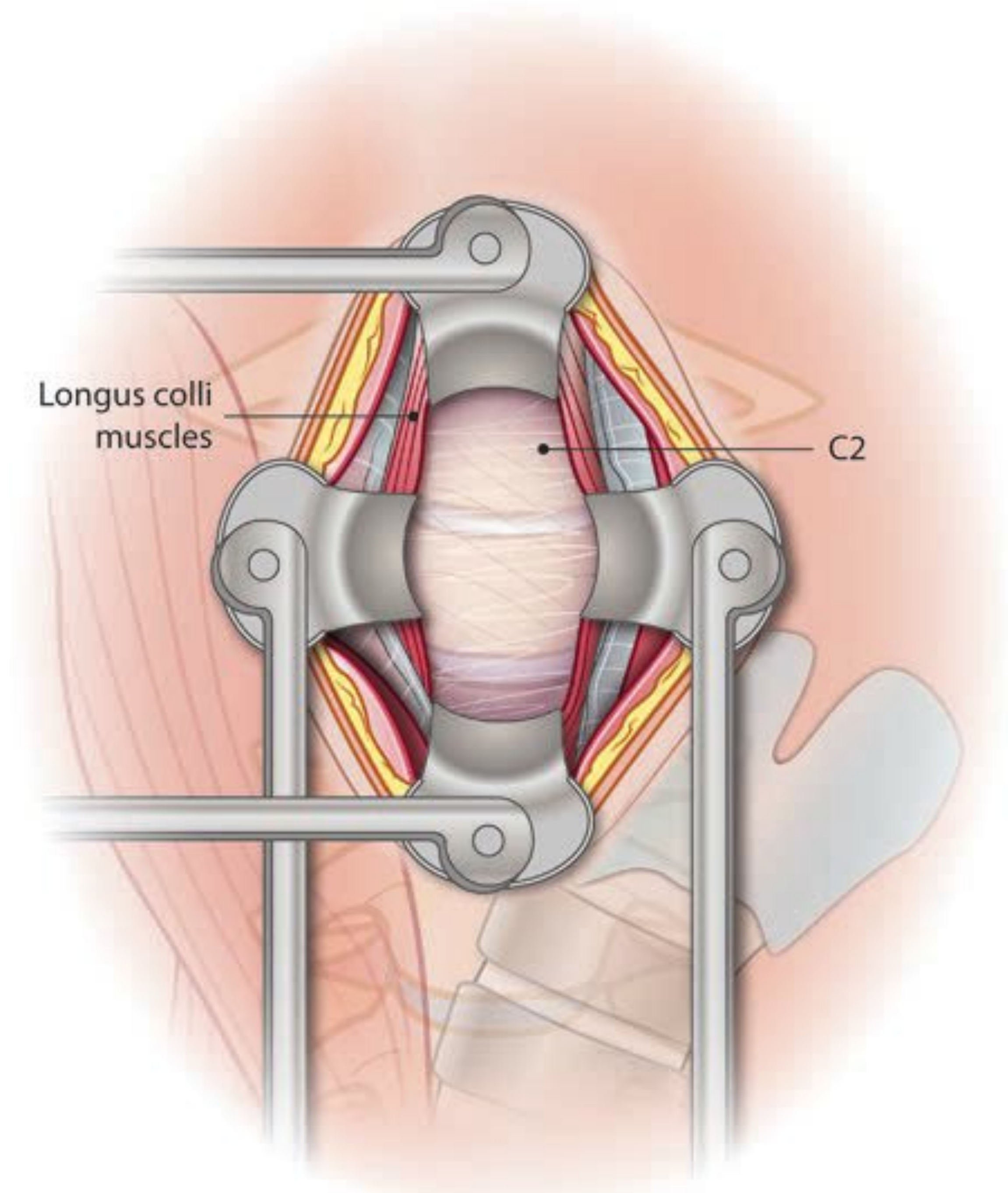

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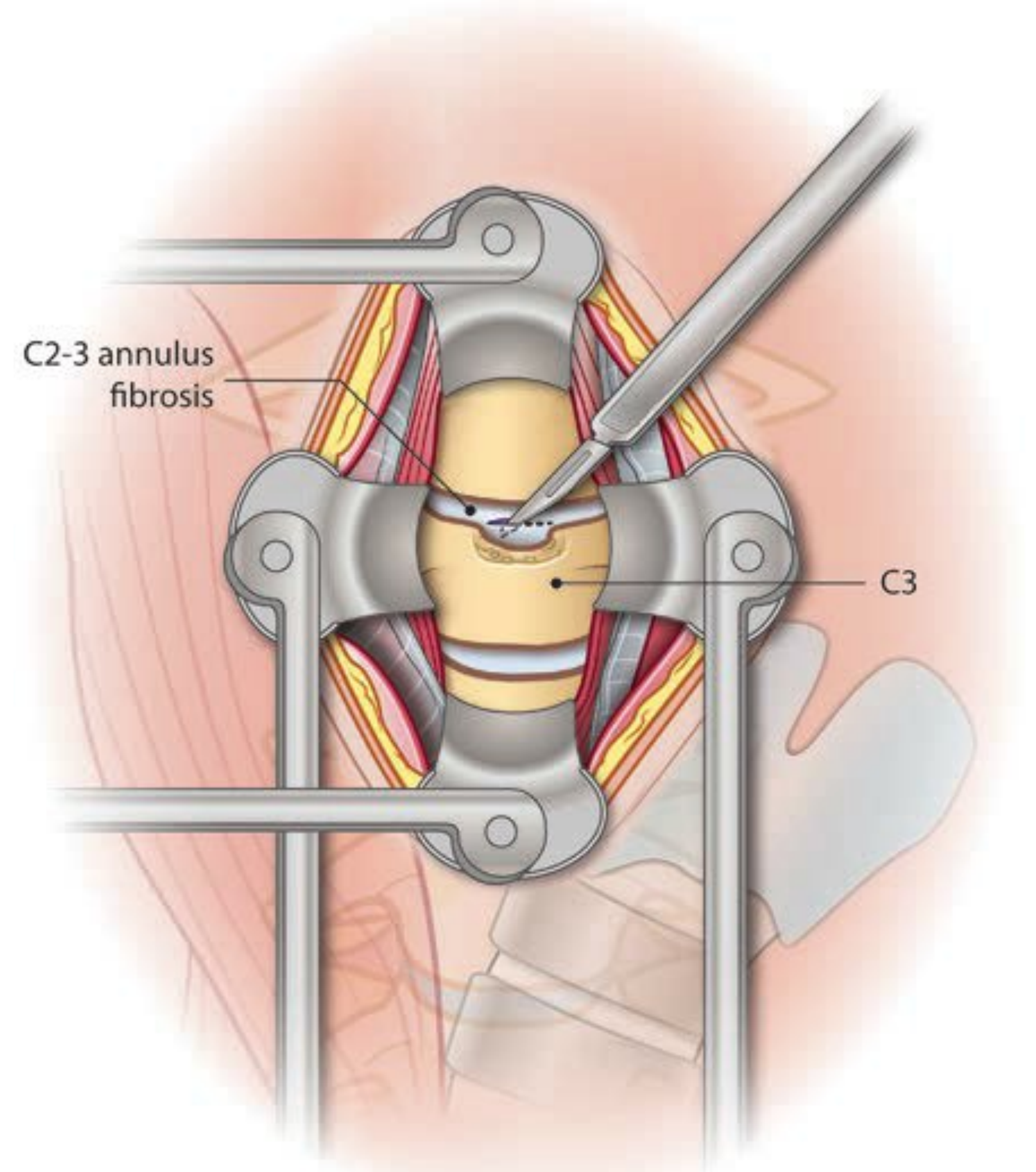
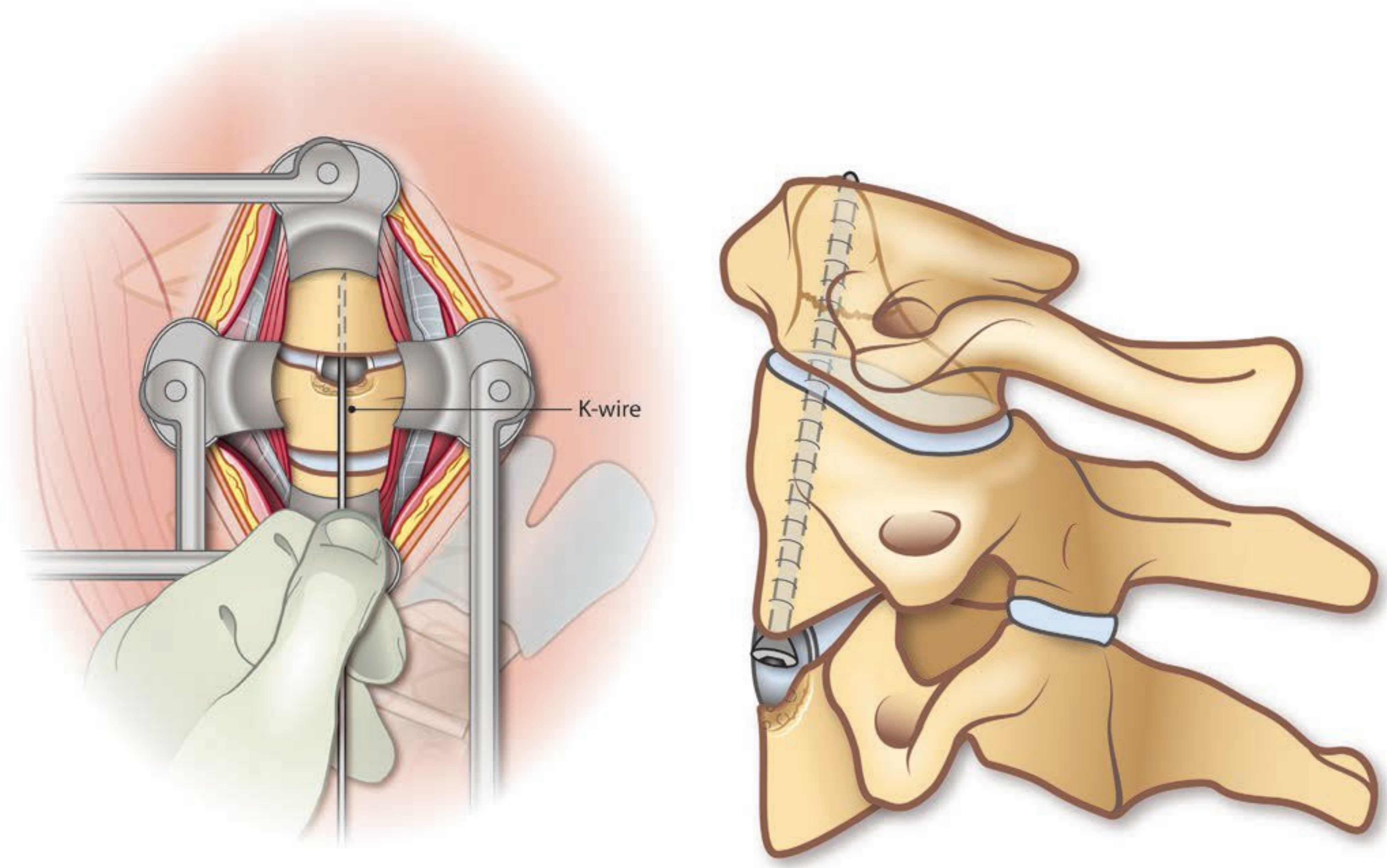


e

Figure	Procedural Steps	Pearls
Fig. 12.4	**(a) A transverse incision is made at approximately the C4-C5 level similar to an anterior cervical diskectomy. The platysma is incised. (b) Incision of the cervical fascia and plane is developed to the spine. (c) Dissection of the longus colli muscles. (d) Placement of radiolucent retractors. (e) The C3 body is notched and the C2-C3 ventral annulus fibrosis is incised.**	• The spine is approached anteriorly at the C4-C5 level using fine dissection between the midline structures and carotid sheath and then blunt dissection from the longus colli muscles to the vertebral bodies.[3] Radiolucent retractors are used to permit intraoperative fluoroscopy. To prepare the screw entry site, the C3 vertebral body is notched anterosuperiorly, and the C2-C3 ventral annulus fibrosis is incised.

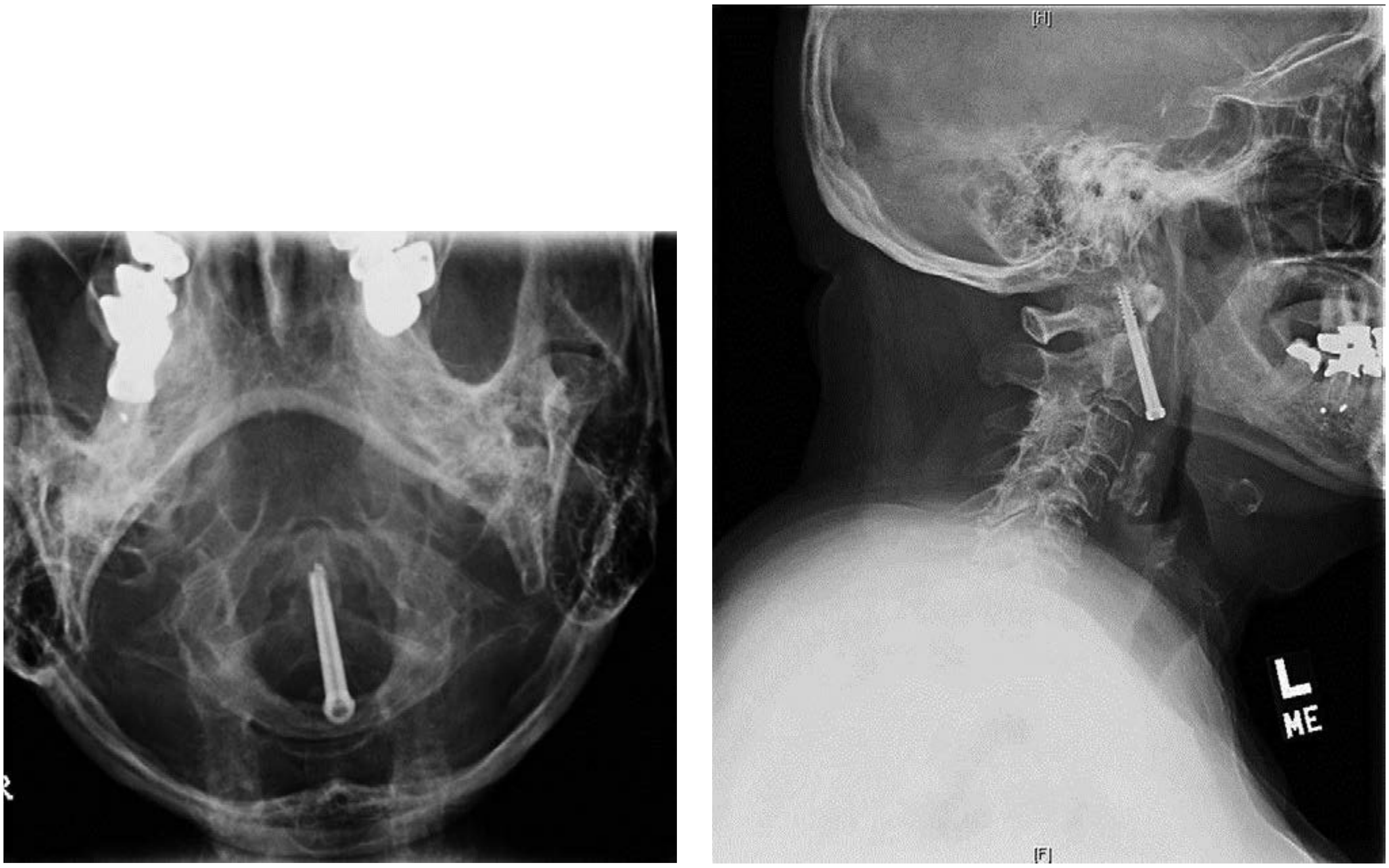
Screw Trajectory and Placement (Fig. 12.5a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 12.5	**(a) A K-wire is advanced through the C2 body to establish the trajectory.** **(b) A single lag screw is rostrally directed through the entry site, the C2 vertebral body, and the tip of the odontoid process. This compresses the two bony segments together, achieving rigid internal stabilization at the fracture site.**	• To establish the trajectory for screw placement, a drill or K-wire is advanced up through the C2 body into the midpoint of the odontoid fragment. Confirmatory visualization of this pilot trajectory is achieved with fluoroscopy. The drill is removed and a lag screw is advanced through the guide hole through the C2 body and through the bony cortex of the odontoid tip. Because the lag screw head is restrained by the C2 body, screw tightening pulls the odontoid fragment inferiorly, internally reducing the fracture.[3,4]

Completed Construct (Fig. 12.6a, b)

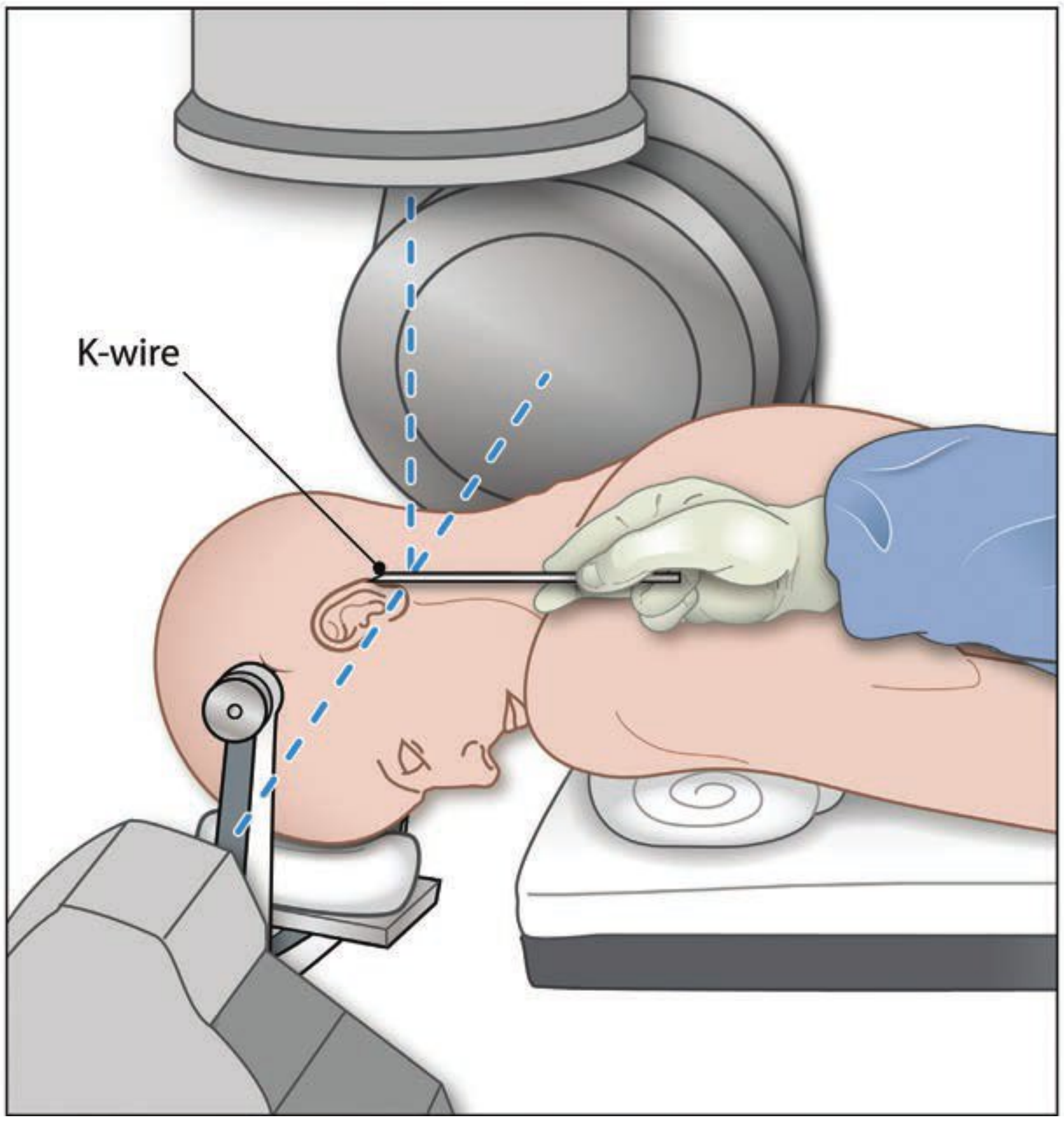


a b

Figure	Procedural Steps
Fig. 12.6	**(a) AP and (b) lateral X-ray images of final odontoid screw construct.**

C1-C2 Transarticular Screw (Magerl Technique)

Positioning (Fig. 12.7a, b)



a

b

Figure	Procedural Steps	Pearls
Fig. 12.7	**(a) The patient is positioned prone under general anesthesia with the neck flexed in the three-pinion head holder. (b) The screw trajectory is established with wire and fluoroscopy prior to prepping.**	• The operating table and room should be arranged to accommodate lateral fluoroscopy with a comfortable viewing angle for the operating surgeon. A three-pinion head holder is used to secure the head in the "military tuck" position, which will allow access to the atlantoaxial joint at the appropriate angle with surgical instruments. Lateral fluoroscopy can be used to confirm that no displacement has occurred and that the neck remains neutral after positioning. Screw entry sites and trajectories can be estimated using fluoroscopy at this point. In older patients with a pronounced thoracic kyphosis, an adequate trajectory may not be attainable.

Surgical Site Preparation (Fig. 12.8)

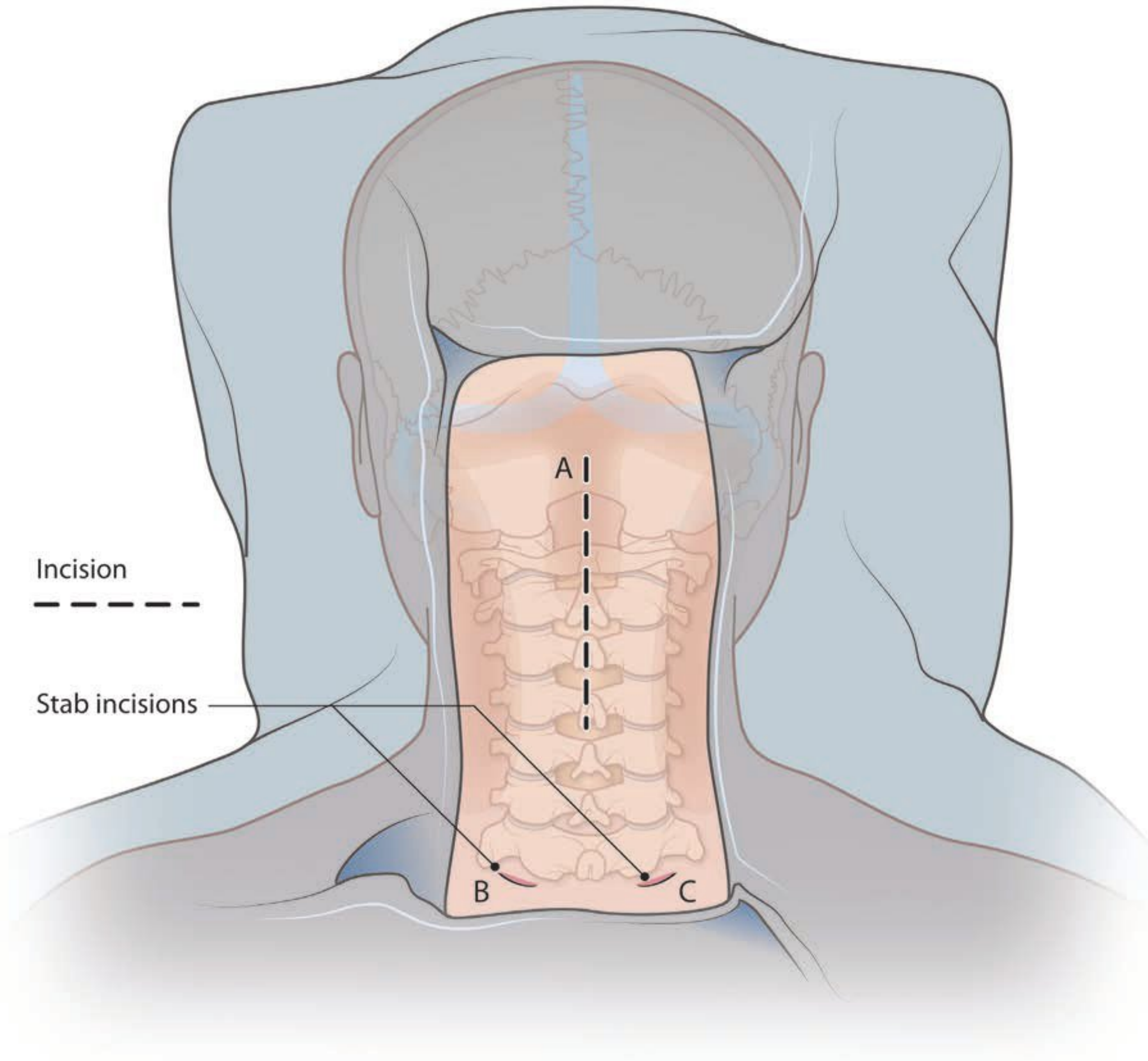
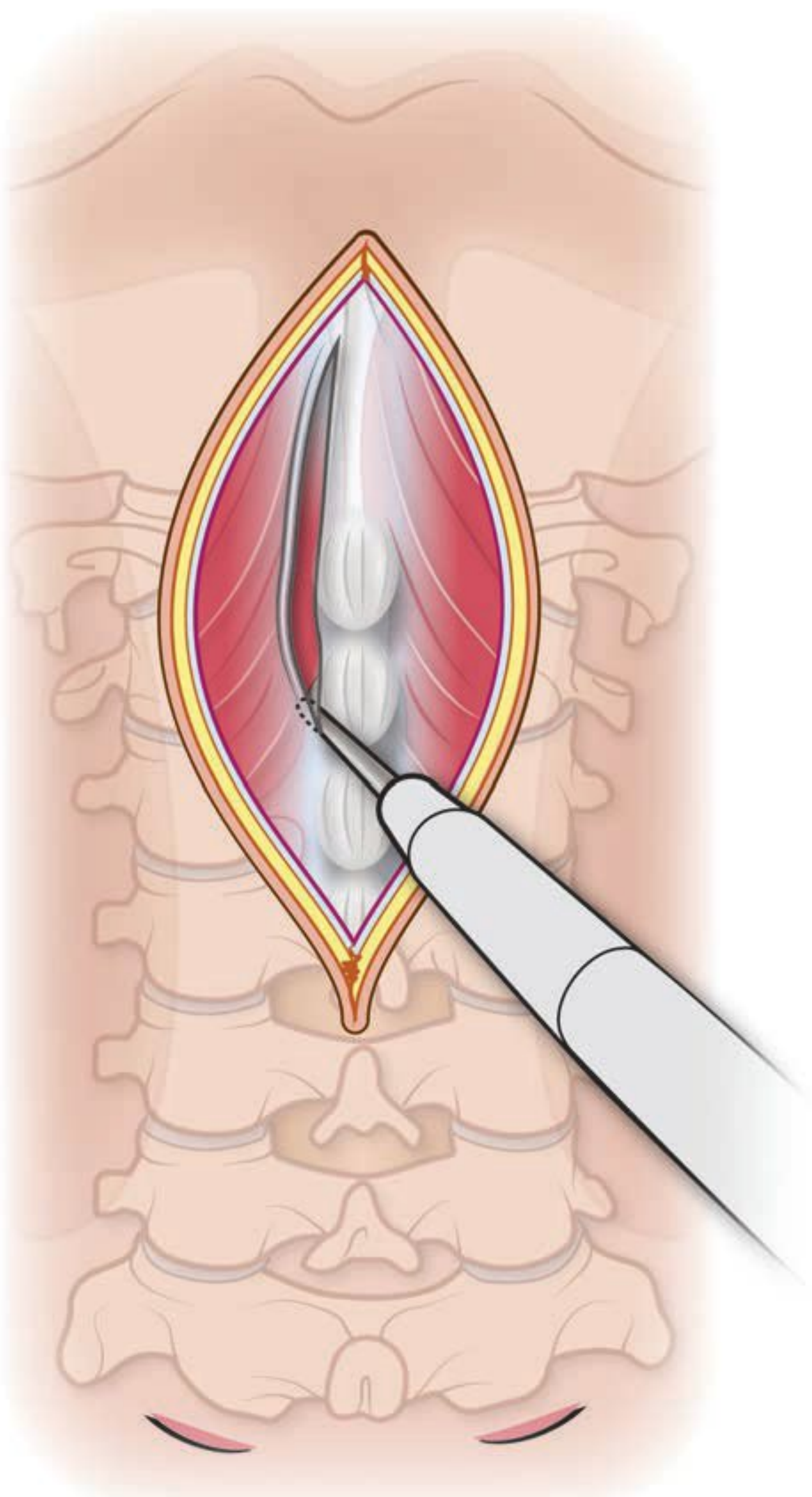


Figure	Procedural Steps	Pearls
Fig. 12.8	**The area is prepped and draped in a sterile fashion to include the cervical and midthoracic spine. Three separate incisions are made: (A) midline from occiput to C4; (B, C) two stab incisions are made at the C7-T1 level for screw-inserting instruments.**	• Three separate incisions are required: a midline incision from the occiput to C4 to expose the C1-C2 levels and two stab incisions at approximately the C7-T1 level for instrument access.

Tissue Dissection and Exposure (Fig. 12.9a, b)



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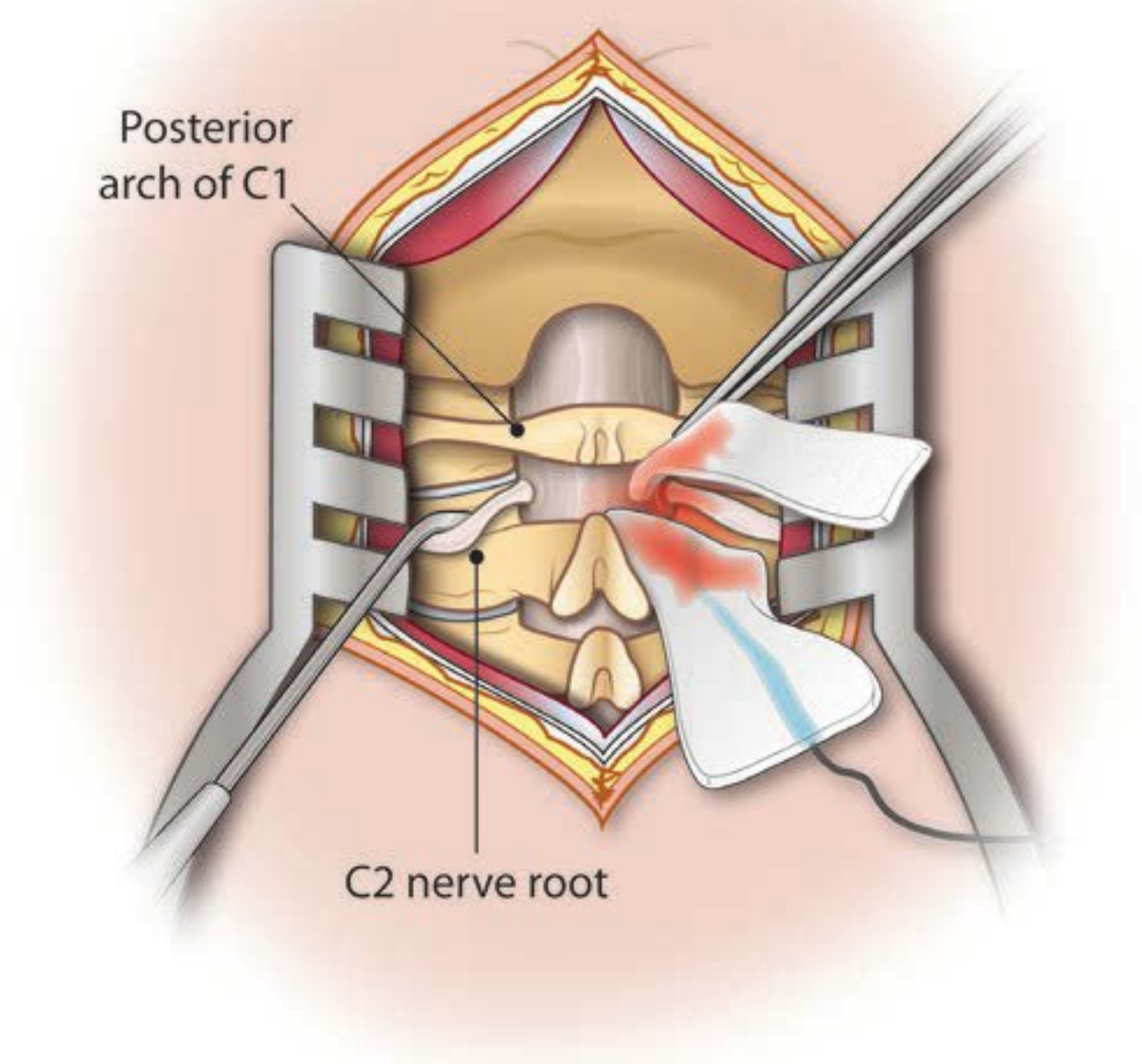
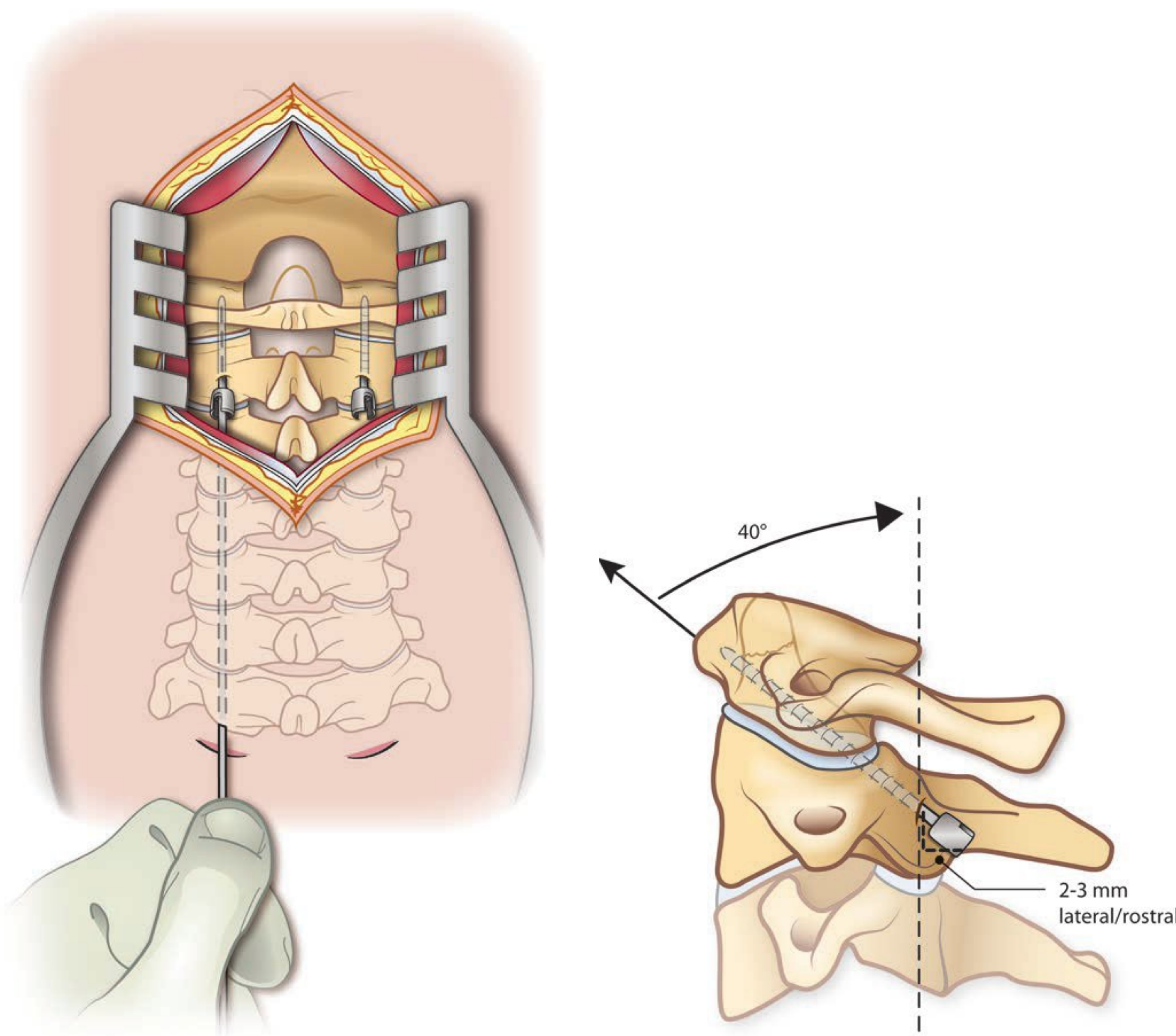


b

Figure	Procedural Steps	Pearls
Fig. 12.9	**(a) Tissue dissection is carried down through the midline along the relatively avascular midline raphe between the paraspinal muscles. The dissection is taken down to the spinous processes and articulating processes of C1 and C2. (b) Brisk venous bleeding may be encountered upon exposure of the C1 facet. This should be anticipated and can be controlled with a thrombin-soaked gelatin sponge. The exiting C2 nerve root is encountered between the posterior arch of C1 and lamina of C2. It can be protected by downward retraction using a Penfield no. 4.**	• A localizing X-ray or fluoroscopy can be used to confirm localization. The C2 spinous process is often bifid and more prominent than the C1 or C3 spinous processes. The C1 and C2 laminae are exposed by subperiosteal dissection with care taken to avoid disruption of the C2-C3 joint.

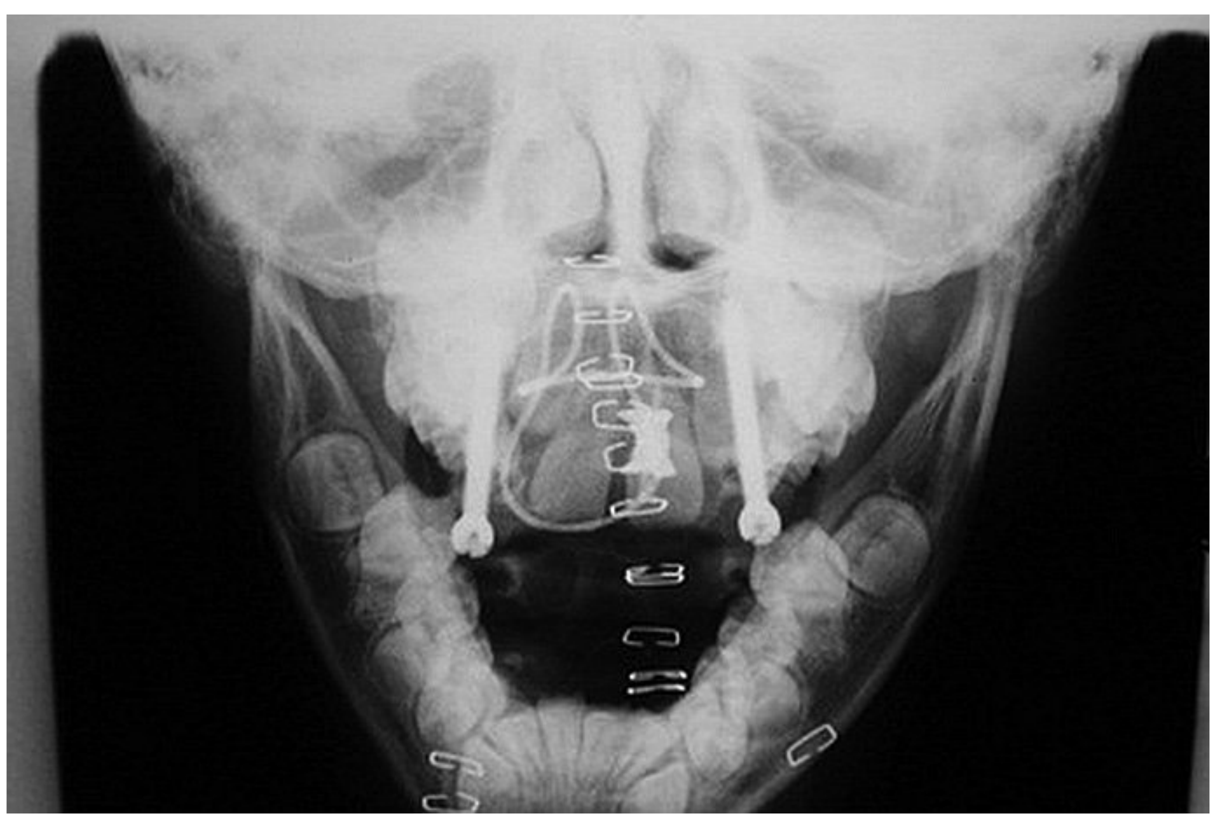
Screw Trajectory and Placement (Fig. 12.10a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 12.10	**(a) The screw entry point is typically 3 mm lateral and 3 mm superior to the inferomedial corner of the inferior articulating facet of C2. A K-wire is used to establish the trajectory followed by a cannulated screw, which is inserted over the K-wire. (b) The ideal trajectory (approximately 40 degrees superior to the entry site) ends at a point that overlies the shadow of the anterior C1 tubercle on lateral fluoroscopy. A cannulated bit is passed over the K-wire to create a pilot hole, which is tapped, and a 3.5- or 4-mm cannulated cortical screw is then advanced to the ideal target.[5]**	• A K-wire is advanced through the stab incision and ideal screw entry point, down the pars of C2, and across the C1-C2 joint under fluoroscopic guidance. The K-wire is advanced to a point 4 mm shallow to the ideal target. The operating surgeon must be aware of the position of the K-wire at all times during its use to avoid inadvertent advancement into vital structures.

Completed Construct (Fig. 12.11)



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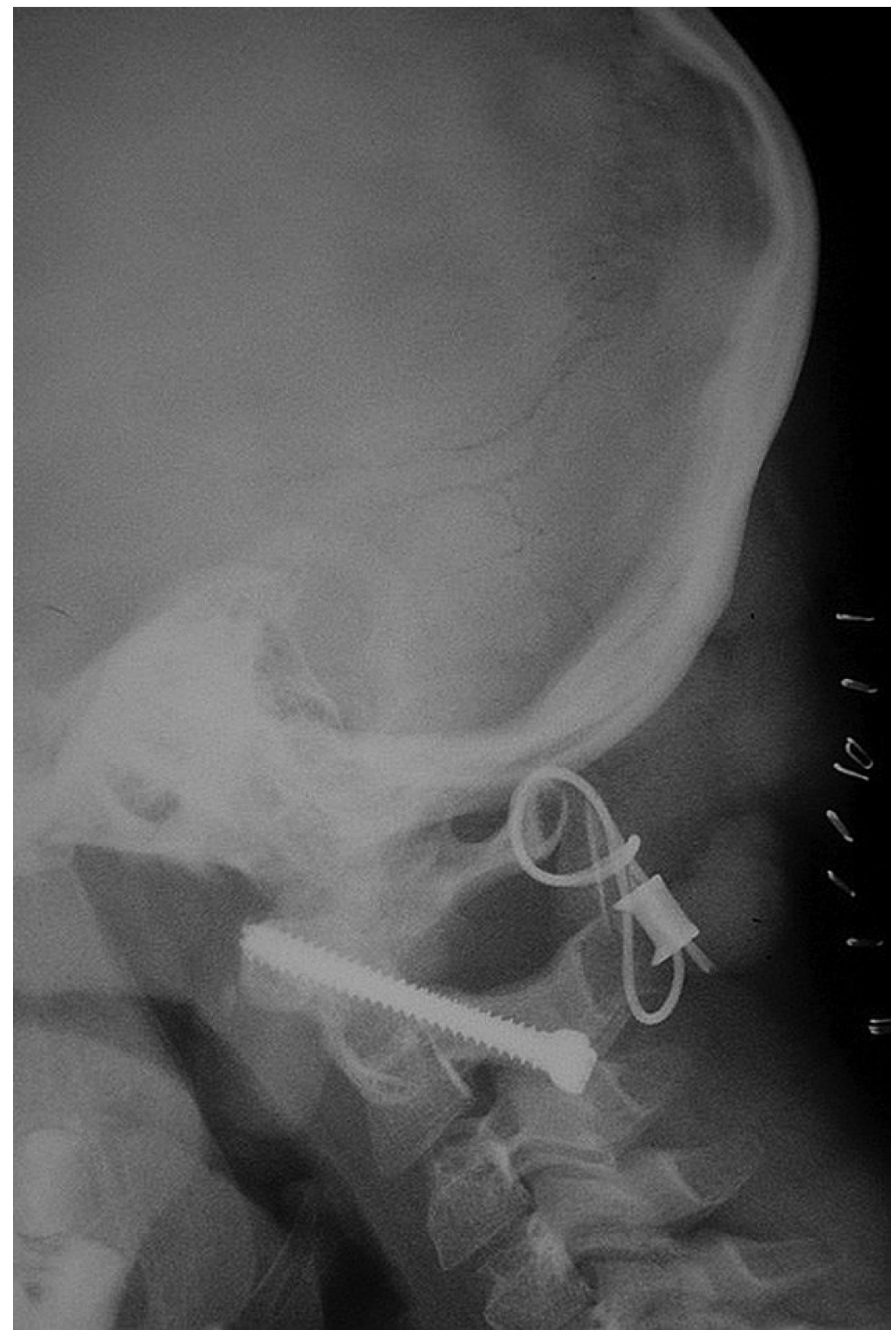


b

Figure	Procedural Steps
Fig. 12.11	**(a) AP and (b) lateral radiographs of C1-C2 transarticular screw placement.**

C1-C2 Lateral Mass Fusion with Polyaxial Screws and Rods

Positioning and Surgical Site Preparation (Fig. 12.12)

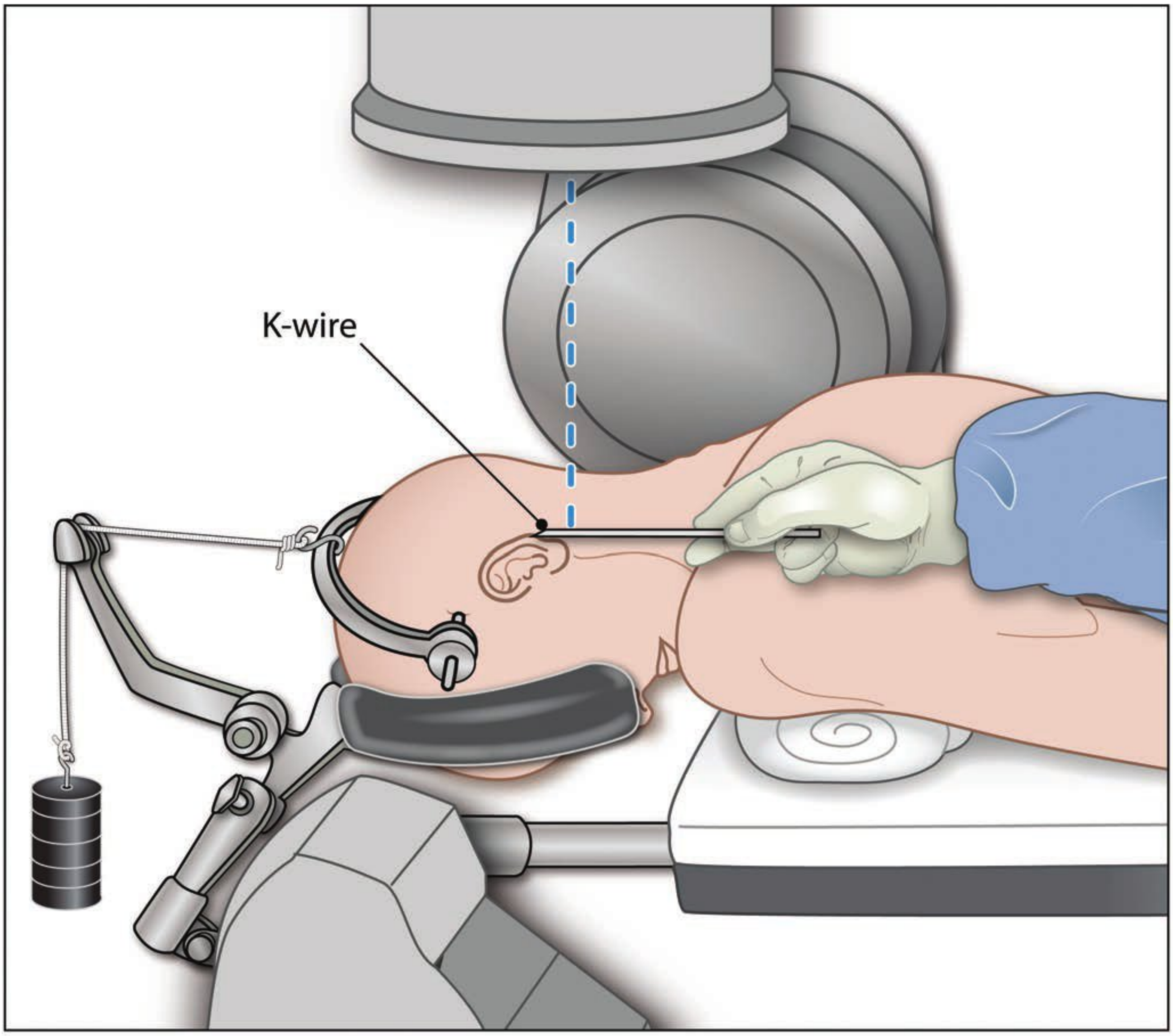


Figure	Procedural Steps	Pearls
Fig. 12.12	**The patient is positioned prone under general anesthesia under cervical traction with skull tongs. The incision is marked from occiput to C4. After prepping, a midline incision is made. Soft tissue dissection is conducted with monopolar cautery along the midline. A relatively avascular plane can be found in the midline raphe between the paraspinal muscles (see Fig. 12.9a).**	• Intraoperative X-ray or fluoroscopy is used to check alignment after positioning. A three-pinion head holder could also be used in lieu of traction.

Tissue Dissection and Exposure (Fig. 12.13)

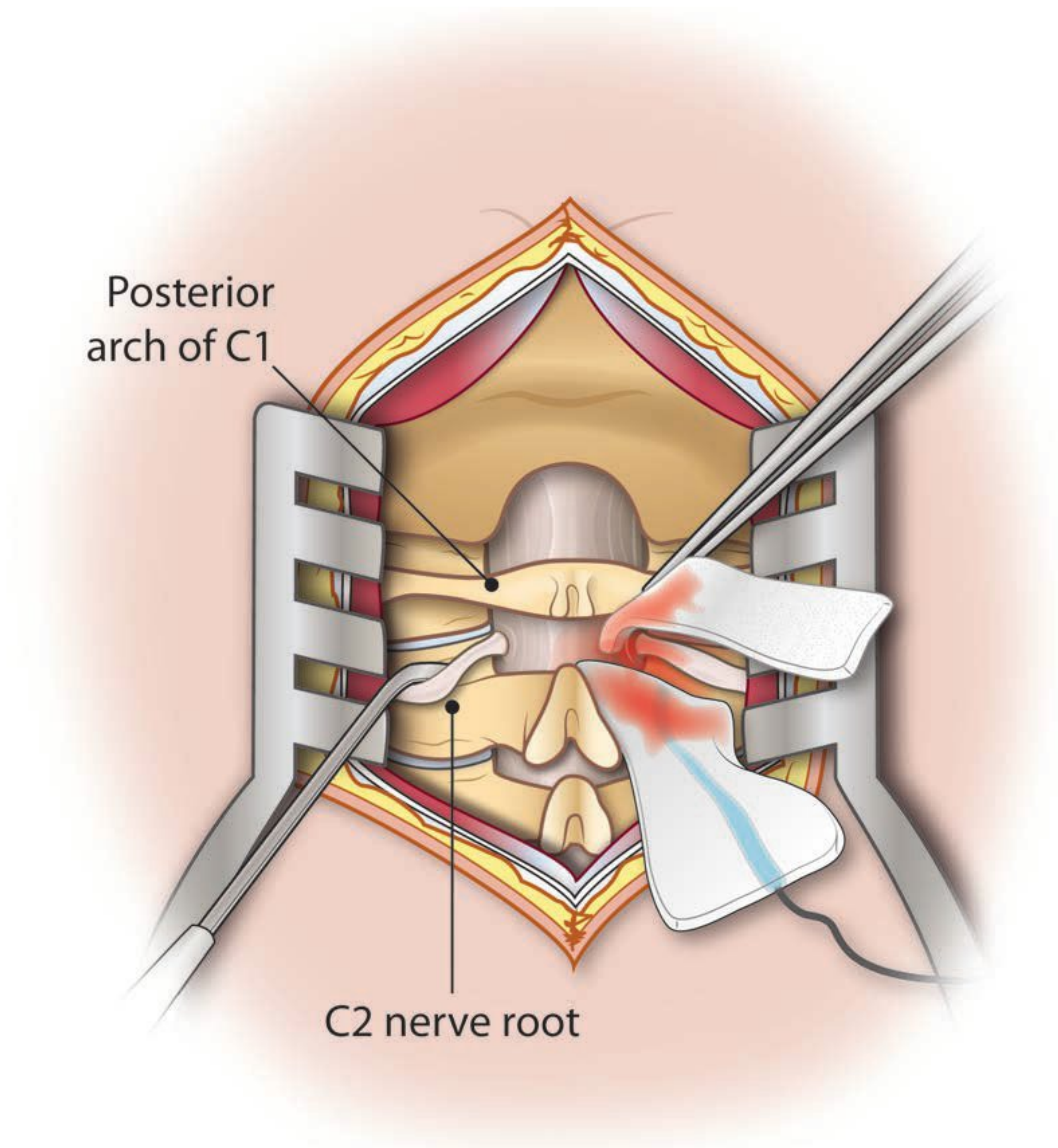


Figure	Procedural Steps	Pearls
Fig. 12.13	**The dissection is taken down to the spinous processes and then to the lamina. Dissection along the inferior border of C1 lamina is performed to expose the C1 lateral mass. Epidural venous bleeding is controlled with gelatin sponge and cotton pledgets.**	• A localizing X-ray or fluoroscopy can be used to confirm localization. The C2 spinous process is often bifid and more prominent than the C1 or C3 spinous processes. The C1 and C2 vertebrae are exposed by subperiosteal dissection. Bleeding from the epidural venous plexus is typically encountered during dissection of the C1-C2 joint. It is usually controlled with a combination of bipolar electrocautery, gelatin sponge, and cotton pledgets.[6] The lateral and medial borders of the C1 lateral mass are identified for accurate placement of the C1 lateral mass screw. The C2 dorsal root ganglia can be retracted caudally to clearly view the C1 lateral mass.

C1 Screw Trajectory and Placement (Fig. 12.14)

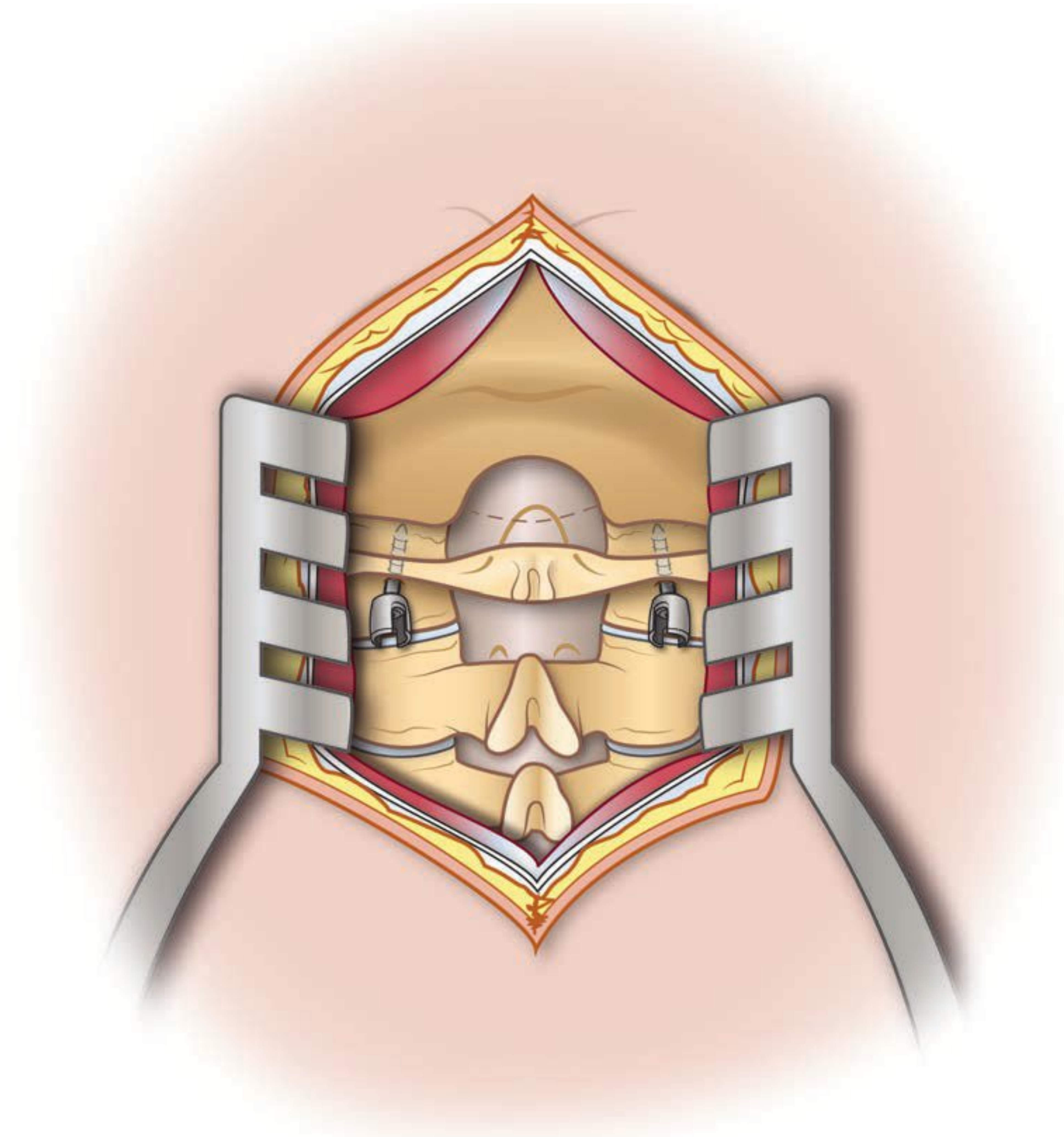


Figure	Procedural Steps	Pearls
Fig. 12.14	**The ideal screw entry point for the C1 screw is at the middle of the C1 lateral mass in the lateral-medial direction and at the midpoint between the inferior border of the C1 lateral mass and the junction of the posterior arch to the C1 lateral mass in the craniocaudal direction.**	• The ideal screw trajectory is 10 degrees medial and 10 degrees superior (in the direction of the anterior C1 tubercle) to the entry point. The hole is tapped and a 3.5-mm screw is inserted. The screw length should be estimated on preoperative imaging so that the screw head sits beyond the posterior arch of C1 (typically 30–35 mm). • Harms and Melcher popularized this C1-lateral mass and C2-pedicle screw construct. It can also be easily modified to accommodate a C2-pars interarticularis screw depending on patient anatomy. As with the transarticular approach, careful preoperative review of CT scans with identification of fracture sites, bony anatomy, and vertebral artery course is necessary to determine whether screws can be placed safely.

C2 Screw Placement and Trajectory (Fig. 12.15)

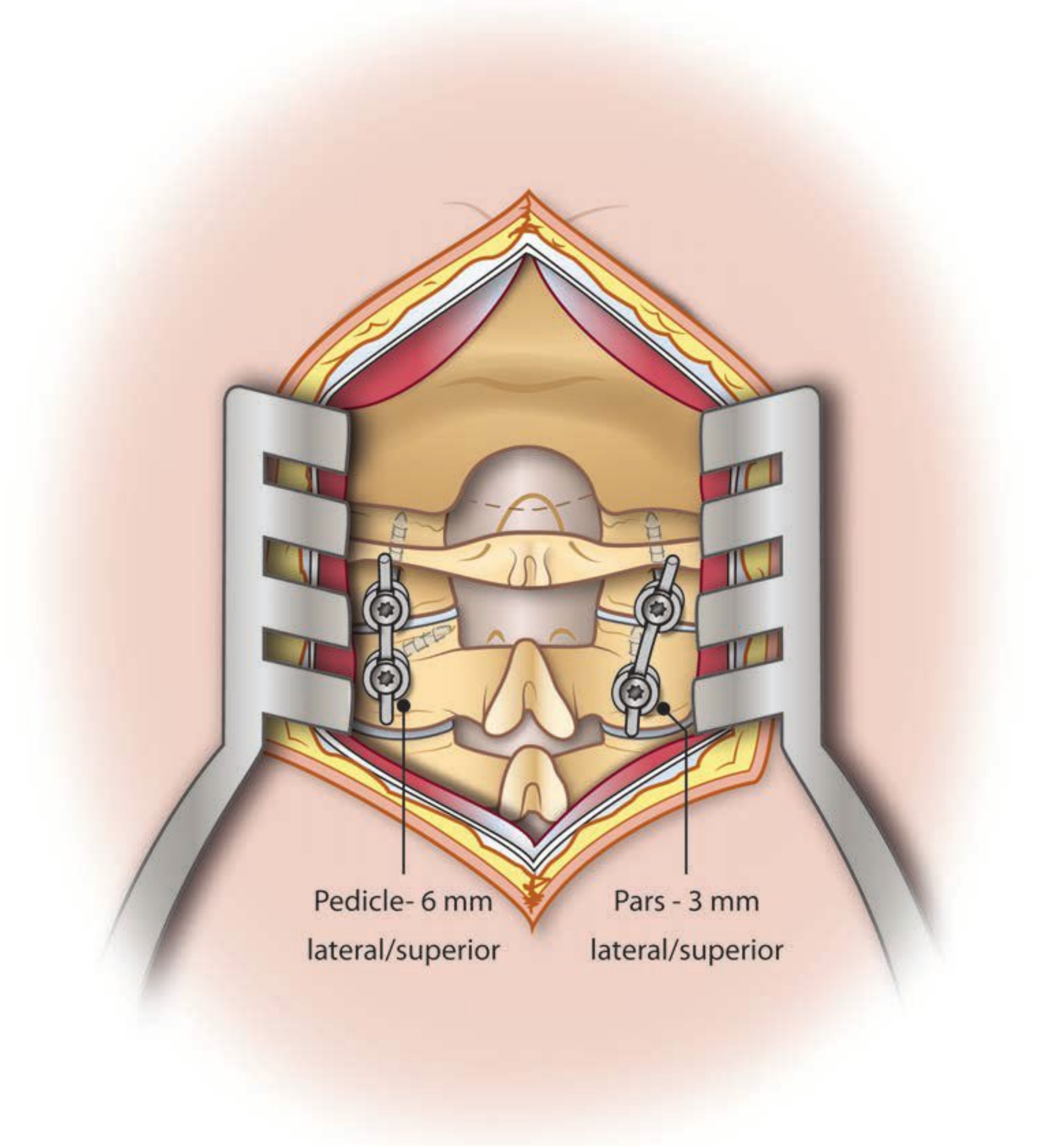
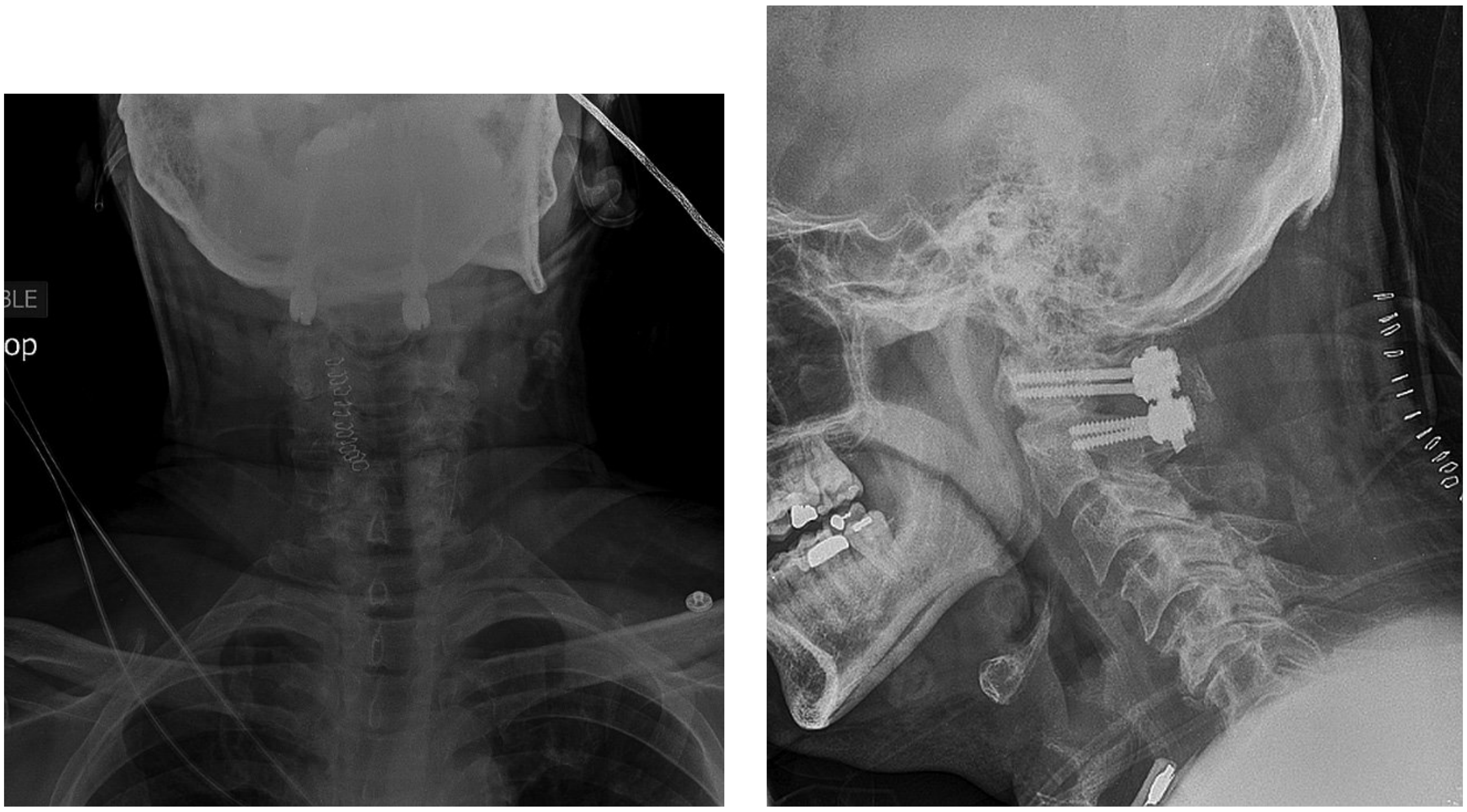


Figure	Procedural Steps	Pearls
Fig. 12.15	**C2 fixation can be achieved with either a pars interarticularis or pedicle screw. (right side) The ideal entry point for a C2 pars screw is 3 mm lateral and 3 mm superior to the inferomedial corner of the C2 inferior articulating facet, similar to the C1-C2 transarticular screw. The pars screw should be aimed at a point in line with the middle of the C1 lateral mass in the lateral-medial direction and 40 degrees cranial to the entry site in the craniocaudal direction. (left side) The ideal entry site for a pedicle screw is 6 mm lateral and 6 mm superior to the inferomedial corner of the C2 inferior articulating facet. The ideal trajectory for the pedicle screw is 20 degrees medial and 20 degrees cranial from this point. The screw length should be measured on preoperative CT. The pilot hole should be tested with a ball-tip probe prior to tapping and placement of a 3.5-mm polyaxial screw.**	• The limitations of transarticular screw placement and the advent of polyaxial head screws contributed to the development of further C1-C2 fusion methods. In 2001, Harms and Melcher popularized this novel technique of C1-C2 polyaxial screw-and-rod fixation that minimizes risk to the vertebral artery, allows for intraoperative reduction of the atlantoaxial joint, and eliminates the need for supplemental bone wiring.[6] The relative technical ease and improved risk profile of this technique has made it the predominant method of posterior atlantoaxial fusion at the authors' institution.[7]

Completed Construct (Fig. 12.16)



a b

Figure	Procedural Steps
Fig. 12.16	**(a) AP and (b) lateral radiographs of final C1-C2 fixation.**

Closing

- The wound is heavily irrigated.
- An optional subcutaneous drain may be placed.
- For anterior procedures, the platysma is reapproximated using 3-0 absorbable sutures in an interrupted fashion.
- The paraspinal muscles and overlying fascia are approximated using 1-0 absorbable sutures in an interrupted fashion.
- The subcutaneous tissues are approximated using 3-0 absorbable sutures in an interrupted fashion.
- The wound is closed using 3-0 monofilament nylon suture in a running fashion.

Postoperative Management

Monitoring

- It is the senior author's (JSH) practice to place the patient in a monitored setting overnight.

Medication

- Perioperative antibiotics are maintained for 24 hours after incision.

Further Management

- Drains are removed on postoperative day 1 or 2.
- Skin sutures are removed after 2 weeks.
- For posterior procedures, patients are typically kept in a rigid cervical collar for 6 to 12 weeks after the procedure, at which point X-rays are taken to assess fusion.
- For anterior procedures, a formal swallow evaluation may be required prior to starting a diet because of the high incidence of postoperative dysphagia, particularly in elderly patients.

Special Considerations

The senior author (JSH) prefers not to use additional bone wiring techniques though several have been described. A posterior bone wiring technique is often performed to provide three-point fixation. The C1-C2 transarticular screw, as initially described by Magerl in 1987, was the first major advance from bone wiring techniques.[8] Using this technique, immediate three-dimensional unisegmental fusion can be achieved and, when performed in combination with bone wiring techniques, the use of external immobilization (e.g., halo vest) is not necessary. One advantage of this technique is that it eliminates rotational motion at C1-C2, which increases the chance of bony fusion. However, its popularity has been limited by its relative technical complexity and associated risks such as hypoglossal nerve and vertebral artery injuries.[5]

The basic principles of multisystem trauma management should not be foregone in the setting of spinal cord injury (SCI). The ABCs (airway, breathing, circulation) should be monitored and treated appropriately. SCI patients may present with other life threatening injuries that make operative intervention for atlantoaxial instability unsafe in the acute setting. If the fracture can be reduced and the patient does not have a progressive neurologic deficit then the patient can be immobilized in a rigid cervical collar, halo vest, or traction until concurrent injuries are stabilized. In the authors' experience, patients with high cervical injuries are best monitored in the intensive care unit until definitive treatment.

There are no standards regarding the ideal timing of surgical intervention. In the only published randomized trial on this topic (for spinal cord injury patients), Vaccaro et al found no difference in length of intensive care unit stay, length of inpatient rehabilitation, or American Spinal Injury Association (ASIA) score improvement between early (, 72 hours from injury) and late (. 5 days from injury) surgical intervention in 123 patients with C3 to T1 injuries.[9] In a recent Cochrane Database systematic review, Bagnall et al found insufficient evidence to establish recommendations on timing of surgery.[10] Early evidence from the Surgical Treatment for Acute Spinal Cord Injury Study (STASCIS), a multi-institutional randomized trial of early (, 24 hours) versus late surgery for isolated cervical SCI, suggests that early decompression may be associated with improved neurologic recovery at 1-year follow-up.[11] Subsequent results demonstrated safety in early surgery with improvement in at least two grades of the ASIA impairment scale at 6 months' follow-up.[12]

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13 Cervical Burst Fractures

Teresa S. Purzner, James G. Purzner, and Michael G. Fehlings

Introduction

Cervical burst fractures are the result of flexion compression injuries and are characterized by loss in vertebral body (VB) height, cortical fracture of the posterior VB wall, retropulsion of fragments into the canal, and an increase in intrapedicular distance (IPD). Burst fractures that present with neurologic deficit have persistent canal compression or that involve the posterior elements usually require surgical intervention—typically in the form of corpectomy and anterior reconstruction. However, burst fractures that do not affect the posterior elements and present neurologically intact can be managed with external orthosis. In the following chapter we discuss the surgical indications, medical management, radiographic findings, surgical approach, and postoperative care of patients with subaxial cervical spine burst fractures.

Indications

There are a variety of classification systems for subaxial cervical burst fractures. The Allen classification[1] categorized subaxial spine injuries into six major groups of injury: three compressive injuries (flexion compression [20%], extension compression [25%], and vertical compression); two distraction injuries (flexion distraction [40%], extension-distraction); and finally one lateral flexion injury. Burst fractures belong to both flexion compression and vertical compression categories.

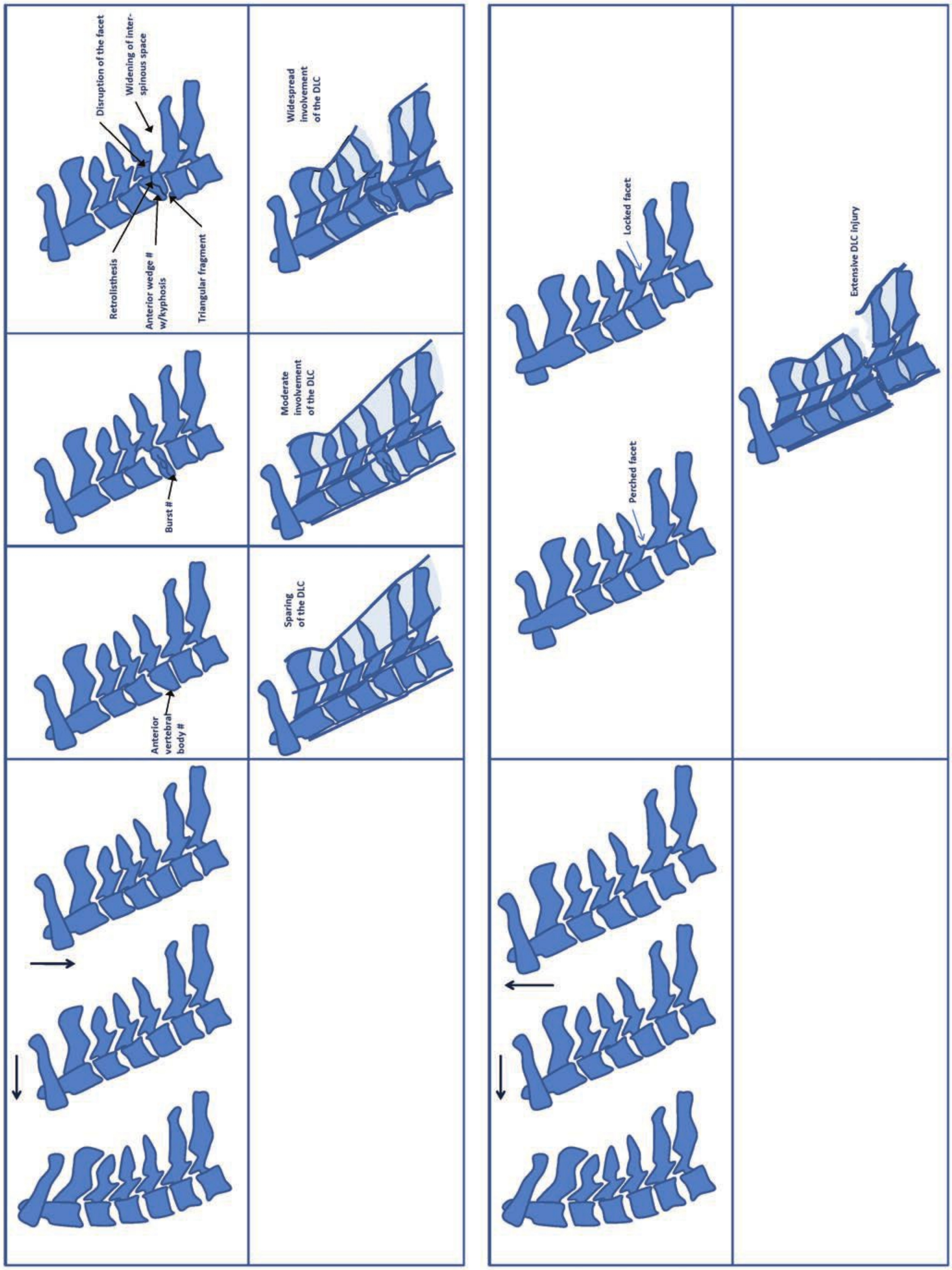
Perhaps the most clinically useful classification system was put forward in 2007 by Vaccarro et al who developed the subaxial cervical spine classification system (SLIC) guidelines (**Table 13.1**).[2] These guidelines are unique in their consideration of bony morphology, involvement of the discoligamentous complex (DLC), and neurologic presentation. Numerical values are given under each category depending on the severity of involvement. When the sum of all three categories amounts to less than 4 points, then conservative management should be considered. Greater than 4 points is suggestive of surgical management. Based on the SLIC scale, burst fractures without disruption of the DLC or change in neurologic status would be given 3 to 4 points and be treated with external orthosis while those with deterioration in neurologic status and disruption of the DLC would have . 4 points and therefore require surgical stabilization. The proposed algorithm included in this chapter is also dependent on neurologic status and the status of the posterior ligamentous complex (**Fig. 13.1**). Isolated burst fractures without neurologic deficit are managed with external orthosis while those presenting with neurologic symptoms and disruption of the posterior elements require both anterior decompression and posterior reconstruction.

Panjabi and White proposed an alternative point-based classification system targeted toward the subaxial cervical spine as well as thoracic and lumbar injuries. They considered angulation . 11% or . 3.5 mm of subluxation as unstable.[3] Cooper et al based their decision on the presence of irreducible facet fractures, retropulsed fragments causing persistent canal compromise in an incomplete SCI, progressive neurologic deficit from spinal instability, root decompression, or chronic progressive deformity with incomplete spinal cord injury or nerve root deficit.[4] Hadley et al recommended the following indications for surgery: irreducible bone alignment, irreducible spinal cord compression, instability post reduction, ligamentous injury with facet instability, . 15% kyphosis, or . 20% subluxation.[5] To better determine the correlation of radiographic findings of canal compromise and neurologic outcome, Fehlings et al performed an evidence-based analysis of published criteria in patients with acute cervical SCI.[6,7] They went on to develop a prospective study investigating magnetic resonance imaging

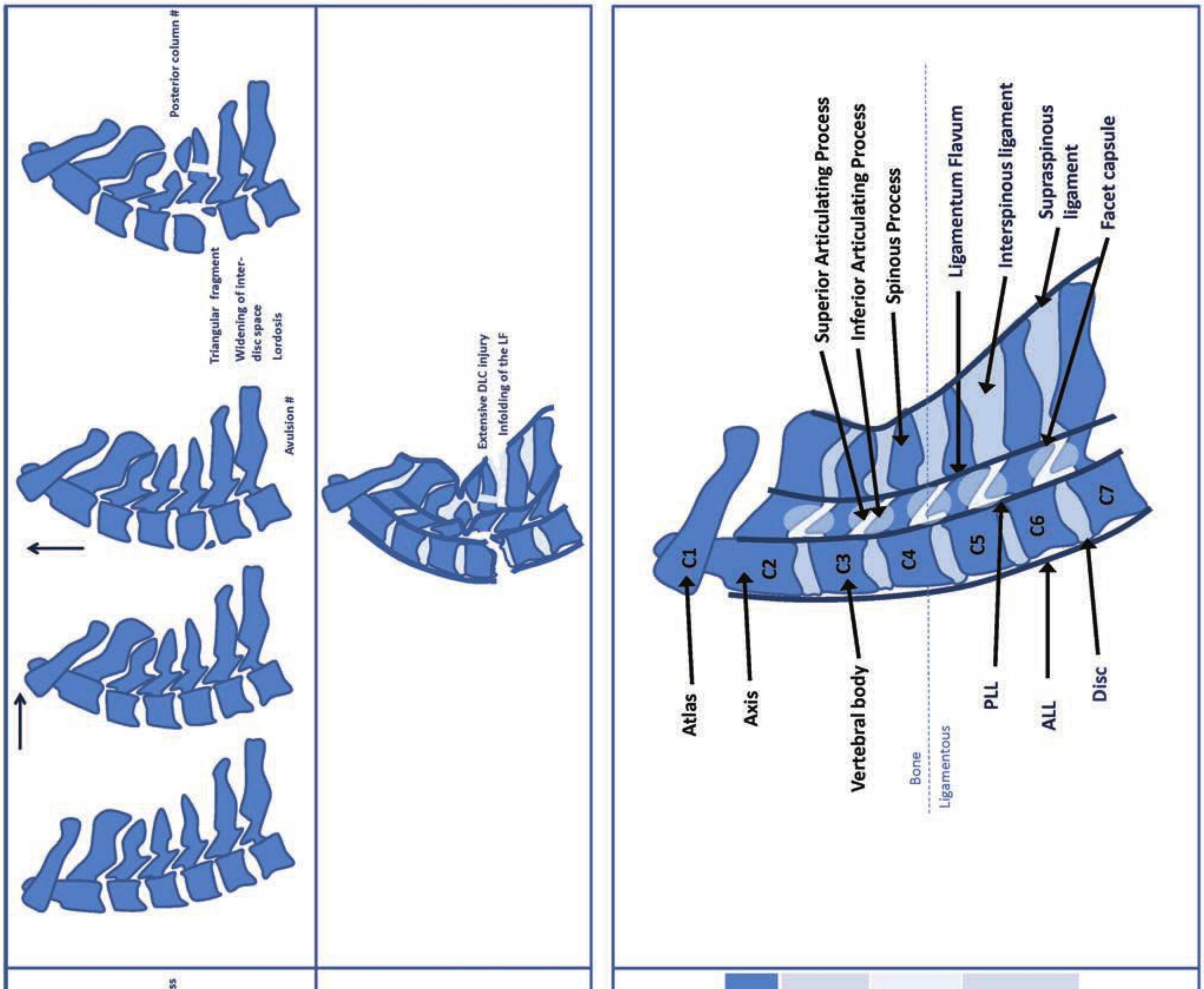
Table 13.1 SLIC guidelines

Category	Points
Morphology	
No abnormality	0
Compression	1
Burst	2
Distraction	3
Rotation/translation	4
Discoligamentous complex	
Intact	0
Indeterminate	1
Disrupted	2
Neurologic status	
Intact	0
Root injury	1
Complete cord injury	2
Incomplete cord injury	3
Continuous compression	1 1

Note: Subaxial cervical spine injury classification system based on bony morphology, involvement of the discoligamentous complex, and clinical presentation. Injuries with a score of less than 4 are managed with rigid orthosis while injuries with a score of greater than 4 should be considered for surgical fixation. Injuries with a score of 4 can be treated with either rigid orthosis or surgical instrumentation.



Anterior vertebral body #
Burst #
Retrolisthesis
Anterior wedge # w/kyphosis
Triangular fragment
Disruption of the facet
Widening of inter-spinous space
Sparing of the DLC
Moderate involvement of the DLC
Widespread involvement of the DLC
Perched facet
Locked facet
Extensive DLC injury


Spinous process and facet #
Minimal disruption of the DLC
Posterior column #
Triangular fragment
Widening of inter-disc space
Lordosis
Avulsion #
Extensive DLC injury
Infolding of the LF
Flexion
Extension
Compression
Wedge/burst #
Posterior column #
Distraction
Facet dislocation/#
Avulsion #
Rotation / translation
Teardrop #
Reverse Teardrop #
Atlas
Axis
Vertebral body
Bone
Ligamentous
PLL
ALL
Disc
C1
C2
C3
C4
C5
C6
C7
Superior Articulating Process
Inferior Articulating Process
Spinous Process
Ligamentum Flavum
Interspinous ligament
Supraspinous ligament
Facet capsule

(MRI) findings associated with canal compromise and found that maximum spinal cord compression as well as spinal cord hemorrhage and cord swelling were most associated with a poor prognosis for neurologic recovery.[8]

Initial Evaluation and Medical Management

The initial management of cervical burst fractures occurs outside of the hospital at the scene of injury. These fractures often occur in the setting of polytrauma where other life-threatening injuries can distract from possible neurologic deterioration. Full cervical spine precautions with immobilization and transfer to an appropriate trauma center should be performed efficiently and safely. Once at the trauma center, the Advanced Trauma Life Support protocol is instituted. In the setting of retropulsed segments and compressive spine injury, particular attention is paid to oxygenation and maintenance of adequate perfusion. Strict blood pressure control is important with a target mean arterial pressure (MAP) above 80. Hypotension can initially be managed with fluid boluses; however, initiation of vasopressors should be considered if adequate perfusion is not achieved with fluid boluses alone. The role of steroids remains ambiguous and is well reviewed elsewhere. Once the patient is stabilized, a thorough history can reveal the mechanism of injury and timing of neurologic deterioration. Cervical flexion compression injuries are particularly concerning for burst fractures.

Following the primary survey, a thorough physical exam is required. Initial inspection and palpation can identify obvious deformities, external soft tissue injuries, and local areas of tenderness or asymmetry. When a history is not available, patterns of injuries can sometimes suggest the mechanism of injury. Next, a dedicated neurologic exam should focus on limb strength, sensation and reflexes, truncal sensation, and perspiration as well as bowel and bladder sphincter function. The American Spinal Injury Association classification system (ASIA) is a common clinical classification system that allows for an organized approach to the neurologic exam and categorizes degree of injury into four groups.[9] ASIA A injuries are complete SCIs where no sensory or motor function is preserved. ASIA E injuries have no motor or sensory deficit. ASIA B to D injuries are incomplete SCIs where sensory function is preserved but with varying degrees of loss in motor function. Importantly, ongoing progression of neurologic deficits can suggest ongoing or progressive compression whether by unstable or retropulsed fracture fragments or an expanding hematoma. These are important to identify early as timely decompression can have significant impact on overall outcome.

Early optimization of medical management has been shown to benefit long-term prognosis; however, the timing of surgical intervention remains somewhat more controversial. There exists a large body of literature investigating the role of early surgical intervention. The best evidence to date was put forward by Fehlings et al in the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS trial).[10] This international multicenter prospective cohort study looked at 313 patients with acute cervical SCI. Of these, 182 underwent early surgery (within 24 hours) and 131 underwent late surgery (after 24 hours). Primary outcome was change in ASIA Impairment Scale (AIS) grade at 6 months. Secondary outcomes were rates of complication and mortality. Twenty percent of patients undergoing early surgery showed a ≥ 2 grade improvement compared to 8.8% in the late decompression group. Mortality and rates of complication were not statistically significant between the two groups. This study would suggest that decompression within 24 hours is beneficial.

Closed reduction, if attempted, is a relatively well-tolerated procedure with an overall reduction rate of approximately 80%, 30% recurrent displacement or malalignment, 2 to 4% chance of transient deficit, and 1% chance of permanent deficit. Overall rates of failure in compression fractures of the subaxial C-spine were found to be around 5% Similarly, Koivikko et al found a rate of reoperation in patients treated with orthosis to be 4% (compared to 3% in surgically managed patients).[11] While nonsurgical management is certainly the appropriate decision in a large percentage of patients, there is some evidence that neurologic improvement, kyphotic deformity, and canal stenosis were all improved in patients treated surgically.[11] Most studies, however, were retrospective reviews and outcomes were generalized to a spectrum of fracture patterns. Furthermore, the differences in recovery between surgical and nonsurgical management is far outweighed by the status at presentation than choice of treatment. Patients who are treated with a halo vest or hard cervicothoracic orthosis for 2 to 3 months should be followed up with flexion-extension X-rays to help determine success of fusion.

Preprocedure Considerations

Radiographic Imaging

- The choice of imaging in suspected cervical burst fractures has changed over the past few decades. Traditionally, anteroposterior (AP), lateral, and odontoid plain films of the C-spine were the first-line imaging of choice. There are several radiographic features suggestive of burst fractures—most importantly, loss of vertebral body height, cortical fracture of the posterior VB wall, retropulsion of fragments into the canal resulting in loss of the dorsal vertebral body line, and an increase in intrapedicular distances or splaying of the facet joints. This is occasionally accompanied by VB kyphotic or translational deformity.
- In many centers, computed tomography (CT) scan is now the first-line imaging modality of choice in cases suspicious of neck trauma. Typically, burst fractures will have disruption of the posterior VB wall with or without retropulsed fragments. As in plain films, they will demonstrate an increased IPD with splaying of the vertebral arch. CT angiography (CTA) should also be considered when there is concern of compromise of the vertebral canal and, in many institutions, it has become part of the standard imaging protocol for confirmed C-spine injuries.
- MRI can often be helpful in better visualizing soft tissue structures, disk, canal stenosis as well as cerebrospinal fluid (CSF) effacement, cord impingement, or signal changes—23% of all blunt trauma patients presenting with a cervical injury have evidence of disk injury on MRI. This increases to as high as 36% of those patients with complete SCI, 54% of

incomplete SCI, and 47% of patients with unstable SCI.[12] MRI should be performed in a timely manner, particularly when the clinical exam is not explained by radiographic findings. In those patients with equivocal exam or radiographic findings, 15.5% have been found to have both disk and ligamentous disruption, while 20% have isolated ligamentous abnormality.[13] T1-weighted images are useful for their enhancement of subacute hemorrhage while T2 weighted images will show hyperintensity at areas of edema. Short inversion recovery (STIR) imaging is a fat suppression sequence that is particularly helpful in highlighting areas of ligamentous injury. Gradient echo imaging and susceptibility-weighted imaging will further evaluate the presence of hemorrhage. Diffusion-weighted imaging (DWI) uses rapid echo planar sequences to highlight acute ischemic events. It has been used very successfully in evaluating traumatic brain injury and cerebral ischemia but is still limited in the spinal cord given the cardiorespiratory motion artifact, CSF pulsation, and the smaller region of interest. Nonetheless, it is an area of active research that has been showing promising preliminary results. MRI should be strongly considered in the setting of burst fractures particularly when there is concern of a traumatic disk protrusion or to assess the degree of canal stenosis resultant from retropulsion of the posterior elements. Either of these would be important in surgical planning.

- Preoperative imaging (**Fig. 13.2**).

Approach

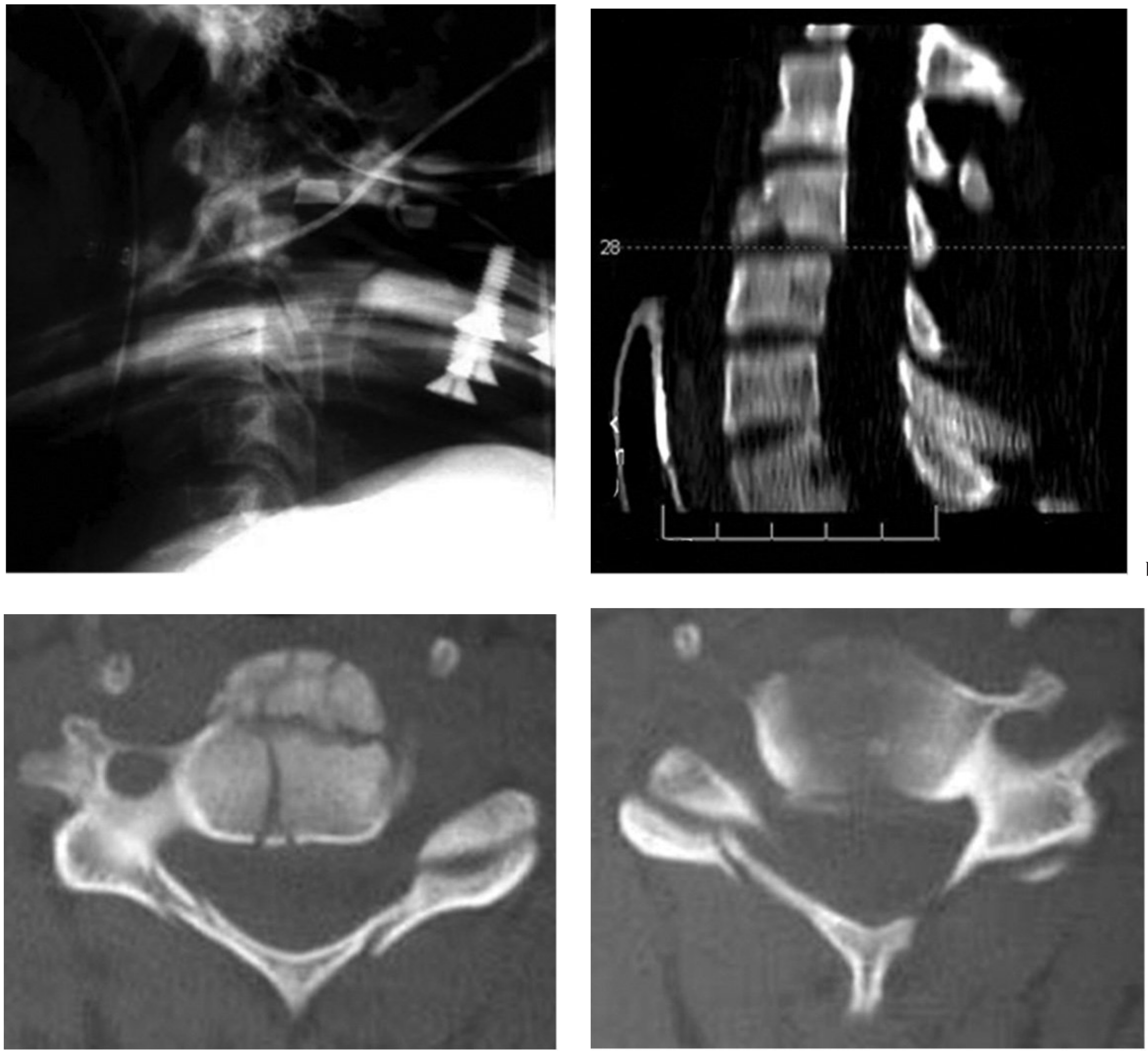
Once the decision to operate has been made, the role of anterior, posterior, or combined approaches must be considered. There are risks and benefits to both and approach is ultimately determined by the areas of compression, neurologic status, status of the posterior elements, and comfort of the surgeon. In cervical burst fractures the approach of choice is predominantly ventral. Neurologic compression is a result of retropulsed anterior elements which can be removed under direct vision with an anterior approach and therefore one can provide optimal decompression. Furthermore, corpectomy with anterior reconstruction provides excellent biomechanical stability and correction of kyphotic deformities. The resected vertebral body provides large amounts of excellent material for autologous bone grafting. Anterior approaches also have less blood loss and postoperative pain. Indeed, when directly compared, Toh et al found anterior fusion preferred to posterior fusion in cervical burst and teardrop fractures.[14] This was echoed by several biomechanical studies looking at the stability of the cervical spine after anterior fusion, posterior fusion, and combined fusions in patients with VB fractures. It was found that although posterior fusions were stronger than anterior fusions both were stronger than the intact spine. This was true in both isolated anterior injury or combined anterior/posterior injuries. Therefore, particularly in the setting of intact posterior elements, the role of corpectomy with anterior reconstruction provides adequate stabilization for long-term bony fusion. Nonunion rate is approximately 3%[15]

More extensive reconstructions, involving combined anterior and posterior approaches, are necessary in cases with suboptimal bone quality, involvement of the posterior elements, or existing long fused segments. Bone mineral density has a significant impact on overall fusion rates[16] and the degree of fusion must be tailored to both the density of healthy bone and degree of bony disruption. Generally, at least the caudal third of the caudal vertebral body and caudal endplate of the rostral vertebral body should be intact for appropriate fusion. Combined anterior and posterior fusion is used in patients with very stiff or spondylotic spines (diffuse idiopathic skeletal hyperostosis [DISH], ankylosing spondylitis) or in the setting of injury to the posterior elements. Combined operations have been shown to provide immediate rigid stabilization, increased fusion, and decreased rates of ventral plate failure. Particularly when both can be performed under a single anesthetic, a combined approach can avoid the requirement of postoperative halo fixation in complex spinal injuries. Isolated posterior approaches are typically considered in the setting of facet fractures or dislocations with endplate disruption without significant compression or disruption of the vertebral body. Posterior approaches are useful when patients have failed closed reduction and there is suspicion that intraoperative reduction will be difficult.

Operative Field Preparation

Fiberoptic intubation while the patient is asleep is recommended in all unstable cervical burst fractures when possible. Povidine iodine or chlorhexidine is applied to the surgical site and allowed to dry for 3 minutes. The use of preoperative local anesthetic is up to the discretion of the surgeon; typically the marked incision is infiltrated with 1% lidocaine with epinephrine 1:100,000.

Prophylactic antibiotics should be given and dexamethasone should be considered particularly in the setting of cord compression or neurologic compromise.



a b c d

Fig. 13.2 These films (**a, b**) depict a patient with a C4 "tear drop" fracture of the vertebral body (**c, d**) that was associated with posterior C4-5 facet and laminar disruption.

Operative Procedure

Positioning (Fig. 13.3)

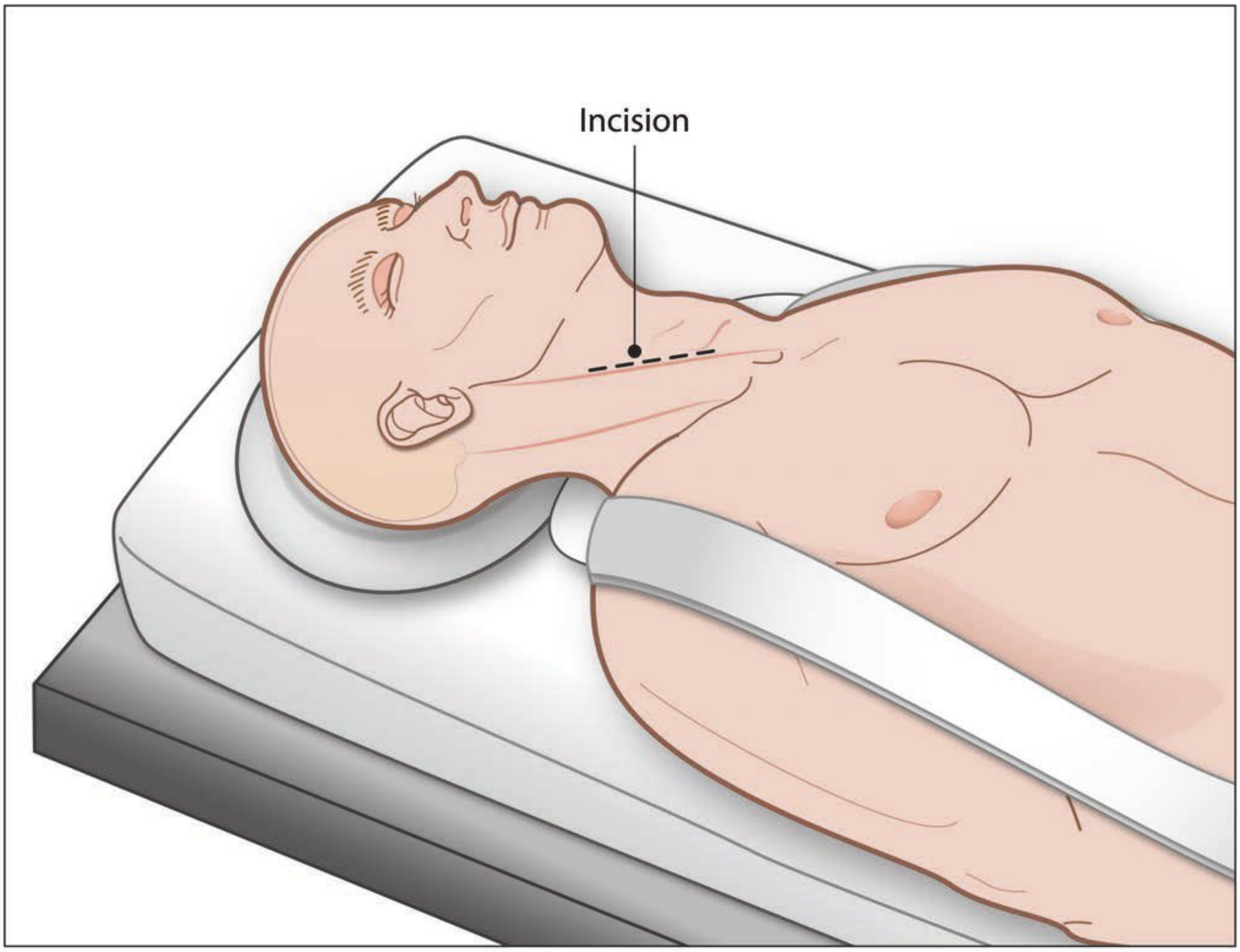


Figure	Procedural Steps	Pearls
Fig. 13.3	**The patient is positioned supine with the face midline. A small bolster is placed between the scapula and the neck is put in general extension with the occiput resting on a donut. Shoulders are taped down.**	• Right-handed surgeons tend to prefer right-handed incisions, while the opposite is true with left-handed surgeons. Anatomically, the recurrent laryngeal nerve runs a less predictable course on the right-hand side while the thoracic duct is a unilateral structure found only on the left-hand side. Previous surgery is a relative indication to approach from the ipsilateral side given the potential for bilateral vocal cord paralysis in the setting of bilateral anterior cervical approaches.

Incision and Subplatysmal Dissection and Identification of Omohyoid (Fig. 13.4)

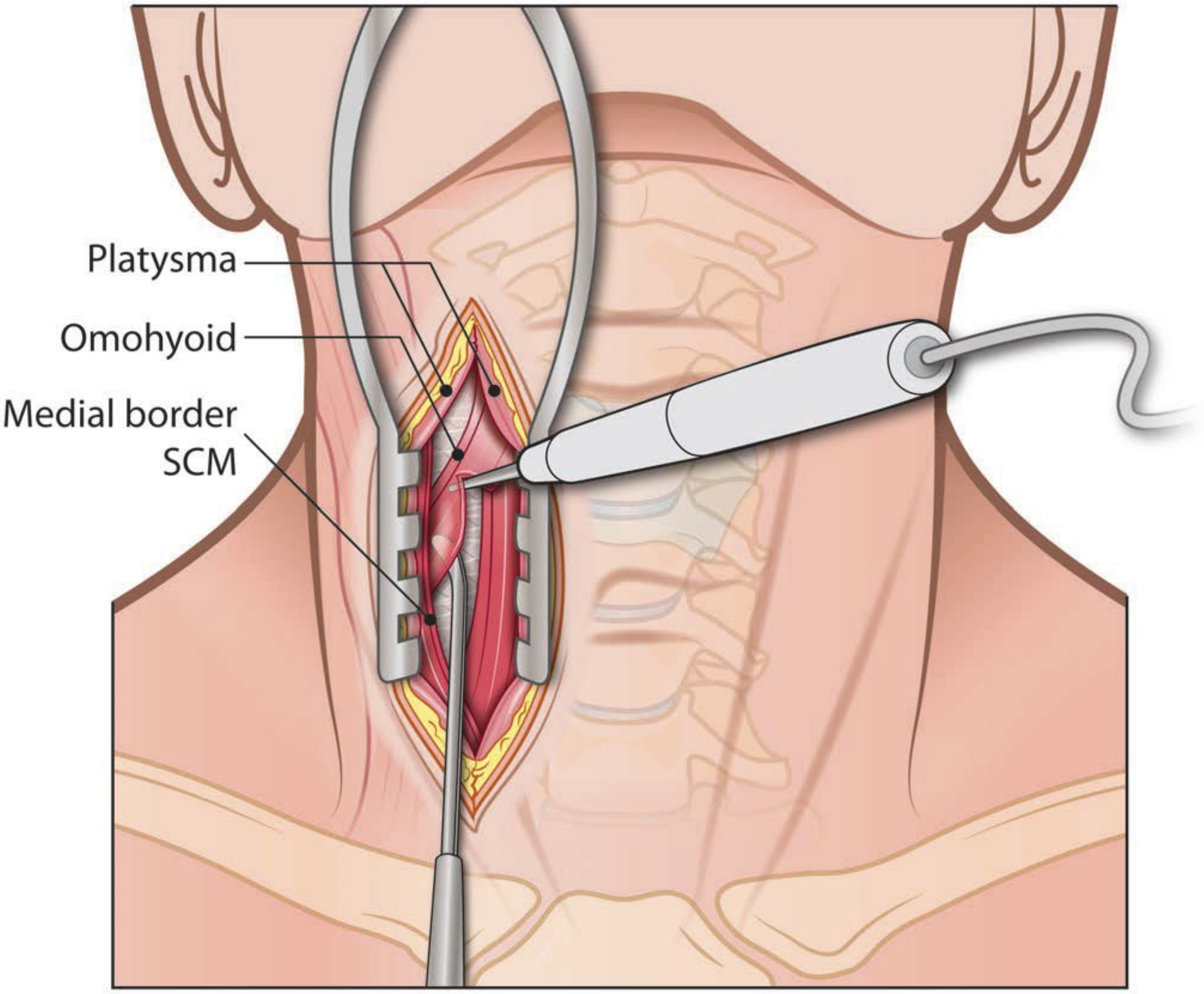


Figure	Procedural Steps
Fig. 13.4	**A right longitudinal paracervical incision is made with a no. 20 blade along the anterior border of the sternocleidomastoid muscle. The incision is extended down through skin, subcutaneous tissue, and platysma.** **Subplatysmal flaps are elevated and the omohyoid muscle is isolated and divided with diathermy cautery.**

Identification of the Deep Cervical Investing Fascia (Fig. 13.5)

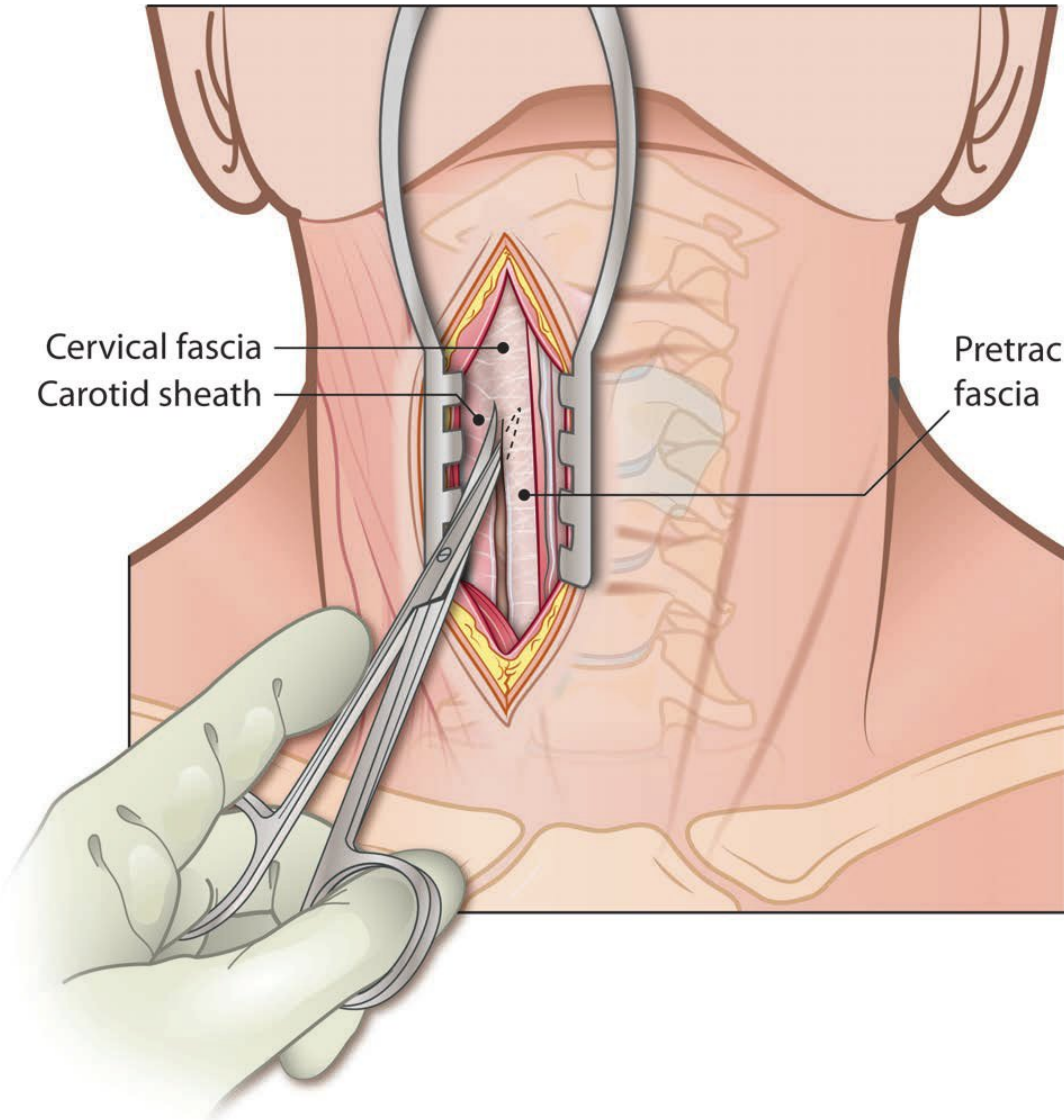


Figure	Procedural Steps	Pearls
Fig. 13.5	**The carotid triangle is entered between the carotid sheath and the pretracheal fascia by exploiting the avascular planes of the deep cervical investing fascia.**	• Through the superior end of incision, the superior thyroid artery and superior laryngeal nerve can be identified and protected. At the lower end of the incision the inferior thyroid vein can occasionally be visualized. At all points it is important to identify and protect the pharynx/esophagus.

Identification of the Prevertebral Fascia (Fig. 13.6)

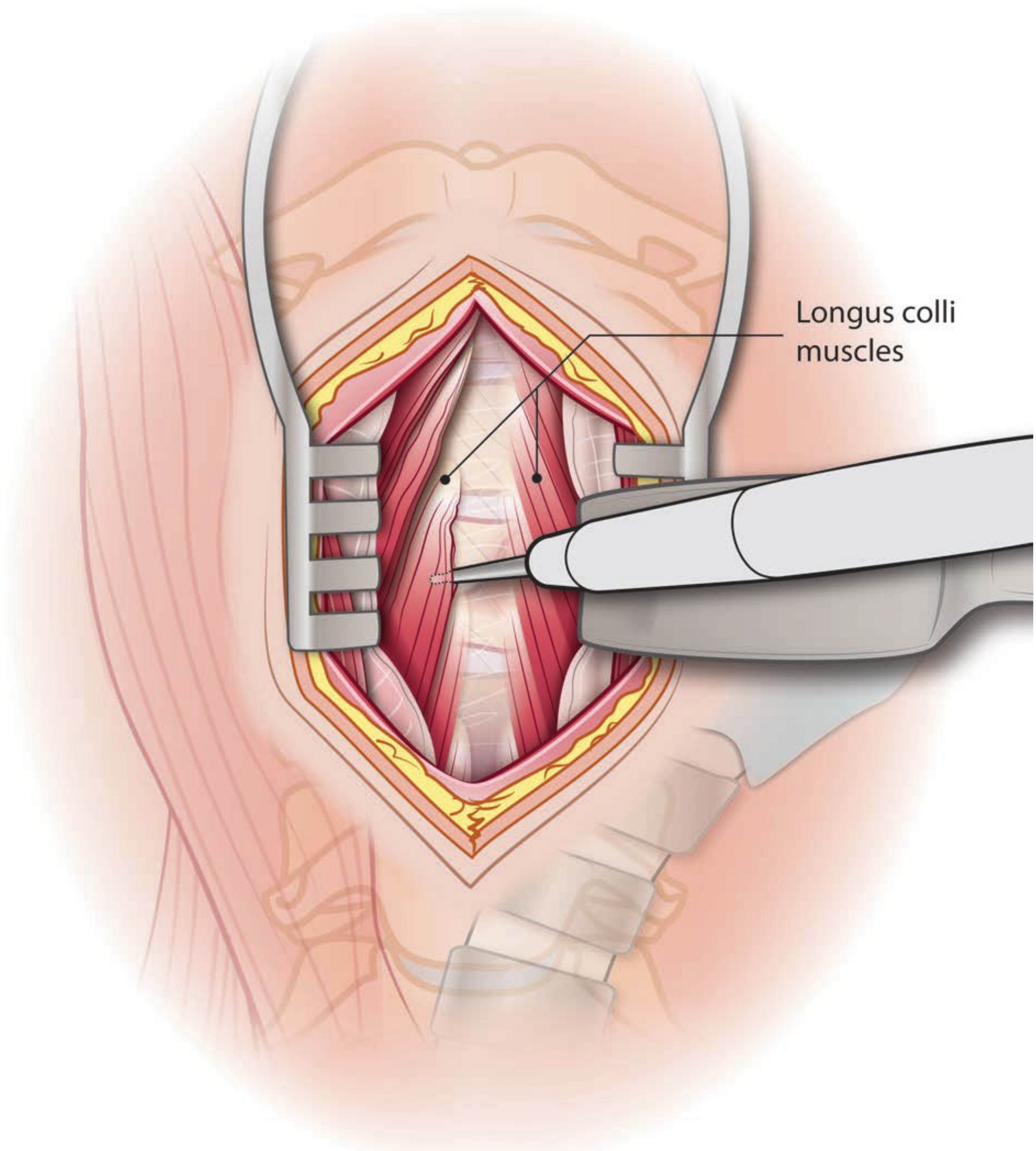


Figure	Procedural Steps
Fig. 13.6	**Blunt dissection is used to identify the prevertebral fascia which is then opened with sharp dissection. Superior osteal dissection ensues under the longus colli muscle bilaterally.**

Placement of Self-retaining Retractors (Fig. 13.7)

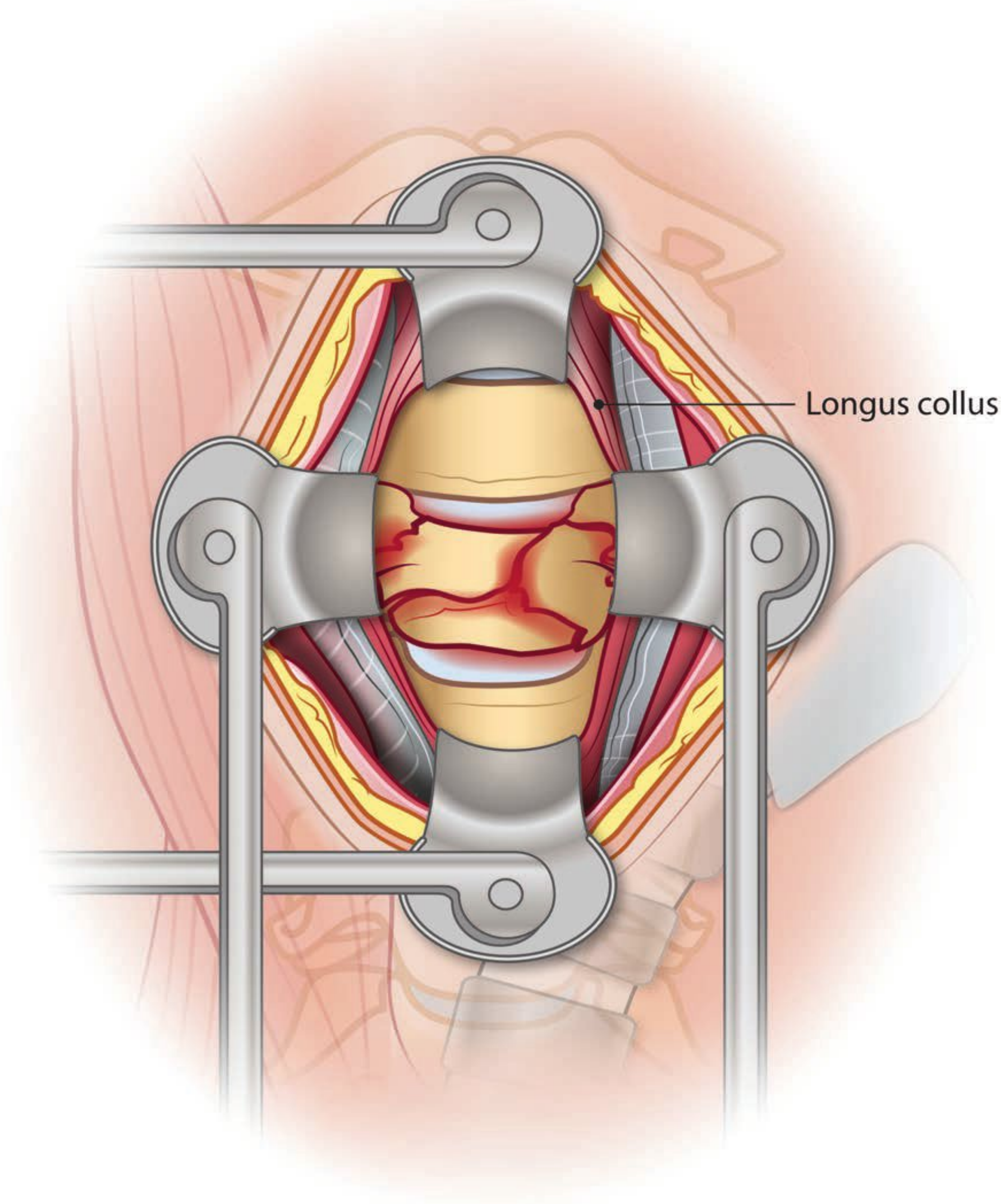


Figure	Procedural Steps	Pearls
Fig. 13.7	**Retractors are positioned to displace esophagus, trachea, and strap muscles medially. The carotid, internal jugular, and sternocleidomastoid muscle are retracted laterally.**	• Retractors should be intermittently released to minimize pressure on the soft tissues. In addition, the endotracheal cuff can be deflated to minimize pressure on the tracheoesophageal groove and thereby decrease the risk of injury to the recurrent laryngeal nerve.

Diskectomy (Fig. 13.8)

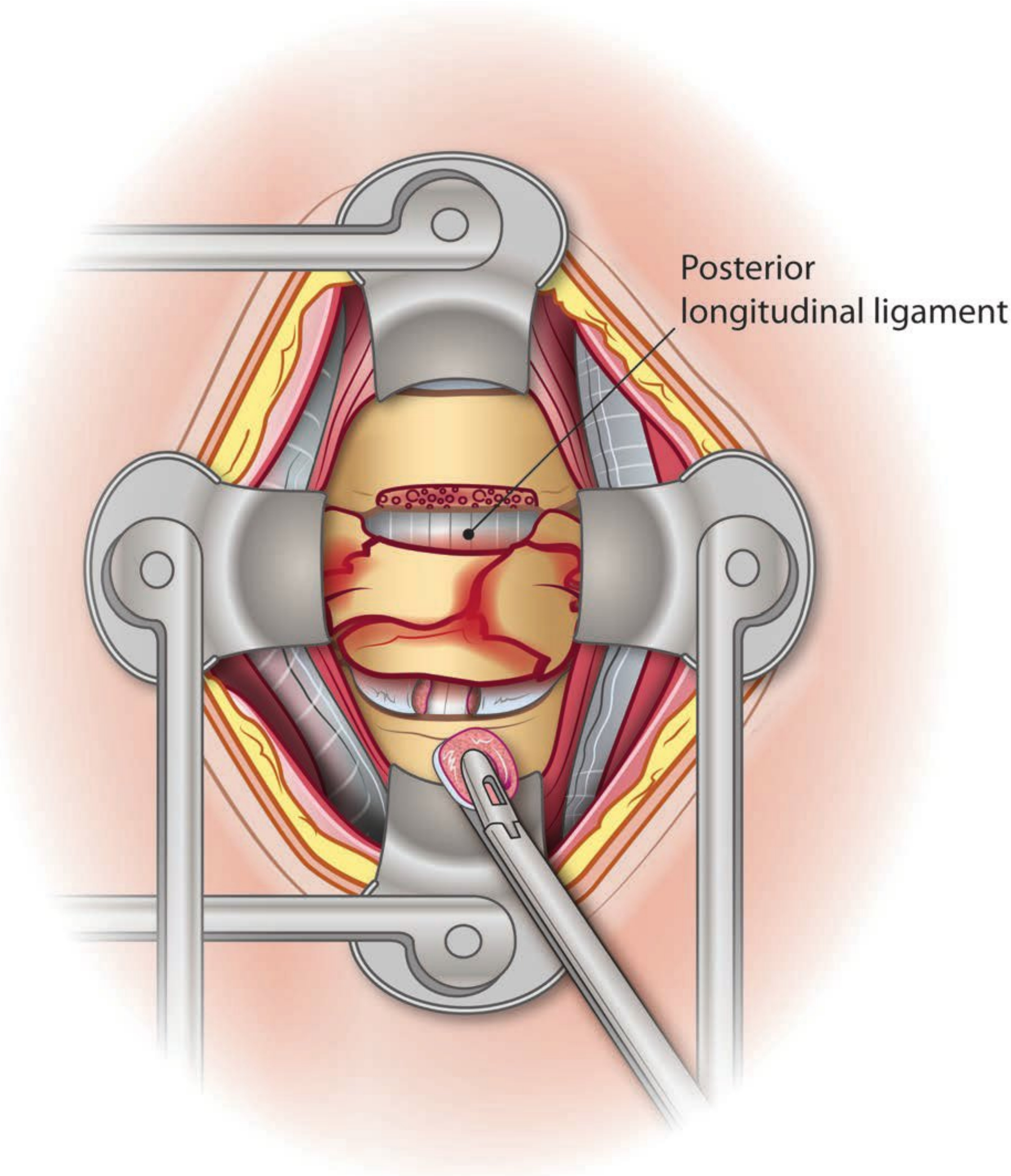


Figure	Procedural Steps
Fig. 13.8	**Disk spaces above and below the injured vertebra are evacuated using a combination of high speed bur, pituitary rongeurs, Kerrison punches, and microsurgical curettes. A longitudinal trough is then fashioned longitudinally in line with the uncovertebral joints. The endplates are thoroughly burred down to posterior longitudinal ligament.**

Corpectomy (Fig. 13.9)

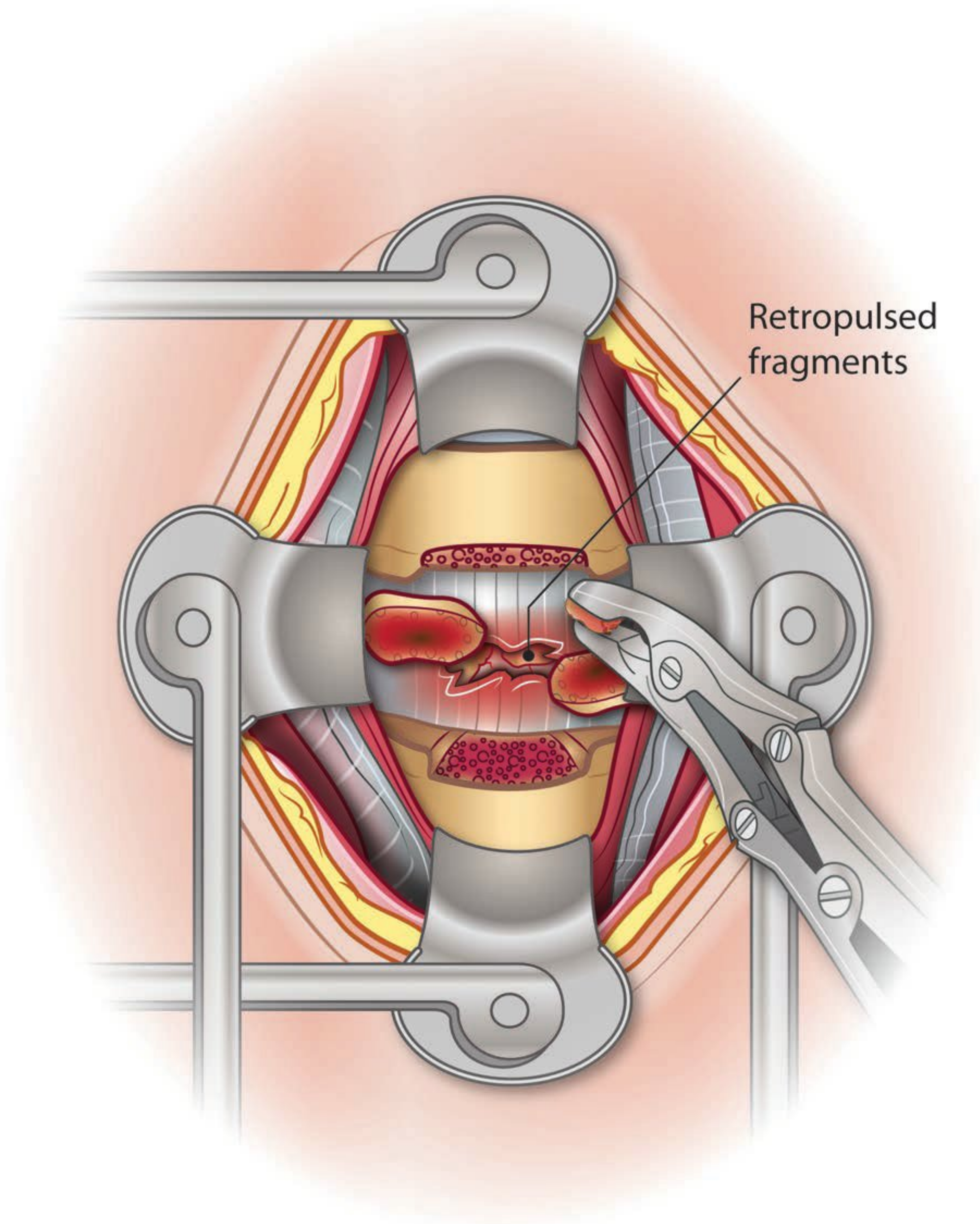


Figure	Procedural Steps
Fig. 13.9	**The injured vertebral body is resected with Leksell rongeurs and high-speed burs. The posterior longitudinal ligament is then opened and all retropulsed fragments are carefully removed via microsurgical dissection under microscopic magnification.**

Placement of Allograft (Fig. 13.10)

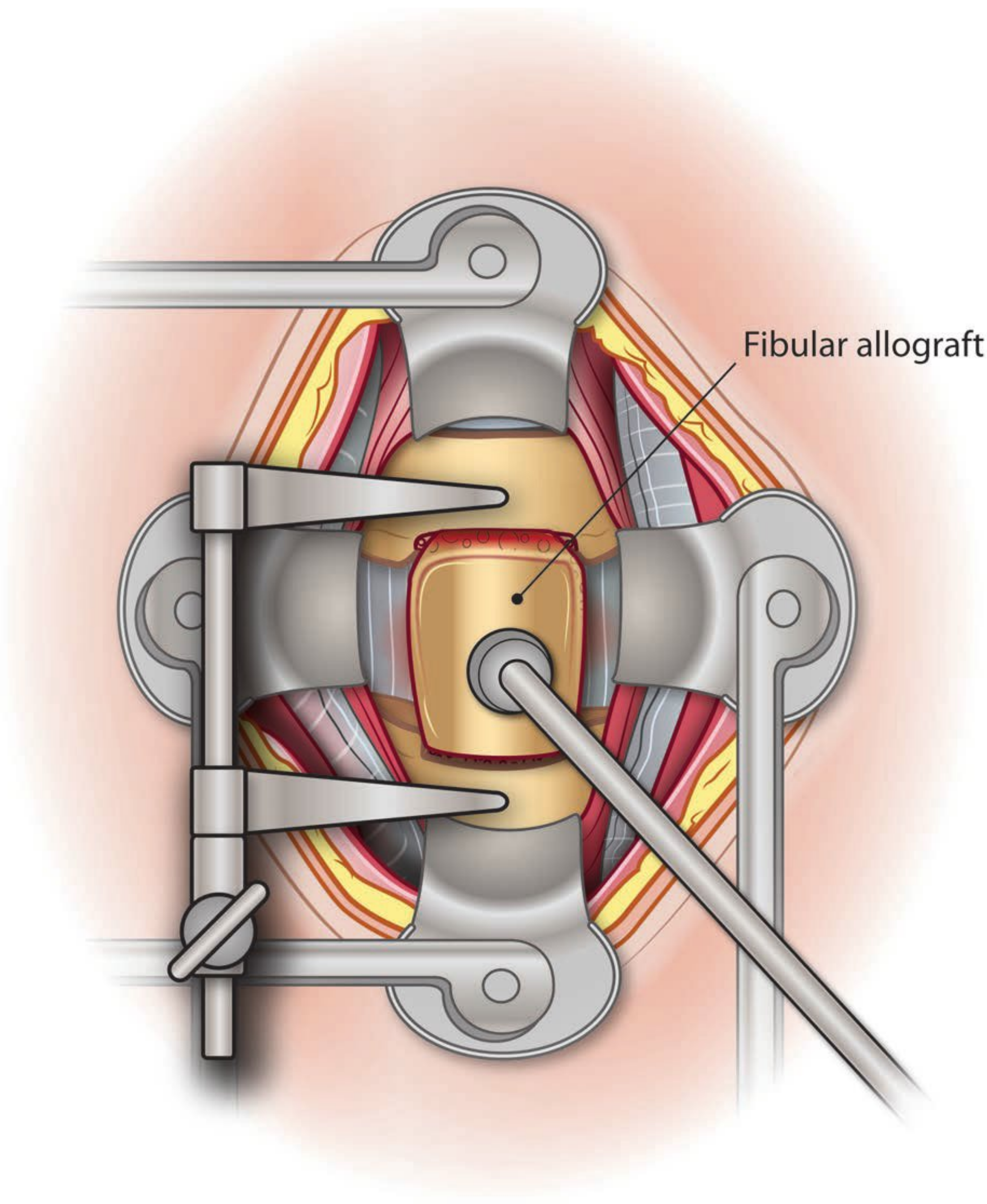


Figure	Procedural Steps
Fig. 13.10	**Distraction pins are placed in the vertebral body above and below the level of injury. Fibular allograft is cut to the appropriate length and packed with local corpectomy bone graft. These are gently tapped in to position. Distraction pins are removed and the security of fit is assessed. Bleeding from the pin sites is controlled with bone wax.**

Placement of Anterior Locking Plate (Fig. 13.11)

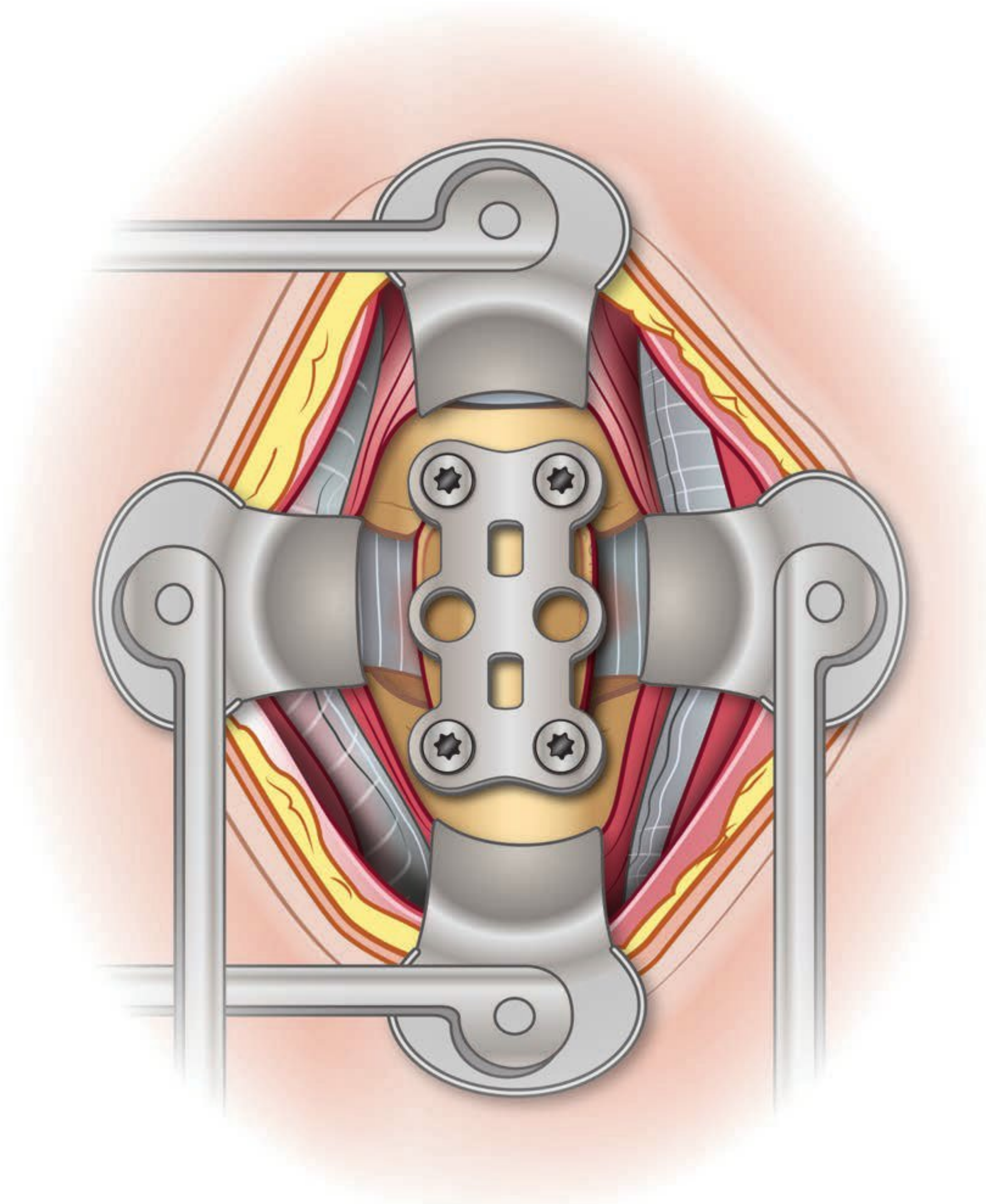


Figure	Procedural Steps	Pearls
Fig. 13.11	**Calipers are used to assess the length of bony defect and an anterior locking plate is chosen. Four 14-mm locking screws are used to fixate the plate.**	• The literature supporting dynamic or static locking plates is divergent[17] and the decision to use one over the other is typically related to the preference of the surgeon. While locking screws do have benefit over nonlocking screws,[18,19] unicortical and bicortical screws have both shown immediate stability so either is a reasonable choices depending on the experience of the surgeon and risk of protrusion through the posterior vertebral bodies.[20] Approximately 4 mm should be left at both the rostral and caudal end to diminish the risk of future adjacent level disease.

Closing

- Retractors are removed and soft tissues are carefully inspected for bleeding. Hemostasis is meticulously checked and secured. Jackson-Pratt drain can be placed in the prevertebral space and externalized through separate stab incision and connected to the bulb suction.
- The wound is repaired in layers using 2-0 braided absorbable suture for subcutaneous tissue and similar 4-0 subcuticular for skin.

Postoperative Management

Monitoring

- Patients should be monitored for blood pressure and neurologic function postoperatively with a target of MAP . 80. A plain CT of the cervical spine will help confirm placement of instrumentation.

Medication

- The use of postoperative antibiotics is controversial. There is no good evidence that routing postoperative antibiotics provides any advantage to postop wound infections.
- The use of steroids in acute SCI is also controversial and its potential benefit must be weighed against the risk of pneumonia, poor wound healing, and recovery from associated injuries.

Radiographic Imaging (Fig. 13.12)

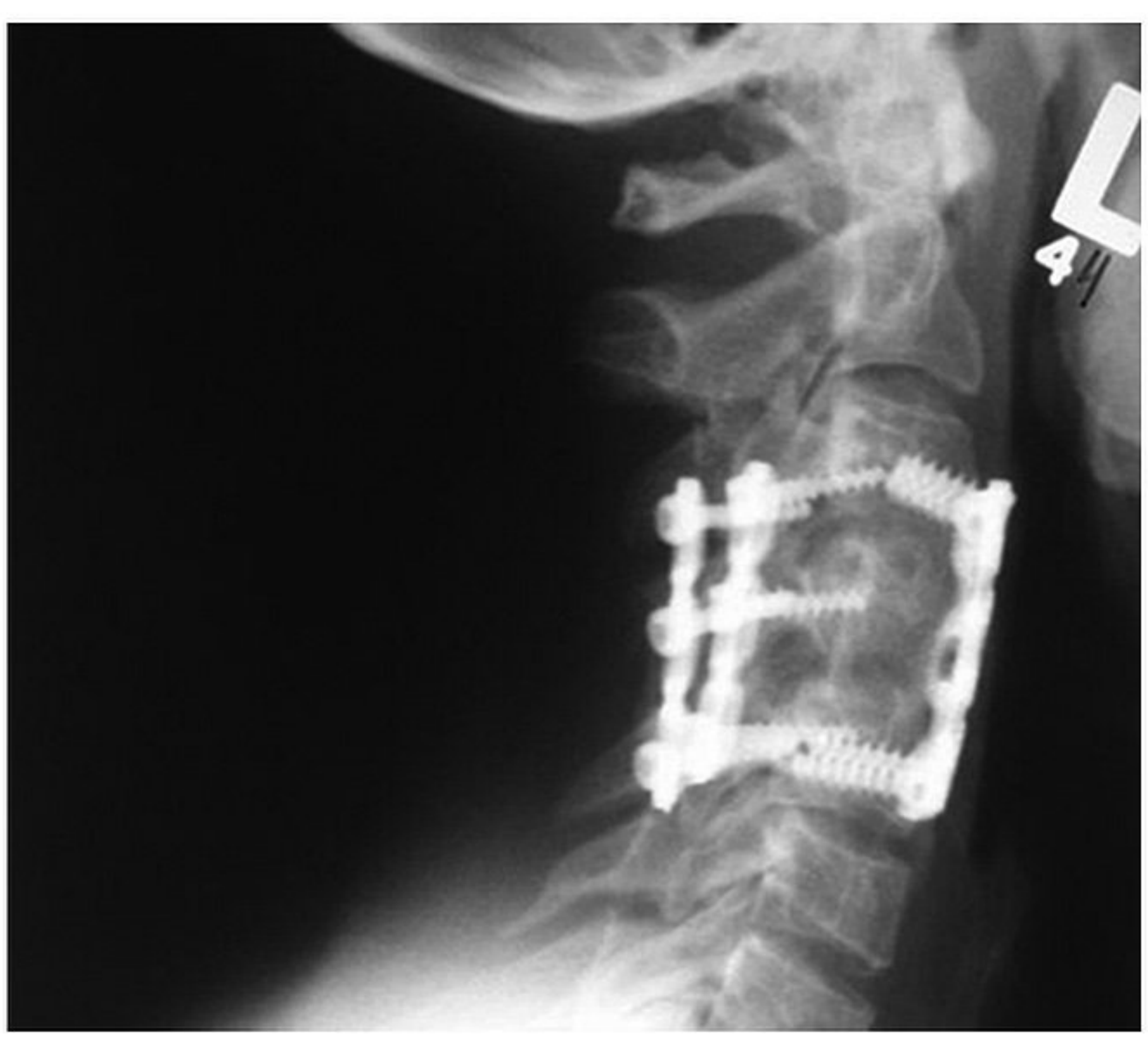


Fig. 13.12 The patient was treated with a C4 corpectomy and C3-5 anterior reconstruction with a fibular allograft (packed with local corticocancellous autograft), and anterior screw-plate fixation. Under the same anesthetic, the patient was turned (using Mayfield cranial fixation and a Jackson table) in the supine position and a C3-5 posterior lateral mass reconstruction was undertaken.

Further Management

- Depending on the degree of injury, use of an external orthosis postoperatively may benefit the patient in terms of both stability and pain control.

Special Considerations

The term "cervical burst fracture" is used in a variety of contexts. The important factors in determining the role of surgical fixation are the involvement of the posterior complex and ongoing neurologic deficit secondary to ongoing cord compression. They are often considered in the context of subaxial cervical spine classification systems, most notably the SLIC classification. While these can aid in determining the stability of the injury, ultimately each patient and their injury is unique and require individual consideration.

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14 Cervical Facet Dislocation

Daniel Resnick and Casey Madura

Introduction

Dislocation of the facets joints of the spine can occur at all levels, but it is most commonly an injury found in the cervical spine. First, the coronal orientation of the joints themselves leaves them susceptible to dislocation with hyperflexion. Second, unlike the substantial size of the lumbar articulating processes, those in the cervical spine are much less robust.[1] Therefore, the articulating processes in the cervical spine are much more prone to fracture and dislocation. Third, the cervical spine is naturally highly mobile in comparison to the thoracic and lumbar spine with the head's weight serving as a contributing factor. This characteristic leaves the cervical spine vulnerable to sudden changes in movement such as that which occurs in a head-on collision.

Dislocation of the cervical facet joints can be both unilateral and bilateral. In the case of unilateral facet dislocation, there is often a rotatory force experienced along with the hyperflexion. The hyperflexion force vector is enough to raise the inferior articulating processes of both facet joints at the affected level with respect to the superior articulating process. The rotation experienced at the same time causes only one of the two elevated inferior articulating processes to translate forward, locking anterior to the superior articulating process of the vertebra below it.[2] A purely hyperflexion moment without rotation is much more likely to cause bilateral facet dislocation as the force vectors experienced by each facet are theoretically similar. In either scenario, the dislocation is visualized as either a perched facet (one in which the inferior projection of the inferior articulating process of the proximal vertebral body articulates with the superior projection of the superior articulating process of the distal vertebral body) or a locked facet (in which the inferior articulating process of the proximal vertebral body is anterior to the superior articulating process of the distal vertebral body).

All regions of the cervical spine are not created equal. Unlike the subaxial cervical spine, the C1-C2 facet joints are oriented in an axial plane making them less vulnerable to dislocation from hyperflexion. The occipitocervical junction is subject to a number of particular injury patterns that are discussed elsewhere. It is the subaxial cervical spine, specifically C4-C7, that is most prone to hyperflexion injuries.[3] In large part, this is due to the dynamic forces the cervical spine experiences as a collision evolves. At the onset of a head-on collision, the lower cervicothoracic junction of the spine compresses and extends while the subaxial cervical spine flexes with great force. As the forces evolve, the cervical spine is eventually thrown into extension. This evolution of forces, commonly referred to as whiplash, causes the spine to assume an S-shape, a phenomenon referred to as "snaking." The hyperflexion, if severe enough, can lead to facet dislocation by itself.

In rear end collisions, the damage can be even more severe. Initially, the victim's neck may hyperextend, forcing the inferior articulating process down into the superior articulating process. If the articular surface fails, fracture of the inferior articulating process can occur, weakening the facet joint as a whole. The inevitable hyperflexion that follows then causes the dislocation, unhindered by the normal ligamentous and joint capsule restraints.

The ultimate result of any facet dislocation in the cervical spine is an unstable spine that requires immediate treatment. Treatment options include nonoperative management with closed reduction followed by immobilization in an external fixation device such as a halo vest or Minerva brace versus operative fixation following either closed or open reduction. The details of the different options are discussed below, but there is a general agreement that the universal presence of ligamentous injury in facet dislocations makes operative fixation a preferred technique for treatment of both unilateral and bilateral facet dislocations of the cervical spine.

Indications

- Hyperflexion injury resulting in unilateral or bilateral facet dislocation such as a head-on motor vehicle collision.
- Combined hyperextension/hyperflexion injury resulting first in facet fracture due to hyperextension with subsequent facet dislocation due to hyperflexion as is experienced during a severe rear-end collision.
- If the examination reveals no neurologic deficit or a complete spinal cord injury, surgical stabilization should occur as soon as the patient is medically stable and an appropriate team is available.
- If the examination reveals findings consistent with a partial spinal cord injury, urgent reduction and stabilization is recommended as soon as the patient is hemodynamically stable. Hypotension should be avoided in all patients, especially those with neurologic deficits.

Examination

- Any patient that suffers a cervical facet dislocation has sustained forces sufficient to cause a myriad of other life-threatening injuries; therefore, a full trauma workup should be completed with priority given to the ABCs (airway, breathing, circulation). Immobilization of the cervical spine during this evaluation must be a priority.
- A full neurologic examination should be performed as this has implications regarding the timing of intervention.
- Additionally, evaluation of neurologic status may allow localization of the injury prior to imaging.

Reduction—Closed or Open[4]

- Class III evidence suggests early reduction of cervical facet fracture/dislocation may be associated with improved neurologic outcome.
- If the patient is awake, this can be performed with mild sedation.[5] If the patient is unresponsive or unable to cooperate, magnetic resonance imaging (MRI) is indicated prior to reduction as the neurologic examination cannot be followed and the presence of a large ventral lesion may be a relative indication for an open reduction via an anterior approach.
- Closed reduction technique includes halo or tongs traction, which is discussed in Chapter 11. Closed reduction and external bracing is associated with increased morbidity and mortality related to prolonged bedrest.
- Success of closed reduction is 80%
- Risk of suffering additional permanent neurologic injury during closed reduction is , 1%
- Risk of suffering additional transient neurologic injury during closed reduction is 2 to 4%
- If reduction fails, the likelihood of other injuries such as facet fracture or herniated disks is increased. This necessitates further imaging studies such as MRI prior to open reduction to determine the initial direction of approach (anterior versus posterior).

Preprocedure Considerations

Radiographic Imaging

- Computed tomography (CT) scan: CT is the workhorse of cervical spine trauma evaluation. Identification of osseus abnormality is straightforward while ligamentous injury is not always detectable. Ligamentous injury may be detected due to enlarged spaces between otherwise normal appearing osseus structures.
- MRI: This test has, in the past, been advocated as a necessary part of any pre-reduction workup, whether that reduction be in the intensive care unit (ICU) or operating room setting. The rationale for this was to identify any ventral intervertebral disk herniations that may cause neurologic injury during reduction. According to an evidence-based review, there was no relationship between the presence of herniated disks and risk of neurologic injury during closed reduction of facet dislocations in the presence of a ventrally herniated disk.[4] While pre-reduction or preoperative MRI may be useful in terms of defining associated injuries and in some cases dictating surgical approach, as in the obtunded patient, in the absence of a clear indication for MRI, reduction of the dislocation should not be delayed in a patient with a severe neurologic injury.
- Cervical X-ray: The role of plain radiographs in the initial assessment of severe trauma has been limited by the advent of aggressive use of CT imaging. Plain films are quite helpful for diagnosing cervical facet dislocations and are employed serially (or with fluoroscopy) during the process of either open or closed reduction.

Medication

- Steroids: Methylprednisolone for spinal cord injury is a topic of great controversy. Drawing from the 2002 and 2013 AANS/CNS Guidelines,[6] Hurlburt,[7] NASCIS I[8] and II[9] as well as subsequent publications,[10] the standard at our institution is to not administer steroids.

Operative Management[11]

Approach

- If closed reduction has been achieved, anterior fixation and fusion, posterior fixation and fusion, or halo immobilization are treatment options. In general, halo immobilization is associated with a relatively high failure rate and the vast majority of surgeons will offer a direct fixation procedure.
- If the dislocation requires open reduction, the surgeon may choose between anterior or posterior approaches depending on the anatomy of the injury and the experience of the surgeon. The presence of a large ventral disk herniation may be a relative indication for an anterior approach as a known unilateral vertebral artery injury. In these cases, the use of MRI is appropriate. If the dislocation is complete enough that the surgeon does not believe an anterior approach feasible for reduction, then a posterior approach is indicated.

Techniques

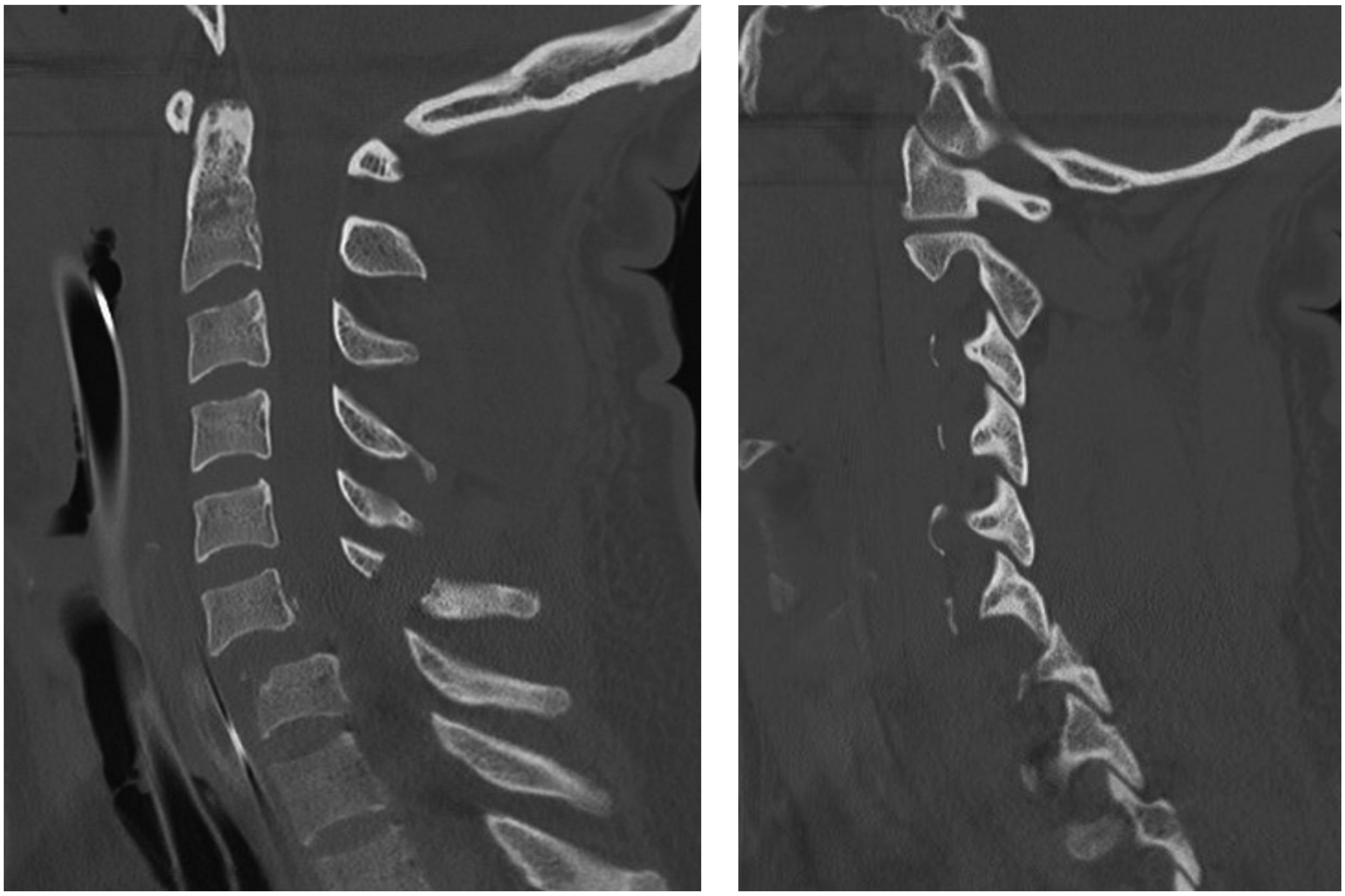
- Options include: anterior fusion with or without plate fixation, posterior fusion and wiring, and posterior fusion with lateral mass plate, rod, clamp, or cable fixation.
- Posterior fusion with lateral mass plate, rod, clamp, or cable fixation provides instant stability (allowing early mobilization of the patient). Choice of technique is based on the integrity of the bony structures and the experience of the surgeon.
- Posterior fusion with wiring may also be associated with an increased risk of late kyphotic angulation compared to more rigid techniques. In one study, 22 of 165 patients with cervical facet dislocation treated via posterior fusion and wiring developed kyphosis compared to just 1 of 40 patients treated via posterior fusion and lateral mass fixation.[11]
- Anterior fusion without plating is associated with a higher incidence of graft displacement and late development of kyphosis than posterior fusion with fixation. Six of 101 patients treated in this fashion developed late instability compared to 6 of 237 patients treated via a posterior fusion with lateral mass fixation.[11] The use of anterior fusion with plate fixation is well described and is associated with excellent outcomes.[12–16]

Operative Field Preparation

- Cervical immobilization must be maintained at all times.
  - With regards to anesthesia, the inherent instability of this type of spinal column injury encourages fiberoptic intubation.
  - Regardless of the final position (prone or supine), the neck should be kept in a neutral position at all times.
  - The operative area is cleared of hair using clippers only and cleansed with alcohol.
  - Povidine iodine or chlorhexidine prep is used to sterilize the operative field widely.
  - The incisions are marked. Infiltration with 1% lidocaine with 1:100,000 epinephrine is optional.

Operative Procedure

Posterior Approach (Fig. 14.1a, b)



a b

Fig. 14.1a, b Case example: posterior fixation. This young man was involved in a motor vehicle accident and presented with a complete spinal cord injury at C6-C7. (**a, b**) CT images demonstrate the bilateral facet subluxation injury along with some additional posterior element injuries and distraction indicating circumferential ligamentous disruption. Because of the degree of distraction and posterior element injuries, a long segment posterior fixation was planned.

Positioning (Fig. 14.2)

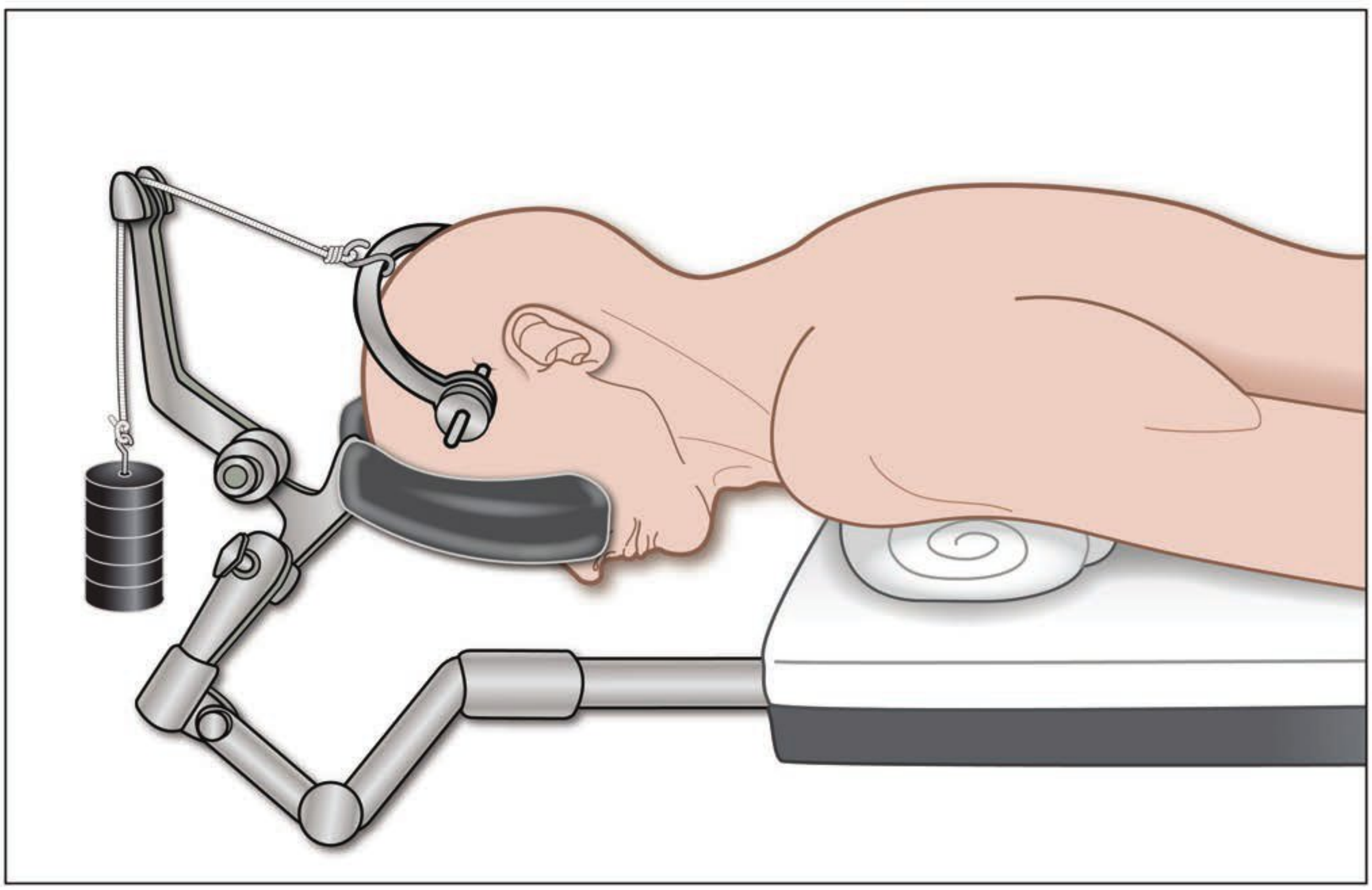


Figure	Procedural Steps	Pearls
Fig. 14.2	**Cervical immobilization is maintained at all times. The neck is maintained in neutral alignment. Tongs with traction are maintained to stabilize the spine.**	• Fiberoptic intubation is a necessity in these patients. Mayfield pins may also be used to stabilize the spine.

Subcutaneous Dissection (1) (Fig. 14.3)

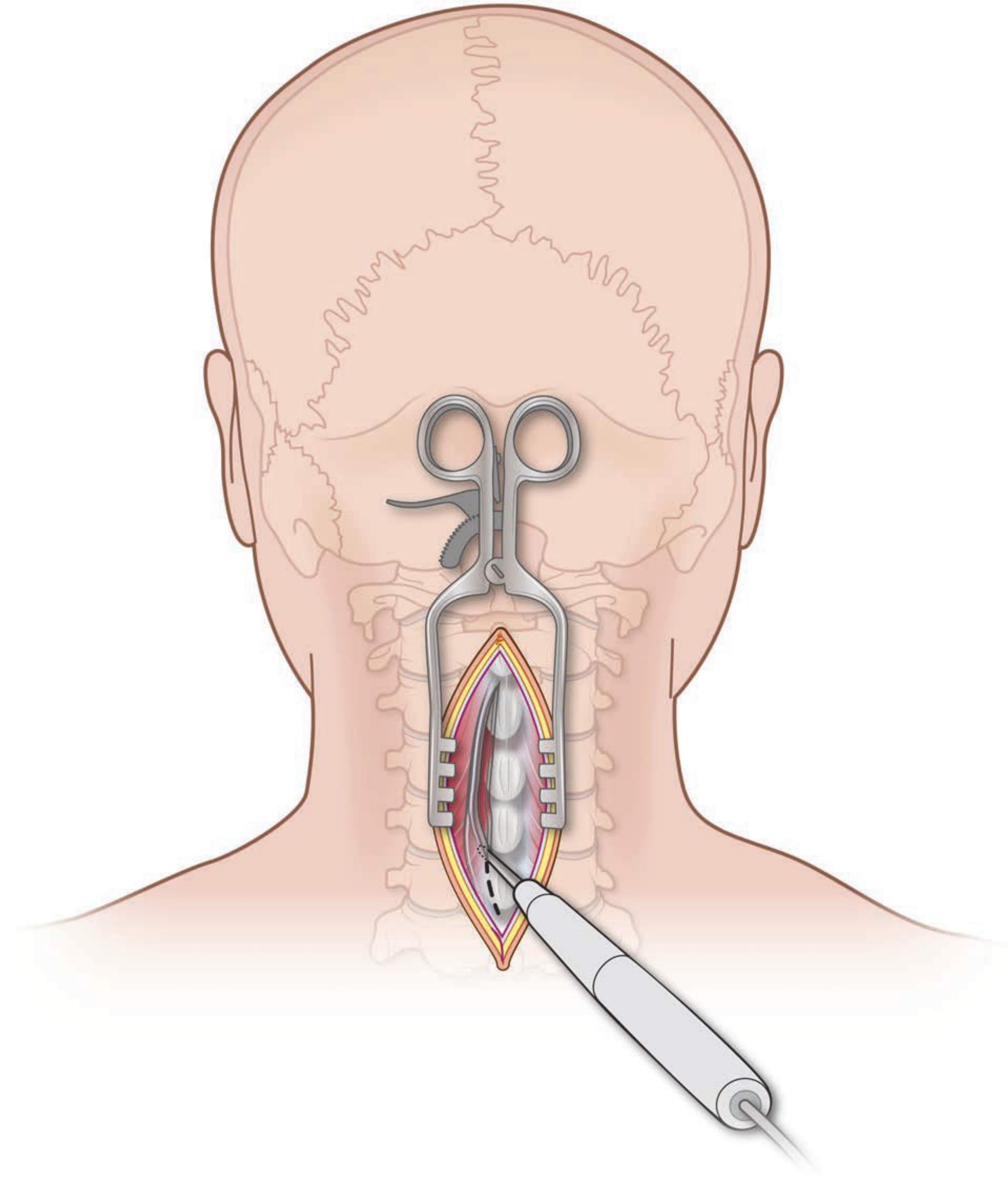


Figure	Procedural Steps	Pearls
Fig. 14.3	**After a midline skin incision is made, dissection is carried down through the subcutaneous adipose tissue and cervical fascia until the spinous processes are exposed.**	• Maintaining midline is crucial not only for localization but also for maintenance of hemostasis.

Subcutaneous Dissection (2) (Fig. 14.4)

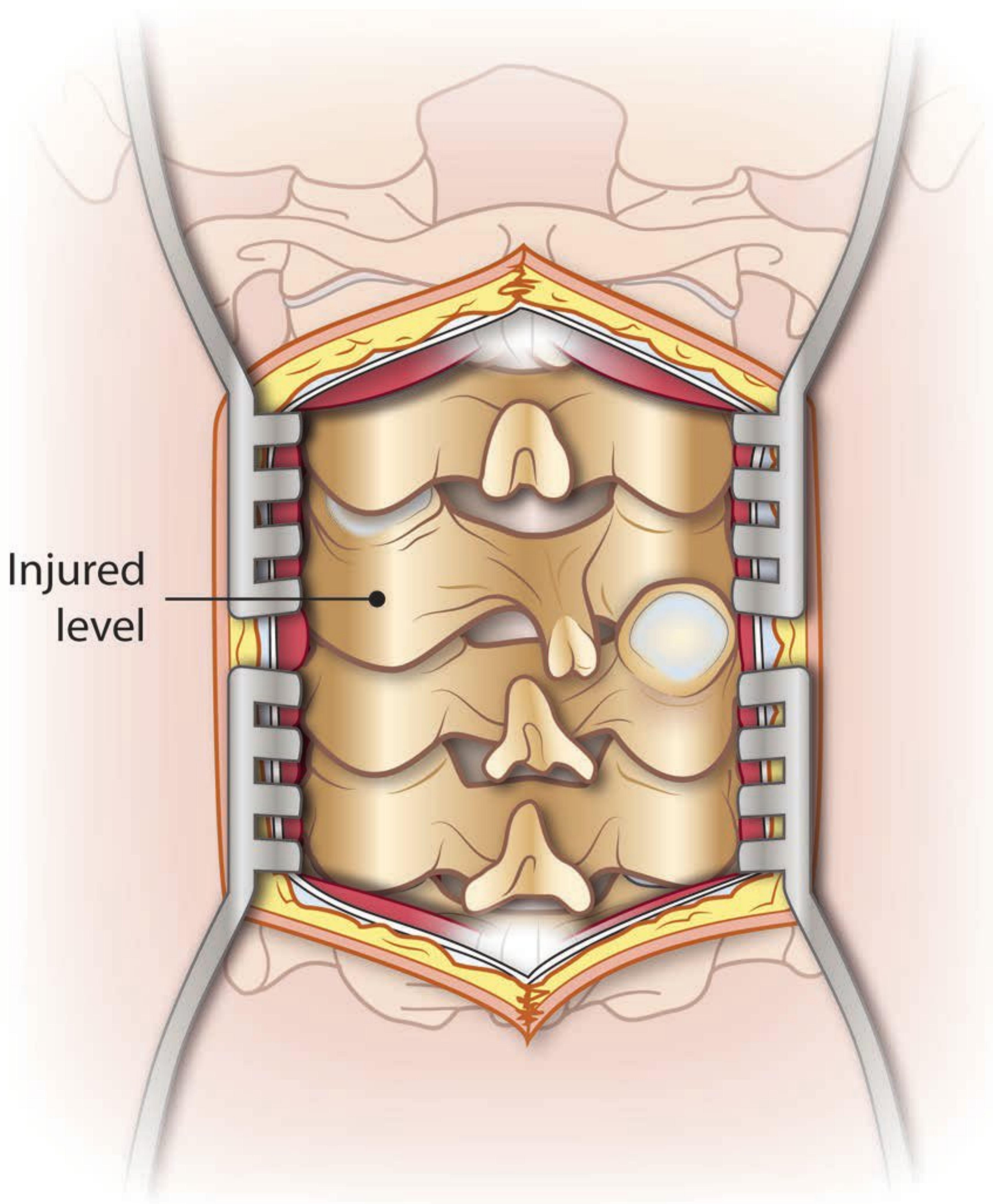


Figure	Procedural Steps	Pearls
Fig. 14.4	**Dissection of the paraspinous musculature is carried out laterally, exposing the facet joints. The muscle is mobilized in the subperiosteal plane.**	• Care must be taken to leave normal facet joints intact, especially directly above and below the injured level(s). The length of the skin incision determines the extent of lateral exposure. Lengthen the incision if needed.

Decompression and Reduction (Fig. 14.5)

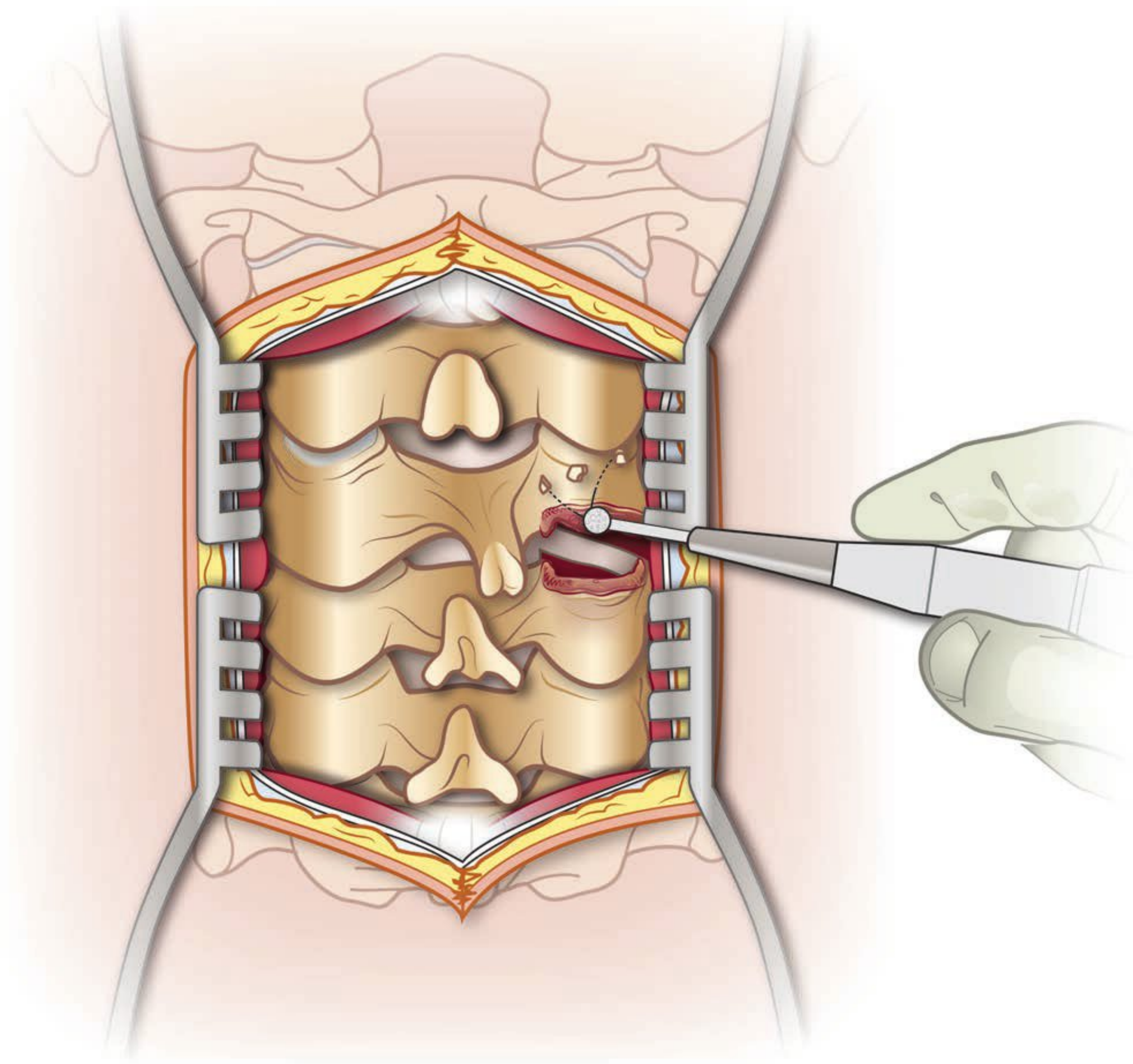


Figure	Procedural Steps	Pearls
Fig. 14.5	**Once the injured level has been identified (visually and via intraoperative X-ray), removal of compressive bony elements and reduction of the dislocated segment can begin using a series of rongeurs, punches, and curettes. Reduction may require drilling of the superior facet. Care is taken to save all bony elements for the fusion.**	• Bone removal should be limited to that which is required for decompression. Reduction of the deformity itself usually provides the decompression.

Preparation for Fusion (Fig. 14.6)

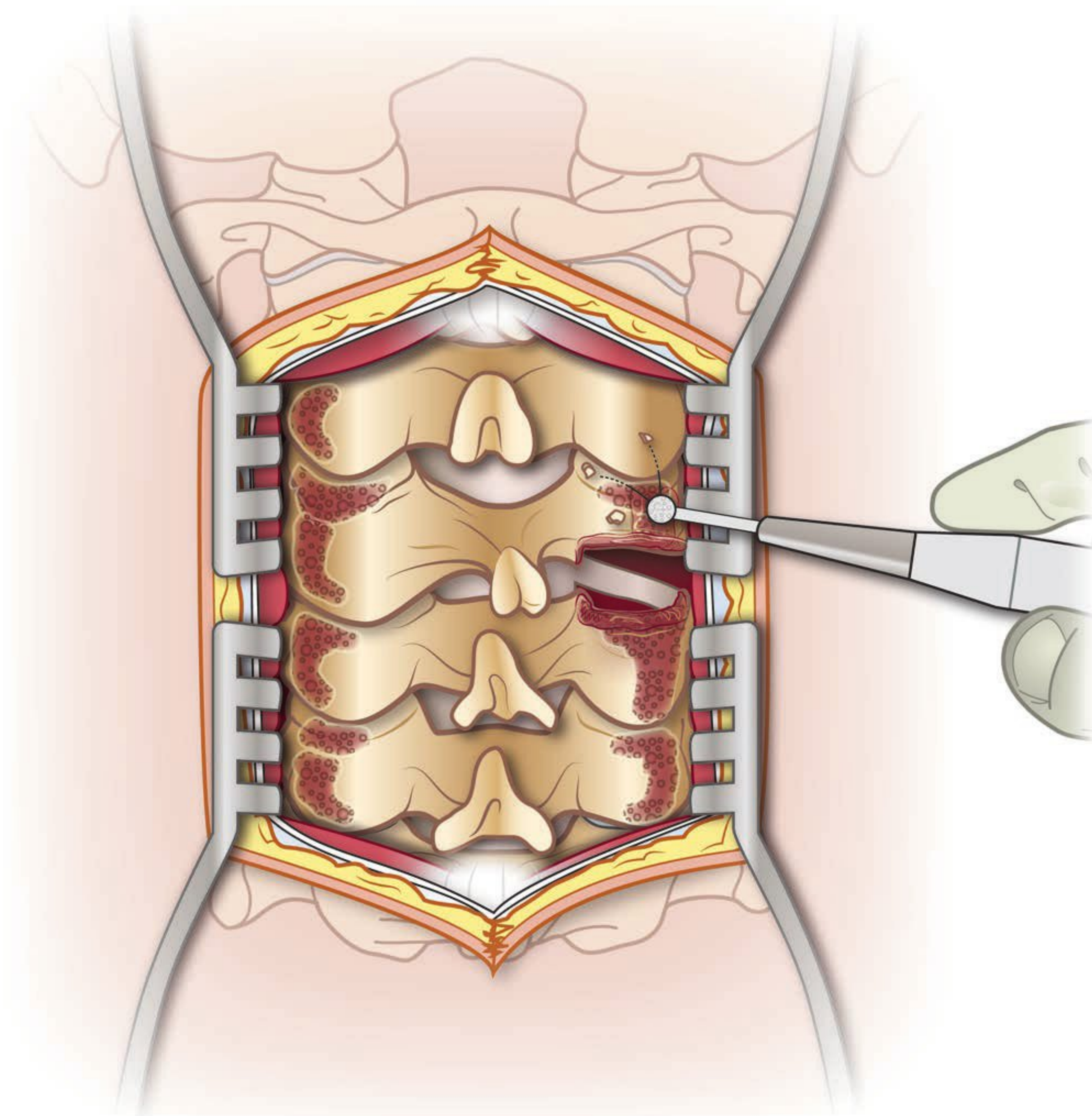


Figure	Procedural Steps
Fig. 14.6	**Following decompression, decortication of the lateral elements and usually the facet joint itself should be carried out to provide an adequate fusion substrate.**

Screw Placement (1) (Fig. 14.7a–c)

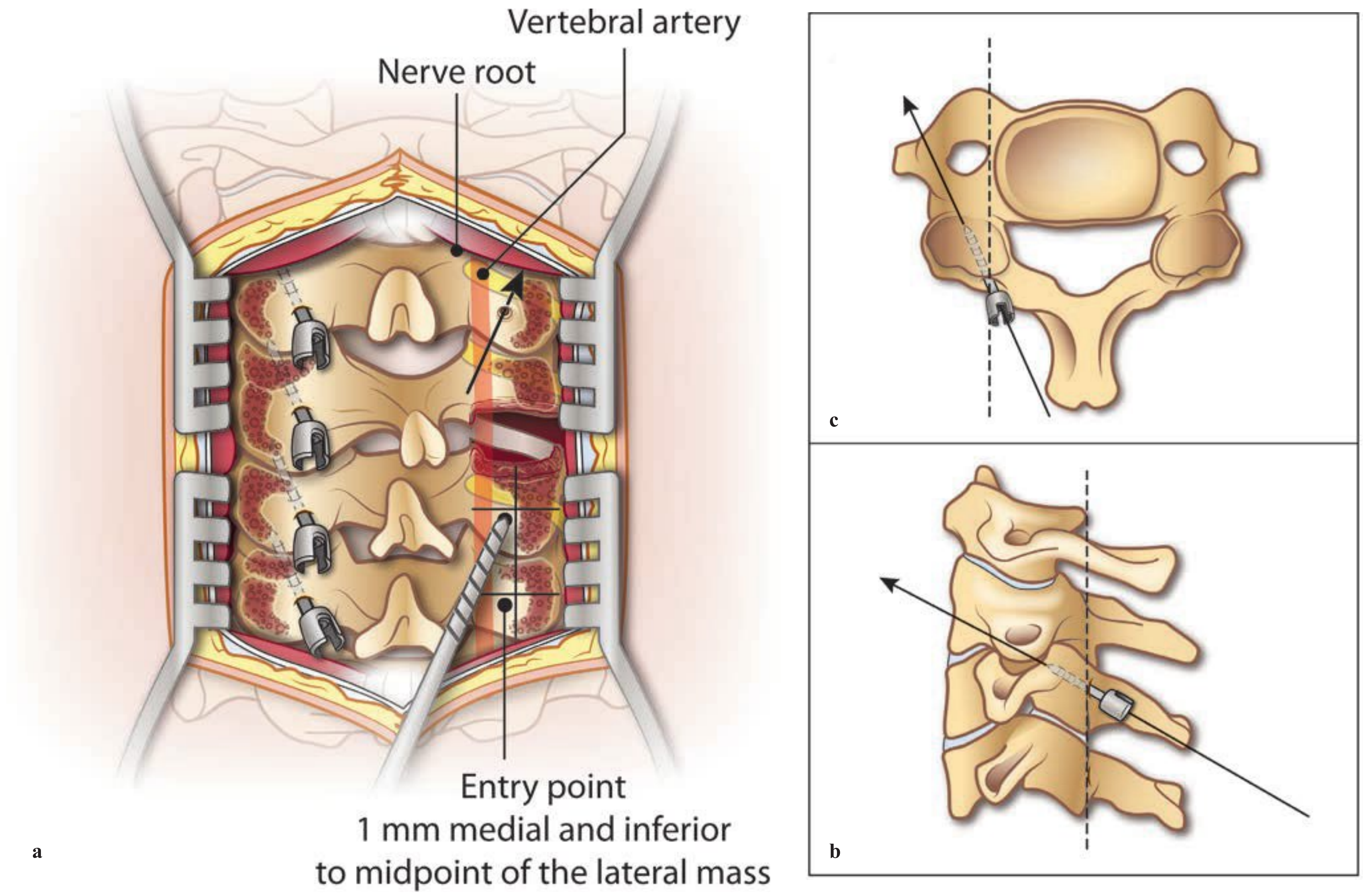


Figure	Procedural Steps	Pearls
Fig. 14.7	**The entry point is 1 mm medial and inferior to the midpoint of the lateral mass. The screw trajectory may be estimated by aligning the drill guide with the rostral edge of the subadjacent spinous process. The angle should be "up (b) and out (c)," aiming away from the vertebral artery (running underneath the medial half of the lateral mass) and the exiting nerve root and subadjacent facet (generally vulnerable if the screw trajectory is too caudal).**	• Screw length is individual and should be determined preoperatively on CT. Either unicortical or bicortical purchase is associated with excellent outcomes and clinically adequate purchase in both the anterior and posterior approaches.[17,18] If the construct crosses the cervicothoracic junction, polyaxial screws afford the greatest flexibility in rod placement. In the subaxial cervical spine, either rod-based or plate-based systems may be used with high success rates.

Rod Placement (Fig. 14.8)

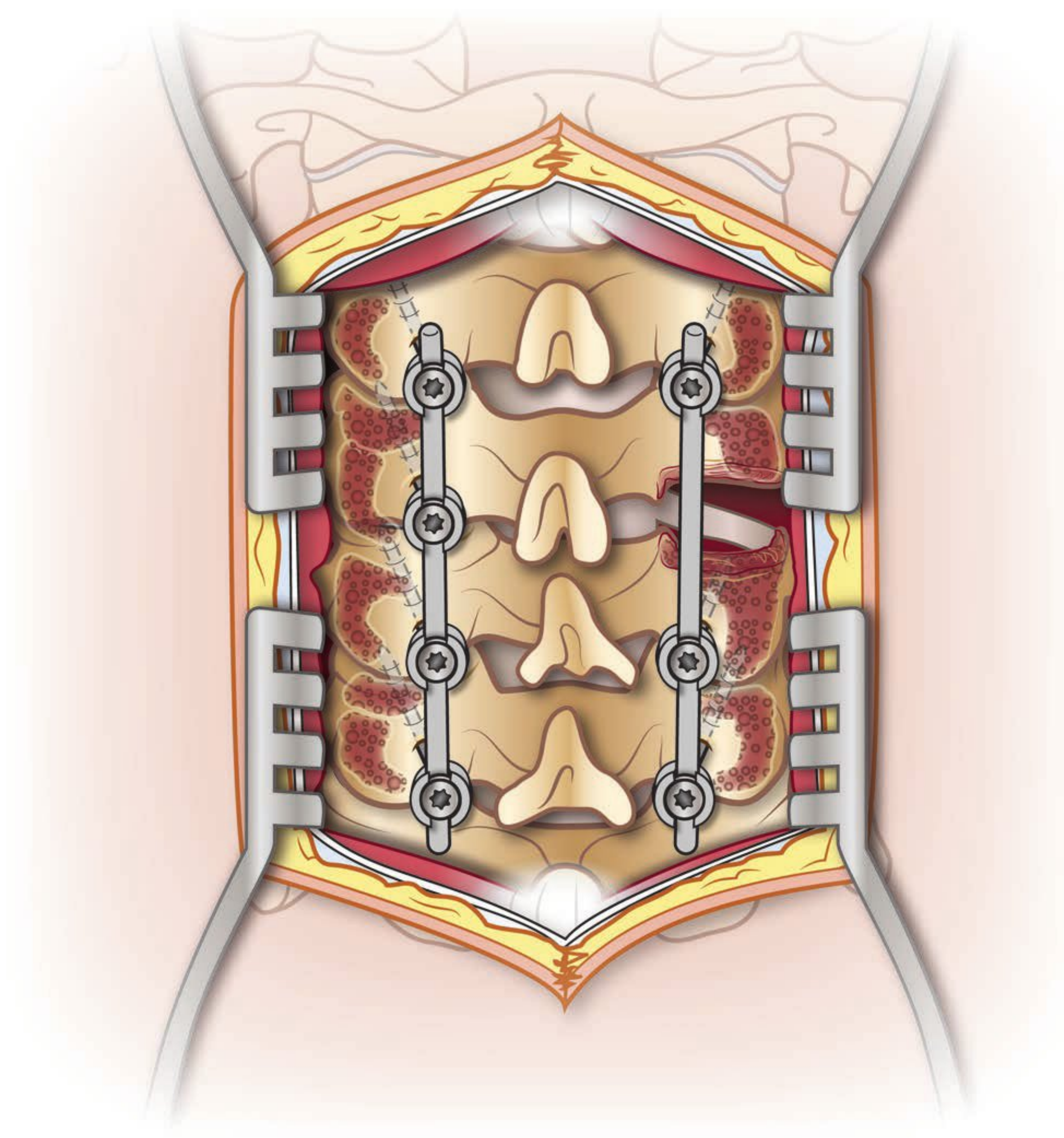


Figure	Procedural Steps
Fig. 14.8	**A rod is fashioned to recreate the natural cervical lordosis and is placed in the screw heads. The caps are tightened in place.**

Posterolateral Fusion (Fig. 14.9)

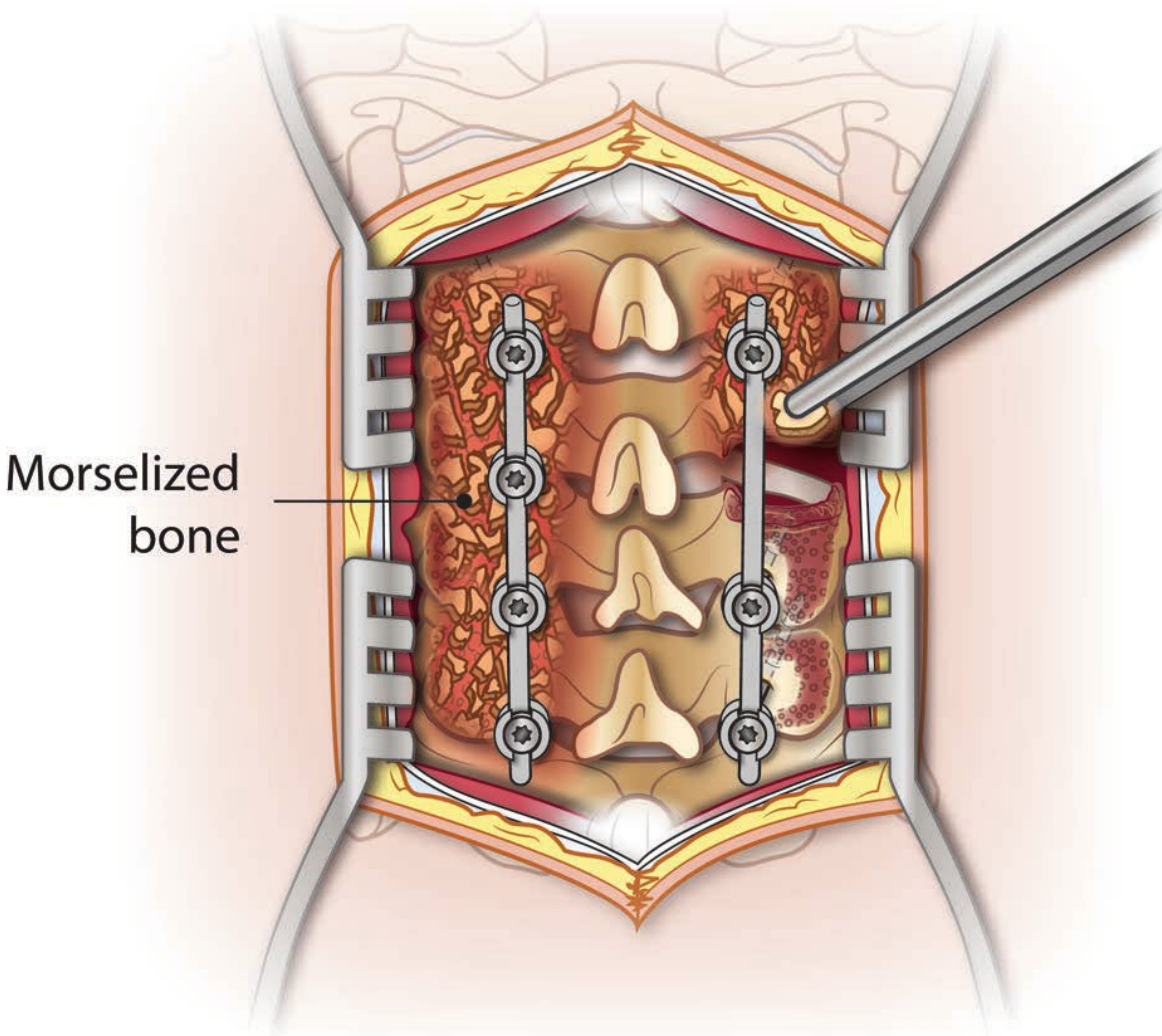


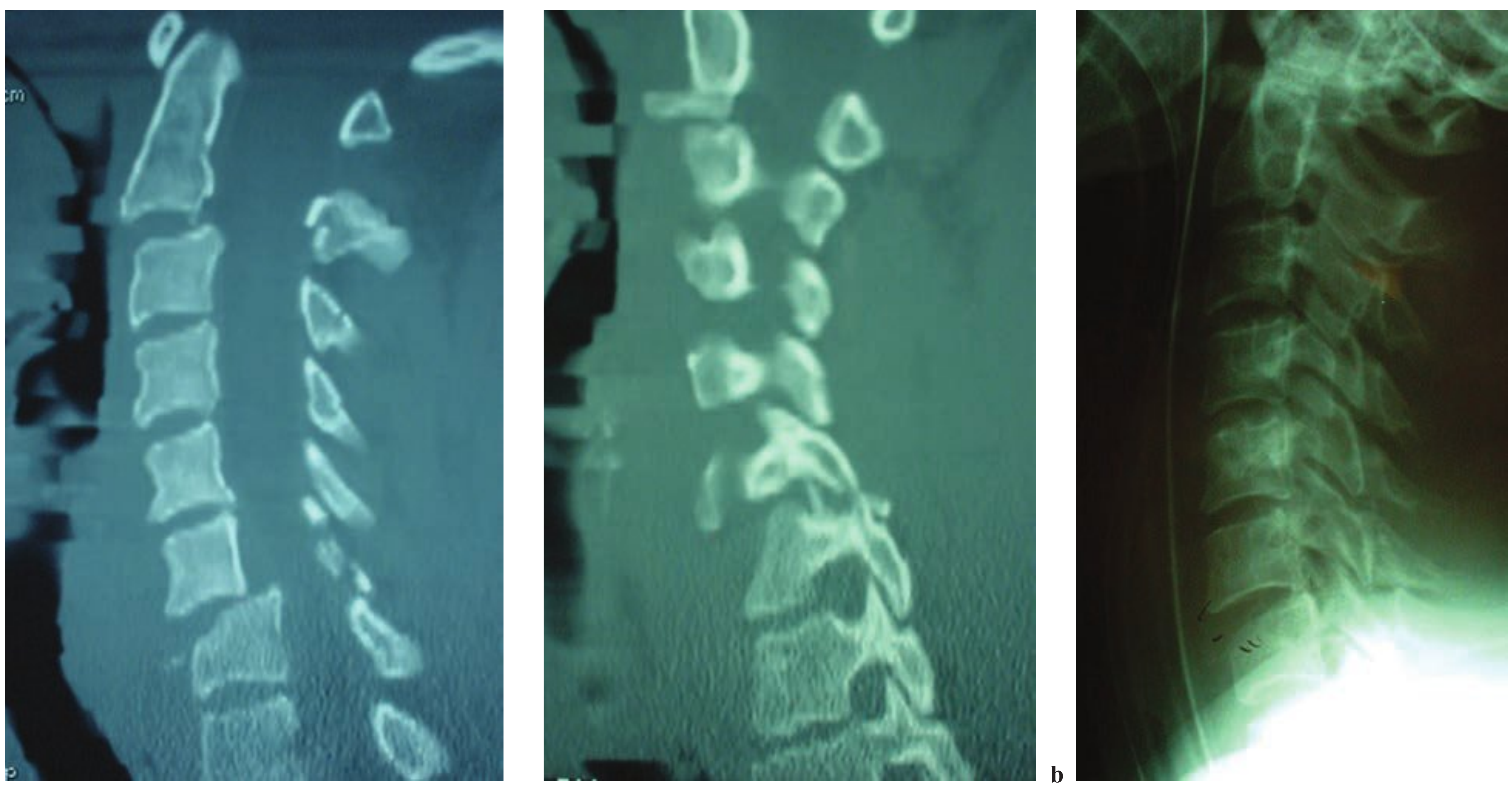
Figure	Procedural Steps
Fig. 14.9	**The bone fragments removed during the decompression, having been cleaned of all soft tissue and morselized, are placed in the decorticated facet joints and over the available lateral mass to complete the fusion.**

Closing

Posterior

- Following achievement of hemostasis, drain placement is optional. If placed, the drain should be placed in a subfascial fashion to allow closure of the cervical fascia.
- The deep cervical fascia is closed using no. 0 absorbable braided sutures in either an interrupted or running fashion.
- The deep subcutaneous tissue is closed using 2-0 absorbable braided sutures in an interrupted fashion. The purpose is to decrease the dead space available for infection. This is not a strength layer.
- The deep dermis is closed using 2-0 or 3-0 absorbable braided sutures in an interrupted, inverted fashion.
- The skin may be closed with staples, a running nonabsorbable suture, or an absorbable subcuticular suture.

Anterior Approach (Fig. 14.10a–c)



a b c

Fig. 14.10a–c Case example: reduction and anterior fixation. This middle-aged woman presented following a fall with a severe C6 (ASIA B) spinal cord injury. (**a**) Sagittal and (**b**) parasagittal CT images demonstrate the facet subluxation injury and fracture. (**c**) She was brought directly to the operating room where traction was applied, almost completely reducing the subluxation.

Positioning (Fig. 14.11)

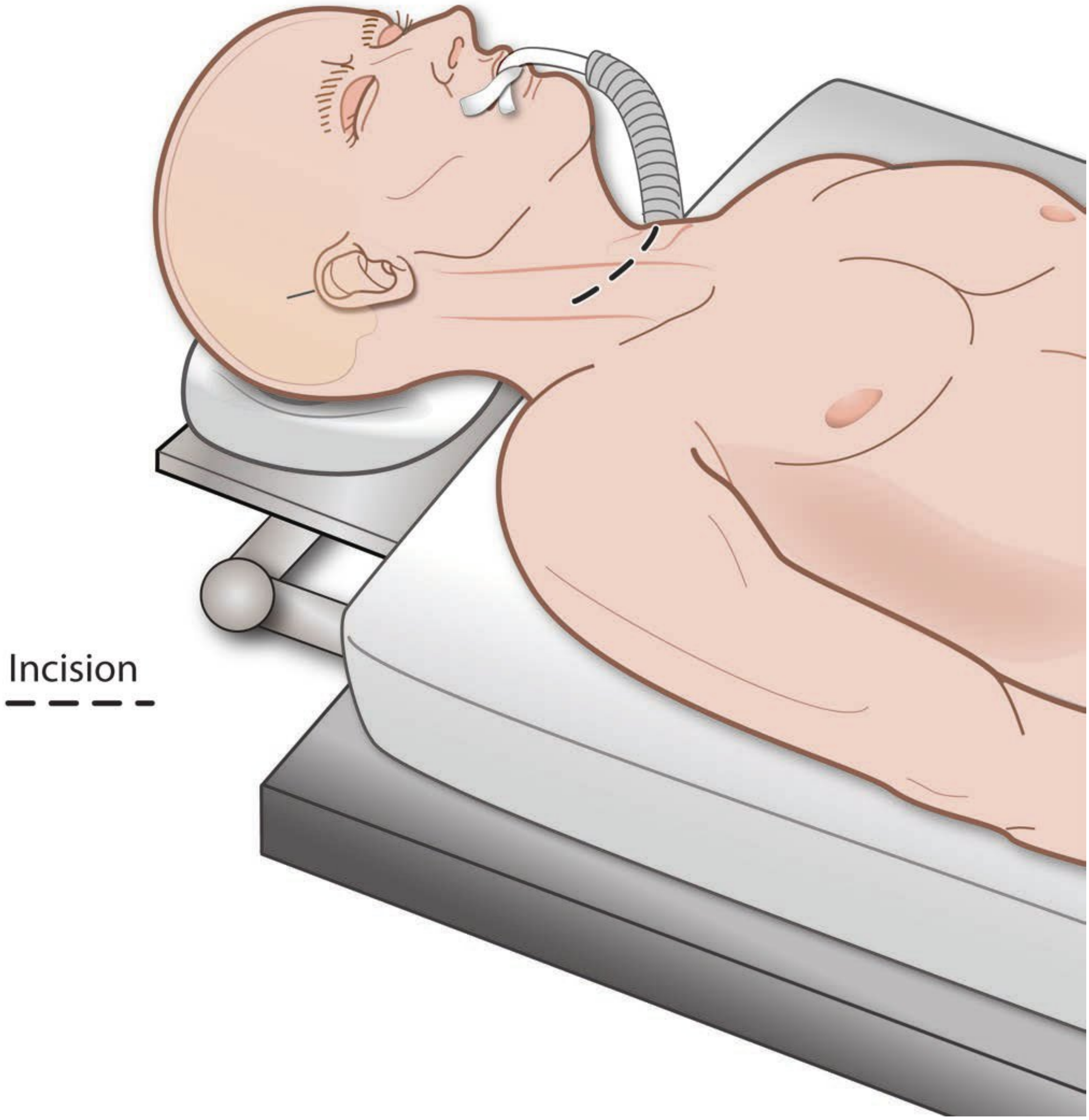


Figure	Procedural Steps	Pearls
Fig. 14.11	**The patient is positioned supine with the neck in a neutral position.**	• Gardner Wells tongs may be placed if desired for intraoperative axial traction. Removal of immobilization devices should be performed by a trained member of the surgical team who is responsible for maintaining a neutral alignment.

Opening (Fig. 14.12)

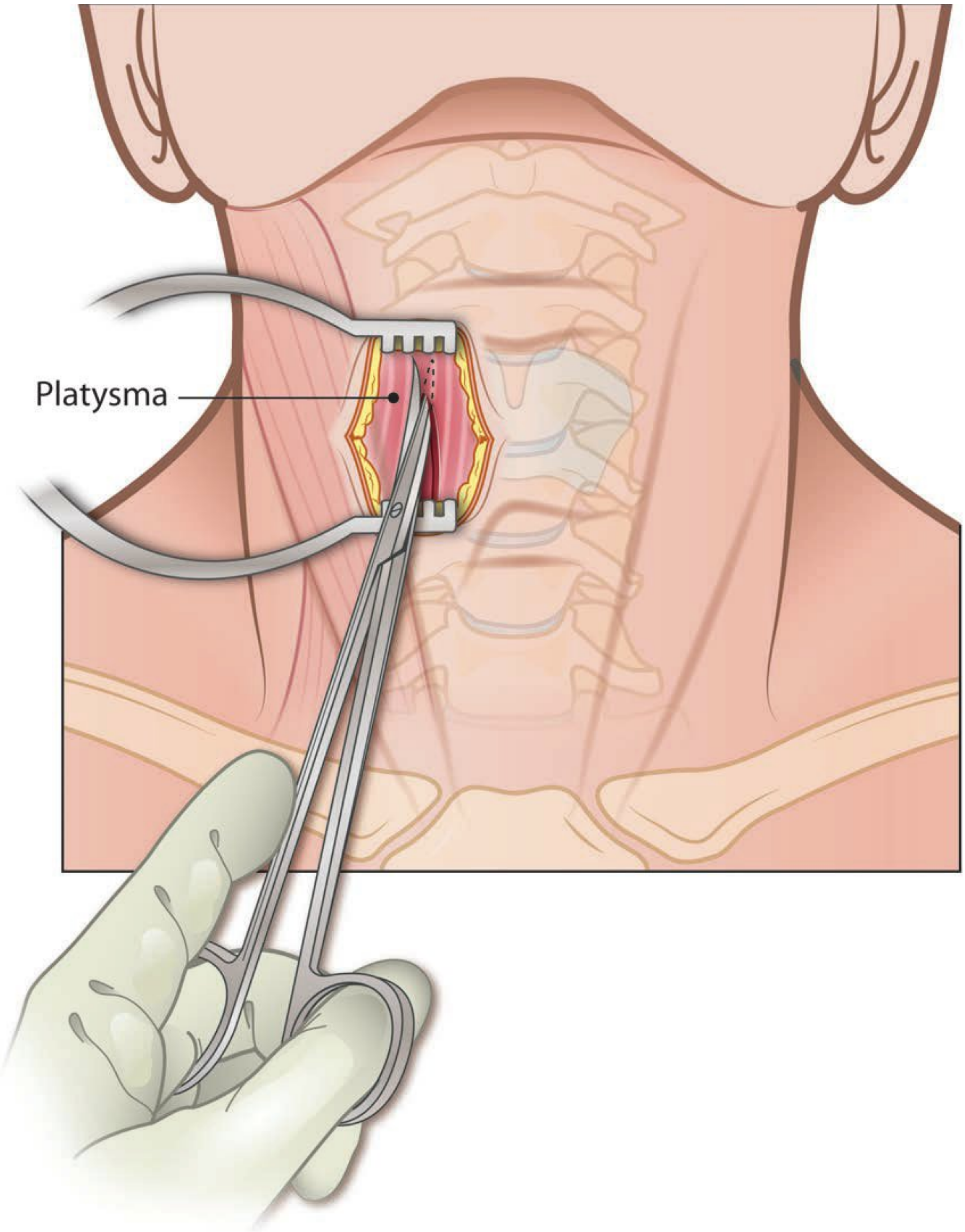


Figure	Procedural Steps	Pearls
Fig. 14.12	**An incision along the contour of the skin of the neck is made. The dissection is carried down to the platysma with monopolar electrocautery. The platysma is then divided sharply along its fibers using Metzenbaum scissors.**	• The incision typically is two-thirds anterior to and one-third posterior to the anterior border of the sternocleidomastoid muscle.

Exposure of the Spinal Column (Fig. 14.13)

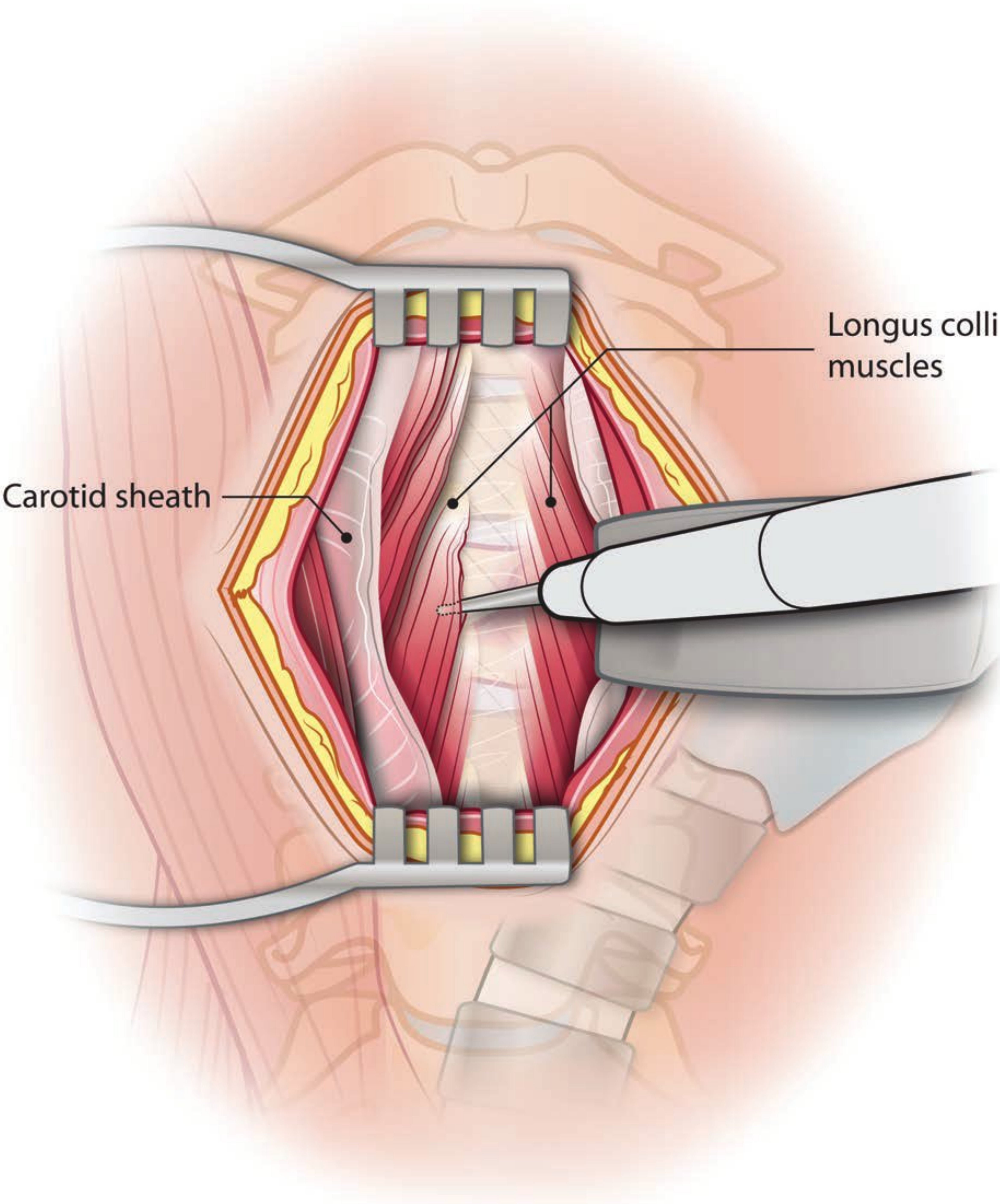


Figure	Procedural Steps	Pearls
Fig. 14.13	**With the carotid sheath and its contents retracted laterally and the trachea and esophagus medially, the prevertebral fascia and longus colli muscles can be seen overlying the bony elements of the cervical spine.**	• The space between the carotid sheath is a potential space that can be created using blunt finger dissection.

Exposure of the Vertebral Bodies and Intervertebral Disks (Fig. 14.14)

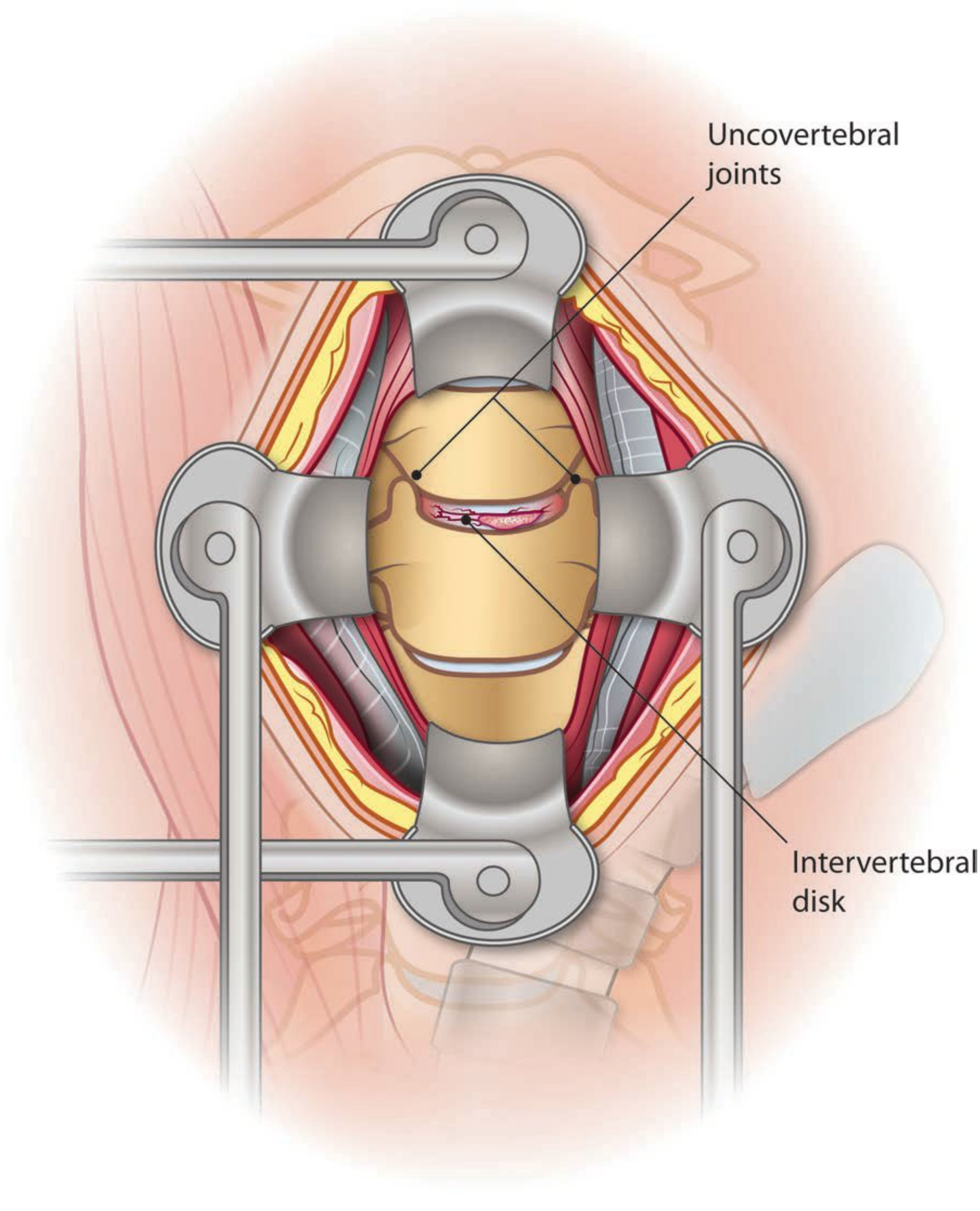


Figure	Procedural Steps	Pearls
Fig. 14.14	**The appropriate level is identified by intraoperative X-ray. The longus colli are elevated and retracted laterally so that the uncovertebral joints are exposed bilaterally. Self-retaining retractors are inserted to afford continuous exposure of the spinal column.**	• The transverse processes lie along the superior border of each vertebral column so that injury to the vertebral artery is prevented here. The opposite is true at the inferior aspects of the vertebral bodies and care should be taken to avoid indiscriminate use of monopolar electrocautery.

Diskectomy (Fig. 14.15)

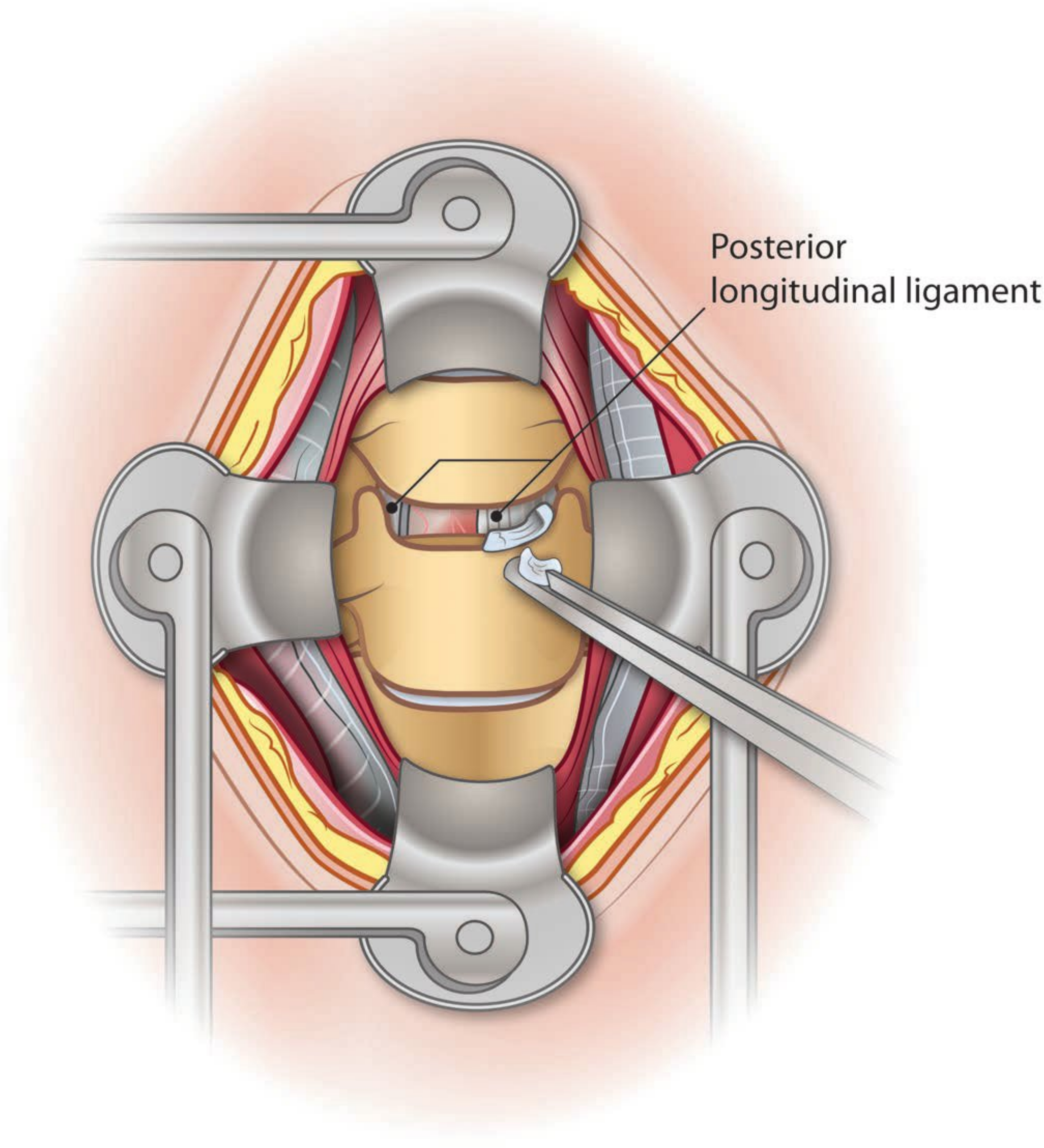


Figure	Procedural Steps
Fig. 14.15	**The intervertebral disk and the posterior longitudinal ligament are removed using Kerrison punches and pituitary instruments, resulting in exposure of the spinal cord dura.**

Reduction (if necessary) (Fig. 14.16)

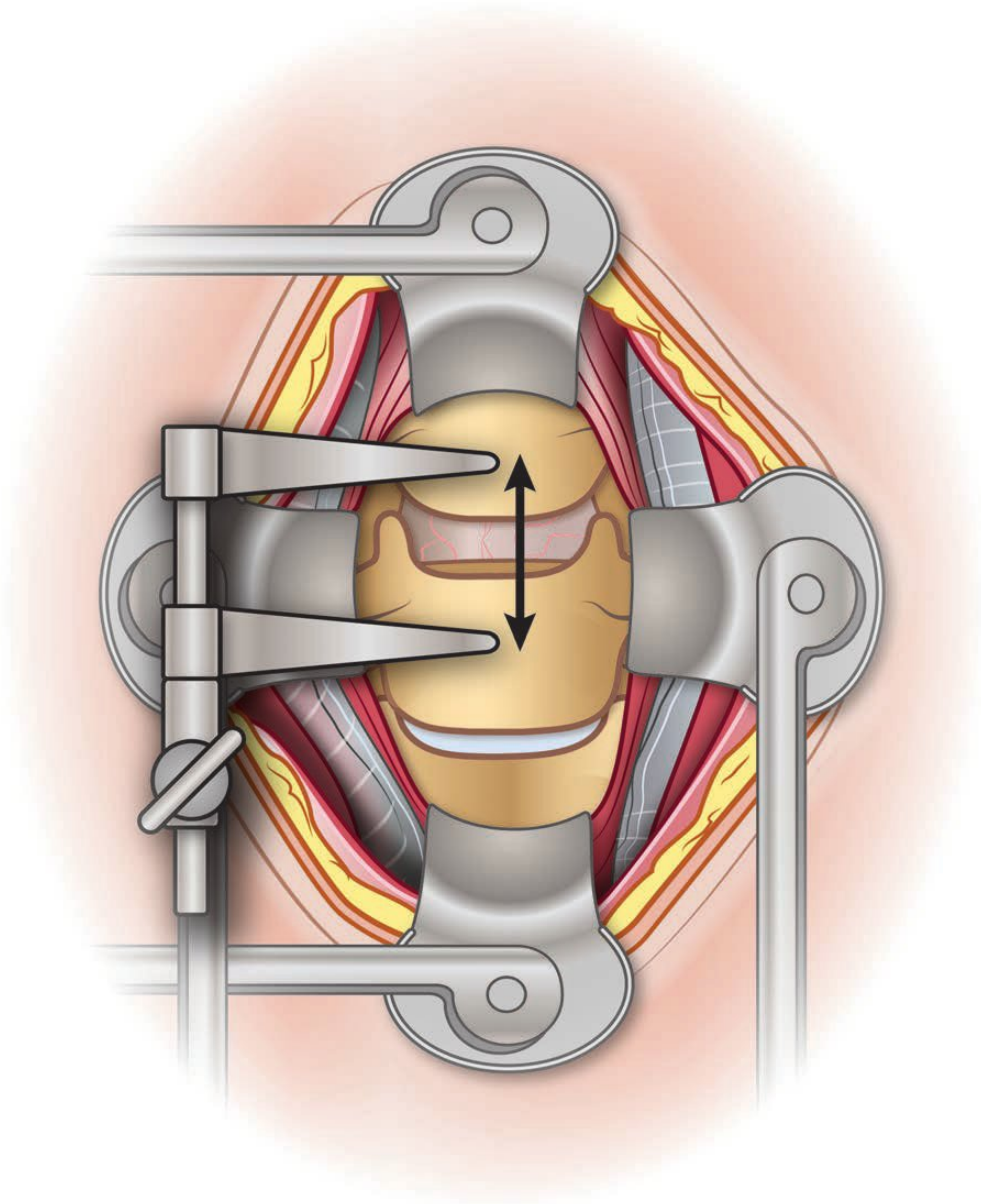
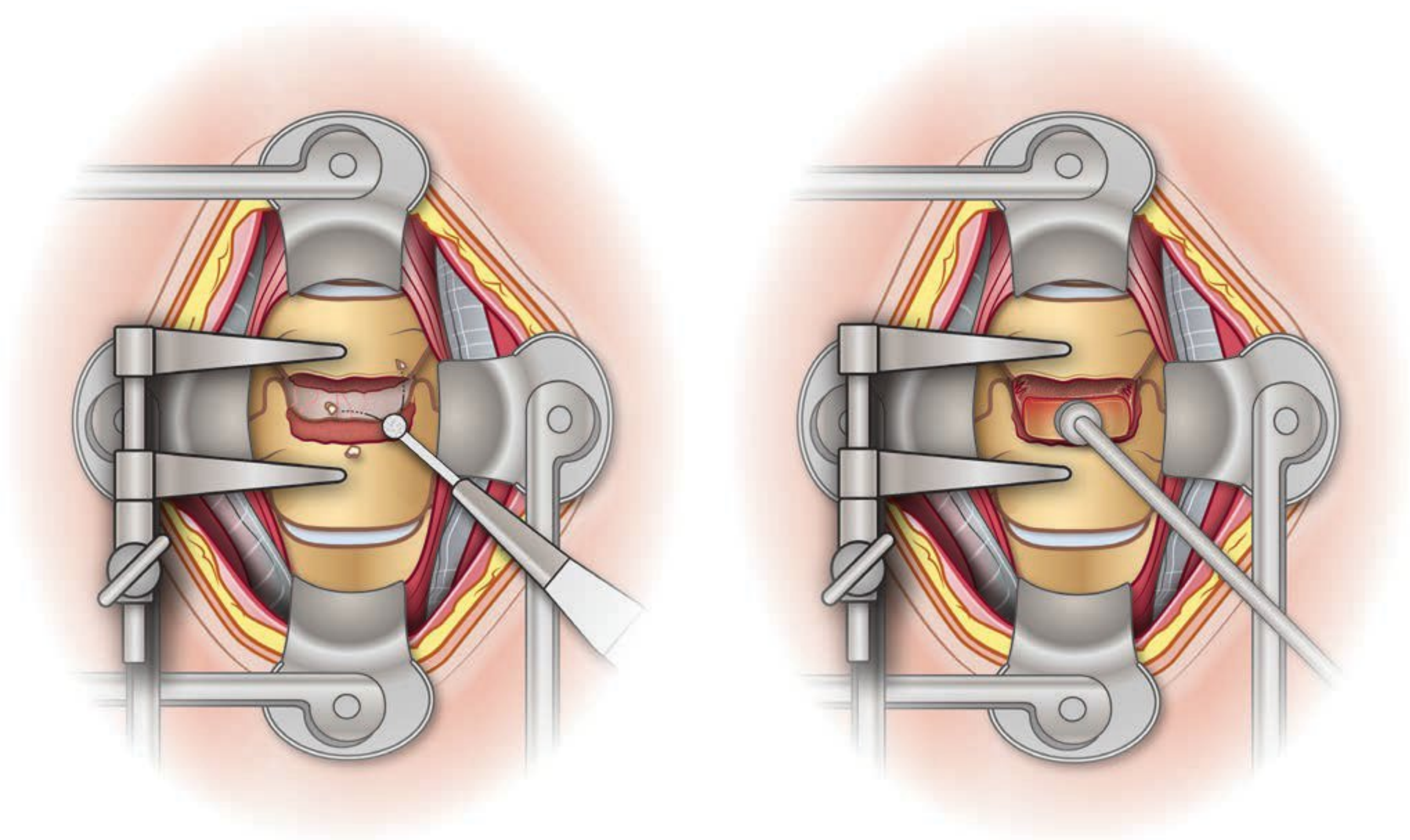


Figure	Procedural Steps
Fig. 14.16	**Caspar pins are placed into the vertebral bodies and distraction and hyperflexion is applied using either the Caspar pin appliers or pliers. Usually, the facet reduction is palpable and the vertebral bodies are then allowed to return to an anatomic position. Fluoroscopy or a lateral radiograph is used to check alignment prior to graft placement.**

Graft Placement and Fusion (Fig. 14.17a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 14.17	**(a) The vertebral endplates are decorticated. (b) A tricortical graft is then fitted in the intervertebral space. The graft should be recessed below the anterior cortical margin to avoid migration of the graft.**	• Care must be taken to avoid overdistraction due to an oversized graft.

Plating (Fig. 14.18)

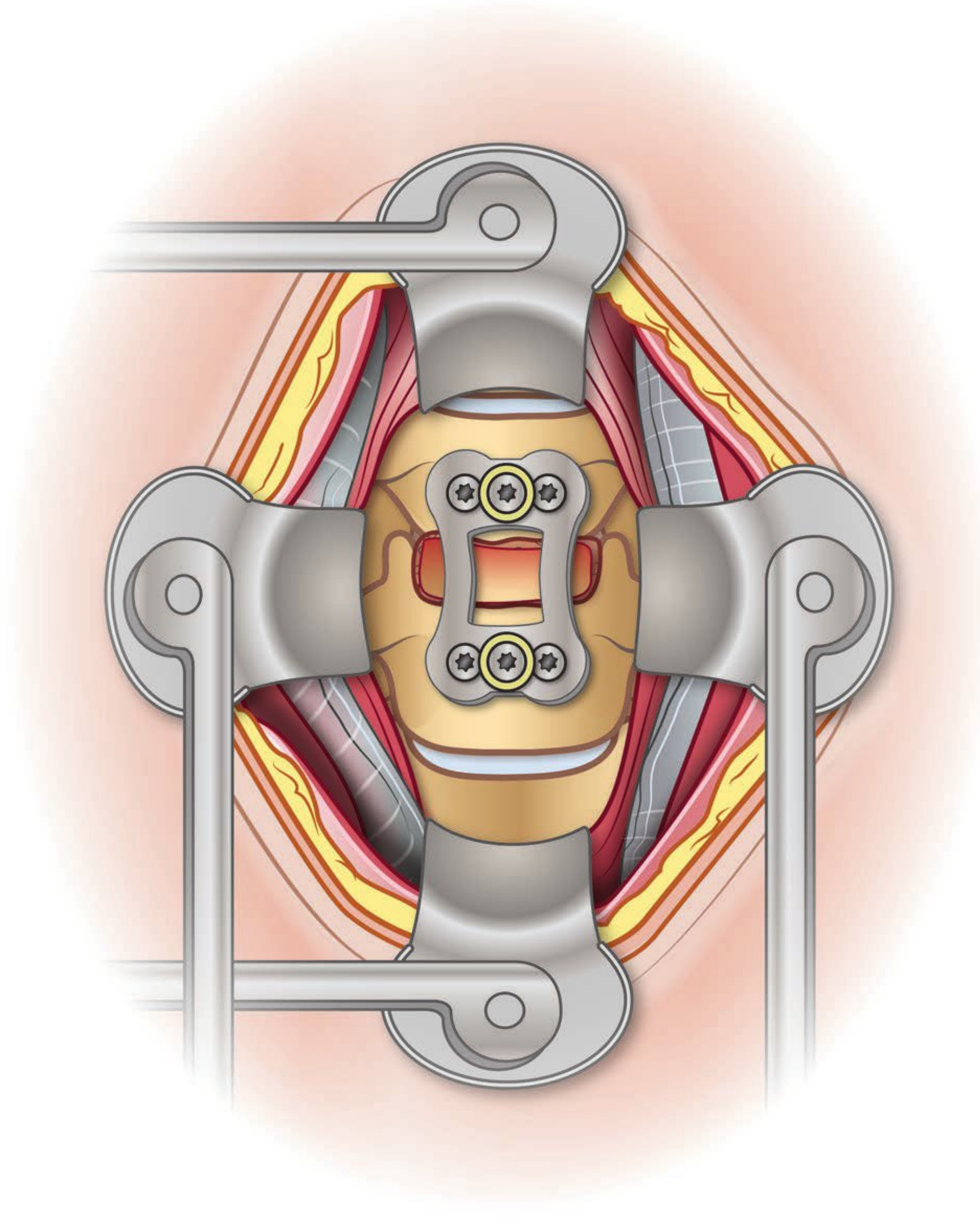


Figure	Procedural Steps	Pearls
Fig. 14.18	**An appropriate size plate is placed in the midline of the vertebral column and affixed using unicortical screws.**	• The screws are directed medially and either superiorly or inferiorly into the superior and inferior vertebral body, respectively.

Closing

Anterior

- Retraction is removed slowly with all points of bleeding coagulated using bipolar electrocautery.
- The platysma is closed using 2-0 absorbable braided sutures. The purpose is reapproximation and does not have to be water-tight.
- Dead-space closure of the subcutaneous tissue with 2-0 absorbable braided sutures is optional.
- Closure of the deep dermis is completed using 3-0 absorbable braided sutures.
- The skin may be closed using a subcuticular stitch, typically 4-0 braided or monofilament absorbable suture, a layer of fibrin glue, or a combination of the two.

Postoperative Management

Monitoring

- Patients with severe neurologic injuries are admitted to the ICU for aggressive blood pressure monitoring with the intent to maintain at least a "normal" mean arterial pressure. Patients with severe injuries frequently require fluid and pressor support to maintain mean arterial pressures of at least 85 to 90 mm Hg.[19] Pulmonary care as well as recognition of associated medical issues is facilitated by ICU placement.
- Patients with no neurologic deficits with uncomplicated procedures may be admitted to a general care floor where monitoring is routine and most commonly related to the treatment of injury-related and postoperative discomfort.

Medication

Pain Management

- Acetaminophen 1000 mg by mouth (PO) three times a day
- Oxycodone 5 to 15mg (up to 20 mg) PO every 3 to 4 hours as needed
- Gabapentin 300 mg (up to 900 mg) PO three times a day
- Diazepam 5 to 10 mg PO every 6 hours as needed for muscle spasms (optional)
- Longer acting oxycodone 10 mg PO twice a day (increase as needed)
- Narcotics and gabapentin are weaned as rapidly as possible.

Other

- All nonsteroidal anti-inflammatory drugs are avoided for at least 3 months.
- Prochlorperazine and droperidol are avoided if possible due to their sedating effects while the patients are requiring significant doses of pain medications.

Radiographic

- A postoperative CT scan may be obtained to evaluate the placement of the screws and the extent of reduction.
- Patients are followed on an outpatient basis with anteroposterior and lateral plain films of the cervical spine at 1 month, 3 months, and 6 months for evaluation of the extent of fusion. **Fig. 14.19** shows final construct of posterior approach and **Fig. 14.20** shows final construct of anterior approach.

Further Management

- It is our practice to remove drains when the output drops below 100 mL in a shift.
- Skin sutures/staples that are not absorbable are removed 2 weeks postoperatively.

Special Considerations

It is important to consider the extent of the injury in choosing an operation. While closed reduction followed by external immobilization is overall a safe modality that can be performed at the bedside,[4,20,21] it is generally most successful in injuries limited to the osseous components of the spine.[20,21] In general, facet dislocation involves the ligamentous structures of the spine in addition to the osseous elements. Therefore, internal fixation is usually felt to be more appropriate. The choice of approach is more debatable. Posterior fusion has been thoroughly studied and found to be appropriate for cervical facet dislocations.[22,23] Both anterior and posterior approaches have been successful, but the guidelines adopted by the American Association of Neurological Surgery and the Congress of Neurological Surgeons favor the posterior approach with some type of lateral mass fixation.[12]

The question of imaging for evaluation of vertebral artery injury is one of significant controversy. A 2006 meta-analysis[24] found the incidence of vertebral artery injury (VAI) in facet dislocation with or without associated fracture to be 21 to 75% (mean, 35%). VAI was more likely to occur in unilateral rather than bilateral facet dislocations. Due to significant collateral flow, only 12 to 20% of the VAIs identified were symptomatic. The 2002 guidelines,[25] in a statement regarding VAI, recommended against anticoagulation for asymptomatic patients as the inherent risk of anticoagulation itself was roughly equivalent to the risk of stroke inherent to a VAI. The 2013 guidelines[26] supports CT angiography in select patients meeting clinical (symptoms and signs) and radiographic criteria. In addition, treatment decision for VAI (anticoagulation, antiplatelet therapy, observation) should be based upon clinical circumstances. The question then is whether to image the patient in order to detect these injuries. In following the guidelines, if the patient is asymptomatic, vascular studies to identify asymptomatic injuries are not necessary as they would not change management. If there are imaging studies planned for other reasons, consideration can be given to imaging of the vertebral arteries.

a

a

Fig. 14.19a, b Postoperative images of patient depicted in **Fig. 14.1**. (**a**) Once stabilized, he was brought to the operating room for an open posterior reduction and (**b**) stabilization using lateral mass screws in the mid cervical spine and pedicle screws in C7 and T1.

Fig. 14.20 Postoperative image of patient in **Fig. 14.10**. An anterior cervical diskectomy and fusion were performed with completion of the reduction achieved through direct manipulation of the vertebral bodies using vertebral pins. Plate fixation provided immediate stabilization and she was discharged to rehabilitation in a collar for 6 weeks.

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15 Classification and Treatment of Thoracic Fractures

Joseph Hsieh, Doniel Drazin, Michael Turner, Ali Shirzadi, Kee Kim, and J. Patrick Johnson

Introduction

Thoracic fractures in healthy individuals are uncommon due to the stabilizing effect of the rib cage. However, high energy trauma and predisposing conditions can increase the likelihood of fracture.[1] Although there is no ideal standard for classification of thoracolumbar (TL) injuries, the evolution of the three-column model of Dennis, the AO/Magerl comprehensive classification, and thoracolumbar injury severity scale and score (TLISS)/thoracolumbar injury classification and severity score (TLICS) point system have provided significant insight into anatomy, mechanism of injury, and the implications and therapies for instability.[2–4] Multiple surgical techniques address spinal instability, but the choice of surgery depends on the level of injury and anatomy.

Indications

The goal of thoracic spine fracture treatment is preventing deformity, providing stability, and protecting the neural elements. If conservative management is deemed insufficient to provide these goals, then surgical management should be considered. Surgery should be also considered as an adjunct to hasten rehabilitation, shorten hospital stays, and particularly in cases of multiple injury.

Anatomy

The thoracic spine is the longest spine segment and a common site for trauma, especially at its lower segments (T10-T12).[5] The thoracic spine consists of 12 vertebrae with a physiologic kyphotic curve due to wedging of the thoracic vertebrae (a 2- to 3-mm difference in anterior and posterior height).[6]

Bony Structure

- The vertebral bodies (VB) anteriorly are load bearing and the arches posteriorly resist tension. The anteroposterior (AP) diameter of the VB increases from T1 to T12, while the transverse diameter decreases from T1 to T3 and then increases to T12.[7]
- The VB sides are concave and the laminae are broad and heavily overlapped. The pedicles project from the superior VB posteriorly. The laminae extend dorsomedially from the pedicles to fuse and form the dorsal wall of the spinal canal.

Facets

- The articular processes arise from the superior and inferior laminar surfaces.
- From T1 to T10, the thoracic facets are oriented coronally. This minimizes anterior translation during flexion. From T11 to T12, the facets have an oblique sagittal orientation to limit rotation.
- The coronal facet orientation of the upper thoracic spine allows for rotation around the craniocaudal axis (75 degrees of rotation to each side) with the greatest rotation at T8-T9.[8] In contrast, lumbar spine rotation is limited by the orientation of the facets and anterior annulus to only 10 degrees.

Ribs

- The most distinguishing features of the thoracic spine are the ribs and their two vertebral articulations. Specifically, the rib heads articulate with the vertebrae and the disk. The rib tubercle articulates with the transverse process at the costotransverse articulation.
- Demifacets above and below the disk articulate with the head of the rib to form the costovertebral joint (a synovial joint divided by an intraarticular ligament into two separate compartments).
- Overall, the rib cage provides the thoracic spine with two to three times the load bearing capacity before instability relative to other spine segments. Sagittal and lateral flexion-extension are also stabilized. Therefore, high mechanical forces must occur to cause thoracic vertebral injuries—often with concurrent injuries to the chest, cervical spine, and head.[9]
- The radiate and costotransverse ligaments bind the ribs to their vertebrae additionally and provide stabilization.[10]

Spinal Cord

- The thoracic canal is narrowed with less free space for the spinal cord compared to the cervical spine.
- The central thoracic spine also has a limited blood supply, with a lower threshold for vascular cord injury on kyphosis or compression than the lumbar spine.
- Spinal cord injury to the upper thoracic spine can have devastating sequelae while root injury in the thoracic spine is far less functionally relevant than in the lumbar spine.

Evaluation and Diagnosis

Initial evaluation of trauma involves assessment for serious life-threatening injuries with rapid resuscitation as necessary.

Spinal injury, while common in multiple-system trauma, is frequently unrecognized.[11]

Physical Spine Examination

- A thorough spine examination is critical in the initial comprehensive trauma evaluation.
- Direct examination includes visual inspection and palpation of all spinal segments.
- A step-off, localized tenderness, or a soft spot (from laceration, swelling, or ecchymosis) may be the only sign of instability.
- Soft-tissue trauma to the chest or abdomen may suggest a seat-belt injury with a TL flexion-distraction injury.

Neurologic Examination

- Neurologic exam should include motor strength, sensory function, and reflexes.
- If spinal cord injury is suspected, serial exams are necessary as the neurologic exam may change, especially in settings of instability.
- Grading by the American Spinal Injury Association (ASIA) Impairment Scale documents the level and severity of the spinal cord injury.
- A repeat evaluation should be performed if initial evaluation is inadequate.
- Patients with spinal cord injury should be tested for perianal sensation, rectal tone, and bulbocavernosus reflex. Any suspicious findings warrant imaging.
- Spine precautions should remain in place until spinal trauma is excluded.
- Spinal fractures are missed frequently in settings of multiple injuries.[12–15]

Indications for Conservative Management

- Conservative management should be considered anytime a patient can maintain alignment and neurologic stability without surgery.[1] Stable fractures such as uncomplicated compression fractures may not require bracing as the rib cage and sternum buttress the spine.

Orthoses

- If support is needed, compression fractures are routinely treated with an orthosis often with inclusion of the cervical spine. Cervical support could include a mandible, occipital pads, or halo ring and may consist of a cervicothoracic orthosis (CTO) or cervicothoracolumbosacral orthosis (CTLSO).
- Orthoses and casts should be used with caution
  - Sensory deficits may lead to wound breakdown due to pressure ulcerations from an orthosis. Skin contact should be checked frequently and routinely. Emaciated patients with poor soft tissue padding are especially at risk.
  - Orthoses and casts maybe difficult for patients to remove and the fit may need to be adjusted over time.

Indications for Surgical Management

- Surgical decompression is indicated when there is neural compression with worsening neurologic deficit, which may include worsening myelopathy or radiculopathy.[1]
  - In cases where the injury is complete, ASIA A, surgery will likely not result in neurologic improvement; however, stabilization of the spine may be beneficial in facilitating rehabilitation and patient transfers.
- Surgical stabilization is indicated for worsening neurologic deficit, disrupted posterior ligamentous complex (PLC), dislocation of the thoracic spine, failure to obtain or maintain correction by nonsurgical means, unacceptable deformity, and intolerance to nonsurgical management.
  - Denis described a three-column model of the spine.[2] Many believe that mechanical instability results from disruption of two or three of the three columns.
  - The TLICS/TLISS provides guidelines for when surgical intervention is warranted.[4]
- While a compression fracture of the anterior column may be mechanically stable in the short term, significant kyphosis or VB collapse may lead to progressive deformity over time.
  - Cohen et al recommend operative reduction and fusion for any neurologic dysfunction that meets the following criteria[16]:
    - If any of the compressed vertebrae wedge fractures measure over 40%in a young or middle aged adult
    - If the compression percentages for the adjacent vertebral wedge fractures combine to greater than 50%
    - Acute kyphosis is present
  - Munting recommends surgery when significant pain combined with altered function is reported for a posttraumatic deformity exceeding 20 degrees of sagittal index.[17]
    - Pain is often located about the apex of the deformity. This kyphotic deformity may lead to compensatory hyperlordosis in the lumbar spine and/or hypokyphosis or even lordosis in the thoracic spine above the lesion and cause painful muscle spasm.
    - Other indicators for surgery include inability to maintain straight vision due to severe kyphosis, pseudoarthrosis, disk degeneration, progressive neurologic deficit, and cosmesis.

Preprocedure Consideration

Radiographic Imaging

Correct diagnosis with physical exam may be difficult, particularly in patients with altered mental status, patients who are intubated or sedated, and patients with multiple pelvis or limb fractures. Initial imaging (plain radiography or CT) is crucial in these cases.

Plain Radiography

- AP and lateral plain X-rays of the thoracic and lumbar spine allow the physician to count the number of rib-bearing vertebrae and the number of lumbar vertebrae to ensure accuracy of surgical planning. Care should be taken to evaluate for possible anatomic variants (e.g., cervical ribs or lumbarized sacral vertebrae). However, the upper thoracic column is poorly visualized on plain radiography.

Computed Tomography

- Modern computed tomography (CT) allows rapid characterization of spinal fracture morphology and provides critical detail in the acute and therapeutic setting.[1] In a study by Smith et al, nonreconstructed CT detected TL fractures more accurately than plain radiographs and is recommended for diagnosis of TL fractures in acute trauma for patients with altered mental status.[18]
- Information includes canal narrowing due to retropulsed fragments, better evaluation of unstable rotational injuries, and indirect assessment of ligamentous and disk injuries.
- Facet dislocation and posterior interspinous widening due to distraction may demonstrate a "naked facet sign."
- CT myelogram may demonstrate areas of compression of the thecal sac.

Magnetic Resonance Imaging

- Magnetic resonance imaging (MRI) demonstrates associated soft tissue injury that will not be visible on the CT.
- Occasionally decompression of the spinal cord from these soft tissue elements will be indicated even for fractures that appear to be stable on CT.
- If the fracture appears to be associated with some pathology, then it may be helpful to include enhanced images in the MRI to determine if the bone appears to have an associated infection or tumor.

Medication

- Steroids have had waxing and waning popularity in the setting of acute spinal cord injury. If there is a neurologic injury, some reports have indicated that high dose methylprednisolone has given some benefit.[19] However, these initial reports has not been replicated, and the risk to the patient concomitant with steroid use including life-threatening infections is not inconsiderable.[20] Recent guidelines have recommended against their use.[21]
- Antibiotics: If the patient has an associated infection, it may be beneficial to obtain a specimen for culture prior to starting antibiotics. Otherwise standard preoperative antibiotics are used, typically cefazolin.

Operative Management

Guidelines for Management

- There is no consensus on the best treatment for TL spine injuries. As a rule of thumb, posterior decompression (e.g., laminectomy) may be effective for posterior spinal cord compression in a stable spine. However, laminectomy without instrumentation may destabilize a spine that already has damage to another column and therefore is inappropriate whenever stability is in question. For anterior compression, typically anterior approach is preferred with consideration of anatomic limitations.
- McAfee et al provided one of the earliest general treatment guidelines based on specific injury patterns.[22]
  - Compression fracture: observation with follow-up or prefabricated brace immobilization for 12 weeks
  - Stable burst: custom fitting orthosis or cast immobilization for 12 weeks. L4 and above: TLSO; L5: HTLSO; if kyphosis . 15 degrees, hyperextension cast.
  - Unstable burst: surgical decompression and stabilization (approach controversial). Consider emergent posterior short-segment decompression and fusion (with external immobilization in a custom TLSO for 12 weeks), and delayed anterior decompression and fusion if the patient has neurologic deficit and residual cord/root compression.
  - Flexion-distraction (and Chance injury): consider hyperextension cast for a purely osseous injury with no associated neurologic deficit. Consider posterior short-segment stabilization and fusion for associated neurologic injury or abdominal injury or when spine injury is primarily ligamentous.
  - Fracture-dislocation: posterior long-segment surgical stabilization with pedicle screw fixation two to three levels above and below the injury with local bone graft fusion.
- In the 1990s, the first multicenter study (MCSI) of the Spine Study Group of the German Association of Trauma Surgery showed limitations for isolated posterior instrument and fusion techniques in cases with a compromised anterior column.
- Since then, operative approaches and adjuncts have advanced considerably to include endoscopic and minimally invasive surgery—advances in interbody support and intraoperative navigation.
- The second multicenter study (MCSII) of the Spine Study Group of the German Association of Trauma Surgery reviewed traumatic TL (T1-L5) injuries as an update to MCSI. Of 733 patients with acute TL injuries treated surgically[23]:
  - 380 (51.8%) patients were operated on by posterior stabilization and instrumentation alone
  - 34 (4.6%) had an anterior procedure alone
  - 319 (43.5%) had combined posteroanterior procedures.
  - Overall they found:
    - Short angular stable implant systems have replaced conventional nonangular stabilization systems.
    - Posttraumatic deformity was restored best with combined posteroanterior surgery.
    - Different surgical approaches did not have a significant influence on neurologic recovery on 2-year follow-up.
    - Five percent of all patients required revision surgery for perioperative complications.
- The most common surgical interventions for thoracic injuries are described below.

Operative Field Preparation

Positioning

- The patient is intubated supine and then positioned carefully as needed.
- Pressure points are padded.

- Intraoperative monitoring including somatosensory evoked potentials (SSEP) and motor evoked potentials should be considered.

Localization

- Imaging and physical exam review is critical to determine the surgical levels. Preoperative imaging may include localization using cross table lateral plain films with a radiopaque marker.

Prior to Incision

- The skin is prepped in sterile fashion and the incision is infiltrated with lidocaine 1% with epinephrine 1:100,000

Approaches

Surgical approaches to the thoracic spine can be divided into posterior, posterolateral, and anterior. These approaches can also be combined in the same procedure or staged. Ultimately, the approach will depend on the pathology, location, spinal cord compression, instability, and medical condition.

Posterior Approach

Posterior approaches to the thoracic spine are the mainstay of spine procedures. The ideal pathology for these approaches is generally posterior to the spinal cord. The most common posterior approach (laminectomy with or without instrumentation) is used commonly for radiculomyelopathy from thoracic disk herniation, spondylosis, and trauma with stable spine along with some tumors and infection. However, it is difficult to access ventral pathology without risk of spinal cord injury.

These approaches can be tailored for access to a region of interest from directly midline to the spinal canal (e.g., laminectomy) to further posterolateral in attempts to reach anterior to the canal (e.g., transpedicular, costotransversectomy, lateral extracavitary approaches).

Posterolateral Approaches to the Anterior Thoracic Spine

Posterolateral approaches to the anterior thoracic spine include the transpedicular, costotransversectomy, and posterolateral extracavitary. These provide progressively greater visualization of the anterior spine as exposure extends farther laterally from midline with greater dissection of the ribs. The transpedicular corpectomy is the easiest progression from the direct midline approach and is illustrated here. It avoids surgical morbidity of anterior exposure while providing relatively good access to the anterolateral spinal cord and may be performed in combination to laminectomy. The costotransversectomy utilizes a midline or paramedian incision and involves complete removal of the rib head and transverse process and provides greater visualization for partial vertebrectomy. The lateral extracavitary approach utilizes a hockey stick posterolateral incision without violating the chest cavity and provides good visualization and decompression of the anterior thecal sac. These approaches are discussed in Special Considerations

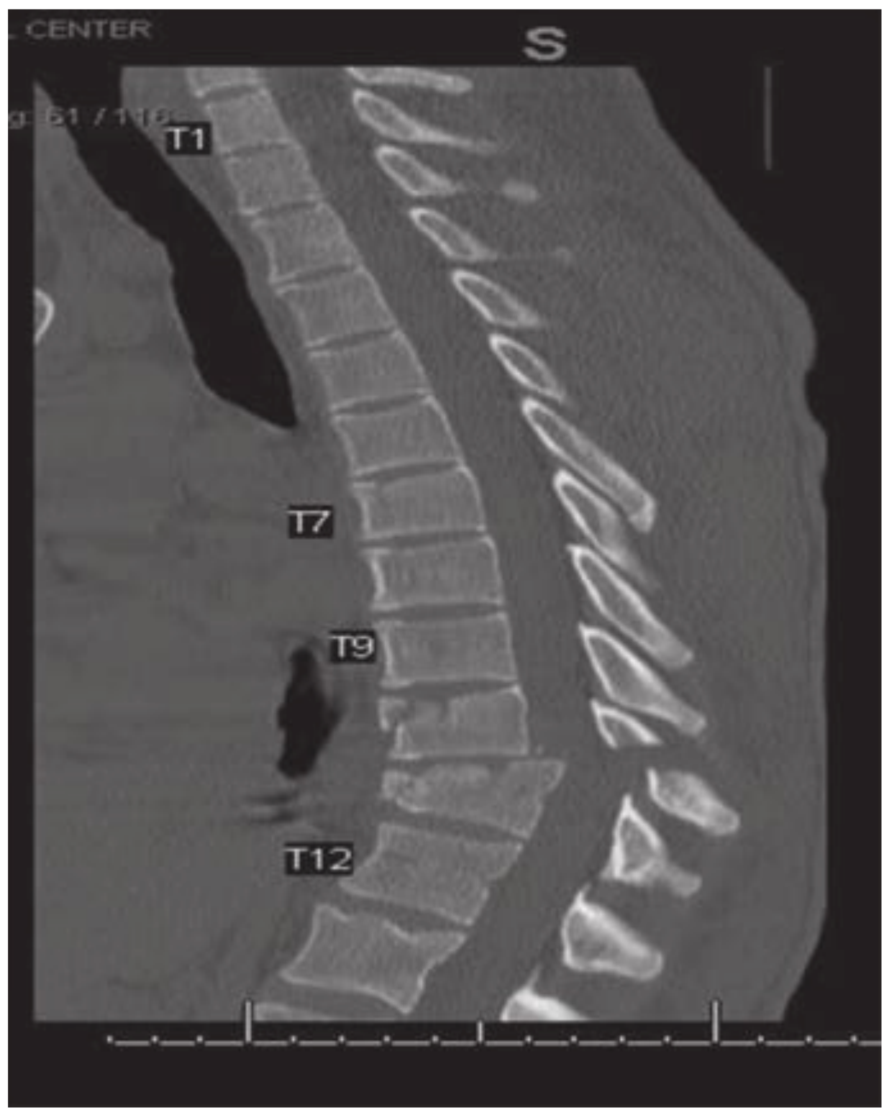
Anterior Approach: Thoracotomy

Anterior exposure to the thoracic spine is often critical in trauma. Anterior exposure makes it far easier to perform multilevel decompression and stabilization through a single approach with possibility of anterior stabilization. For fractures involving the anterior elements of T1 or T2, an anterior approach can be used that is similar to an anterior cervical corpectomy and fusion. However, T3-T5 cannot be reached effectively from the front unless the chest is opened by performing a manubrial resection or sternotomy and are often best accessed through a transthoracic approach.

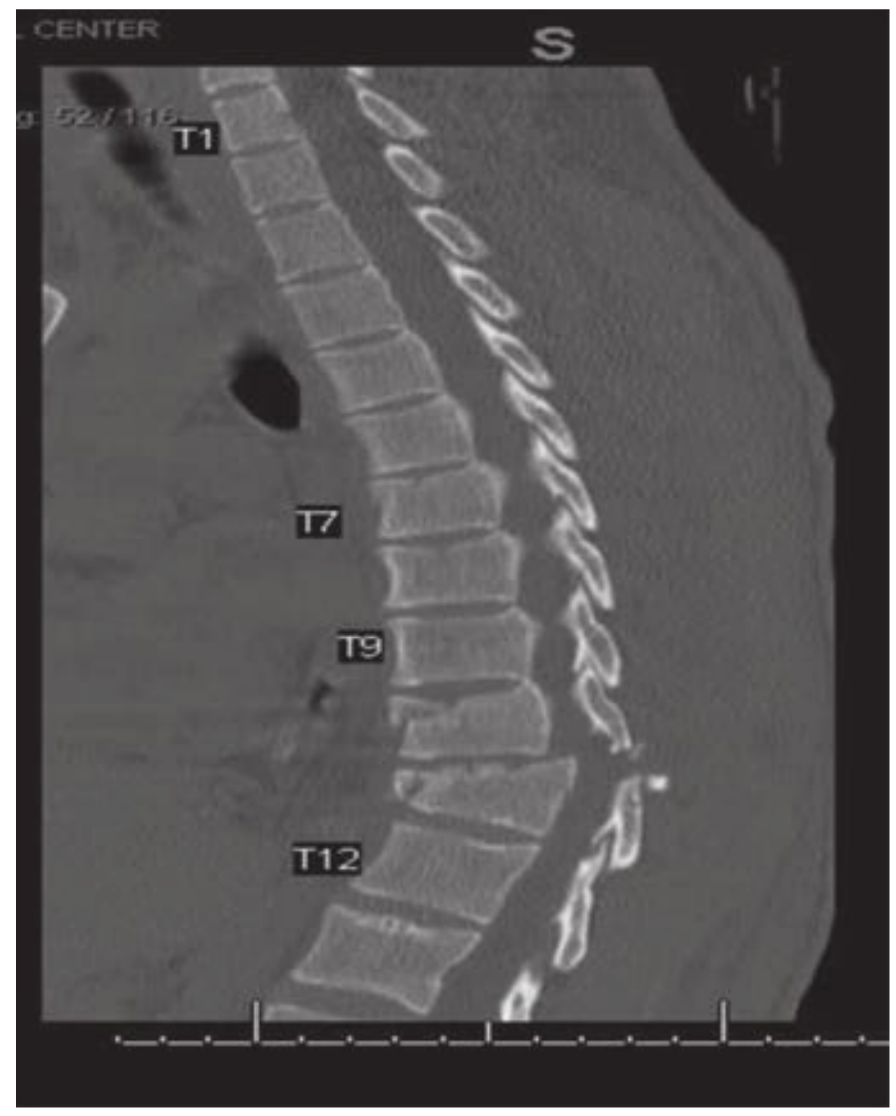
Transthoracic approaches (e.g., thoracotomy and thoracoscopy) provide several benefits in comparison to posterior or posterolateral approaches. A transthoracic approach provides optimal exposure of the anterior dura and posterior longitudinal ligament. However, the tradeoff includes reduced exposure to the posterior spine. There are also associated complications including pneumothorax, pulmonary contusion, pneumonia, pleural effusion, empyema, and possible need for an access surgeon. While thoracotomy is the mainstay, thoracoscopy has become increasingly an option.

Operative Procedure

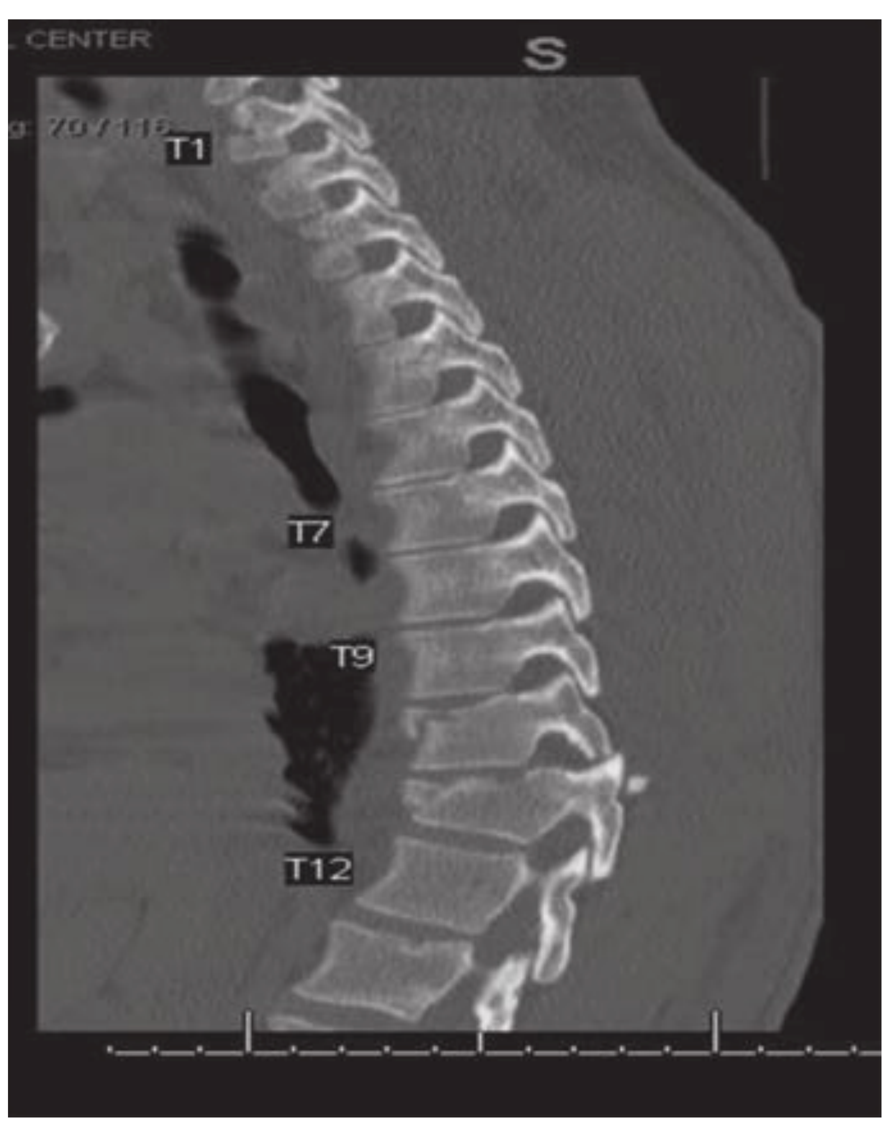
Posterior Approach (Fig. 15.1a–c and Fig. 15.2)



a



b



c

Fig. 15.1a–b Twenty-six-year-old man involved in an all-terrain vehicle accident. CT showed a T10-T11 fracture-dislocation with significant angulation of the thoracic spine. The spinous process of T10 is **(a)** fractured along with **(b)** dislocated and **(c)** jumped facets.

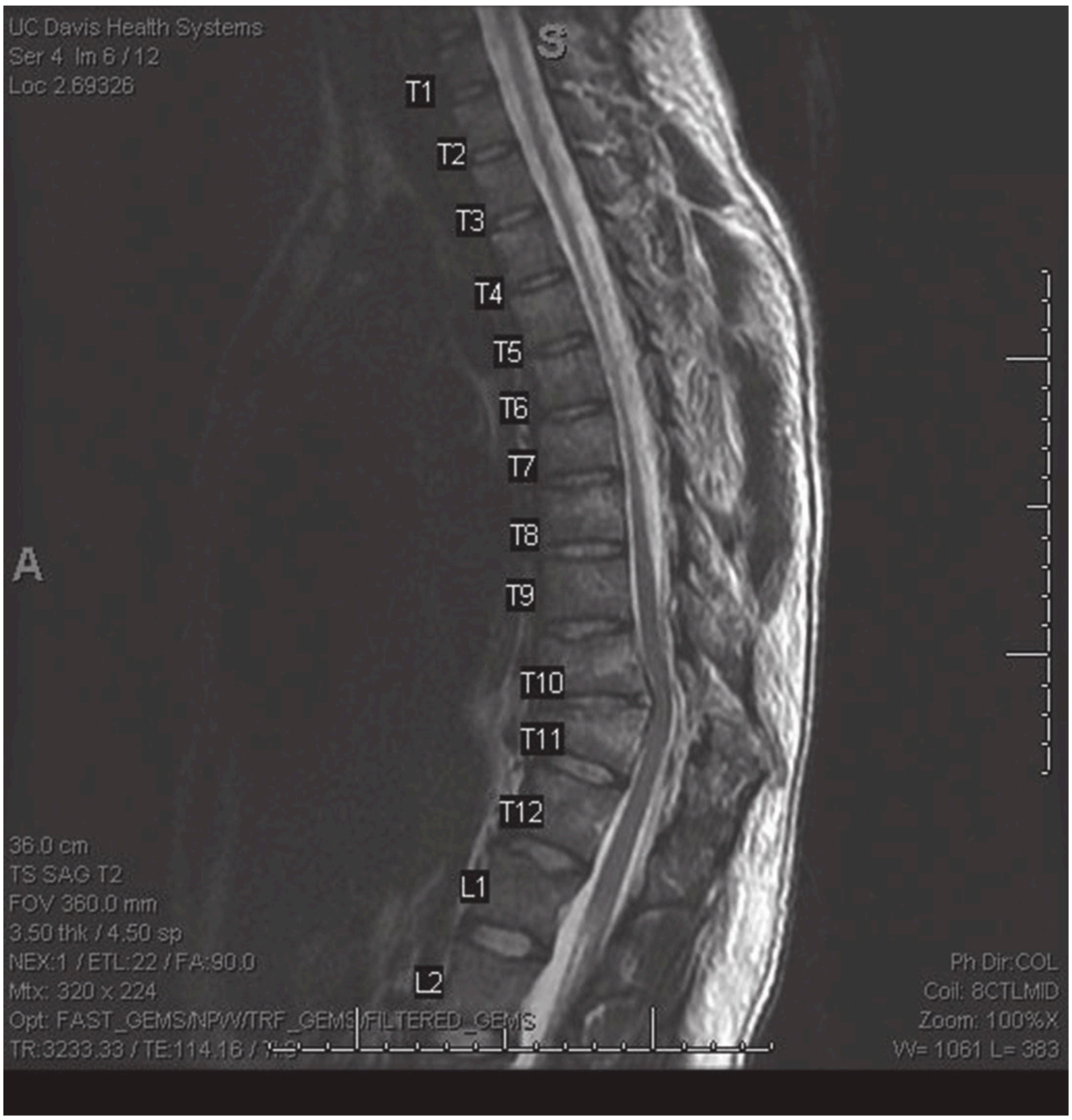


Fig. 15.2 MRI in same patient showed narrowing of the spinal canal with cord compression at that level. Fortunately, the patient was moving his lower extremities.

Positioning and Localization (Fig. 15.3)

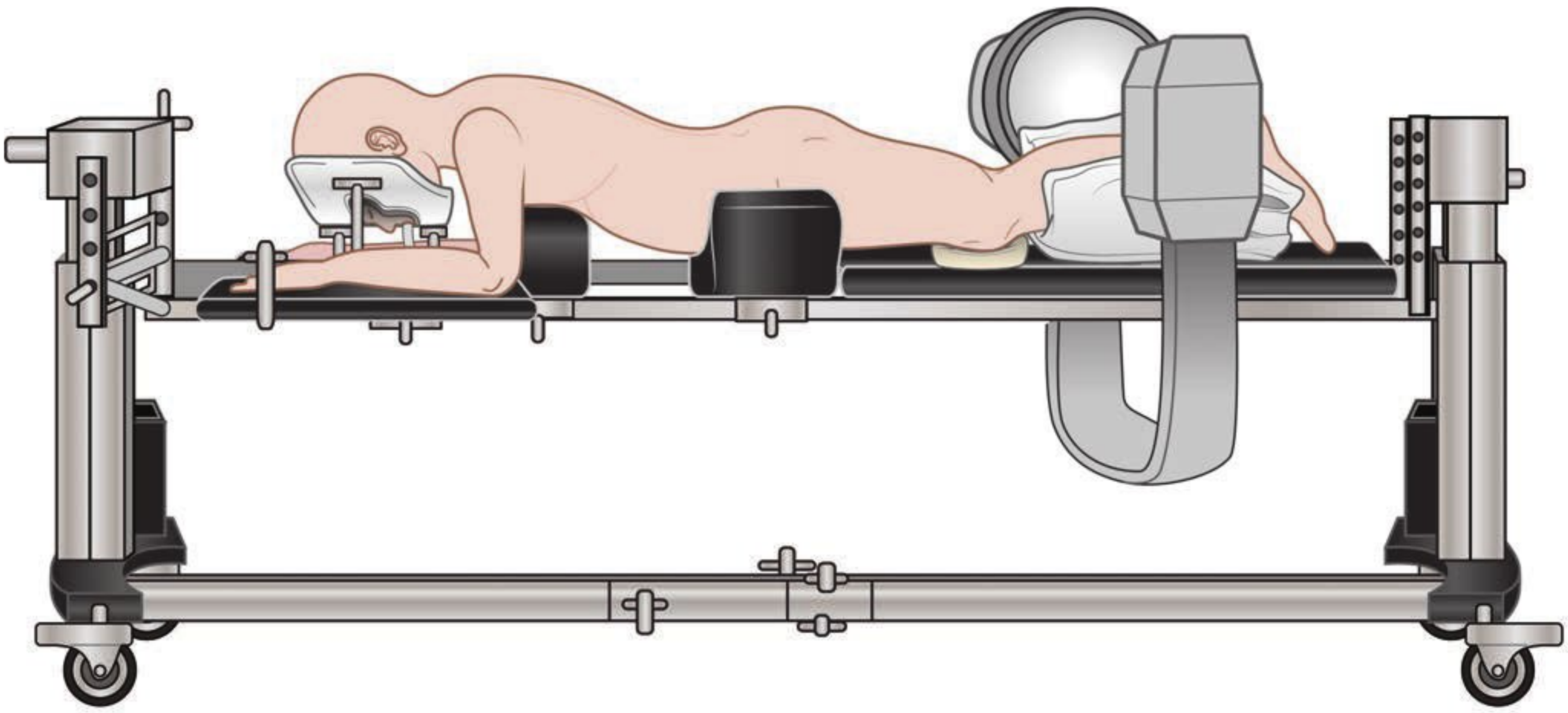


Figure	Procedural Steps	Pearls
Fig. 15.3	**The patient is positioned prone on a radiolucent table with chest bolsters. Pressure points are padded. The level of surgery is determined and a posterior midline incision is planned. The surgical field is prepped and draped.**	• Positioning can lead to deterioration of the patient. In patients with severe stenosis or instability, it is helpful to obtain baseline SSEP prior to positioning. Surface electrodes are placed on the patient in the preoperative area to save time during patient positioning. Needle electrodes are placed after anesthesia is induced. Baseline is run in the room after anesthesia is induced for comparison after the patient is positioned and throughout the case. • The level is determined anatomically and marked by taping a paperclip to the chest wall at the surgical level. A cross table lateral plain X-ray is taken and the surgical site marked. It is optimal to count from the top and bottom if possible. Prep a large area rostrally and caudally to allow for extension of the incision and to allow drain placement.

Skin, Subcutaneous, and Subperiosteal Dissection (Fig. 15.4)

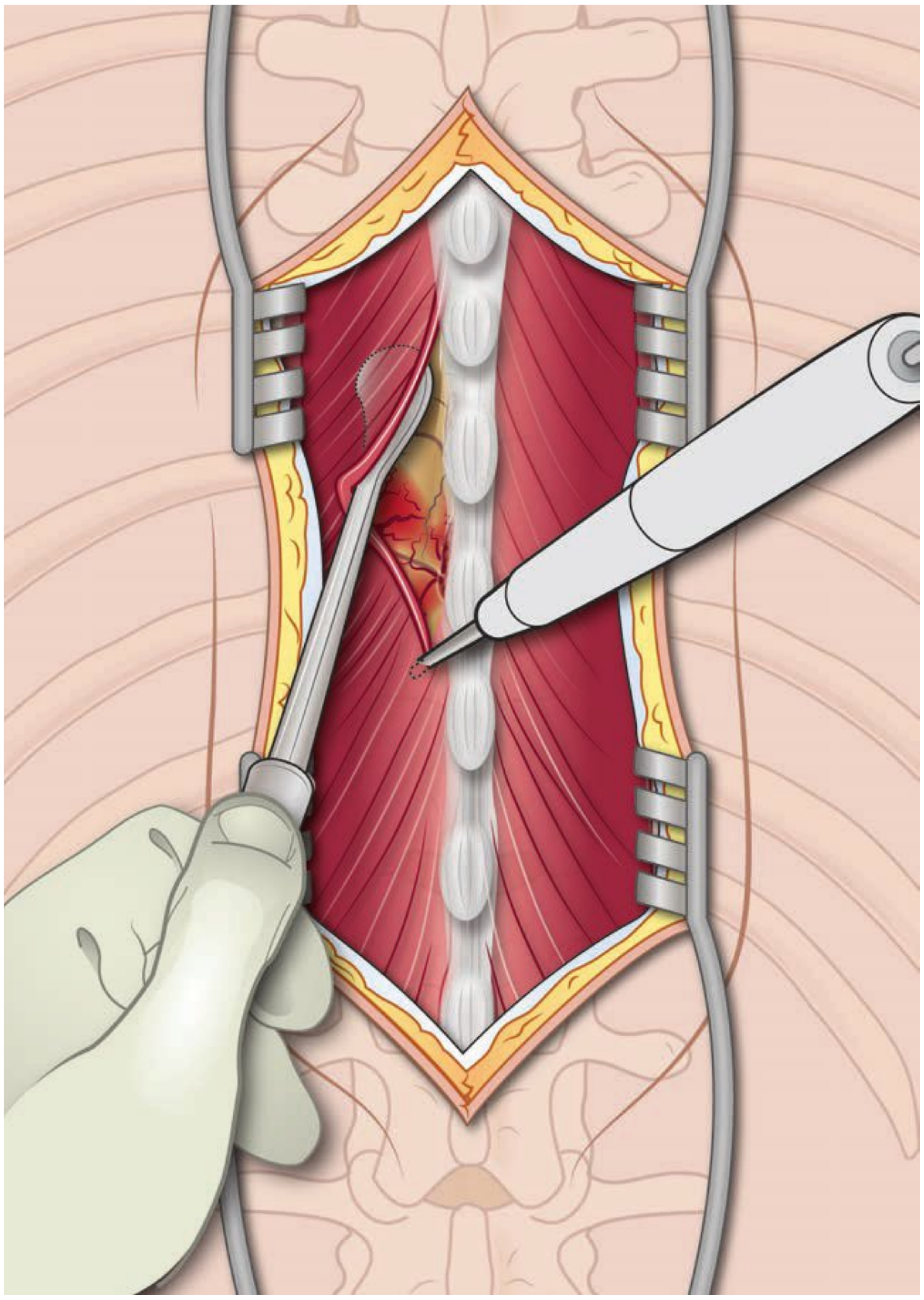


Figure	Procedural Steps	Pearls
Fig. 15.4	**The skin is infiltrated with lidocaine and the incision is opened with a no. 10 blade to the subcutaneous tissue. Hemostasis is obtained with monopolar cautery. The subcutaneous tissue is dissected down to the fascia with monopolar cautery. Cerebellar retractors are used at this point to reflect the tissue. The bone of the spinous process is palpated and a subperiosteal dissection is made by cutting the muscular and tendinous attachments directly off the bone. Dissection should continue down, following the lamina, and out laterally to the beginning of the facet complex. If there is significant bleeding then it may be more effective to switch to bipolar cautery to achieve hemostasis. The levels are verified by placing two metal instruments in the incision such that the tips mark the rostral and caudal extent of the anticipated bony dissection. A cross-table plain X-ray or fluoroscopic image is taken to verify the correct level of surgery.**	• A cell salvage machine, if available, should be utilized. • Care must be taken to prevent the monopolar cautery from slipping though the interlaminar space.

Spinous Process Removal (Fig. 15.5)

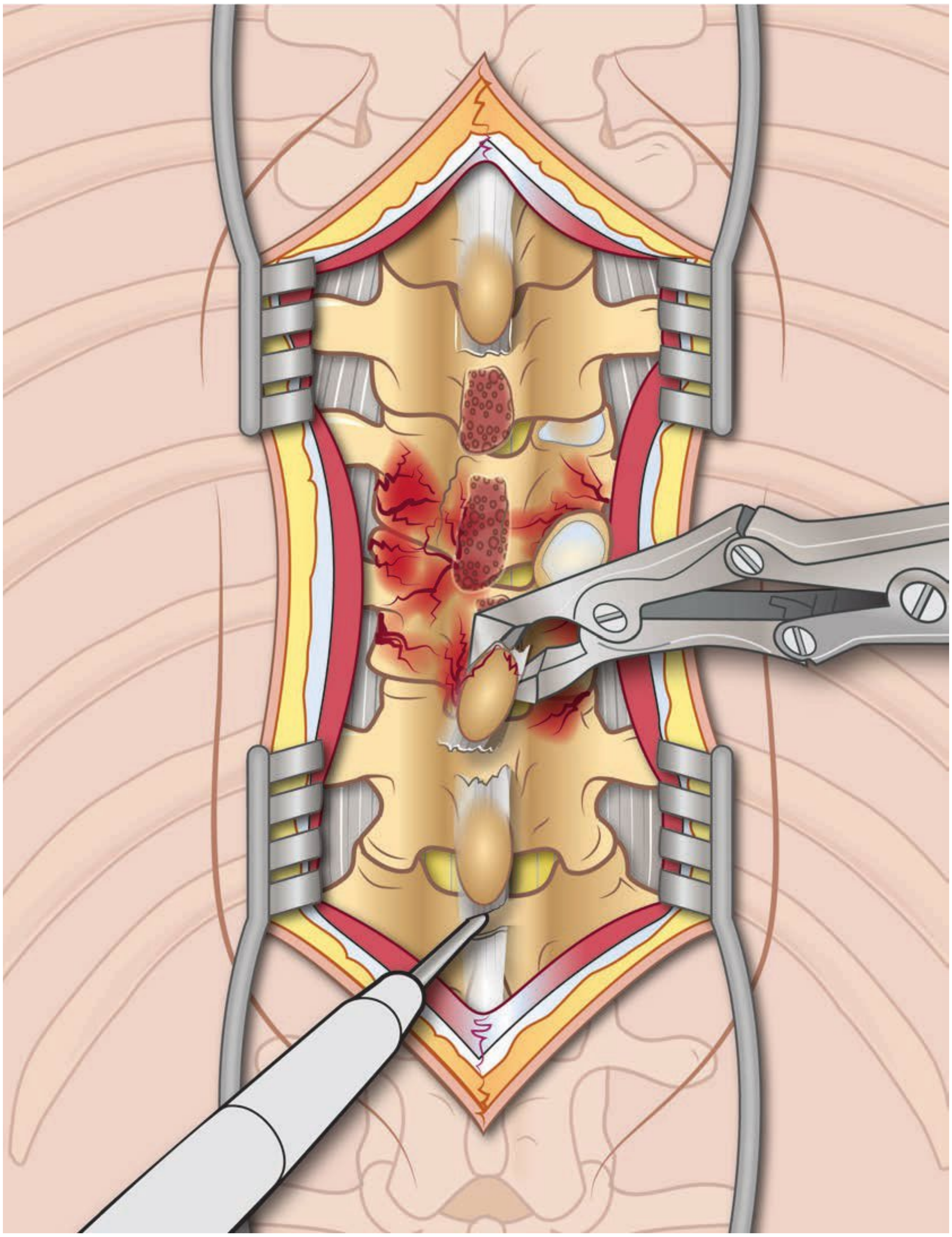


Figure	Procedural Steps
Fig. 15.5	**The interspinous ligament can be cut using monopolar cautery or scissors allowing removal of the spinous process with a Horsley.**

Laminectomy, if Indicated (Fig. 15.6)

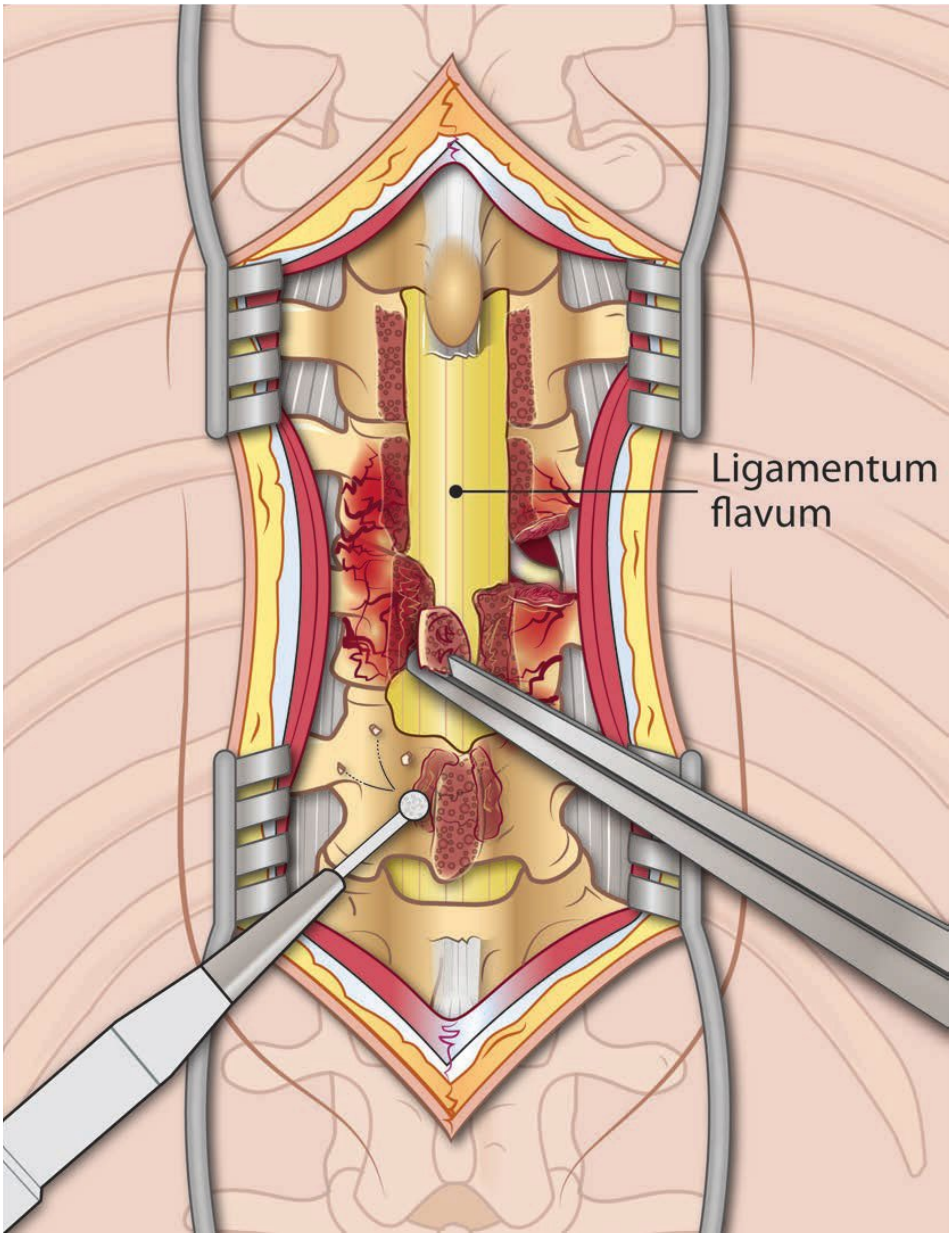


Figure	Procedural Steps	Pearls
Fig. 15.6	**Using a high speed drill, the lamina is thinned to a layer of cortical bone over the ligamentum flavum. The bone can then easily be removed with a 2-mm Kerrison punch. Hemostasis should be achieved by application of bone wax to the bleeding cut surface of the bone.**	• Take care to avoid downward pressure with the Kerrison.

Removal of Ligament (Fig. 15.7)

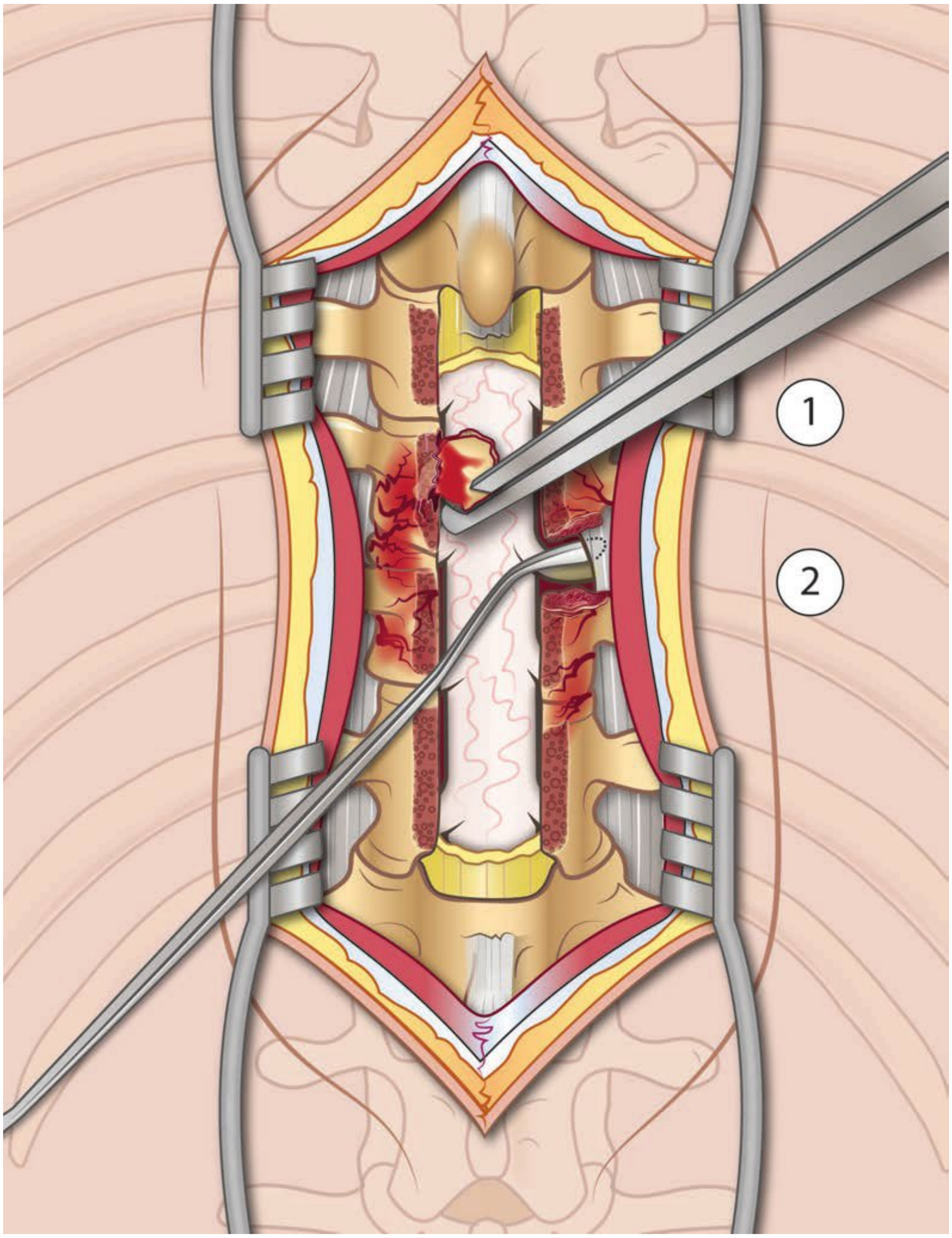


Figure	Procedural Steps	Pearls
Fig. 15.7	**Once the laminectomy has extended anteriorly beyond the attachment of the ligamentum flavum, it is easy to elevate away from the thecal sac and remove with a Kerrison punch. Removal of the ligament will likely result in bleeding of epidural veins. If these are visible, these can be cauterized with bipolar cautery. Remove any remaining bone and ligament in the lateral recess (1). Probe the foramen with a ball probe or Woodson to make sure that the nerve roots are not severely compressed (2).**	• Decrease the strength of the bipolar cautery prior to using the instrument near the thecal sac. • For hemostasis, apply bone wax to bleeding bone, and then apply a line of gelatin-thrombin matrix down the length of each gutter. Cover with a pattie and wait a few minutes to allow clot formation. Wash out the excess and repeat as needed.

Thoracic Pedicle Screw Entry Point (Fig. 15.8)

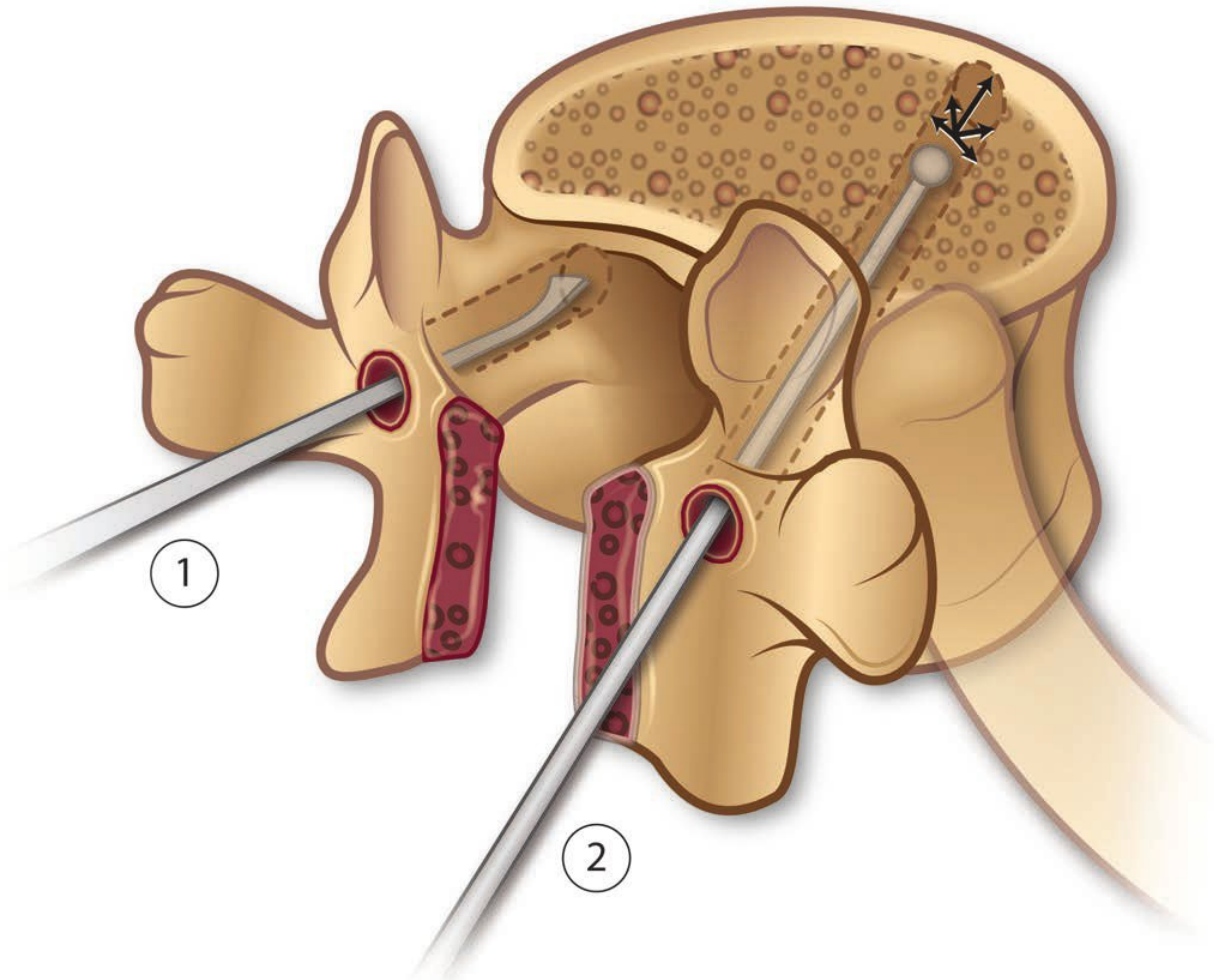


Figure	Procedural Steps	Pearls
Fig. 15.8	**Start the entry point with an awl or high speed drill. Use fluoroscopy to verify position. Insert the pedicle finder through the cancellous bone of the pedicle (1). Use fluoroscopy to verify position. Using a fine ball tipped probe, feel all four sides and the bottom of the hole to make sure that there is no breach (2).**	• Screw entry point differs at each level but is generally toward the medial anterior quadrant of the facet complex. The pedicle finder generally has a slight curve to it and should be facing outward initially, and then turned inward when the vertebral body is reached.

Screw Placement (Fig. 15.9)

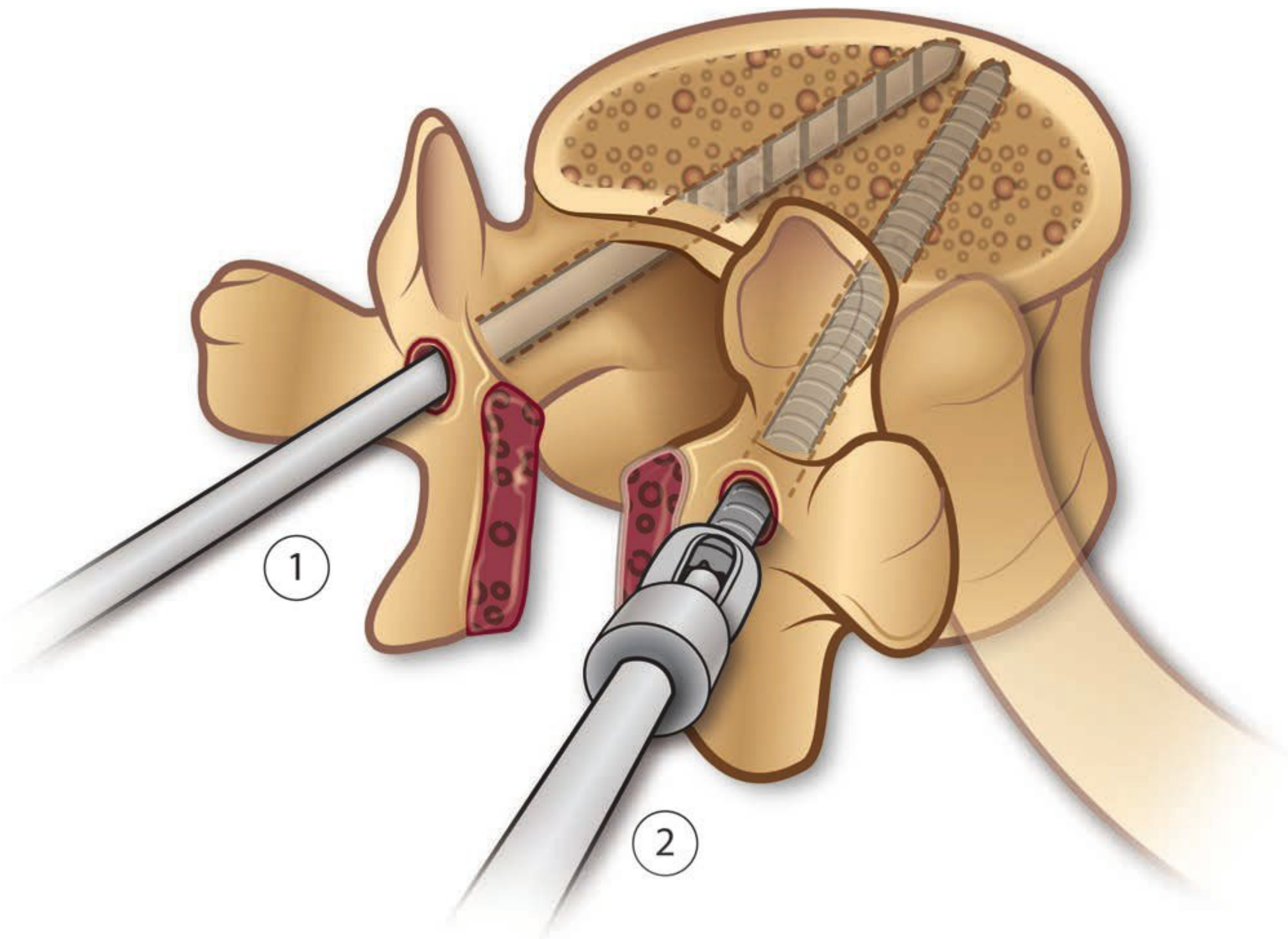


Figure	Procedural Steps
Fig. 15.9	**Tap the hole with the appropriate sized tap (1). Insert the screw into the hole (2). Use fluoroscopy to verify position.**

Rod Placement (Fig. 15.10)

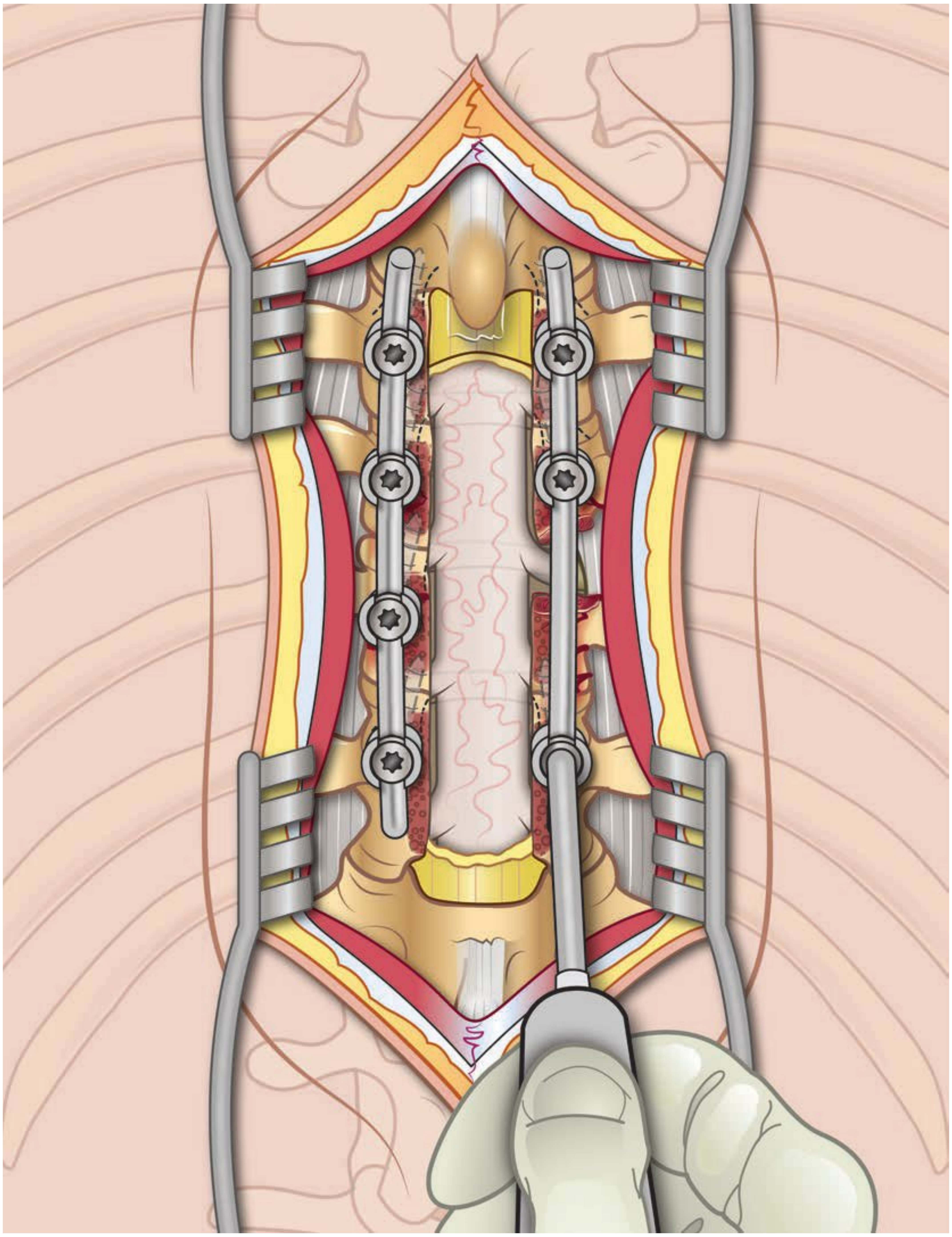
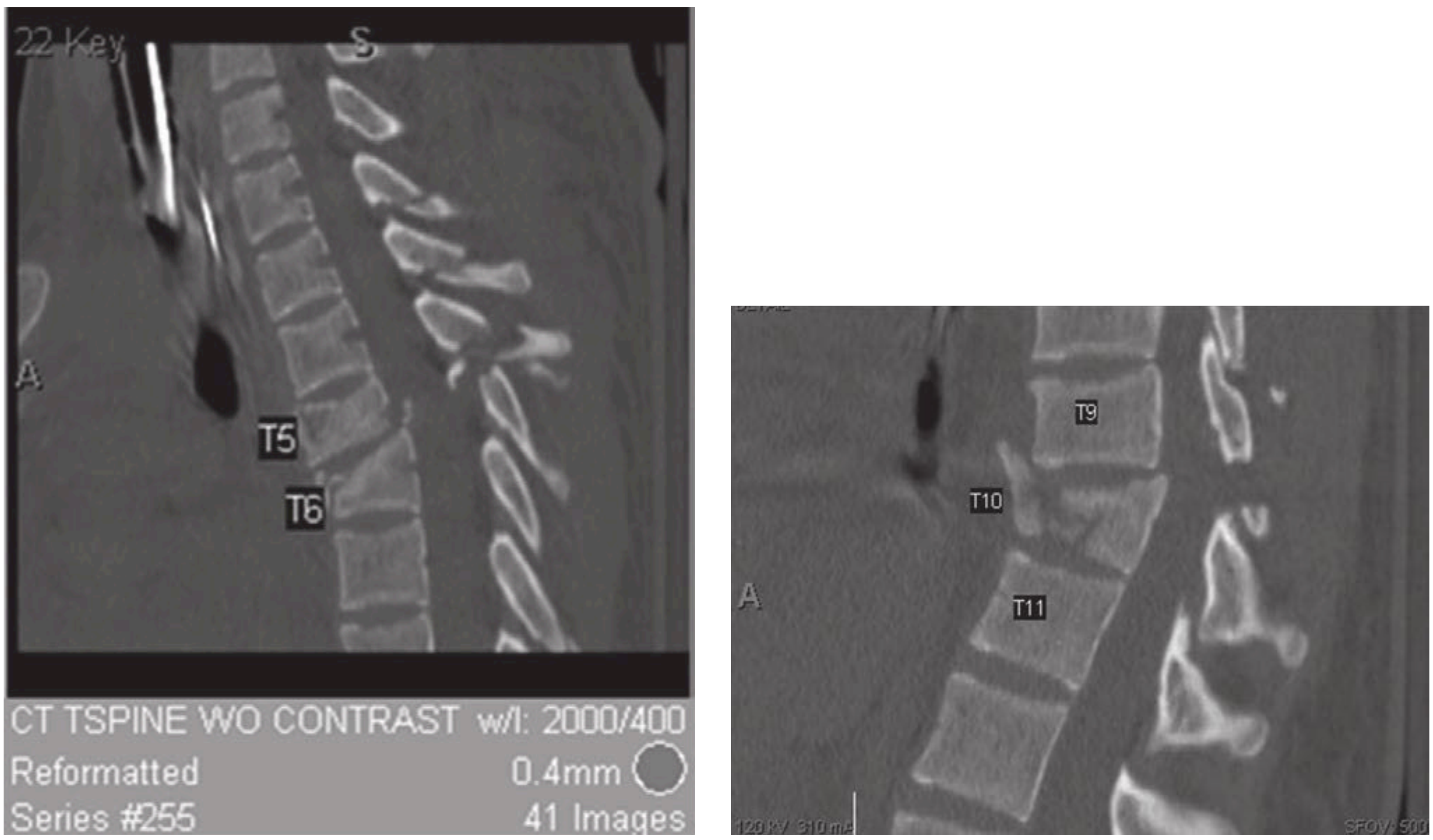


Figure	Procedural Steps
Fig. 15.10	**When all pedicle screws have been placed, insert a malleable temporary rod through the polyaxial screw heads to determine the shape and length of the rod. Cut the rod to the appropriate size, and bend it to fit. Fit the rod though the screw heads and affix screw caps. When the rod fits and all screw caps are in place, use the final tightener to lock the screw caps down.**

Posterolateral Approach: Transpedicular Corpectomy (Fig. 15.11)



a b

Fig. 15.11 Sagittal CT reconstructions of an 18-year-old woman who was involved in a motorcycle accident, sustaining thoracic fracture demonstrating **(a)** T6 and **(b)** T10 burst fractures with kyphotic angulation. **(a)** In addition, at the T5-6 level she had a fracture-dislocation with T5 laminar and spinous process fractures. The patient was able to move her lower extremities with some sensation. However, due to the fact that she had grossly unstable spine, she was kept on bedrest until surgical stabilization could be performed.

Removal of Facet Complex (Fig. 15.12)

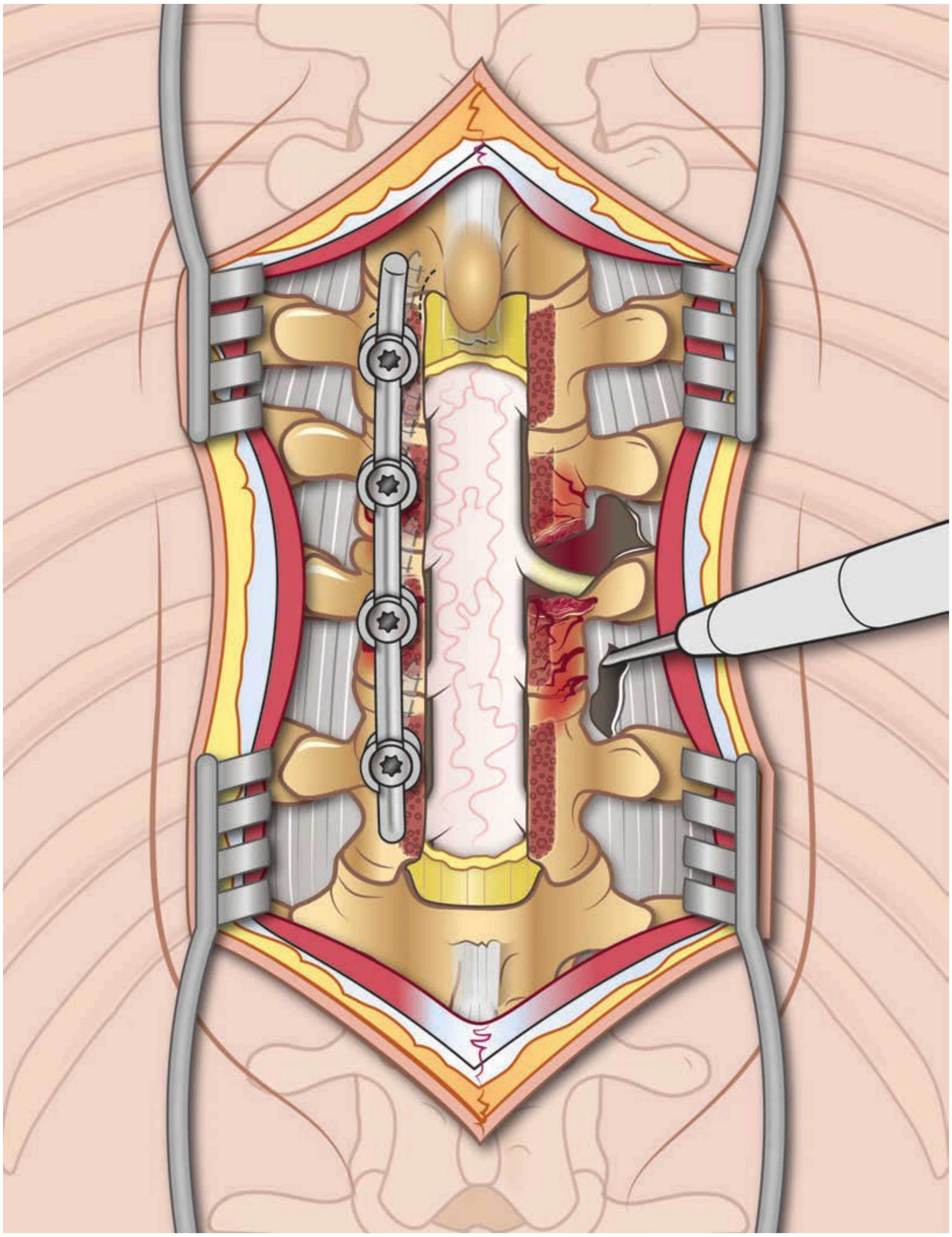


Figure	Procedural Steps	Pearls
Fig. 15.12	**After pedicle screw placement, a single rod contralateral to the side of surgical approach is placed to stabilize the spine during the corpectomy. The muscular and tendinous attachments need to be removed wider than with a laminectomy. Remove tissue using monopolar cautery out to the edge of the facet complex and rib head.**	• Prior to performing the corpectomy, the spine will need to be stabilized to prevent stretching, torque, or translocation.

Drill (Fig. 15.13)

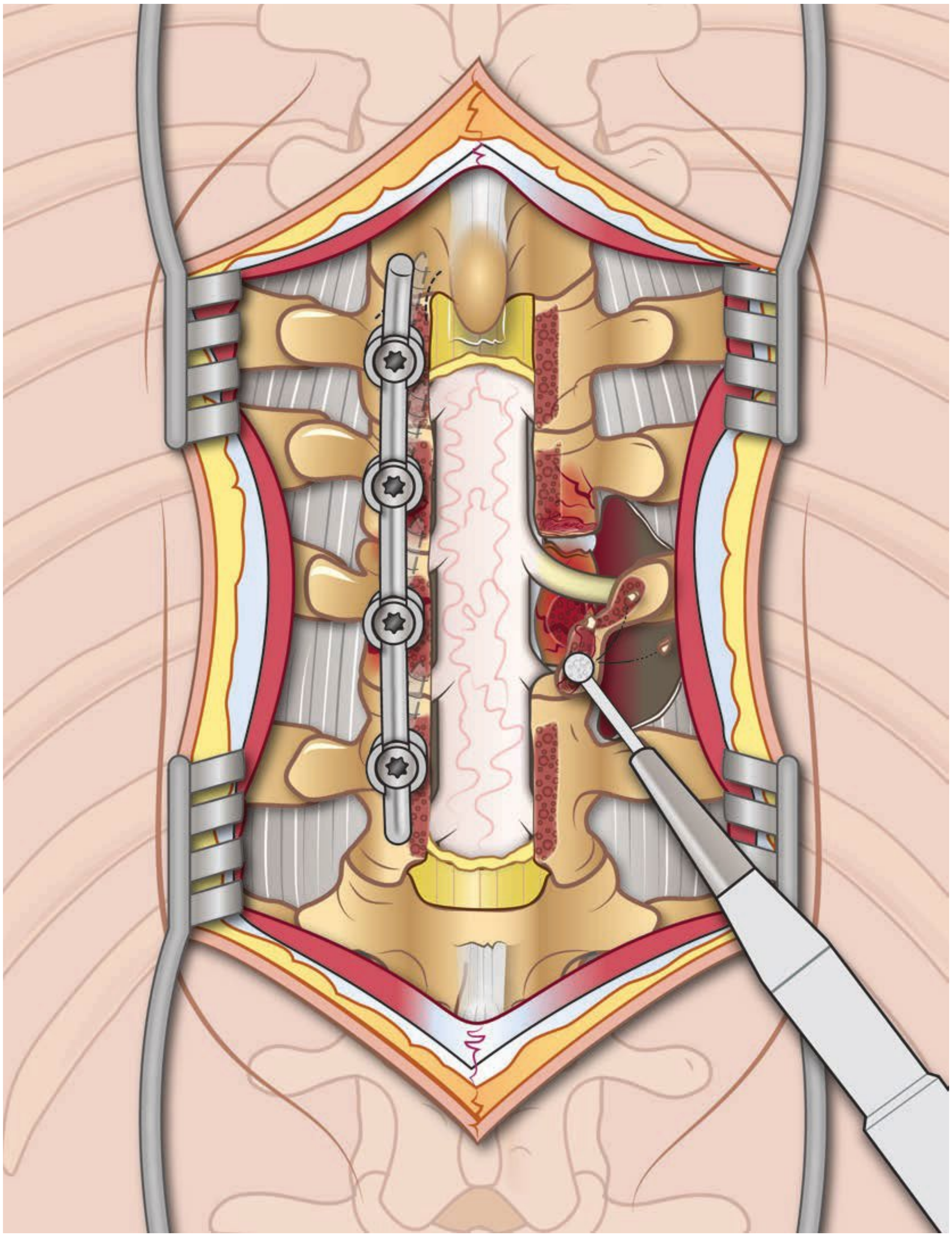


Figure	Procedural Steps
Fig. 15.13	**Using a high speed drill, remove the facet complex, lamina, pars interarticularis, and pedicle on the side of the chosen approach. The neurovascular complex is ligated. The exposure should be from the pedicle of the level above to the pedicle of the level below.**

Corpectomy and Diskectomy (Fig. 15.14)

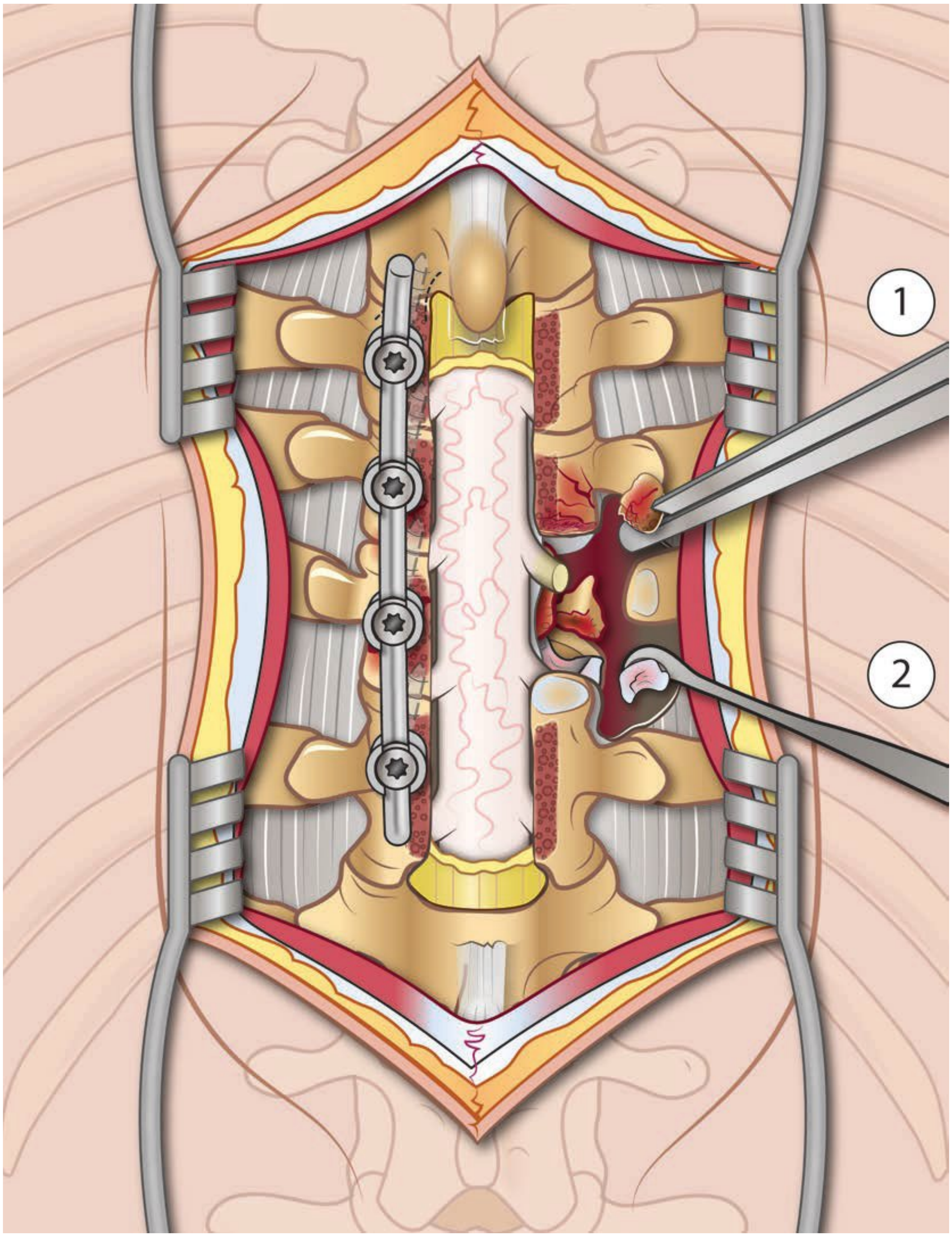


Figure	Procedural Steps	Pearls
Fig. 15.14	**The corpectomy is done with a combination of drilling and using the Kerrison rongeur (1). Use curette to scrape disk material off the endplate (2). Remove the disk with a pituitary.**	• Use fluoroscopy to check depth often so as not to overshoot the depth of the vertebral body.

Rib Head Trap Door Osteotomy (Fig. 15.15)

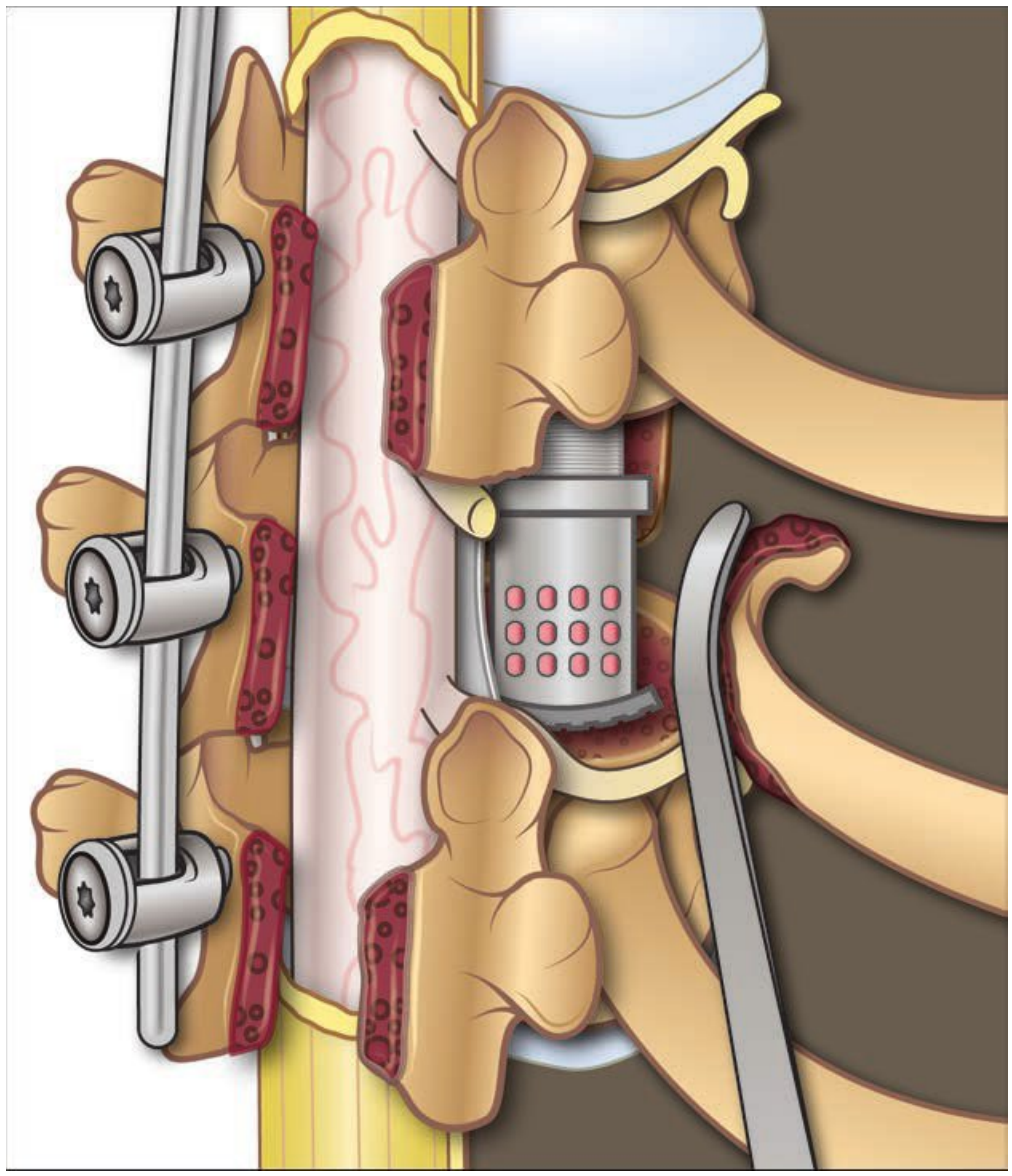


Figure	Procedural Steps	Pearls
Fig. 15.15	**Partially cut through the rib head until the deep surface becomes thin enough to bend. When this is achieved, the spacer can be slid past the rib head for placement. Size the distance from the rostral to caudal endplates of the levels above and below. Then insert the spacer lateral to the thecal sac taking care not to put any pressure on the cord.**	• Expandable titanium cages, nonexpendable graft, cadaveric femur, and other implants are all possibilities following corpectomy. Regardless of option, fusion across a corpectomy is often hindered by the long distances that the fusion needs to occur. Therefore, additional measures must be taken to ensure adequate stabilization.

Pedicle Screws (Fig. 15.16)

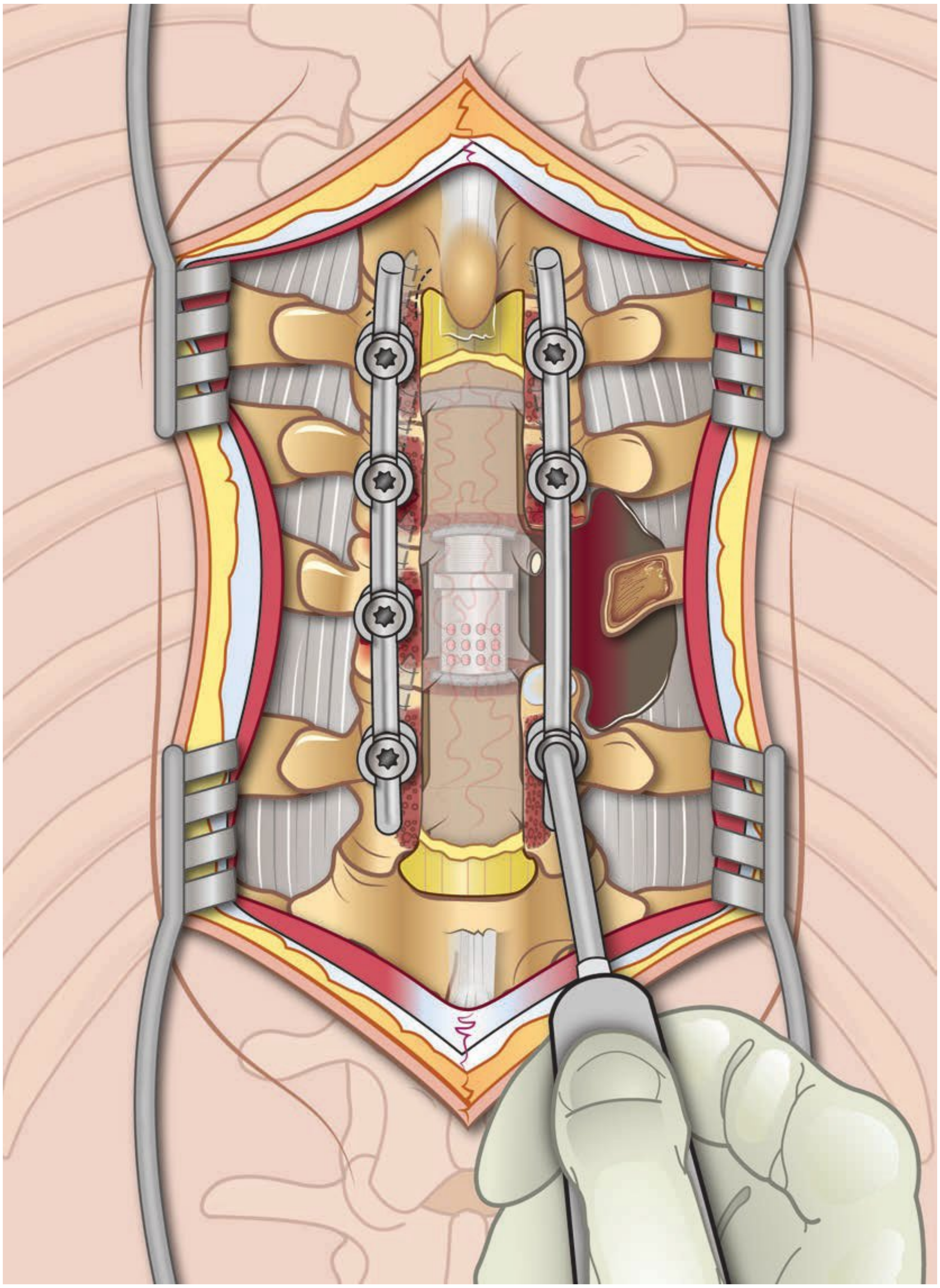


Figure	Procedural Steps
Fig. 15.16	**Insert the remaining pedicle screws on the operative side then fit and lock in a second rod.**

Anterior Approach: Transthoracic Vertebrectomy (Fig. 15.17a, b)

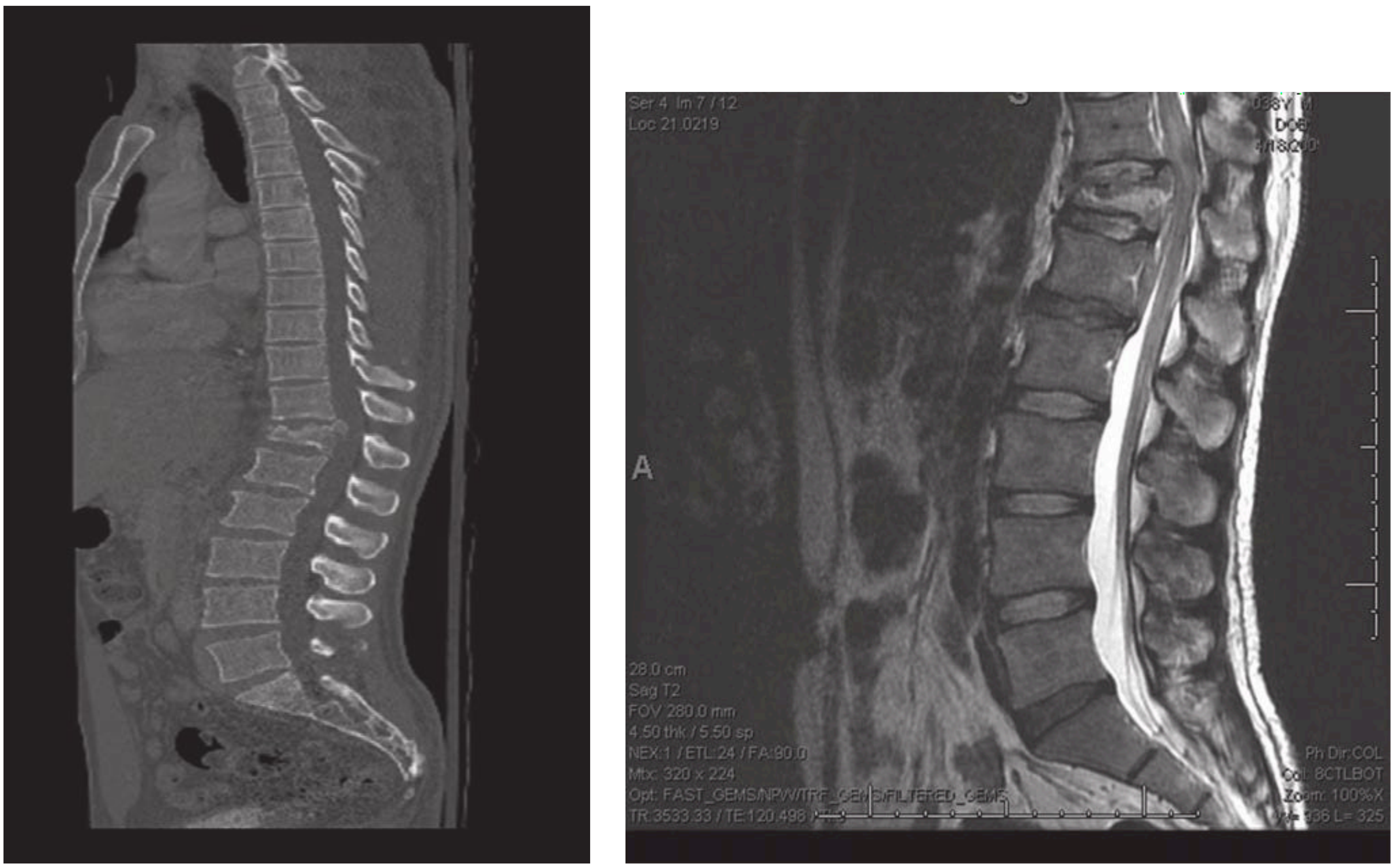


Fig. 15.17 **(a)** Sagittal CT and **(b)** MRI images of a 38-year-old man who was riding on a monster truck at a rally when he crashed, sustaining a T12 burst fracture with spinal cord injury. The imaging shows retropulsion of the T12 vertebral body with approximately 50% canal compromise with a conus injury and cord signal changes. There was also associated kyphotic deformity.

Transthoracic Vertebrectomy

Positioning and Approach Planning (Fig. 15.18)

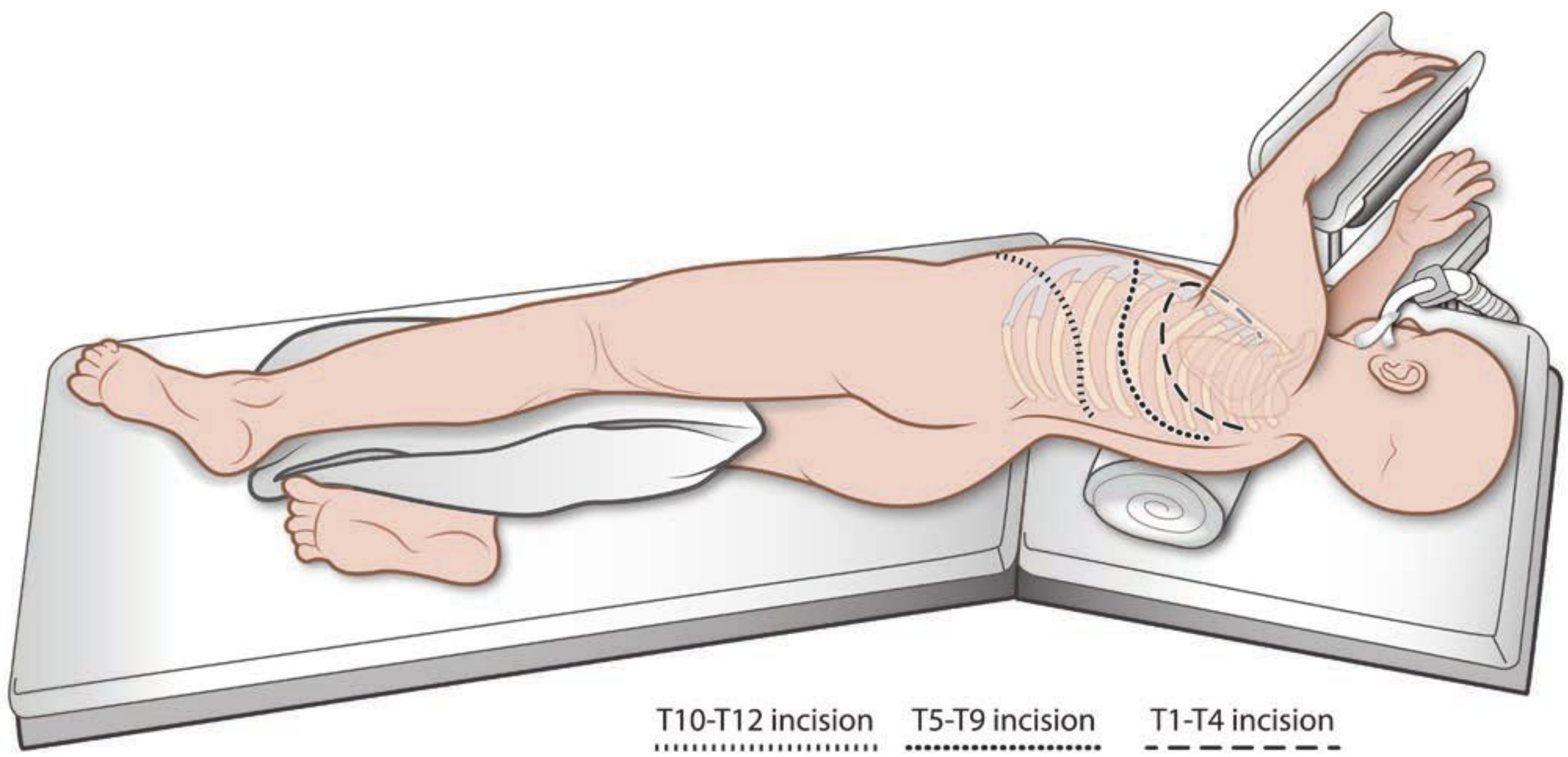


Figure	Procedural Steps	Pearls
Fig. 15.18	**The patient is positioned in the lateral decubitus position. An axillary role is placed to prevent injury to the brachial plexus. The dependent leg is bent forward and the upper leg is supported on pillows. A dual lumen endotracheal tube is used so that the dependent lung is ventilated and the superior lung, ipsilateral to the lesion, is collapsed. A wide area is included in the prep to allow exposure of the entire thoracic spine and ipsilateral rib cage. The table is elevated under the patient's chest to spread the ribs on the ipsilateral side.**	• The patient must be intubated with a double lumen endotracheal tube in order to allow single lung ventilation. This underscores the fact that the patient must be able to tolerate single lung ventilation for the procedure. If the patient has too many comorbidities, then this approach may be rejected over a posterior approach. If direct lateral mini thoracotomy with specialized retractors is utilized, single lumen ventilation will suffice.
	T1 to T4 can be approached anteriorly utilizing resection of the third rib. The incision will follow the medial border of the scapula and extend caudally. The incision will end at the sternocostal junction of the third rib. For levels T5 to T9, the rib above the level to be operated on is removed. For levels T10 to T12, the rib two levels above the level in question is removed.	• Often the lesion will determine the laterality but in cases of midline lesions or lesions that span the entire vertebral body, the vascular anatomy may dictate the approach. The position of the aorta needs to be reviewed on CT to determine if it will be in the way. The vena cava is typically midline and rarely affects the choice of left versus right. The aorta has a more variable position, but often surgery above T9 is best approached from the right. Below T9 the left side is an easier approach as the liver pushes up on the diaphragm on the right.

Dissection (Fig. 15.19)

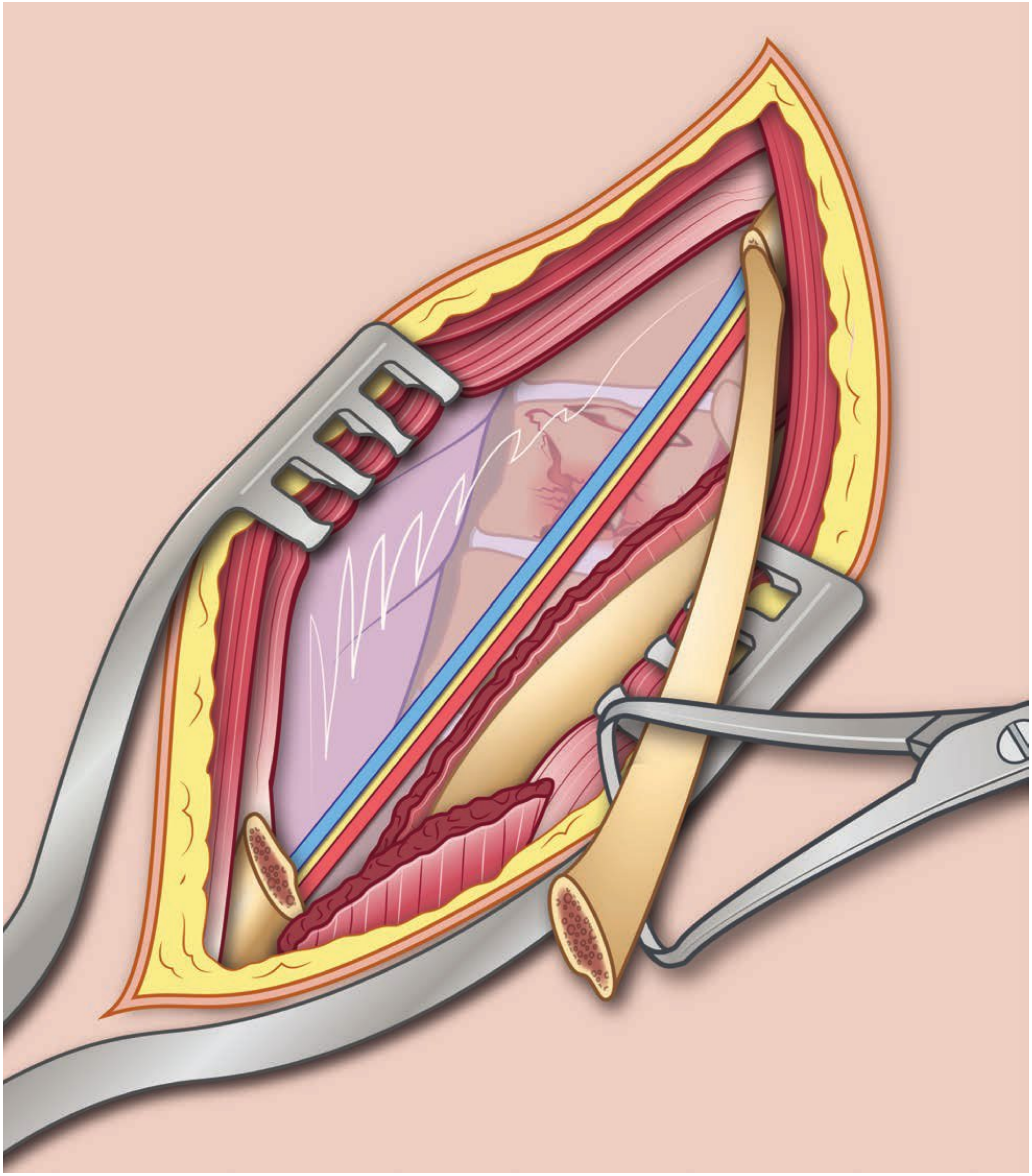


Figure	Procedural Steps
Fig. 15.19	**The muscular layers are divided using electrocautery. The muscles transected are the trapezius, latissimus dorsi, then the rhomboids, and finally serratus. The rib is identified, dissected free, and resected. The neurovascular bundle is identified, ligated, and cut.**

Vertebrectomy (Fig. 15.20)

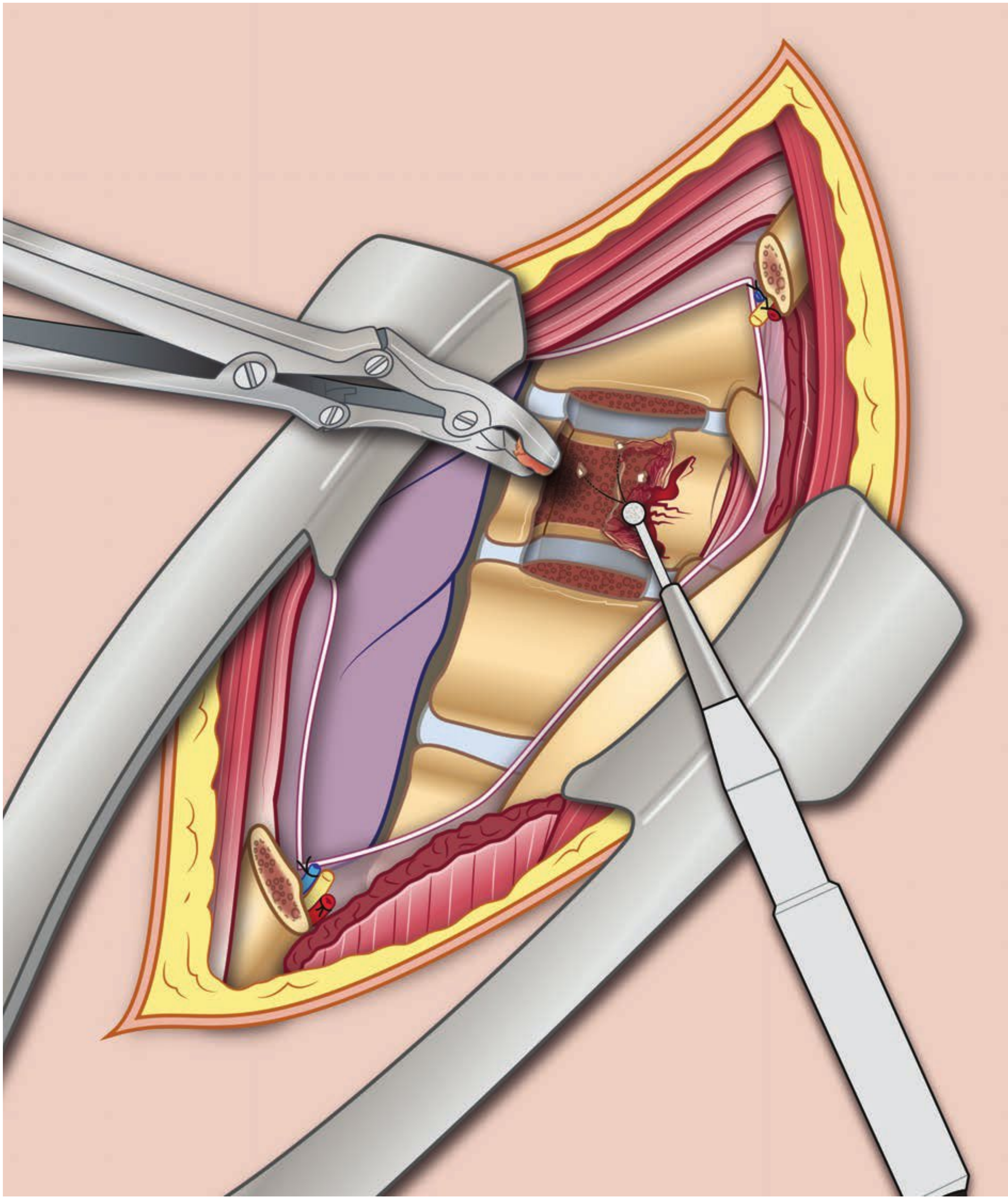
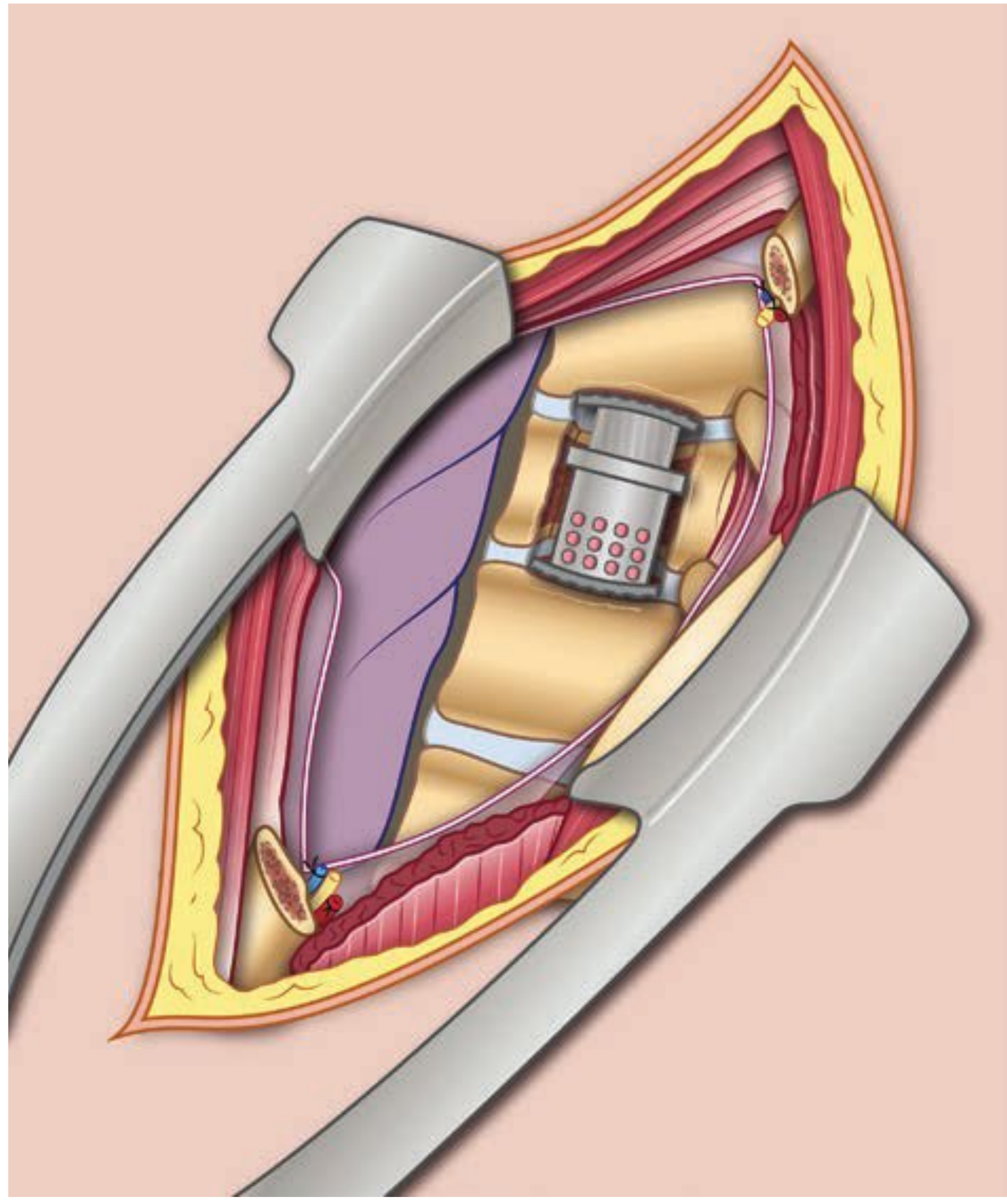


Figure	Procedural Steps	Pearls
Fig. 15.20	**The vertebral body is removed with the drill and Kerrison rongeurs. The disks above and below are removed down the endplates. The thecal sac should be protected at all times if decompression is required.**	• Remember that from T1 to T9 the rib articulates with the vertebral bodies of the corresponding thoracic level and the level above. Below T9, the rib articulates with the same thoracic level.

Fusion and Instrumentation (Fig. 15.21a, b)



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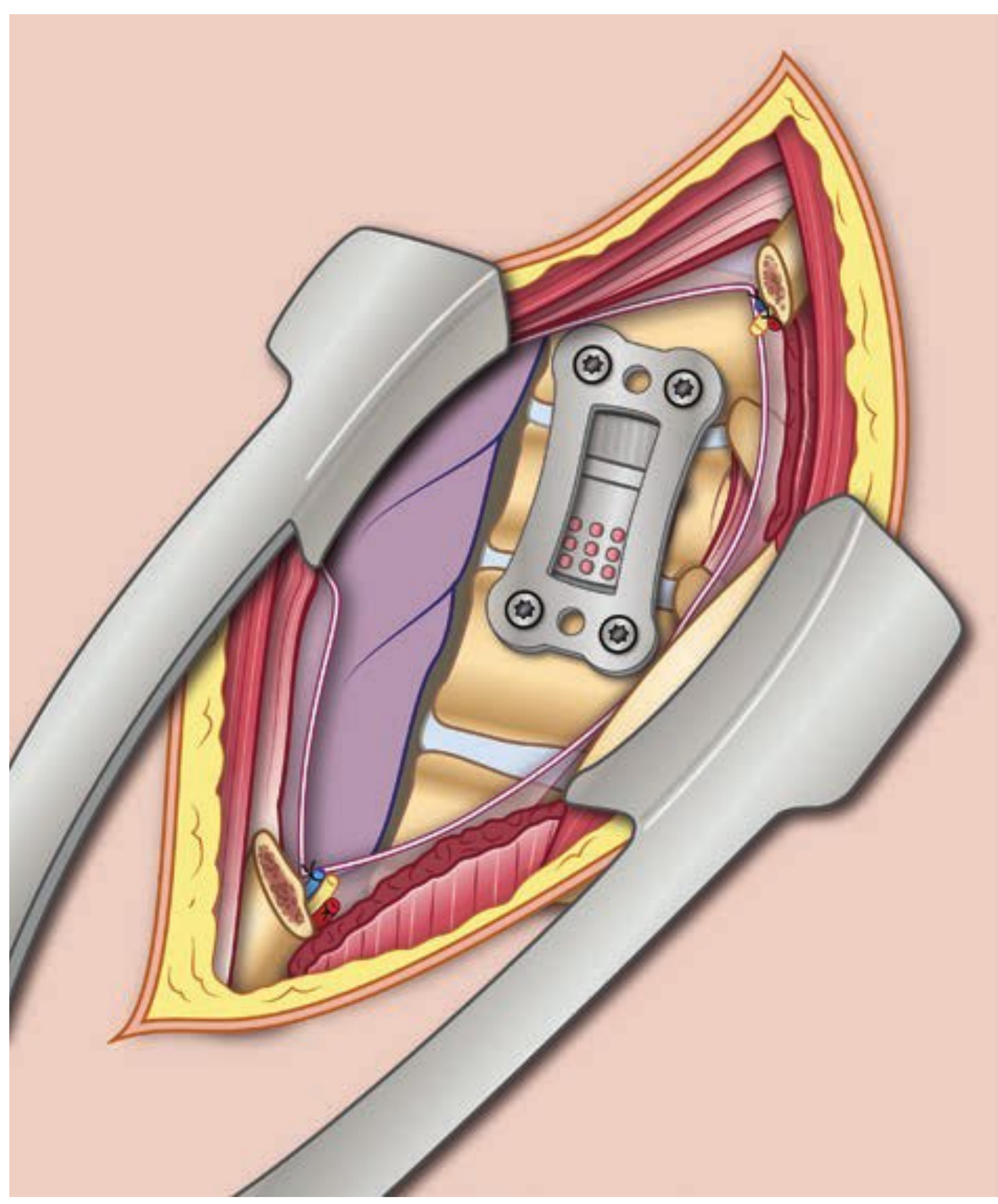


b

Figure	Procedural Steps
Fig. 15.21	**(a) An appropriately sized spacer, either rib autograft, femoral allograft, or cage is inserted. (b) A plate and screws are placed to provide rigid fixation.**

Closing

- Surgical wounds are closed in layers.
- A drain is placed above the fascia to prevent hematoma formation.
- The skin is closed with inverted 3-0 absorbable sutures followed by benzoin and adhesive strips.
- Anterior procedures require wound closure around a chest tube to allow drainage from the pleural space. A chest tube is placed under direct visualization. It can be placed directly on water seal if no leak is suspected. The wounds are closed. A postoperative chest X-ray is obtained to check for pneumothorax or hemothorax. The chest tube can be removed when output is less than 100 mL/day.

Postoperative Management

- Patients should be followed closely postoperatively with neurologic checks. The acuity of care will depend on the extent of the surgery and the extent of neurologic compromise. Patients with more extensive procedures that are at risk for more extensive blood loss should be observed overnight in the intensive care unit.

Medication

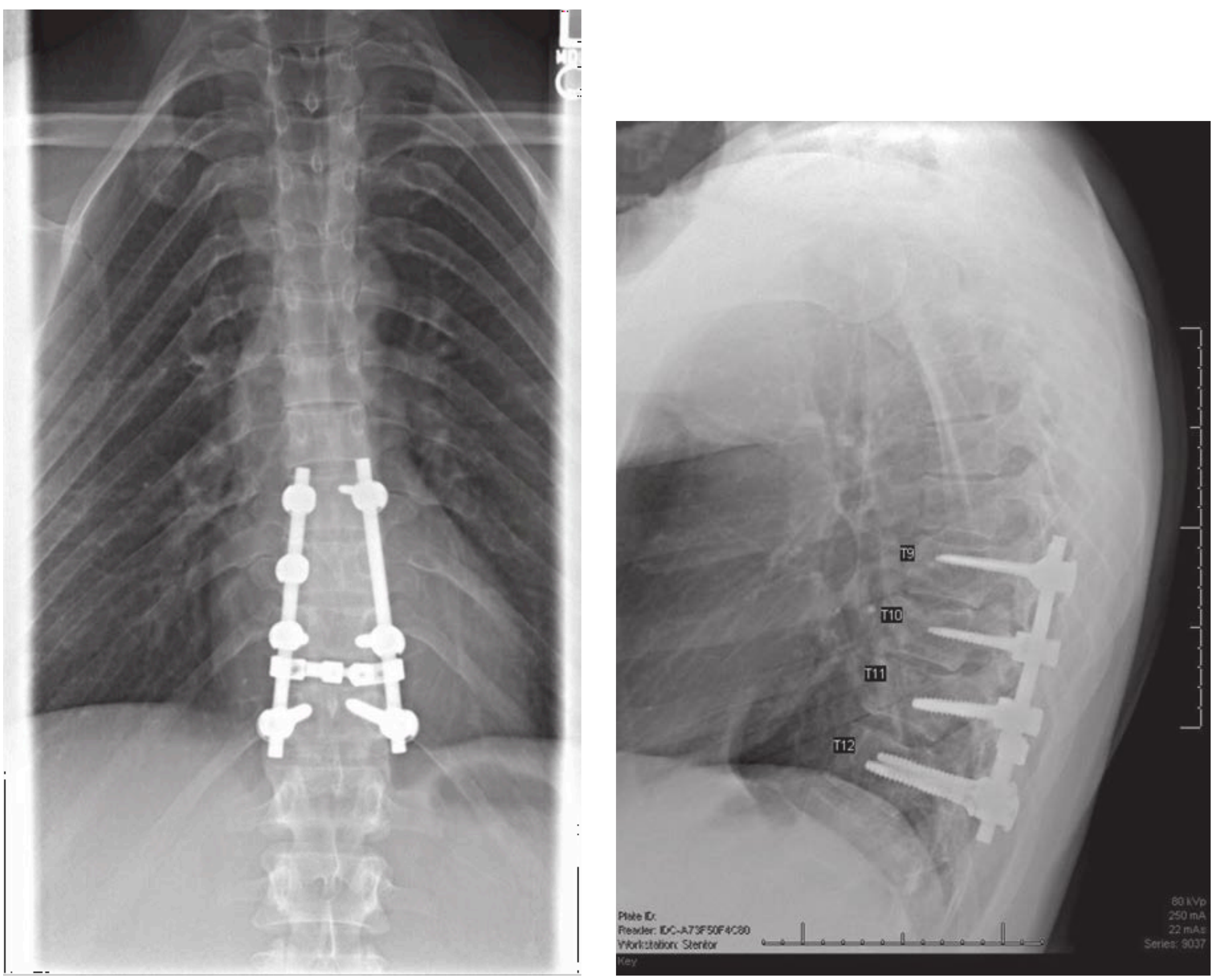
- Postoperative antibiotics should be administered for 24 hours or as long as the drain is in place.

Radiographic Imaging

- Postoperative films should be obtained to visualize the construct and the degree of realignment of the spine. This allows comparison of the fusion construct during follow-up (**Figs. 15.22, 15.23,** and **15.24**).
- If the patient has any new symptoms or fails to improve, then more detailed imaging is indicated such as MRI.

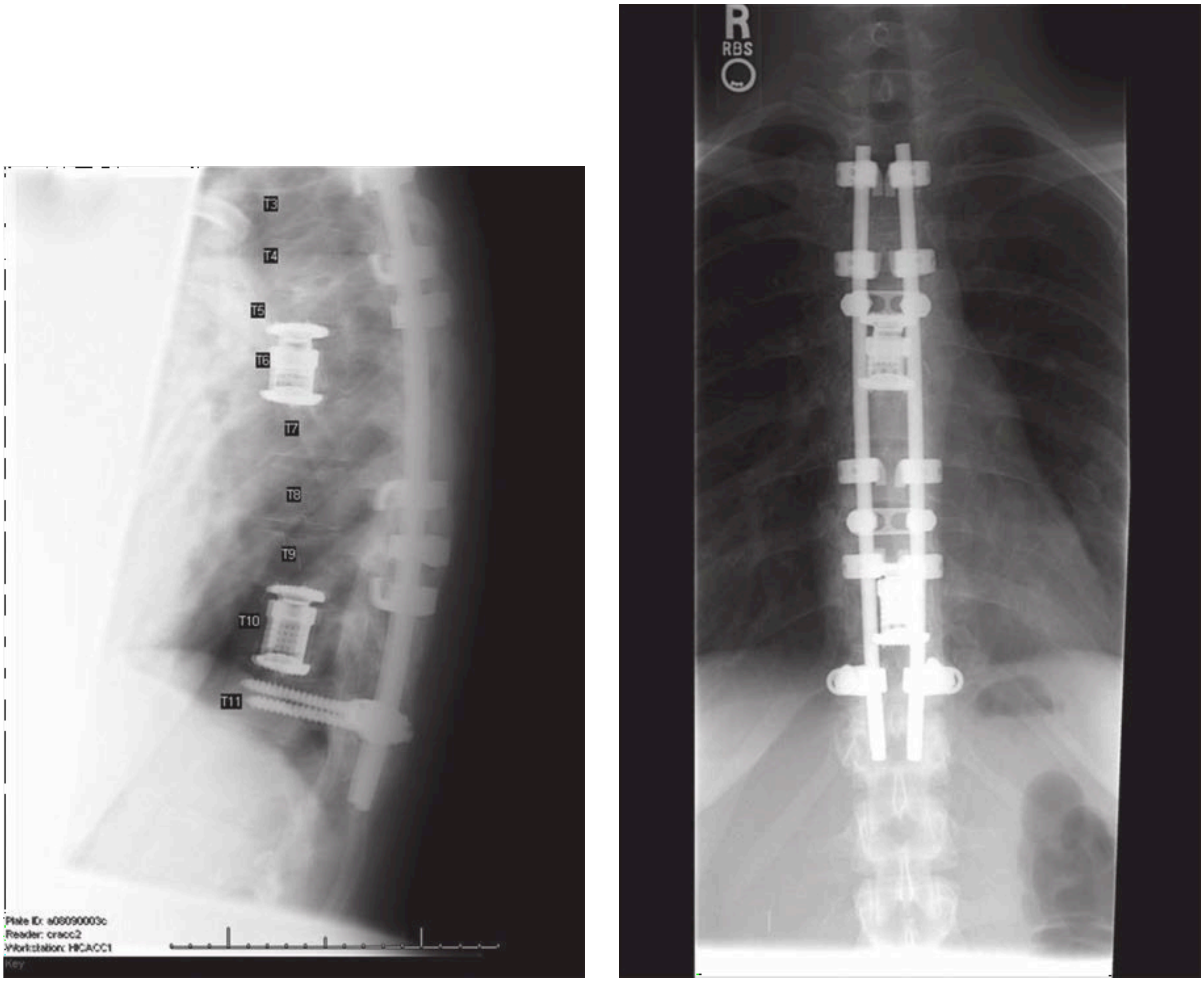
Further Management

- The patient should have limited physical activity with no bending, lifting, or twisting until the fusion has had time for completion, best visualized by postoperative X-ray or CT.
- After that time, then the patient may benefit from physical therapy to regain strength.



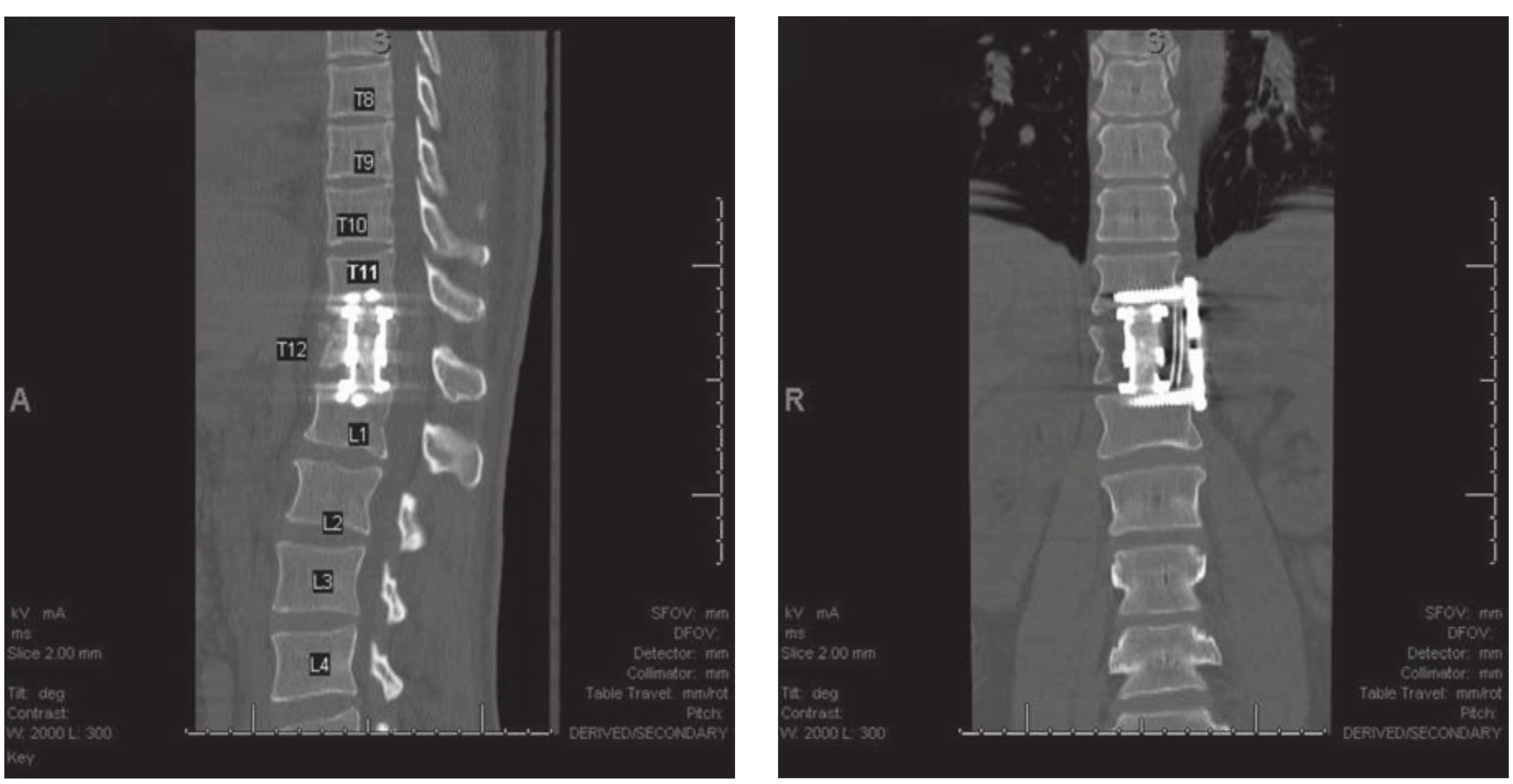
a b

Fig. 15.22a, b Postoperative (**a**) AP and (**b**) lateral radiographs of the patient depicted in Figs. 15.1 and 15.2 underwent open reduction and T9 to T12 arthrodesis instrumentation using pedicle screws, rods, and a cross connector with in situ autograft, cancellous allograft 90 mL, and demineralized bone matrix 20 mL. He was fully recovered at his 1-year postoperative visit.



a b

Fig. 15.23a, b (**a**) Lateral and (**b**) AP radiographs of open reduction procedure in patient depicted in Fig. 15.11. This procedure included anterior T6 and T10 corpectomies using two titanium cages packed with in situ autograft. Also performed were T5 laminectomy, T6-7 decompression laminotomies, and T3-T11 arthrodesis—instrumentation using sublaminar hooks, pedicle screws, rods, and cross links, supplemented with in situ autograft, demineralized bone matrix, and cancellous allografts.



a b

Fig. 15.24a, b Postoperative (**a**) sagittal and (**b**) coronal images of the same patient depicted in Fig. 15.17. He underwent a minimally invasive transthoracic transdiaphragmatic exposure from T11 to L1 and T12 corpectomy and decompression on spinal cord. T11 to L1 arthrodesis instrumentation was performed using an expandable titanium cage packed with in situ autograft, rib strut autograft, and thoracolumbar plate with screws.

Special Considerations

Posterolateral approaches such as the costotransversectomy and lateral extracavitary approaches provide greater exposure to the lateral portion of the vertebral canal and the anterolateral portion of the thoracic vertebral bodies. Costotransversectomy may be used in the removal of traumatic bone fragments or other foreign bodies in trauma and is useful in cases where a patient may not tolerate a formal thoracotomy either due to age or pulmonary pathology. It is less useful in cases where the anterior canal needs to be fully visualized or for other midline pathology.

In costotransversectomy, the patient may be placed prone, semiprone, or in modified lateral decubitus position. Intubation with a double lumen–cuffed endotracheal tube is again recommended as pneumothorax is a possibility. The approach should be on the side of the injury, or if midline, on the right to avoid the artery of Adamkiewicz which usually originates on the left side between T8 to L2. The incision is midline (sometimes with a T) or paramedian with or without a hockey stick relaxing incision. If the incision is paramedian, the muscles (trapezius and latissimus dorsi) are reflected medially. Midline incisions require subperiosteal dissections. The ribs to be removed are skeletonized subperiosteally. Entrance to a disk space requires exposure of the inferior rib (e.g., T9-T10 disk space requires exposure of the 10th rib). The articulations that must be addressed include the superior and inferior costal facet and transverse costal facet. The pleura is mobilized and reflected from the underside the rib and anterolateral position of the spine. The rib of interest is then transected approximately 5 cm from the rib head. The foramen can then be identified by following the neurovascular bundle travelling on the inferior surface of the rib. The pedicles can then be identified above and below the foramen which can be resected to visualize the lateral thecal sac. The pleural and intercostal muscles are bluntly dissected away from the vertebral body. Bone from the lateral vertebral body or disk may be removed as required with care not to damage the radicular arteries. Once the decompression or diskectomy is complete, instrumented or noninstrumented fusion may be considered based on pathology. Again, partial vertebrectomy may be achieved. Pleural tears are repaired if present and chest tubes are used if necessary.

The lateral extracavitary approach is a more extensive posterolateral approach which again does not violate the chest cavity. The patient is placed in a prone position. A hockey stick (midline incision curved 45 degrees off midline for 6 to 8 cm in the lower portion) or paramedian incision (centered over the lateral paraspinal muscles) can be used. A plane is developed between the superficial and deep paraspinal muscles, and a myocutaneous flap is lifted off to expose the lateral paraspinal muscles and rib cage. The paraspinal muscles are then mobilized from the rib and transverse process. The ribs, ligamentous attachments, and associated transverse processes are then removed. Similarly to above, the neurovascular bundle is isolated and acts a guide for identification of the respective foramen and pedicles. The remainder of exposure is completed similarly to the other posterolateral techniques.

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16 Thoracolumbar Fractures

Michael Y. Wang and Brian Hood

Introduction

The transition zone at the thoracolumbar junction differs biomechanically from the stiff thoracic spine to the mobile lumbar spine. This zone of transition is related to the loss of the rib cage as well as the changing orientation of the facet joints. Because of these factors this area is prone to traumatic injury and accounts for approximately up to 50%of all vertebral body fractures and up to 40%of all spinal cord injuries.[1,2]

Management of thoracolumbar fractures is a controversial topic in contemporary spine surgery. Early surgery for decompression and stabilization is generally accepted for patients with clear instability and an incomplete neurologic injury. Advantages of surgery include a better correction of deformity than closed reduction and bracing, an opportunity to perform direct or indirect decompression of the neural elements, decreased requirement for external immobilization, and fewer complications due to prolonged recumbency. The surgical treatment is more controversial for patients with mild to moderate deformity, without neurologic deficit, and residual spinal canal compromise, and the ideal solution remains largely unknown.[1,3–9]

Classification

The most common fracture patterns at the thoracolumbar junction include compression fractures, burst fractures, flexion-distraction injuries, and fracture-dislocations.

Denis Classification

Compression Fractures

Failure of the anterior column in flexion/compression

A: Failure of the superior and inferior endplates
B: Superior vertebral endplate failure (most common type of compression fracture)
C: Inferior vertebral endplate failure
D: Failure of the central vertebral body with less involvement of the endplate

Burst Fractures

Compression failure of the anterior and middle spinal columns

A: Failure of both superior and inferior endplates
B: Superior endplate failure only (most common type of burst fracture)
C: Inferior endplate failure only
D: Axial loading and rotational injury
E: Axial loading and lateral flexion

Flexion-Distraction

(Chance): Primary anterior force vector acting along an axis of rotation located anterior to middle column. The posterior and middle columns fail in tension and the anterior column fails in tension or compression depending on the axis of rotation.

Fracture-Dislocation

Results from violent complex shearing force and by definition involves all three spinal columns. Highest rate of complete neurologic injury.

AO Thoracolumbar System (of Magerl)

Defines the major mechanism of spinal injury compression (A), distraction (B), and torsion (C) to indicate increasing injury severity occurring with increasing grade of injury. Three groups exist within each type (A1, A2, A3) and each group is divided into subgroups (A1.1, A1.2, A1.3). The classification is based on morphological criteria. The categories are established according to the main mechanism of injury, and take in to consideration the prognostic aspects of potential healing. The types are determined by the three most important mechanisms acting on the spine: compression, distraction, and axial torque. The type A is a vertebral body compression injury; type B injuries involve anterior and posterior element injuries with distractions; and type C lesions refer to anterior and posterior element injuries with rotation consistent with axial rotation injuries. The AO system is very comprehensive and good for describing fracture patterns, but it is a victim of its comprehensiveness; it does not consider neurologic status, and does not aid in decision making.[10]

Thoracolumbar Injury Classification and Severity Score (TCLIS)

This system was developed due to the need for a classification system that could be used to prognosticate the need for surgical intervention. The system was based on a review of the existing literature as well as consensus opinion from a multinational group of leading spinal trauma surgeons. Three major injury characteristics were defined: injury morphology, neurologic

Table 16.1 Thoracolumbar Injury Classification and Severity Score

Injury characteristic	Qualifier	Points
Injury morphology		
Compression	—	1
	Burst	1 1
Rotation/translation	—	3
Distraction	—	4
Neurologic status		
Intact	—	0
Nerve Root	—	2
Spinal cord, conus medullaris	Incomplete	3
	Complete	2
Cauda equine	—	3
Posterior ligamentous complex integrity		
Intact	—	0
Suspected/Indeterminate	—	2
Disrupted	—	3

1 5 1 additional point given to morphology

status, and integrity of the posterior ligamentous complex (PLC) (see **Table 16.1**).

Severity score: A score of . 4 suggests a need for surgical treatment because of significant instability, whereas a score , 4 suggests nonsurgical management. A patient with a score of 4 may be treated surgically or nonsurgically.[5,11–13]

Indications

- Grossly unstable injuries with or without neurologic deficit
- To facilitate neurologic recovery via direct decompression or indirect decompression through ligamentotaxis
- To correct deformity
- To provide immediate stabilization
- To decrease requirements for external immobilization, and complications due to prolonged immobilization

Preprocedure Considerations

Radiographic Imaging

- Anteroposterior (AP) and lateral radiographs of the cervical, thoracic, and lumbar spine are standard imaging studies following spinal trauma. In some centers this has been largely replaced for survey purposes by whole body computed tomography (CT) scanning.
- Because there is a high percentage of noncontiguous associated spinal fractures, entire neuraxis imaging may be warranted if clinical suspicion is high.

Fig. 16.1 Sagittal reconstruction of trauma CT scan showing fractures of T12 and L1 in a 55-year-old man who had fallen from a height.

- CT is generally the next step after plain films. Axial fine cuts and sagittal reconstruction help define fracture patterns and determine the degree of canal compression (**Fig. 16.1**).
- Magnetic resonance imaging (MRI): Generally not required in a neurologically intact patient in the acute setting, but can help evaluate the PLC. With a neurologic deficit, MRI is recommended to identify any ongoing spinal compression, evaluate cord anatomy, and rule out epidural hematoma.

Medication (Neuroprotection and Nonoperative Management)

- According to the second NASCIS trial, in patients with confirmed spinal cord injury, patients started on methylprednisolone within 3 hours of injury had a substantial benefit in terms of ultimate neurologic recovery. We do not use steroids at our institution. Recent published guidelines do not recommend steroid usage.[14]

- Intravenous fluid, colloid, and vasopressors are used as needed to maintain a mean arterial pressure of 85 mm Hg or greater.[15]

Surgical Management

The goals of surgical treatment include: (1) decompression of the spinal canal and nerve roots to facilitate neurologic recovery, (2) restoration and maintenance of vertebral body height and alignment to minimize posttraumatic deformity, (3) obtaining rigid fixation to facilitate nursing care and allow early mobilization, (4) obtaining a solid arthrodesis of damaged segments or fracture healing, and (5) limiting the number of instrumented vertebral motion segments. Surgical algorithms can generally be classified into one of five groups: (1) posterior decompression and stabilization, (2) costotransverse/lateral extracavitary/transpedicular decompression and reconstruction/stabilization, (3) anterior corpectomy/stabilization, (4) combined anterior/posterior decompression/stabilization (360), and (5) percutaneous fracture fixation.

Posterior approaches allow for realignment of the spine, direct and indirect decompression of the neural elements, and protection against late deformity and instability. Spinal canal decompression via ligamentotaxis is optionally achieved within the first 2 to 4 days post injury. We prefer to stabilize thoracolumbar fractures within 48 hours of presentation if medically stable. For thoracic injuries, a posterolateral, either costotransversectomy or transpedicular, approach allows some decompression of anterior pathology and allows a circumferential fusion through a posterior only approach.

This chapter addresses the posterior approach, both open and percutaneous.

Operative Field Preparation

- The skin is cleansed with alcohol then a betadine scrub is used.
- Alternatively, alcohol and chlorhexidine can be used.
- The authors use vancomycin and ceftriaxone for antibiotic prophylaxis provided the patient does not have renal failure or other contraindications.

Operative Procedure

Open Approach

Positioning (Fig. 16.2)

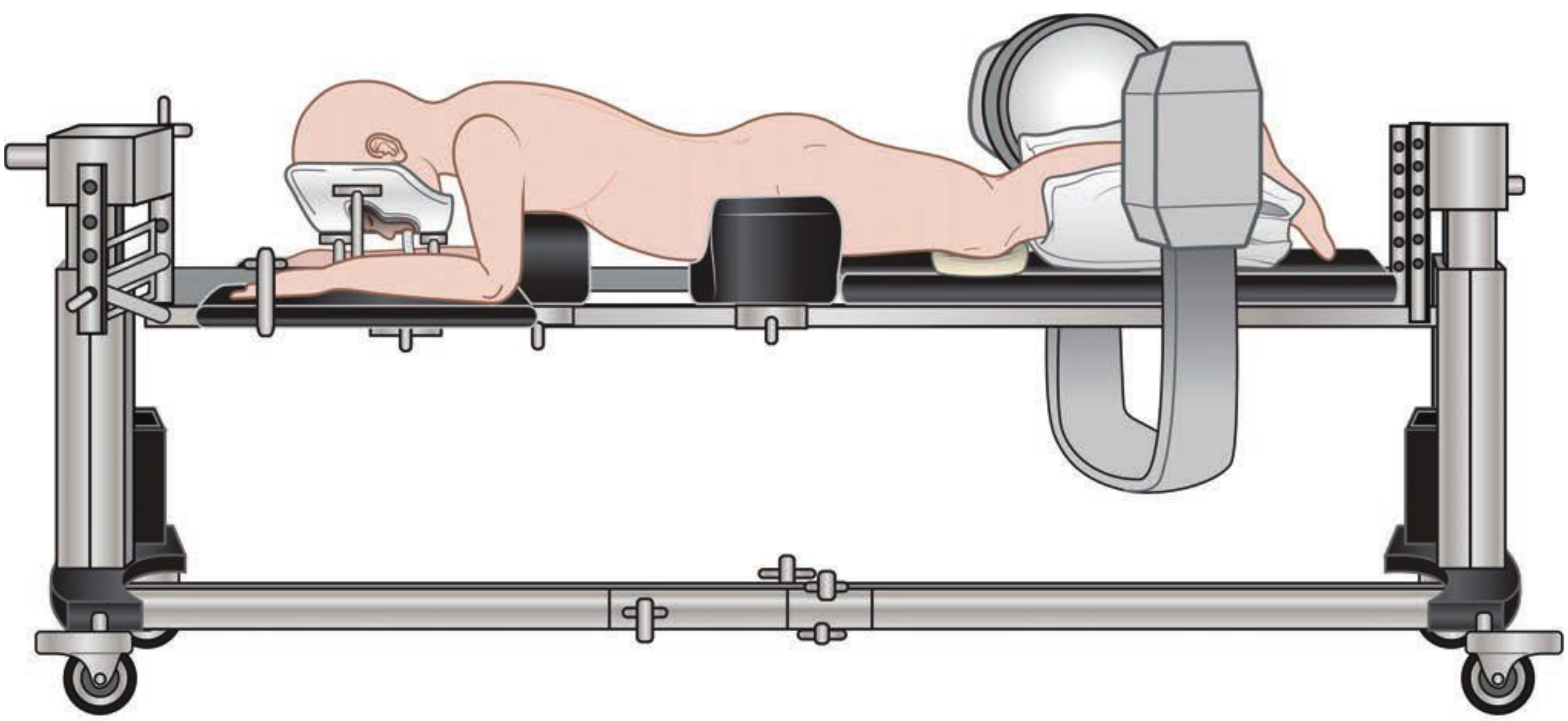
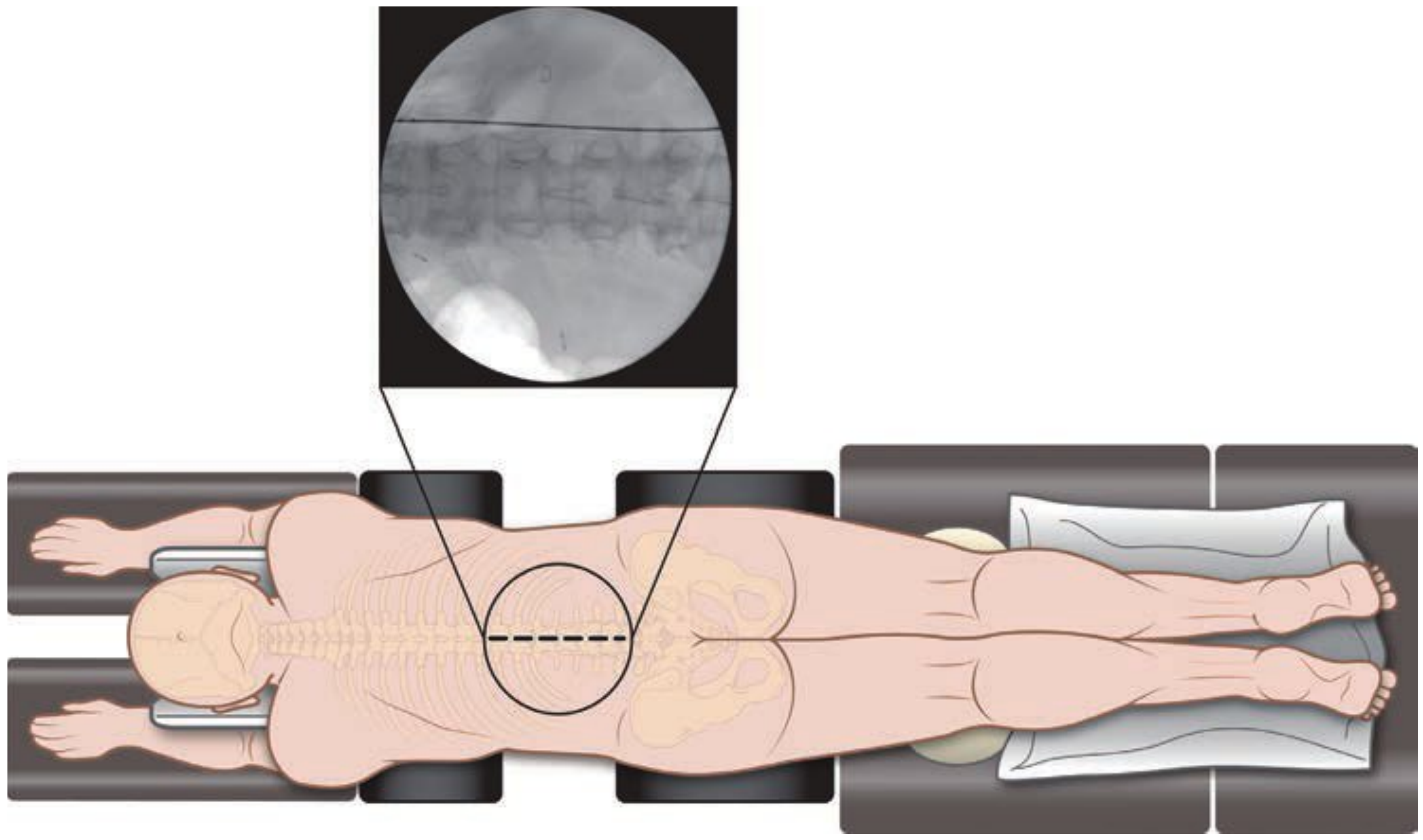


Figure	Procedural Steps	Pearls
Fig. 16.2	**The patient is positioned carefully on a radiolucent frame to obtain optimal preoperative reduction of deformity.**	• A four-posted spinal table is used. Preincision fluoroscopy verifies ability to visualize pedicles radiographically after exposure. One can conduct an awake turn or perform neuromonitoring with pre and post turn electromyography (EMG)/somatosensory evoke potentials (SSEPs) in patients with incomplete neurologic injury.

Exposure (Fig. 16.3a, b)



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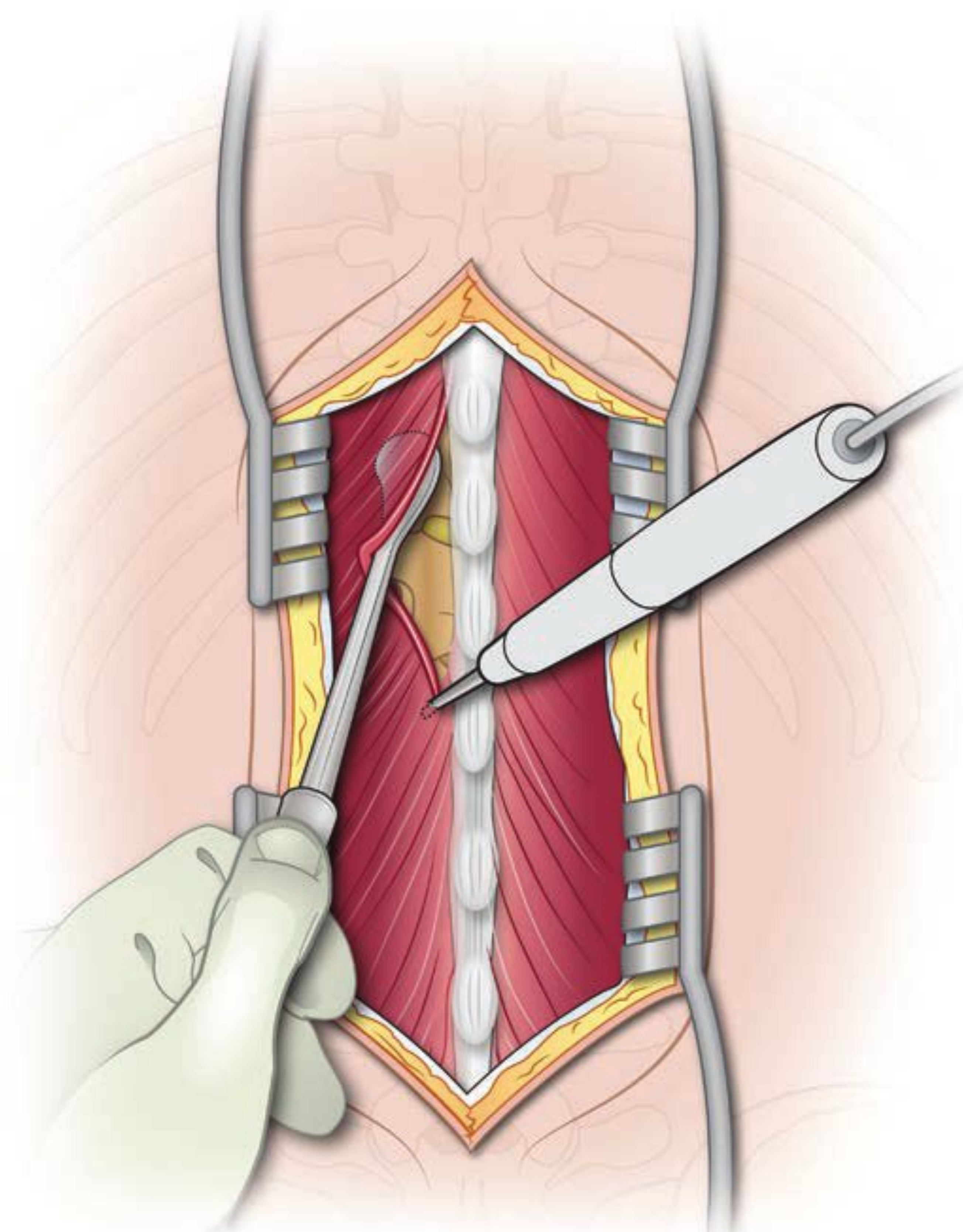


b

Figure	Procedural Steps	Pearls
Fig. 16.3	**(a) A midline posterior approach is most common for thoracolumbar instrumentation. (b) Subperiosteal exposure of the posterior elements is carried out laterally over the tips of the transverse processes.**	• Instrumentation requires a wider exposure for optimal placement of instrumentation. Inadequate exposure risks screw malposition.

Decompression (Fig. 16.4)

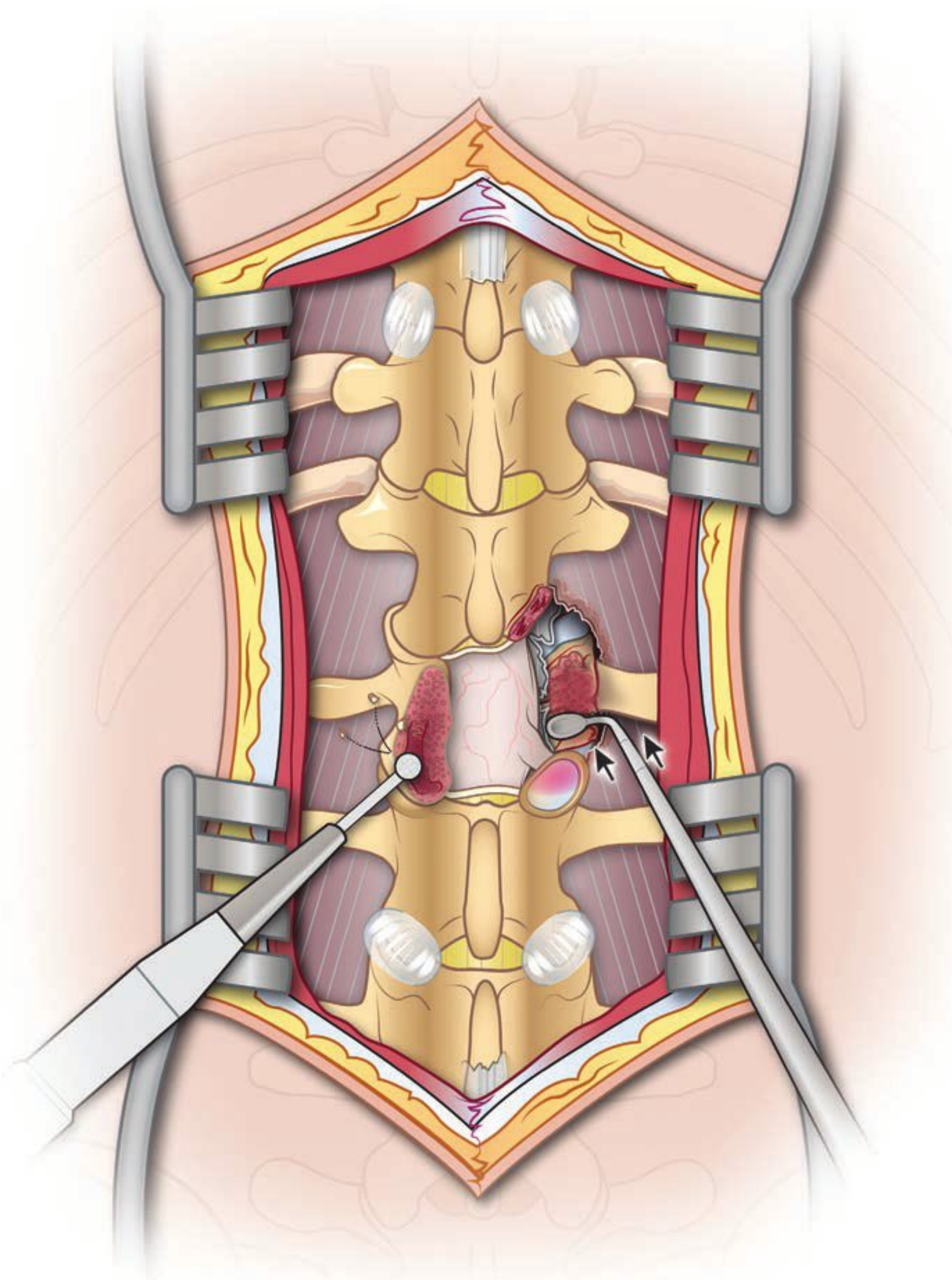
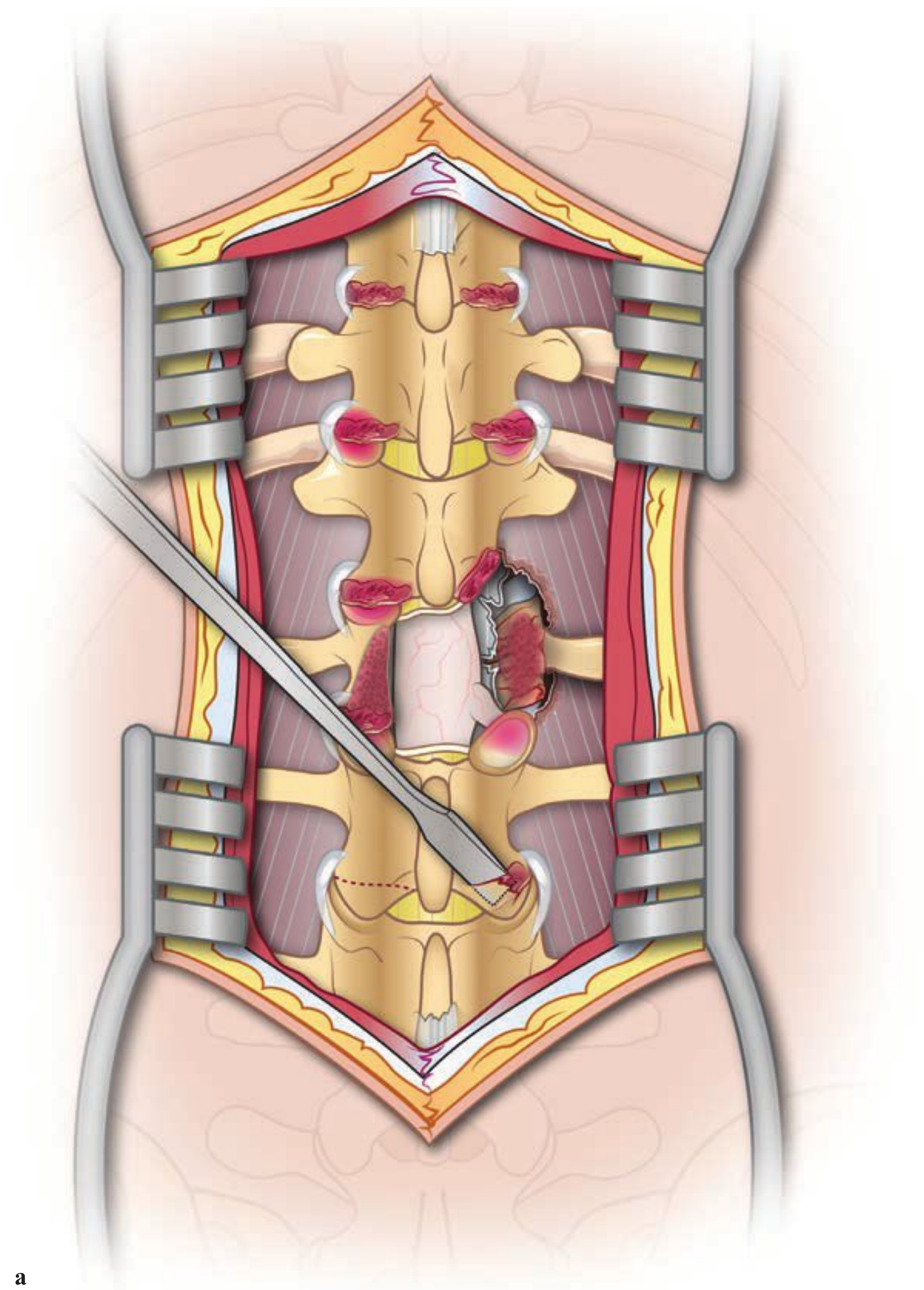


Figure	Procedural Steps	Pearls
Fig. 16.4	**The lamina is removed with a drill and rongeurs. At this point a costotransversectomy, or a transpedicular vertebrectomy, can be performed if indicated (see Chapter 15).** **Ligamentotaxis may be used to mobilize anterior fracture fragments away from the spinal cord. Alternatively, a downward directed curette can be used to tamp bone fragments anteriorly away from the spinal cord** (arrow)**. This technique may be facilitated by removing the pedicle on one or both sides to achieve more exposure of the superior endplate, which is typically the area of greatest impingement.**	• Laminectomy alone as a decompressive procedure has been shown to be ineffective in achieving anterior spinal cord decompression. • The only indication for a standalone laminectomy is to evaluate for dural tears or posterior compression.

Facetectomy and Pedicle Cannulation (Fig. 16.5a–c)



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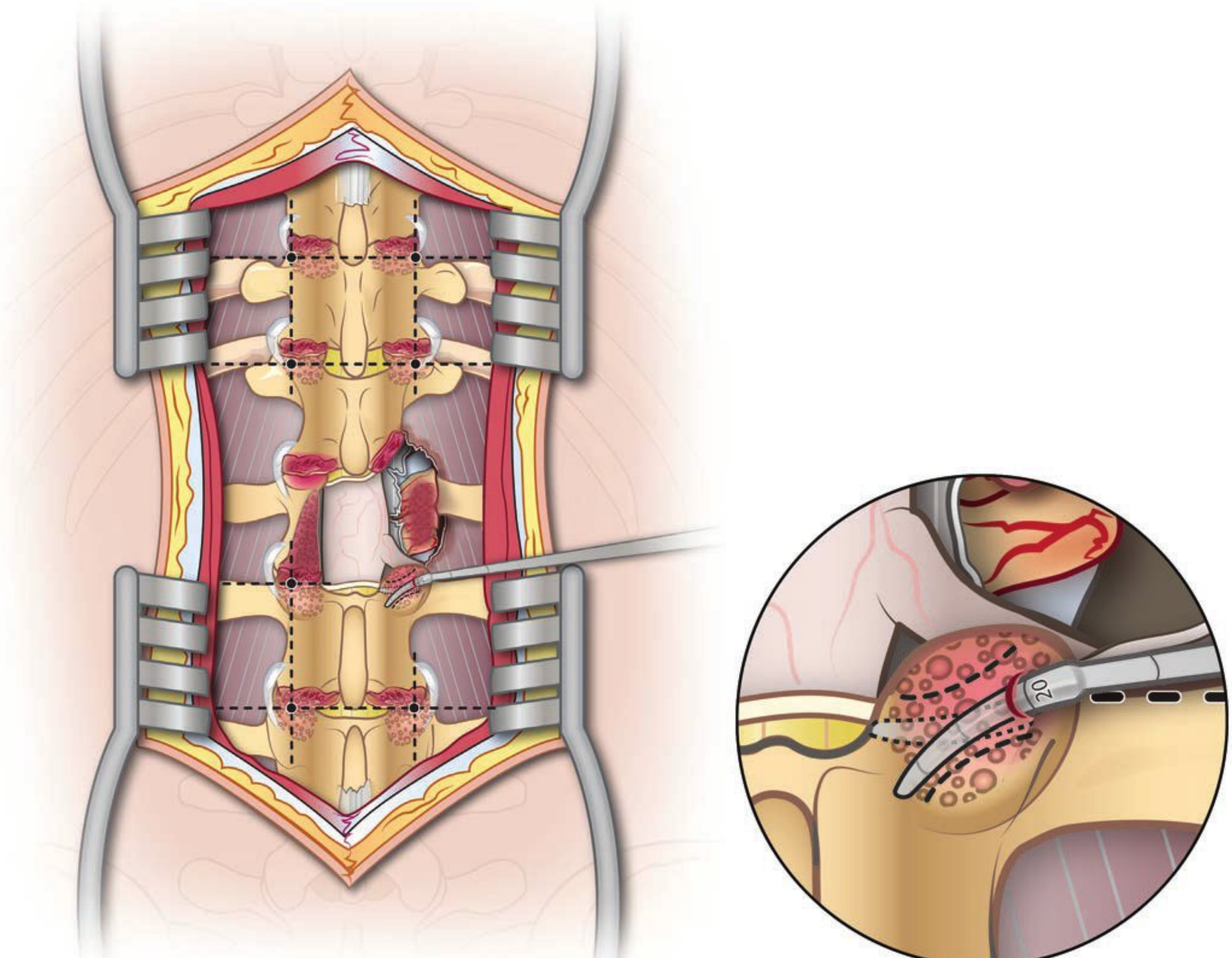


b c

Figure	Procedural Steps	Pearls
Fig. 16.5	**(a) The facet joint is stripped of its capsule. The inferior portion of the inferior facet is removed with a rongeur or osteotome. Partial facetectomy should reveal a pedicle "blush."** **(b) At T12 the starting point is the junction of the bisected transverse process and border of the lateral pars. The starting point trends medially and cephalad as one moves cranially toward the midthoracic region.** **A thoracic (blunt, curved) probe is placed in the "blush" or starting point as determined by AP fluoroscopy. The curve is directed laterally and advanced 15 to 20 mm letting the probe "fall into" the pedicle.** **(c) After advancing 15 to 20 mm, the probe is removed and replaced facing medially and advanced to a depth of 30 to 40 mm in the midthoracic spine. A feeler/sounder probe is then introduced. Only blood should return from the tract and not cerebrospinal fluid. A floor and then four walls should be palpated.**	• Removing the inferior portion of the inferior facet allows more soft tissue removal and helps to find the entrance to the pedicle. • Anatomic starting points can be verified with AP fluoroscopy and pedicle markers can be placed. Lateral fluoroscopy can then be used for pedicle cannulation. • Any abrupt step off when cannulating the pedicle should raise suspicion of a pedicle breach and should be investigated with a sounding probe and radiographic evaluation. Pay attention to the medial portion of the tract where violations of the pedicle are critical.

Tapping and Screw Placement (Fig. 16.6)

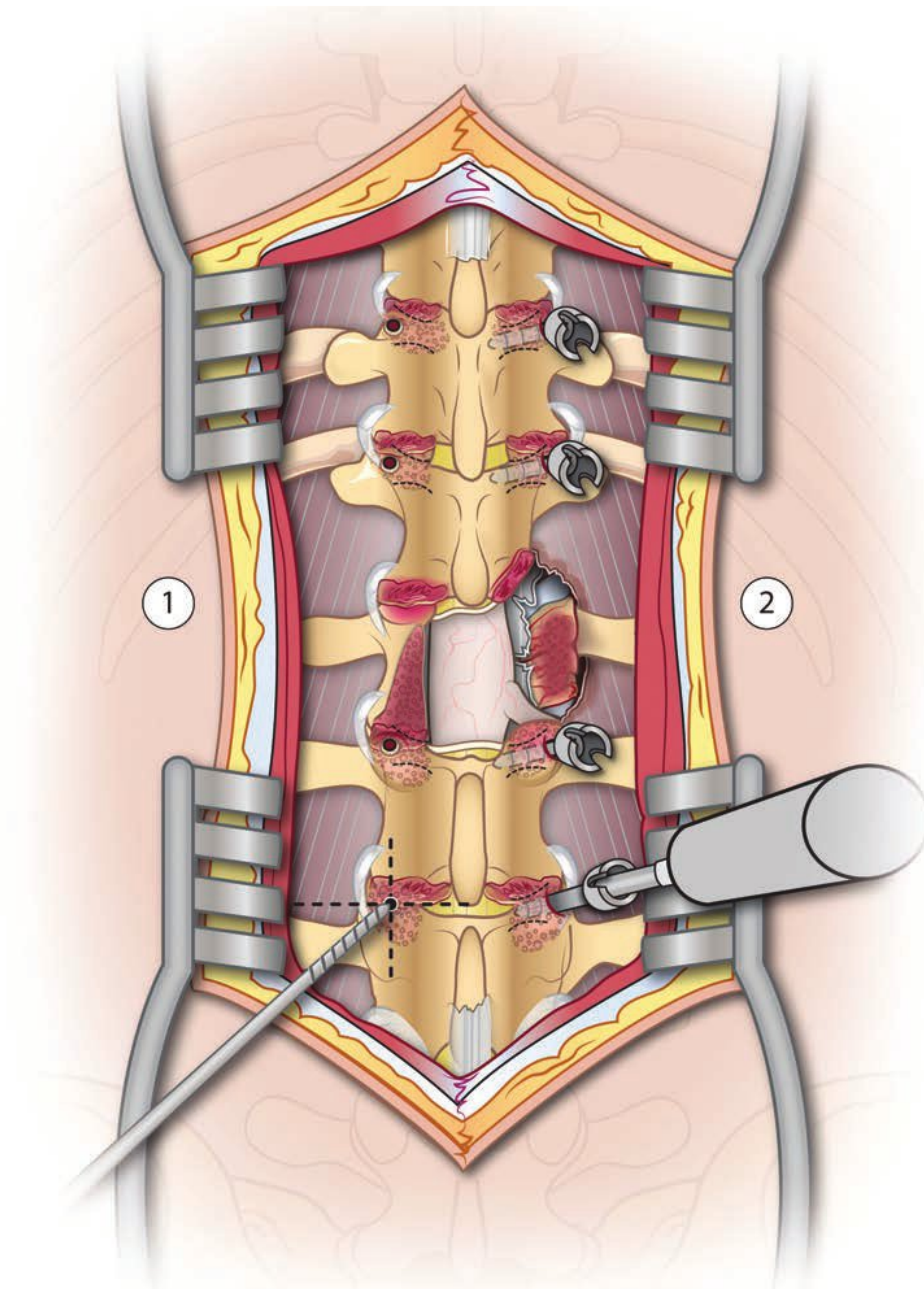


Figure	Procedural Steps	Pearls
Fig. 16.6	**The pedicle is then under-tapped 0.5 mm. Preoperative assessment of pedicular size guides the appropriate tapping and screw placement (1). After tapping, the tract is once again sounded with a feeler probe searching for violations. Slow screw placement allows utilization of viscoelastic properties of the pedicle and avoids pedicle fracture (2).**	• Charting pedicle size and depth preoperatively facilitates appropriate screw selection. • All screws placed should be verified by intraoperative imaging. In addition, electrodiagnostic testing can be performed with abdominal leads.

Rod Placement (Fig. 16.7a–c)

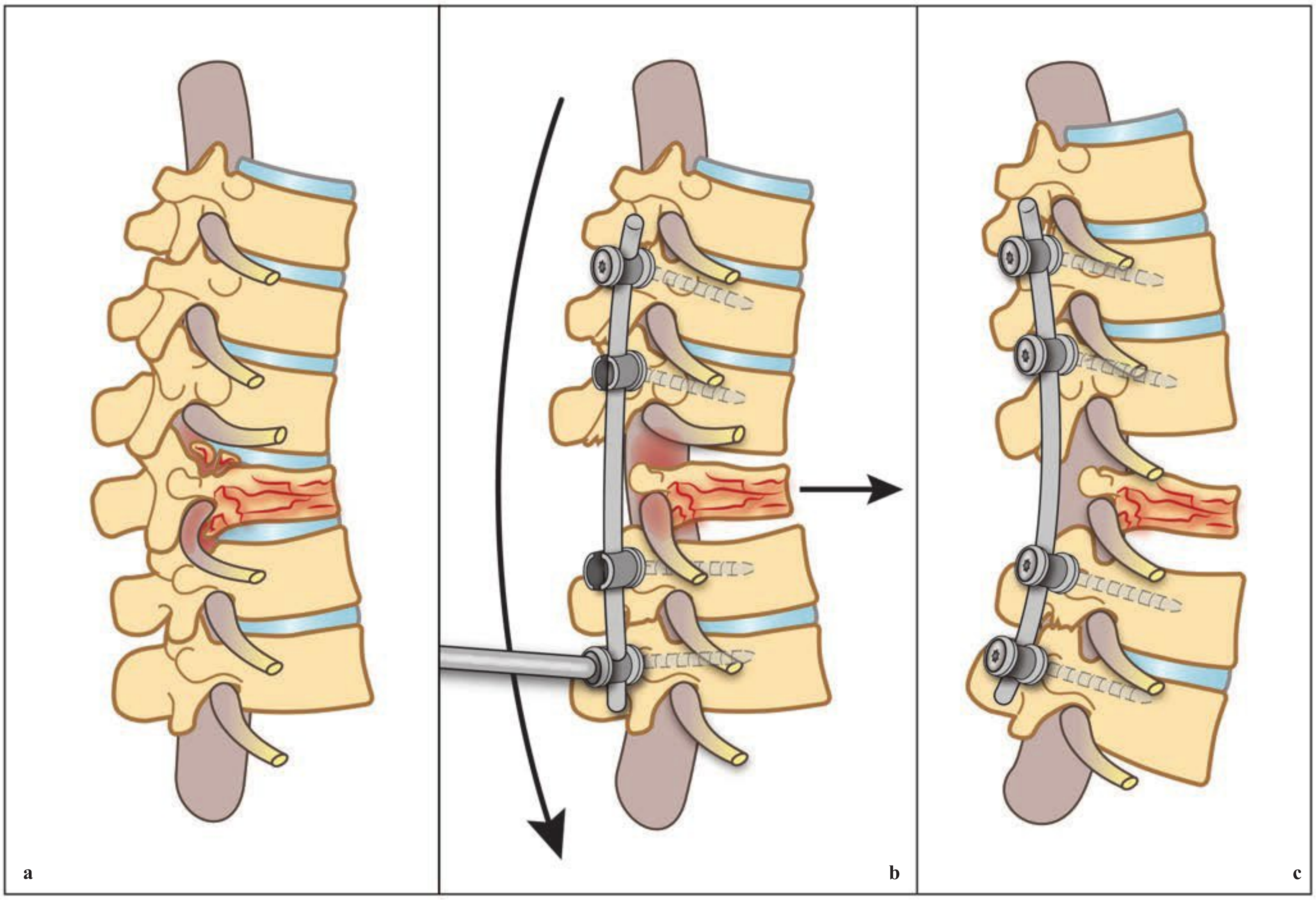


Figure	Procedural Steps	Pearls
Fig. 16.7	**A rod is selected and contoured appropriately. Distraction and reduction maneuvers can be applied to aid in reduction of compression via ligamentotaxis.**	• The rod should be passed approximately 5 mm beyond the most cranial and caudal screw. Compression maneuvers gain little in achieving additional rod length.

Bone Grafting (Fig. 16.8)

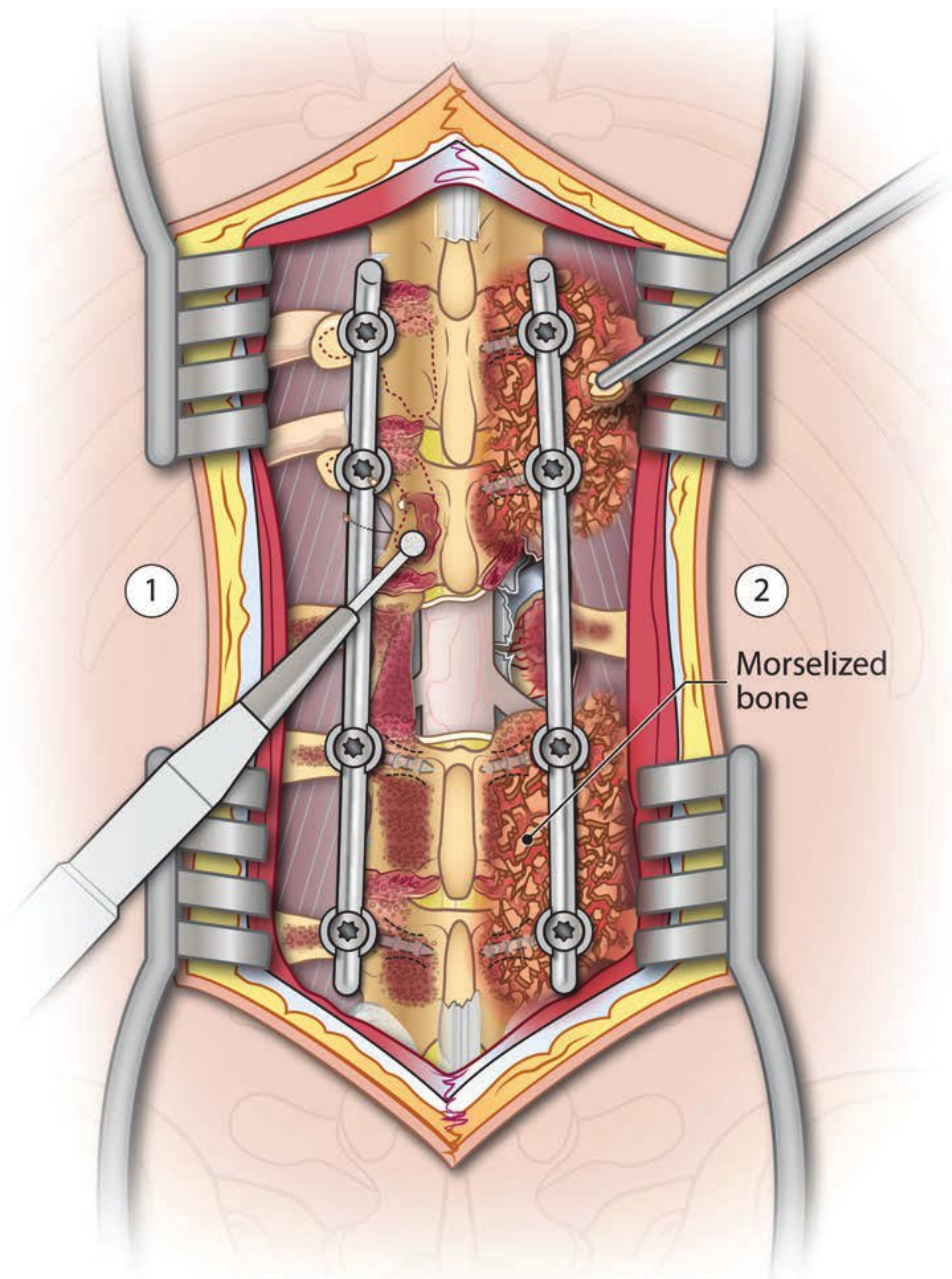
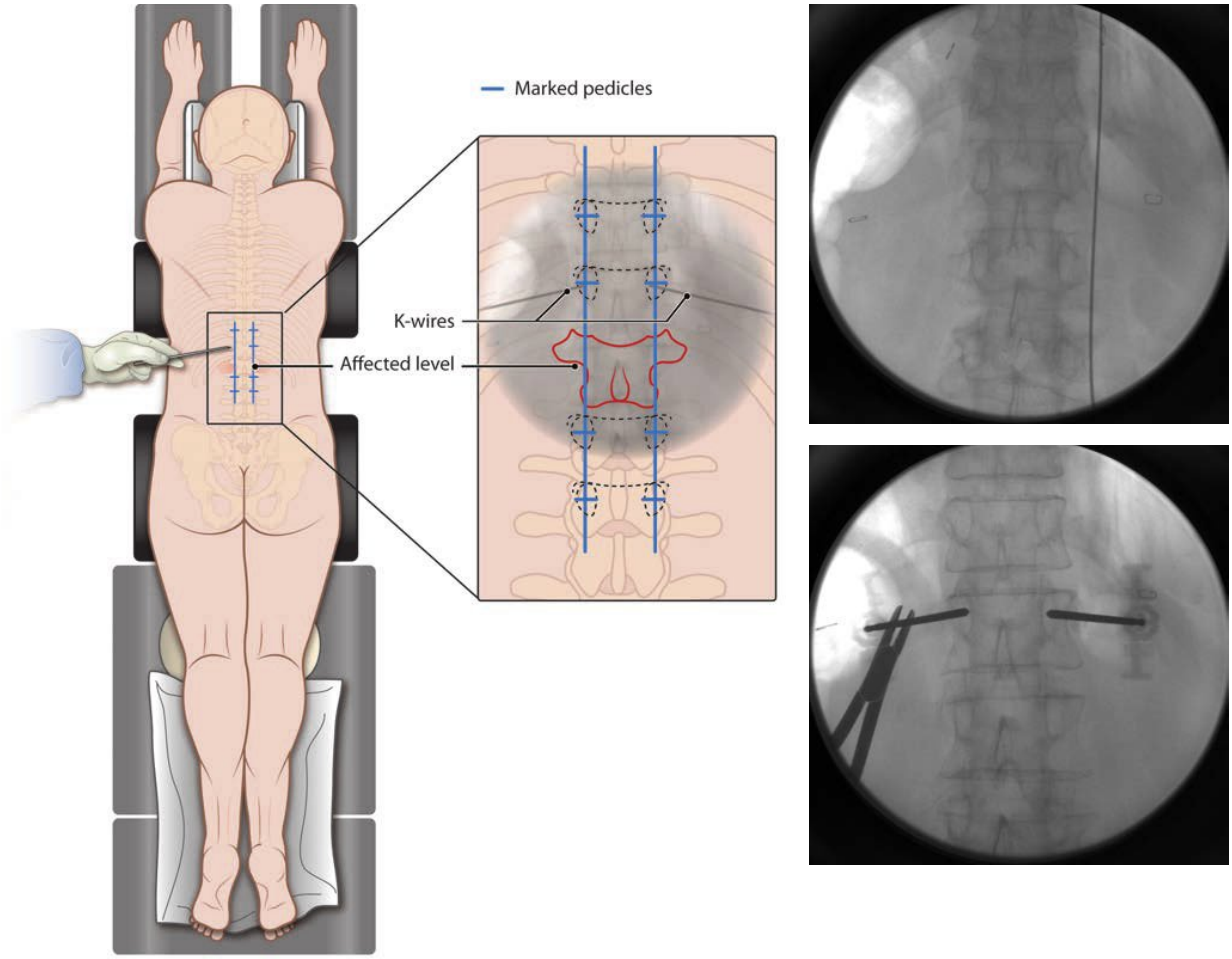


Figure	Procedural Steps	Pearls
Fig. 16.8	**Spinous processes and lamina local autograft removed are morselized. The remaining lamina, transverse process, and facets are decorticated with a high speed drill (1). The bone graft is then laid on bleeding bone (2). Iliac crest bone autograft remains the gold standard.**	• Intraoperative relaxation of retractors periodically facilitates blood flow and preservation of extensor musculature. Careful preservation of regional blood supply supports rapid graft incorporation and focuses on fusion versus construct failure.

Percutaneous Approach

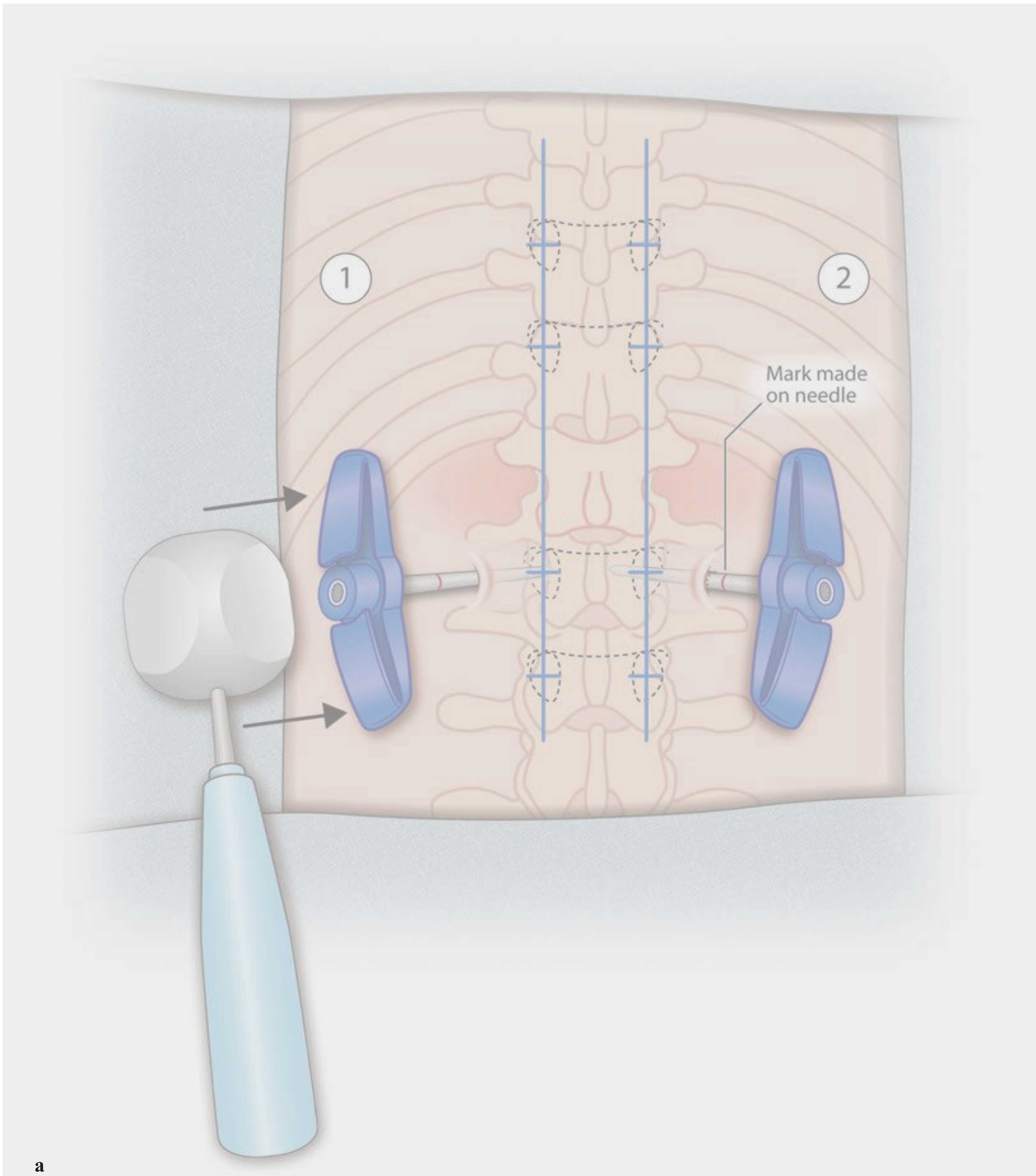
Positioning and Pedicle Targeting (Fig. 16.9a–c)

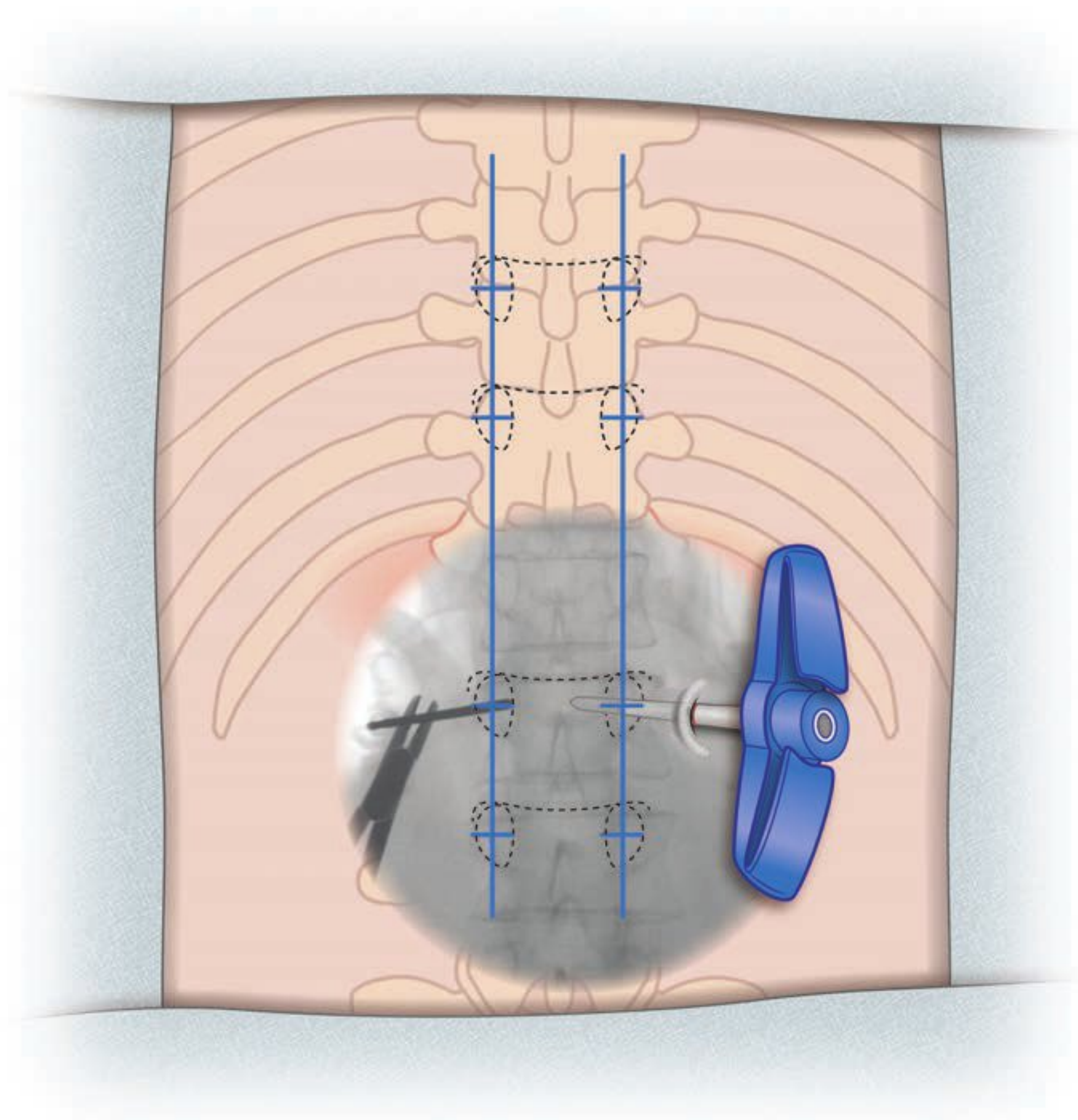


a b c

Figure	Procedural Steps	Pearls
Fig. 16.9	**(a) The patient is carefully positioned prone on a radiolucent table, as in Fig. 16.2, in order to obtain the best preoperative reduction of deformity.** **(b) Prior to prepping and draping, the pedicles are targeted using AP fluoroscopy. (c) Kwires are placed at the 9 o'clock position on the left sided pedicles and the 3 o'clock position of the right pedicles. These lines are marked on the patient. We also mark the mid pedicle levels in the horizontal plane at each level.**	• A good AP image is imperative. The endplates must be absolutely parallel, and the spinous process equidistant between the pedicles. At each level, it is helpful to mark the degree of rotation of the C-arm needed to obtain the view. This help to decrease fluoroscopy time, as well as operative time.

Jam Shidi Placement (Fig. 16.10a–c)





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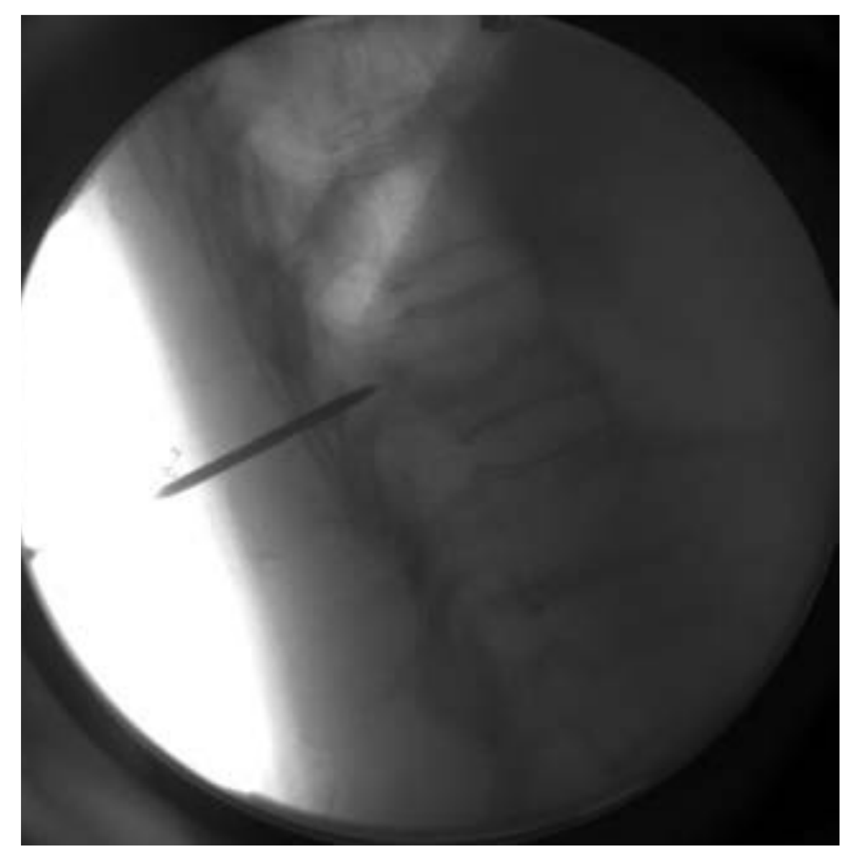
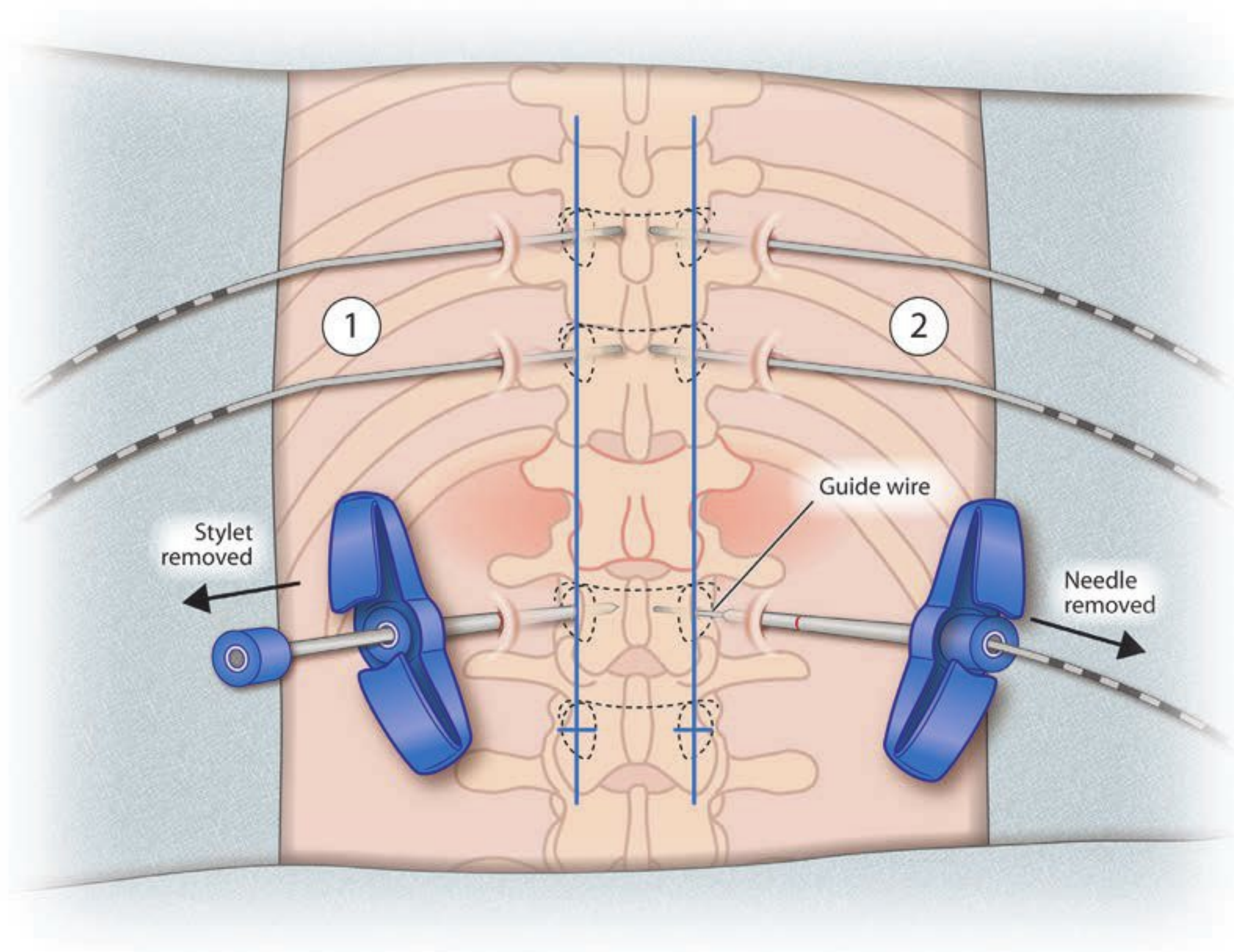


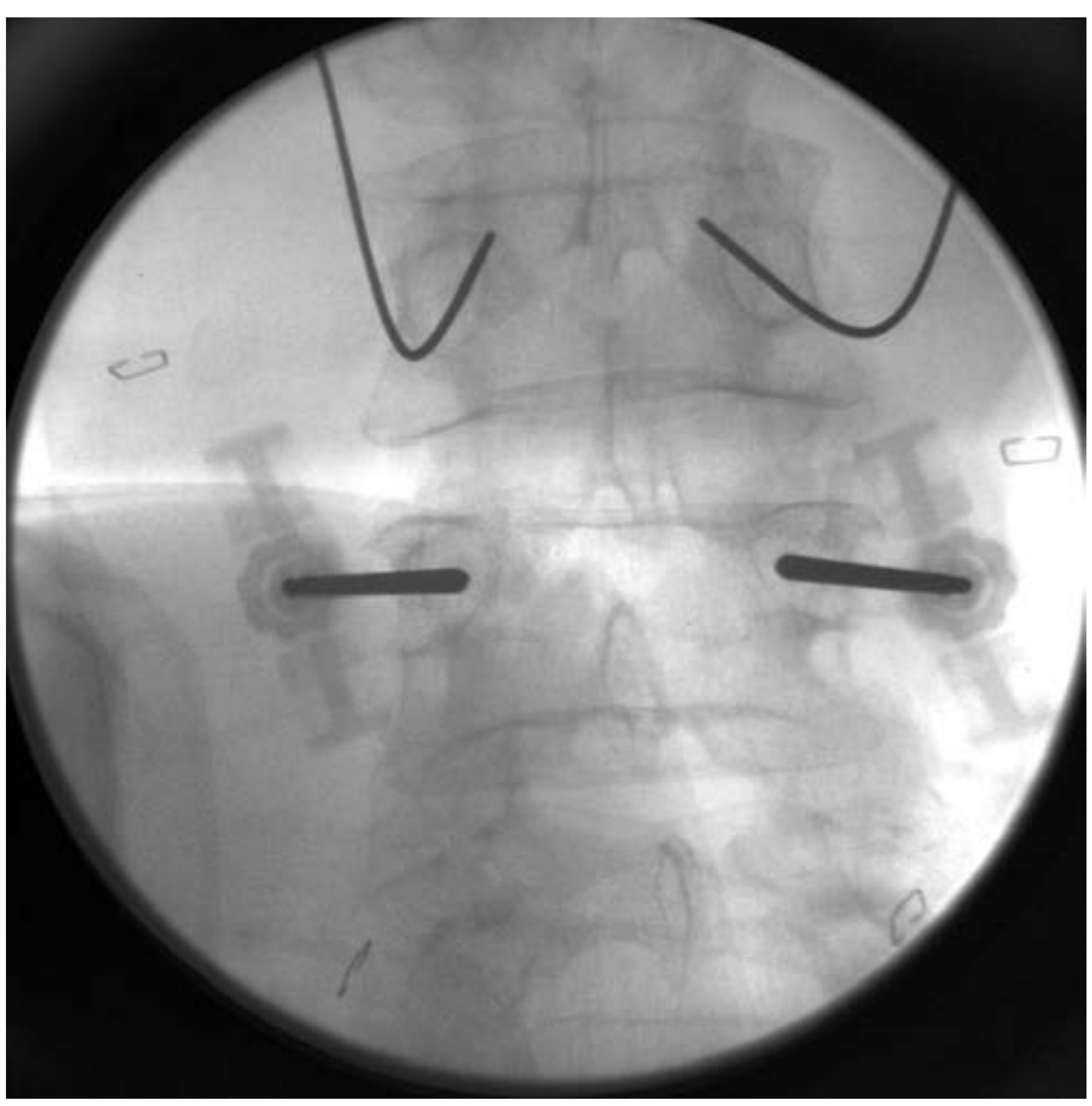
c

Figure	Procedural Steps	Pearls
Fig. 16.10	**(a) The bone trephine needle is started in the skin just lateral to the marked pedicle and advanced to the starting point (3 o'clock on the right, 9 o'clock on the left). Once bone is encountered, an image is obtained. The needle is lightly malleted to engage the tip into the cortical bone (1). A mark is made on the needle approximately 25 mm from the skin surface (2). The needle is then advanced into the pedicle approximately 15 mm. An image is taken. (b) If the needle has traversed less than 50%the width of the pedicle, it can be safely advanced the remained of the distance without fear of medial wall breech.**	• We use AP images to place the bone trephine needles. Alternatively, the needles can be advanced to 20 mm under AP imaging, and then switched into a lateral view to advance the remainder of the distance into the vertebral body (**c**).

Guidewire Placement (Fig. 16.11a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 16.11	**(a, b) The stylet is removed from the bone trephine needle and a Kwire is placed (1). The Kwire is advanced several mm beyond the bone trephine needle and then the needle is removed (2).**	• The Kwire can be used as a flexible "feeler" probe to ensure that bone is encountered when advancing.

Facet Fusion (Optional) (Fig. 16.12)

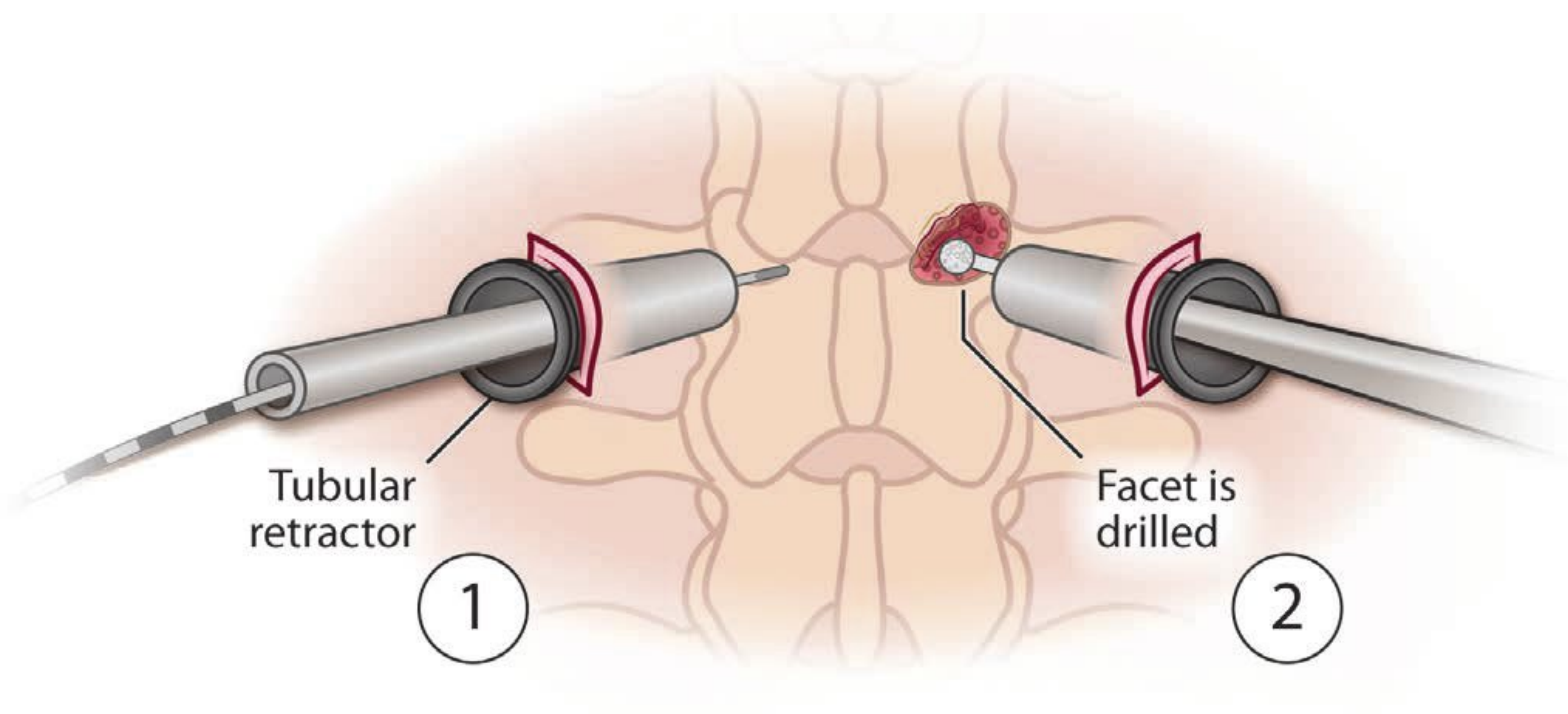


Figure	Procedural Steps	Pearls
Fig. 16.12	**If a long-term fusion is required, dilators are then placed over the Kwire and docked on the pedicle screw starting point. A tubular retractor is then placed (1). The facet is superior and medial to the starting point. The soft tissue is then removed with electrocautery, and the facet decorticated with a high speed bur (2). Bone graft is then laid on the facet.**	• The necessity for fusion is decided on an individual basis.

Screw Placement (Fig. 16.13a, b)

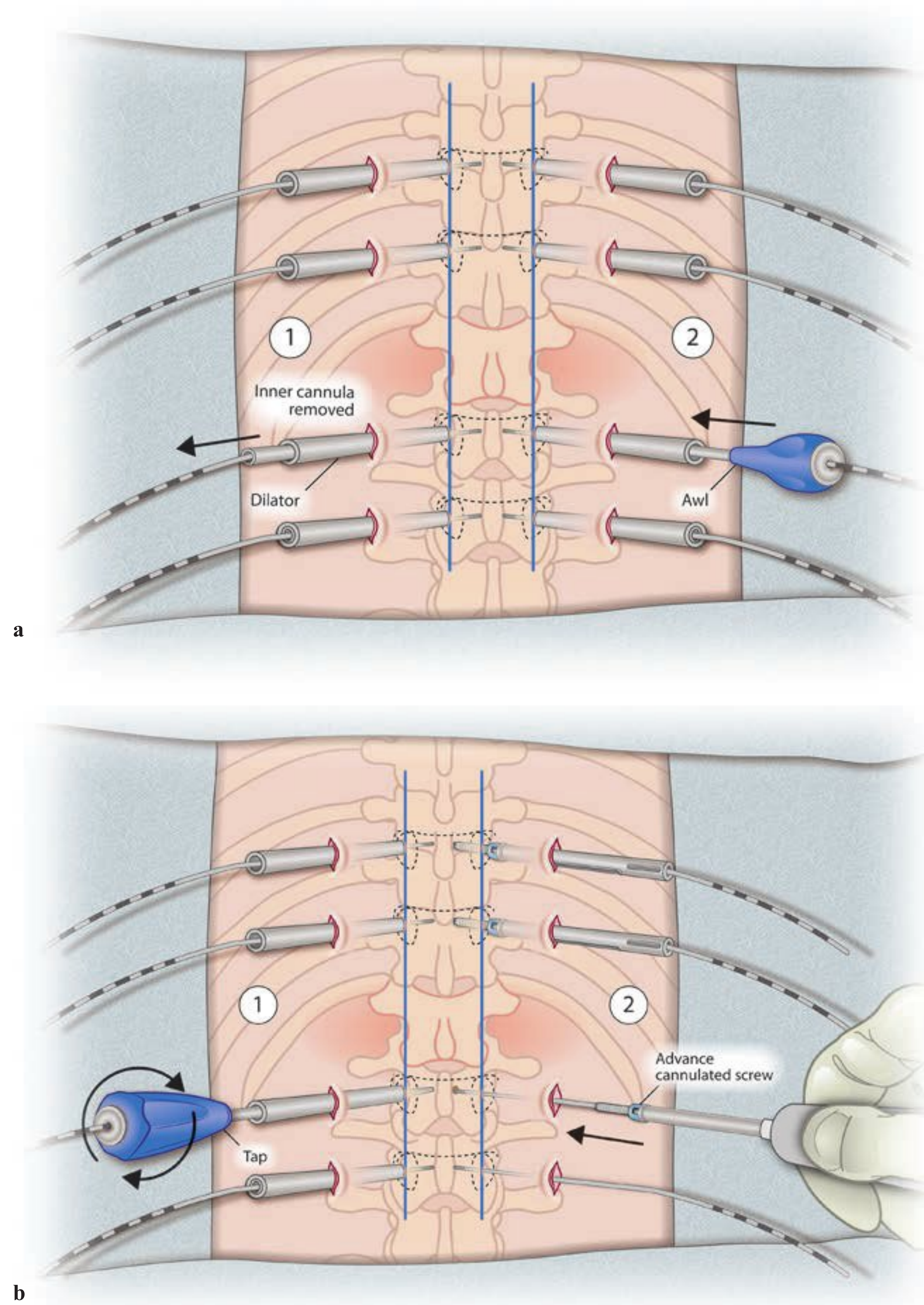


Figure	Procedural Steps	Pearls
Fig. 16.13	**If a facet fusion is not performed, next make a 15 mm skin incision about the Kwires. (a) A dilator is passed to open the fascia, and docked at the starting point. The inner cannula of the dilator is removed (1). An awl is placed over the Kwire to enhance the starting point for the tap (2). Next, the C-arm is brought into lateral position.** (b) **We tap the pedicle under lateral imaging (1). At this point, the tap can be stimulated to assess for a medial pedicle breach. The tap is removed with care to not dislodge the Kwire. A cannulated screw with a screw extension is then advanced (2). Several images are taken as the screw is advanced. It is important to not advance the K wire with the screw. The Kwire is then removed.**	• It is imperative to maintain control of the Kwire at all times. If the Kwire is inadvertently removed, it is best to switch back to AP imaging to try to replace the wire. If unable, it is possible to try to replace the bone trephine needle without the stylet. • We typically under tap for trauma cases. Try to keep the position of the screw heads the same for all screws to facilitate passage of the rod.

Rod Placement and Deformity Correction (Fig. 16.14a, b)

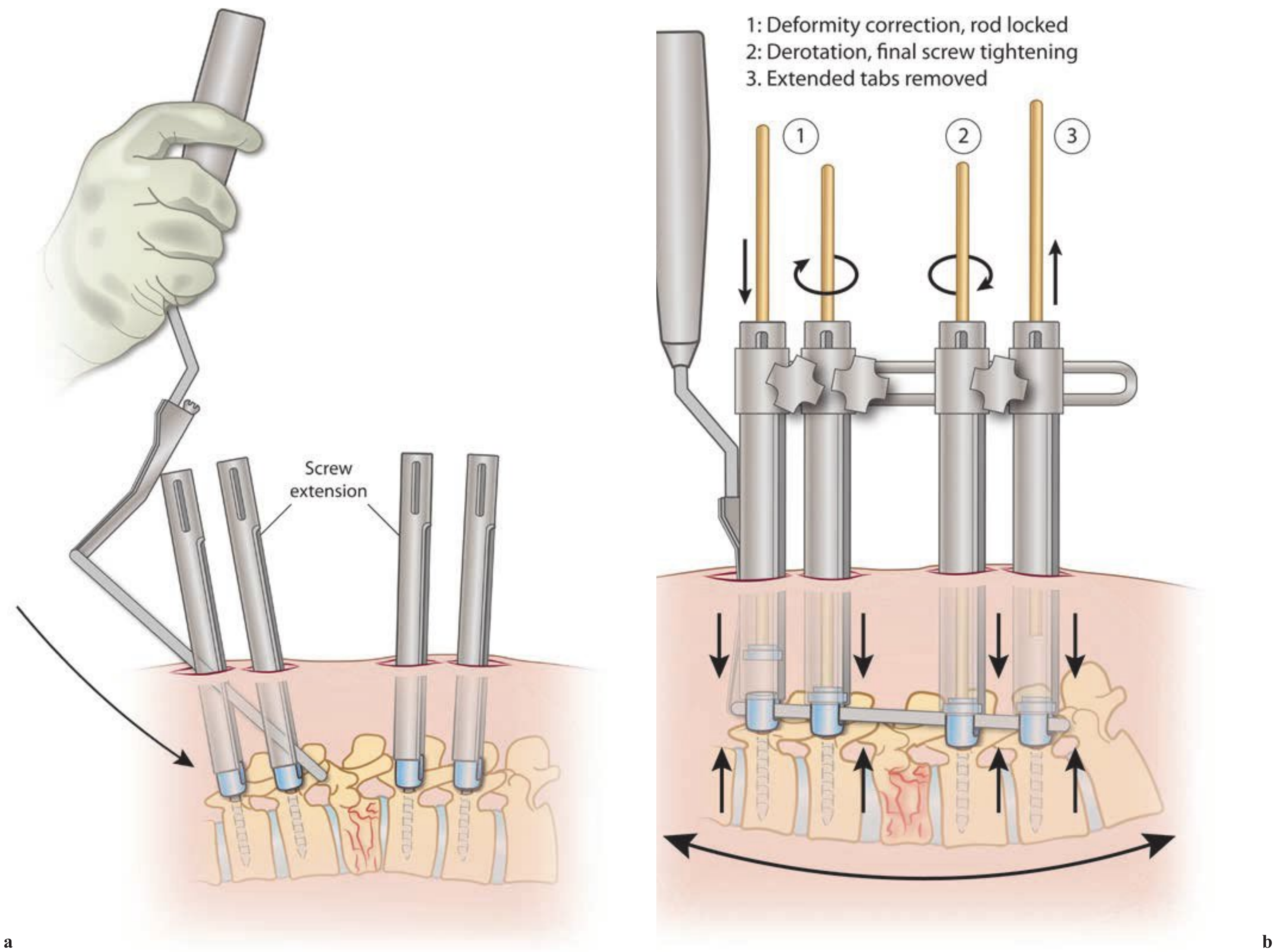


Figure	Procedural Steps	Pearls
Fig. 16.14	**(a) A rod is measured and cut. It is extremely important that the rod is passed subfascially when inserted into the first screw head. (b) Through a cantilever approach, deformity correction occurs as the rod is locked into place (1). A derotation device is used and the screw caps are final tightened (2). The extended tabs are then removed (3). If the tabs are inadvertently removed prior to passing the rod, a rod can still be placed, but it makes rod placement very difficult.**	• It is important to leave the rods on the rod holders until all the caps have been applied. Minimal distraction and compression can be performed with the minimally invasive system; therefore, positioning is imperative.

Closing

Open Approach

For the open approach, meticulous handling of the extensor musculature followed by a tight fascial closure improves the muscles' ability to promote sagittal balance and appropriate skeletal loading. The wound is closed in successive layers (deep fascia, superficial fascia, then skin) using resorbable suture.

Percutaneous Approach

- For the percutaneous approach, the individual stab wounds are irrigated with antibiotic impregnated saline. Little bleeding is encountered due to a tamponade effect from the dilators and screw extensions.
- The fascia is reapproximated with interrupted 2-0 resorbable sutures.
- The skin is closed with a 3-0 monofilament, resorbable suture.
- Final AP and lateral images are obtained with C-arm fluoroscopy before the wound is closed.

Fig. 16.15 Lateral X-ray of patient depicted in Fig. 16.1 showing posterior rod construct and vertebroplasties at T12 and L1 to add structural support.

Postoperative Management

Monitoring

- The level of care is dictated by the comorbid conditions of the patients. For patients with a paucity of other injuries, we typically observe them overnight in a step down unit.

Medication

- It is our practice to place patients on a patient-controlled analgesia device with either morphine or hydromorphone in the initial postoperative period.
- Patients are gradually transitioned to oral medication on the second or third postoperative day.
- We continue antibiotic prophylaxis for approximately 24 hours after surgery.
- We routinely start patients on deep vein thrombosis prophylaxis with low molecular weight heparin on the first postoperative day if there are no other bleeding contraindications.

Radiographic Imaging

- We typically obtain upright AP and lateral images prior to discharge (**Fig. 16.15**).
- Imaging is then performed at 3, 6, and 9 months postoperatively.

Special Considerations

- The optimal surgical approach and treatment of unstable thoracolumbar spine injures are poorly defined because of a lack of widely accepted level I clinical literature. When treating patients with thoracolumbar fractures, the surgeon must first decide if the injury requires an operation. If an operation is required, a decision must be made whether a decompression is warranted in addition to stabilization. A decision must be made as to whether the surgical goals can best be accomplished via an anterior, posterior, or combined approach.
- We gauge the length of our construct based on the degree of instability. In most instances we fixate two levels above and two below. For burst fractures it is possible to perform a cement augmentation of the fractured level (vertebroplasty or kyphoplasty; see **Fig. 16.15**). Short pedicle screws can also be placed into the fractured level, thus allowing some cases to be instrumented only one level above and below the fracture. The thoracic segments are relatively immobile so sacrificing motion segments is biomechanically irrelevant. Lengthening the construct distally into the lumbar spine has different biomechanical considerations and should be individualized on a per patient basis.
- Removal of percutaneous instrumentation may be required if an intersegmental fusion is not performed as the success of the surgery will require fusion of the primary fracture. Based on literature from the AO Fixateur Interne, removal is performed typically 12 months postoperative and after radiographic evidence of fusion.[16–21]

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17 Spinal Epidural Compression

Asha Iyer and Arthur Jenkins

Introduction

Nontraumatic spinal epidural compression can result from several different entities, but acute deterioration almost always occurs as a result of a few conditions, three of which are highlighted in this chapter: spontaneous epidural hematoma, spinal epidural abscess, and metastatic epidural spinal cord compression syndrome.

Incidence

Spontaneous Spinal Epidural Hematoma

Spinal epidural hematomas (SEHs) are a rare cause of spinal cord compression. However, they constitute the majority (up to 75%) of spinal hematomas. The peak incidence occurs in patients in their sixth decade of life, though a second peak is seen in adolescents between 15 and 20 years of age. A male predominance has frequently been documented.

Spinal Epidural Abscess

Spinal epidural abscesses (SEAs) are an infrequent cause of spinal cord compression, representing 0.2 to 2 per 10,000 hospital admissions. The majority of affected patients are between 30 and 60 years old, though they span a wide range from neonates to geriatric. A male predominance—approximately twice as common as in women—exists. Risk factors include diabetes mellitus, end-stage renal disease, HIV or other immune-compromised states, intravenous (IV) drug use, and alcoholism. Local factors additionally include spine surgery or trauma, and catheter placement into the vertebral canal.

While nearly one-third of affected patients died at the beginning of the twentieth century, the mortality is now less than half of that number given improvements in antibiotic therapy and surgical technique. Correspondingly, the percentage of patients with either complete recovery or only minor residual neurologic deficit has more than doubled.[1]

Metastatic Epidural Spinal Cord Compression

In the United States, there are ~1.4 million new cases of cancer annually and every year over half a million cancer patients succumb to metastatic disease. The skeletal system serves as the third most common site of metastatic spread (after pulmonary and hepatic), and within the skeletal system the spinal column is most frequently affected.

Current estimates based on postmortem studies imply 30–90% of cancer patients (large variability depending on primary) will have metastatic spinal disease. A total of 5 to 10% of cancer patients have metastatic epidural spinal cord compression (MESCC), with this proportion increasing to 40% in those with other, nonspinal bony metastases. These numbers translate into < 25,000 cases of symptomatic MESCC per year, an incidence that is rising as antineoplastic therapies evolve and life expectancies increase. MESCC is an epidural lesion causing true displacement of the spinal cord from its normal position in the spinal canal.

Etiologies

Spinal Epidural Hematoma

Spontaneous SEH can be divided into traumatic and nontraumatic. Causes of traumatic SEH include lumbar puncture or epidural anesthesia, fracture, spinal surgery, physical exertion, birth trauma, and chiropractic manipulation. Causes of spontaneous SEH include hemorrhage from an arteriovenous malformation (AVM), hemangioma, or tumor. In up to 30% of cases, no etiology is discerned.[2] Following these idiopathic cases, anticoagulant therapy and vascular malformations are most often implicated. Anticoagulation or any bleeding diathesis is a risk factor for SEH.[3]

Spinal Epidural Abscess

Infection can spread hematogenously or contiguously. Any distant site of infection can spread hematogenously; however, skin and soft tissue infections represent the most common sources. SEAs arising in this fashion generally develop in the posterior epidural space. SEAs that spread by direct extension predominantly originate from a vertebral body focus, or less commonly from adjacent soft tissue. This vector of spread usually involves the anterior aspect of the spinal canal.

Inoculation can also occur iatrogenically. In a large meta-analysis of over 900 cases, epidural anesthesia or analgesia were associated with a 6% rate of infection, and invasive procedures, either spinal or extra-spinal, with 14–22%[4] Usually a severe pyogenic infection with *Staphylococcus aureus* is the most common causative agent. *Streptococcus* species and coagulase-negative *Staphylococcus* follow in frequency. Gram-negative rods such as *Pseudomonas* and *Escherichia coli*, account for a small fraction, being more prevalent with IV drug use. Finally, *Mycobacterium tuberculosis*, fungal species, and parasitic organisms are rare except for immune-compromised states.

MESCC

Metastatic disease spreads to epidural space in two ways: (1) directly into the spinal canal through intervertebral foramen from a paravertebral mass (15% of metastatic cord compression); and (2) the remaining 85% from hematogenous spread (historically thought via Batson's plexus, now believed to be more likely arterial) to the vertebral body, from where the lesion grows posteriorly into the epidural space. These metastatic lesions can cause bone erosion, pathologic fractures, and extrusion of bony fragments into canal, which can all further compound canal narrowing or cord compression.

Pathophysiology

Spinal Epidural Hematoma

Bleeding is generally the result of tearing of epidural veins, although tearing of epidural arteries or hemorrhage from a malformation is also possible. Even in circumstances involving anticoagulant therapy, other factors are posited to contribute, including increased pressure in the interior vertebral venous plexus and foci of vascular "decreased resistance."

Spinal Epidural Abscess

As with any form of compression, vascular compromise with consequent hypoxia has been one favored pathogenetic explanation. However, in animal models of *S. aureus* epidural abscesses, even when SEAs caused para- or quadriplegia, no compression of spinal arteries was noted,[5] thus supporting a paramount role for direct mechanical compression.

MESCC

Hypothesized mechanisms by which damage occurs include (1) direct compression that leads to demyelination and axonal damage; (2) vascular compromise, where occlusion of venous plexus promotes breakdown of cord–blood barrier and thus vasogenic edema; and (3) terminal arterial occlusion with ischemia/infarction may follow leading to irreversible damage. Certain authors have hypothesized that in patients rapidly deteriorating arterial infarction may underlie decline whereas venous congestion may initially be more relevant in patients with slow decline.[6] This disparity may explain the worse outcome associated with a more rapid evolution of motor weakness.[7]

Presentation

Spinal Epidural Hematoma

SEH is usually acute and progressive, leading to permanent neurologic deficit if not managed immediately. Symptoms consistently begin with severe back pain in the location of the hemorrhage, with or without a radicular component. The common segmental levels involved vary by age; in the patients of the 46- to 75-year-old year age group, the lower thoracic and lumbar regions are most common, with a smaller frequency maximum in the cervical levels.[8] A pain-free interval may occur, but then is generally followed by progression of neurologic deficit over hours to days toward flaccid paresis or plegia.

Spinal Epidural Abscess

Seventy-one percent of patients present with back pain as the initial symptom; 66% have fevers. This proceeds to radicular irritation, with subsequent neurologic deficits, including muscle weakness, sensory disturbances, and sphincter incontinence. Progression to frank paralysis occurred only in one-third of patients.[9]

MESCC

Pain (83–95%) is a common presentation. Local pain is thought to be related to periosteal stretching or local neoplastic inflammatory process. This pain responds well to steroids and is worse with recumbency. Mechanical pain is pain that is exacerbated by movement/activity and is often caused by pathologic fracture or vertebral body collapse, and indicative of spinal instability. This pain is recalcitrant to steroids/narcotics; radicular pain is that which involves nerve root compression and usually conforms to a dermatomal distribution.

Motor dysfunction is present in 60–85% of patients and is characterized by weakness and long tract signs. There are correlations between neurologic status at time of diagnosis (particularly with respect to motor function) and prognosis from MESCC. Sensory loss is in close proximity to motor findings and autonomic/sphincter dysfunction is a later finding, with bladder dysfunction being the most common. Though the rate varies, patients with these deficits inevitably progress to paralysis without intervention.

Indications

Spinal Epidural Hematoma

Most SEHs are located dorsal to the spinal cord, with a large meta-analysis quoting $< 75\%$ in this sagittal location.[8] Emergent or urgent decompression within hours is associated with better outcomes. In the same meta-analysis, for patients who received treatment within 12 hours of onset of symptoms, 66% recovered completely, 13% recovered with mild residual neurologic deficit, and 13% continued to have severe impairment or show no improvement. In contrast, for patients whose treatment was initiated 13–24 hours after symptom onset, 64% had severe deficits or no improvement, versus 36% with substantial recovery. Therefore, the treatment of choice is immediate decompression in those patients that can tolerate surgery. Asymptomatic patients without neurologic deficit can be considered for observation, especially in children and teenagers in which a laminectomy may destabilize the posterior column.

Spinal Epidural Abscess

The first operative intervention—a laminectomy—for SEA was performed in 1892; after increasing reports of successes, surgery became the mainstay of treatment by the 1930s. An early series[10] noted that SEA patients without paralysis or whose paralysis had developed less than 36 hours before the operation had better postoperative outcomes with respect to survival and function. In contrast, in patients whose paralysis developed more than 48 hours before surgery, none recovered neurologic function; all mortalities in the series were reported in this latter group. This correlation of outcome with time to intervention has been repeatedly confirmed.[11,12] Conservative treatment is rarely indicated: either for those who cannot tolerate surgery, or who have large abscesses extending a considerable length of the spinal cord.

MESCC

Consensus and expert opinions regarding indications for surgery largely derive from studies investigating the prognostic value of surgical intervention given various patient group attributes. The evidence dictating the appropriate approach to tumor decompression has evolved significantly over the past 50 years. Early treatment underscored indirect decompression of the epidural space via straight laminectomy, followed by radiation therapy (RT).[13,14] However, later studies[15,16] demonstrated no advantage for laminectomy, rendering radiation alone the preferred therapeutic strategy for a period of years. More recent studies with modern anesthetic and imaging techniques have led to a resurgence of surgical decompression as part of the treatment strategy.[6,17] A large randomized control trial[6] assessed decompressive resection in conjunction with RT versus RT alone. Criteria for study inclusion required MESCC restricted to a single area; acceptable surgical candidates with life expectancy . 3 months; one neurologic symptom (including pain); not totally paraplegic for . 48 hours. Radiosensitive tumors and sole root compression or cauda equina syndromes were excluded; 84% of the surgery group versus 52% of the RT group were able to walk after treatment, 62% versus 19% regained ambulation whence lost, and 94% versus 74% remained ambulatory. Additionally, the study revealed significant differences between treatment groups with respect to maintenance of continence; muscle strength; functional ability; and increased survival (126 versus 100 days), with ambulation and continence persisting for the lifetime of the surgery group.

Spinal instability can independently contribute to symptoms, by directly causing mechanical injury to the spinal cord. As RT is unlikely to ameliorate spinal instability, surgery may be more appropriate in these circumstances. An analysis focusing on forms of compression for patients who were, at the onset, either independently ambulatory, assisted ambulatory, paraparetic, and paraplegic: without bony compression, post -RT ambulation rates were 100%, 94%, 60%, 11%, respectively. These rates dropped to 92%, 65%, 43%, and 14%, respectively, when all patients (with bony and nonbony compression) were considered.[18]

A comprehensive literature review[19] suggested that with RT alone, 36% subjects improved while 17% worsened; with decompressive laminectomy 6 RT, 42% improved while 13% worsened; with posterior decompression with stabilization, 64% improved; and finally with an anterior approach, 75% improved with <10% mortality.

Prevailing conviction holds that if compression is of short duration, neurologic deficits may be reversible, as re-myelination and recovery of function are possible. However, with prolonged compression, secondary vascular injury with infarction of the spinal cord may occur with irreversible consequence.

Based on these and similar studies, generally accepted indications for surgery include: the need for tissue for diagnosis; spinal instability; cord compression with dysfunction from bone or tumor not radiosensitive; and deterioration or recurrence during/despite RT. Surgical decompression to prevent irreversible damage should be immediate. Conversely, RT is a reasonable alternative for patients with radiosensitive tumors, stable neurologic status, no spinal instability, no significant bony compromise of canal, or life expectancy less than 3 months.

The location of the origin of the tumor (isolated epidural disease versus arising from osseous lesion with extension) as well as considerations of spinal stability should dictate choice of operative procedure. A thorough description of all surgical approaches is beyond the scope of this chapter. However, a simple laminectomy should be reserved for dorsally located disease, and a posterolateral or ventral approach should be utilized whenever ventral disease is present, as tumors may continue to grow or swell and thus without a direct removal of the offending pathology, an indirect decompression will result in further deformation of the spinal cord. At the spinal cord level (occiput to bottom of conus medullaris), the cord should never be retracted to gain access to ventral tumor; the approach should be selected that obtains the most advantageous angle to access the tumor instead.

Preprocedure Consideration

Radiographic Imaging

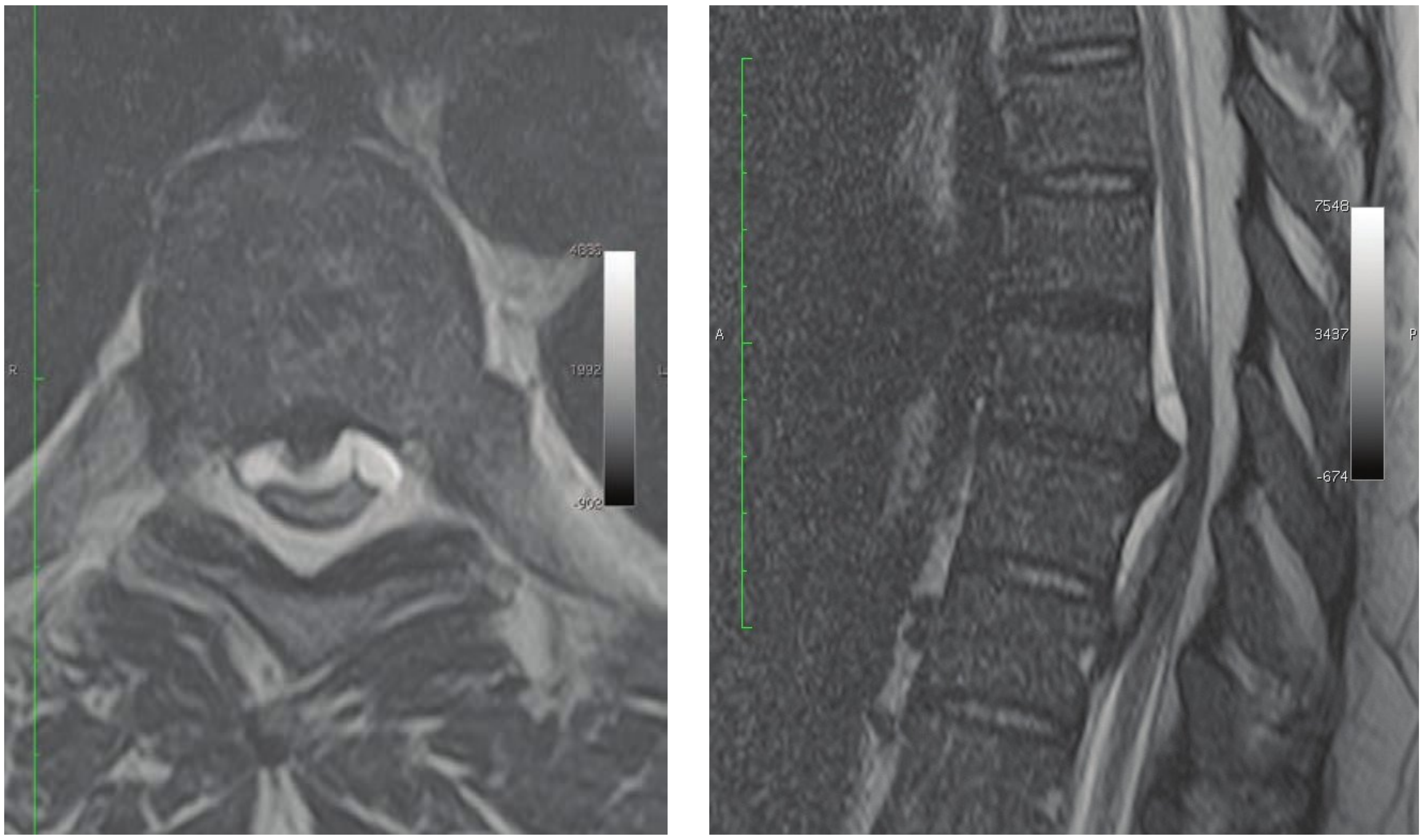
Computed tomography (CT) myelography was once the diagnostic tool of choice for evaluation of SEH. CT myelogram also is more invasive and carries the risk of seeding infection. It is therefore no longer recommended in the context of spinal epidural abscess. Magnetic resonance imaging (MRI) with or without CT has emerged as the less invasive and more available method of choice. MRI also offers the advantage of differentiating between tumor, infection, herniated disk, and hematoma[20] (**Figs. 17.1** and **17.2**). CT is also necessary to evaluate for bony invasion and stability (**Fig. 17.3**).

Medication

For SEH, in patients who cannot tolerate surgery, anticoagulation should be stopped and possibly reversed; high dose steroids should be considered although their use is controversial.[21]

For SEA, broad-spectrum IV antibiotics should be initiated immediately, including coverage for Gram-positive cocci and Gram-negative rods.

For MESCC, steroids decrease edema and may have an oncolytic effect on some tumors such as lymphoma and breast cancer.



a b

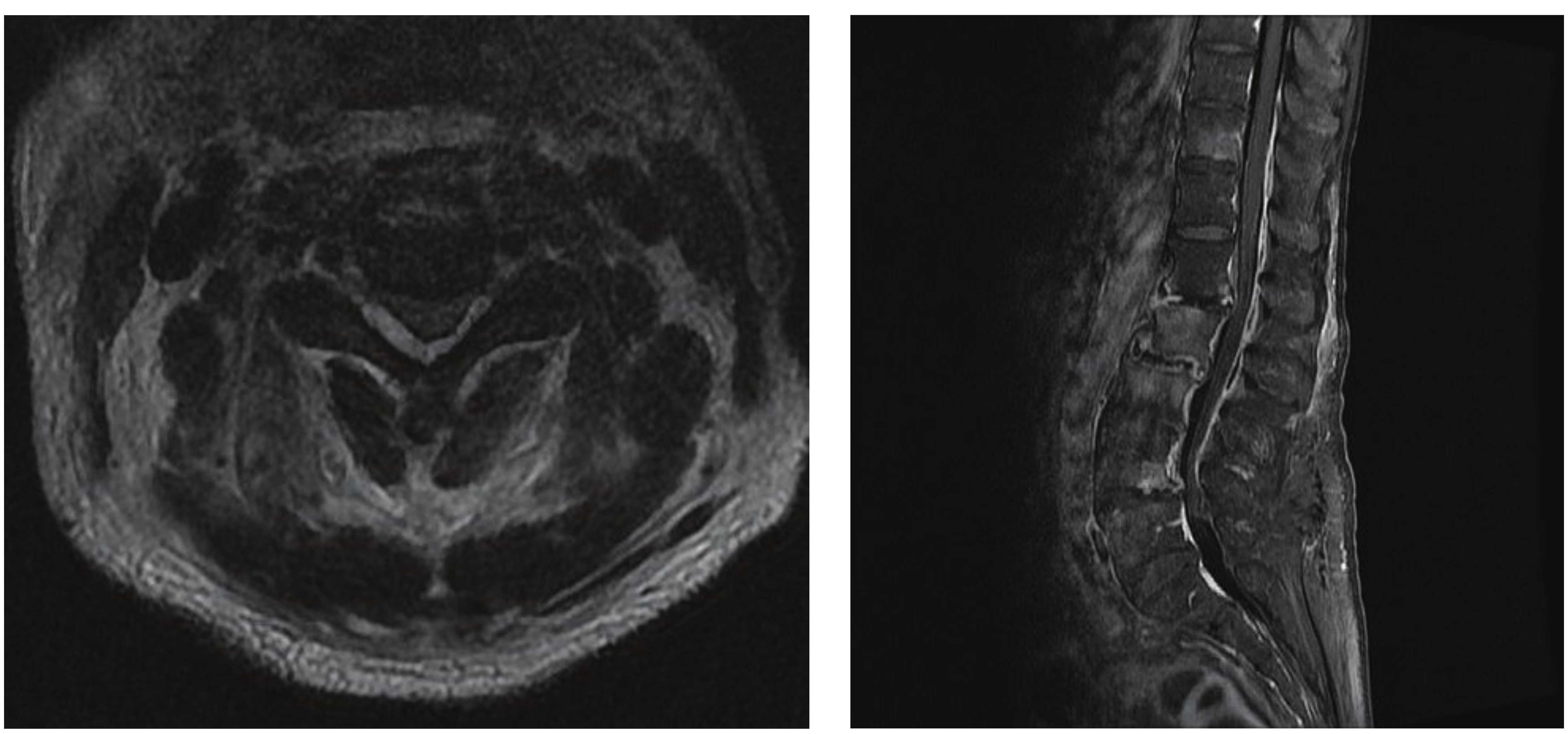
Fig. 17.1a, b Spinal epidural hematoma. (**a**) Axial and (**b**) sagittal MRI in a patient with focal spontaneous hematoma around the central herniated disk located ventral to the cord.

Operative Management

Anesthesia

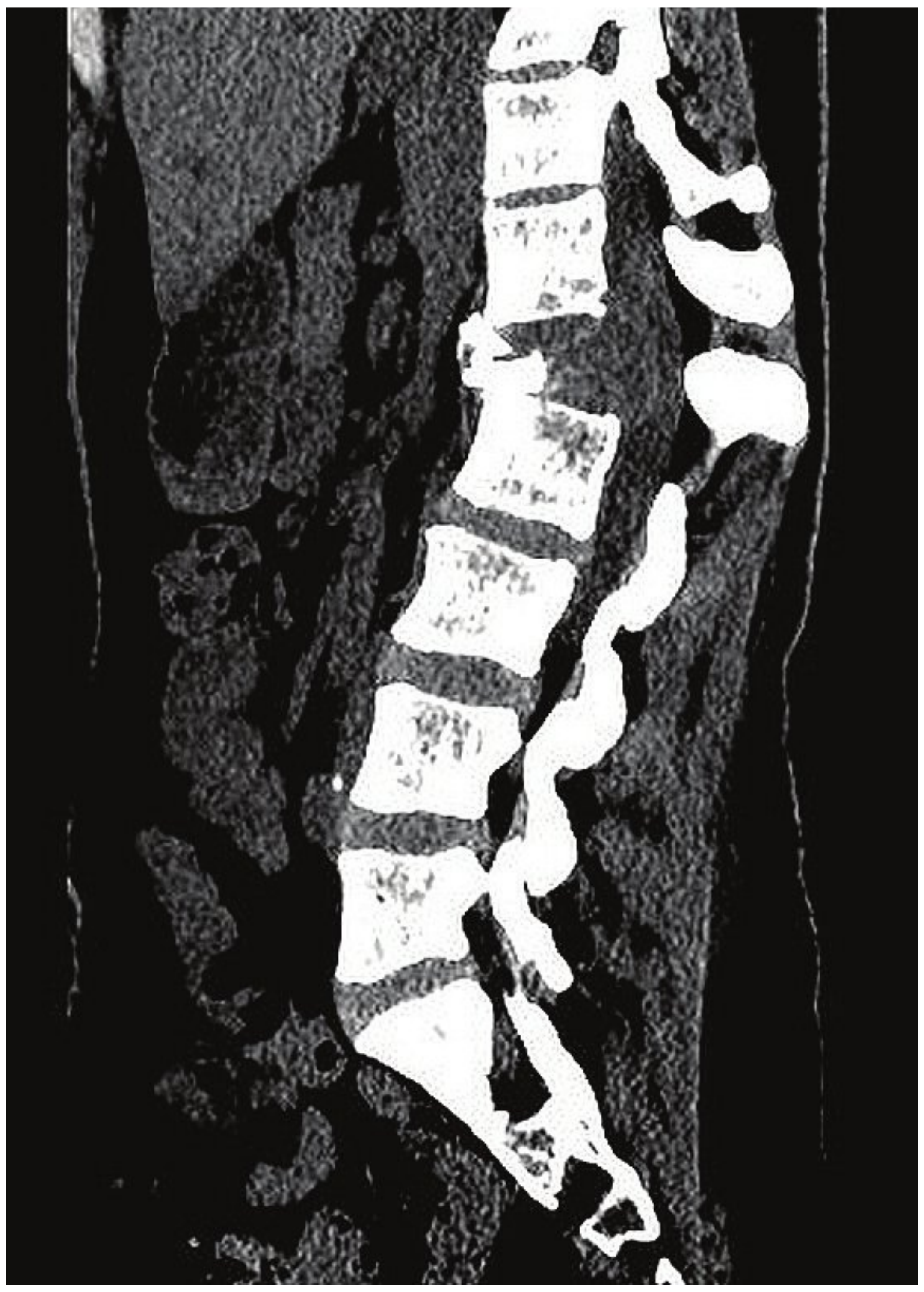
For all cases, general endotracheal anesthesia is the preferred technique, assuming favorable anatomy and the patient's condition. Intubation-related manipulation of the neck concerns in patients with cervical spinal cord compression need to be weighed against the urgency of obtaining a reliable airway. Where possible, a minimally manipulation technique—such as awake fiberoptic, laryngeal intubation with an illuminated laryngoscope with camera, or nasal intubation in a patient with no risk factors for cribriform fracture or incompetence—should be used.

When emergent airway compromise is present and intubation is not likely to be able to be performed in a timely fashion, then emergent cricothyroid or tracheostomy intubation will need to be performed, and it would be prudent to have a tracheostomy kit at the side of any patient with emergent spinal cord compression in case they deteriorate on their way to or from



a b

Fig. 17.2a, b Spinal epidural abscess. (**a**) Axial T2-weighted MRI of the cervical spine in a patient who presented with acute rapidly progressive paraplegia and respiratory failure. There is a large dorsal epidural abscess collection with cord compression. (**b**) Sagittal postcontrast image of a posterior thoracolumbar spine abscess associated with multiple areas of vertebral body osteomyelitis including T11, L2 through L5, and diskitis at L23.



a

b

Fig. 17.3a, b Metastatic epidural spinal cord compression. (**a**) Sagittal CT reconstruction and (**b**) axial CT image in a patient with known metastatic breast cancer with sudden paraplegia and incontinence after a fall. A large destructive L1 vertebral body lesion is also invading both pedicles, left more than right, with significant ventrolateral cord compression. There is a resultant kyphotic deformity at T12.

any procedure, or even in the operating room during standard endotracheal intubation.

For those cases where the opportunity presents and the surgeon wishes, if intraoperative monitoring is to be used, then the anesthetic should take into account any potential effects on electromyography or motor evoked potential (MEP) monitoring by focusing on a total intravenous anesthetic (TIVA) technique to prevent the detrimental impact of inhalational anesthetic. TIVA also includes the absence or minimal use of paralytics to prevent their impact upon the muscle activity being monitored by electromyography (EMG) or MEP. Somatosensory evoke potentials (SSEPs) are used to avoid potential peripheral nerve complications such as arm positioning apraxias, or even infiltration of an IV leading to compartment syndrome, which if caught intraoperatively instead of identified postoperatively may result in immediate treatment of the problem and prevent permanent morbidity.

Where practical and feasible, mean arterial pressures (MAP) should be maintained as high as can be tolerated (up to 100 mm Hg), and when a neurologic deficit is present, if the patient can tolerate, MAPs in the 901 mm Hg range should be the goal, to maintain spinal cord perfusion given the presumably edematous state of the spinal cord. This can be correlated with intraoperative evoked potential monitoring, and many times a decrement in evoked potentials can be corrected with elevation of the MAP.

Surgical Approach

General Principles

Position selection depends on several factors, including the location of the primary pathology (anterior, posterior, or lateral within the canal), number of levels, and difficulty approaching the pathology directly, such as when a tracheostomy, anterior scar, spinal deformity, or other condition makes the approach more challenging or has higher risks of complication. Where possible, the most direct approach leads to the best resulting treatment, but one or more factors may change that decision process, including availability of an access surgeon, resulting postoperative instability, and patient appropriateness for stabilization techniques, among others. When the disease process or the approach to the disease causes spinal instability, fusion of the unstable levels is additionally recommended. Several treatment options exist (allograft bone, polymethyl methacrylate [PMMA] cement with Steinman pins, titanium cages, carbon fiber cages, anterior titanium plate/rod fixation devices, etc.), the discussion of which is beyond the scope of this chapter.

A dedicated spinal table can help to position properly and possibly prevent different positioning complications, as well as being radiolucent to optimize imaging. Knee-elbow position on a standard nonspinal operating room table can be used for dorsal thoracic or lumbar procedures. While an on-call neuromonitoring team may be desirable, one should not delay the case to wait for a team to be available.

For dorsal/dorsolateral pathology, a unilateral approach is often sufficient. For short-segment pathologies, such as focal abscess or lateral and dorsal epidural spinal metastases, a microsurgical intralaminar approach can be used as is done for herniated disks. Ventral lumbar pathology, located ventrolaterally or below the conus medullaris, can be approached in a similar way with gentle retraction of the thecal sac.

Soft (i.e., not calcified, bone, or hard fibrous lesions) lesions at the cord level, such as in the cervical or thoracic spine, can be approached via several approaches, depending on the surgeon's comfort level and the facility's resources (including the experience of the evening or on-call staff). One approach is via unilateral hemilaminectomy with partial transpedicular decompression to gain access to the ventral locus of purulence, leaving the posterior midline and contralateral structures intact to minimize delayed instability, reduce the size of the wound and cavity to be closed, and reduce intraoperative bleeding. The less pedicle removed, the more stable the spine will be over time. Should a more extensive exposure need to be performed (complete pedicle removal, bilateral decompression plus transpedicular, or removal of the pars interarticularis), a fusion of the potentially unstable segments may be necessary, and where appropriate, instrumentation should be used. Instrumentation should not be forgone just because the primary pathology is infection. Where appropriate, a bilateral posterolateral minimally invasive approach from a partial transpedicular or costotransverse approach on either side can be performed as well, with angled instruments pushing pathology down and away from the cord. When the pathology is liquid (acute abscess or relatively liquefied hematoma), an angled insertion technique can allow for placement of a small-caliber drain (like a ventriculostomy catheter) that can be used to remove ventral pathology and facilitate irrigation in the abscess plane.

In general, we do not recommend a straight laminectomy for predominately ventrally located infections at cord-level cases, unless there is enough room to reach through laterally located purulent collections and pass a right-angled instrument ventral to the theca into the ventral pus without pressure on the already tenuous spinal cord.

In acute cases, there is rarely much epidural bleeding, but in more chronically infected cases, there may be an inflammatory rind that has significant vascular input. Epidural drains should be left behind, and drainage continued longer than standard duration to prevent any further collection or contamination of infected material in the epidural space.[22]

For metastatic epidural disease, the location of the origin of the tumor (isolated epidural disease versus arising from osseous lesion with extension) as well as considerations of spinal stability should dictate choice of operative procedure.[23] A thorough description of all surgical approaches is beyond the scope of this chapter. However, a simple laminectomy should be reserved for dorsally located disease, and a posterolateral or ventral approach should be utilized whenever ventral disease is present, as tumors may continue to grow or swell and thus without a direct removal of the offending pathology, an indirect decompression will result in further deformation of the spinal cord. At the spinal cord level (occiput to bottom of conus medullaris), the cord should never be retracted to gain access to ventral tumor; the approach should be selected that obtains the most advantageous angle to access the tumor instead.

Posterior Approaches

Laminectomy alone is to be used at the spinal cord level only when the disease is wholly dorsal or just posterior to the nerve root if lateral. Any mass ventral to the nerve root, unless primarily liquid and able to be drained with a catheter passed in an existing mass channel (e.g., an abscess that wraps around the lateral aspect of the dura), should be resected or drained via a posterolateral approach, and the more ventral and medial the location, the more lateral the approach should be. The posterolateral approaches, in order of successively more lateral (and therefore more ventral access) location, include: laminectomy, transpedicular, costotransversectomy (in thoracic spine only), and lateral extracavitary. The parascapular approach is a variant of the costotransversectomy or lateral extracavitary at the levels of T2–7 where the muscles of the scapula need to be carefully separated and the scapula mobilized for the exposure, and reconnected carefully afterward to prevent morbidity.

Anterior Approaches

Cervical

- Transoral, which gives good access from the clivus to C3
- Standard ventromedial anterior cervical, which gives good access from C2 to T1 or T2

Cervicothoracic and Thoracic

- Supraclavicular, which gives access at the cervicothoracic junction (down to T3) via an approach that is similar to the traditional ventromedial anterior cervical approach, but uses a more acute angle to approach the thoracic vertebrae.
- Transsternal, which gives good access to the T3-T10 region, but there is an association with an increased risk of mediastinitis.
- Transmanubrial, which can be combined with ventromedial to give access to C5-6 down to T2-3, although there is a risk of injury to major vascular or chylous structures.
- Transthoracic, which gives excellent ventral access to the T4-T11 regions and can be used to expose multiple levels, but increased pulmonary morbidity limits its use today.
- Thoracoscopic approaches, which give similar access as the transthoracic with less pulmonary morbidity, include a significant learning curve and the port size limits some of the access and procedures that can be performed.
- Thoracoabdominal, which gives a wide exposure to the vertebral bodies and ventral cord at the region of T10 to L2, but requires splitting of the diaphragm, and has a heightened risk of injury to abdominal and thoracic viscera.

Lumbar

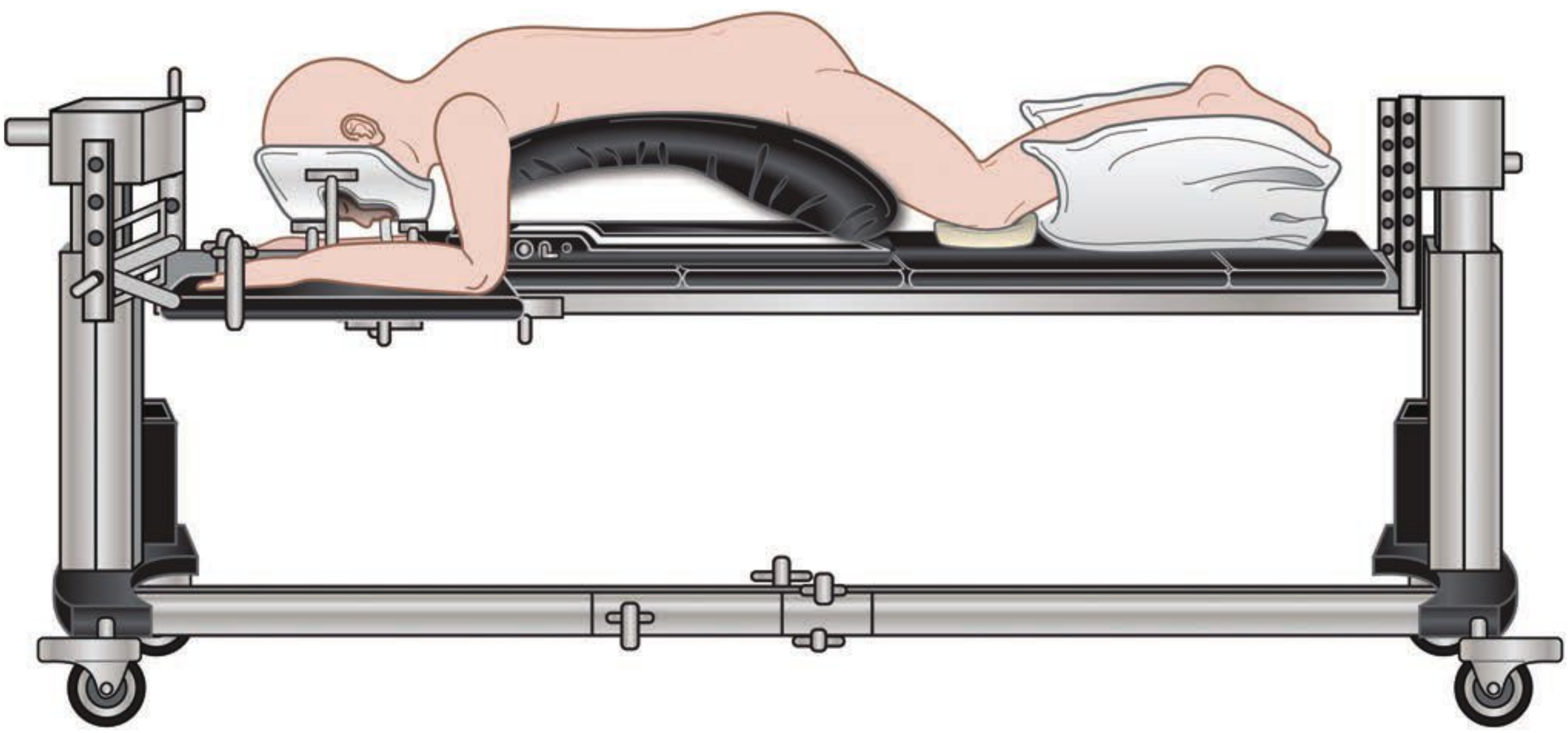
- Retroperitoneal or direct lateral exposures from L1-S1. Variations of these can be used at different levels, with good exposure of the vertebral bodies with less risk to intraperitoneal organs, although the transpsoas techniques do have greater risks to the nerves, and the more ventral approaches have a greater risk of injury to ureters and great vessels.
- Transperitoneal, which gives good exposure from L1/2 to the upper sacrum; this can give good exposure to the bodies and thecal sac, but limitations include working around the aorta and inferior vena cava (IVC); risk to bowel, bladder, or ureter; and in males a risk of sexual dysfunction due to retrograde ejaculation, believed by some to be related to injury to the sympathetic plexus.

The following illustrations demonstrate some of the more common emergency procedures for epidural compression. While open approaches are demonstrated here, minimally invasive approaches can be chosen depending on the surgeon's judgment and experience as noted in the case examples. Some of the other approaches mentioned are addressed in detail in other chapters.

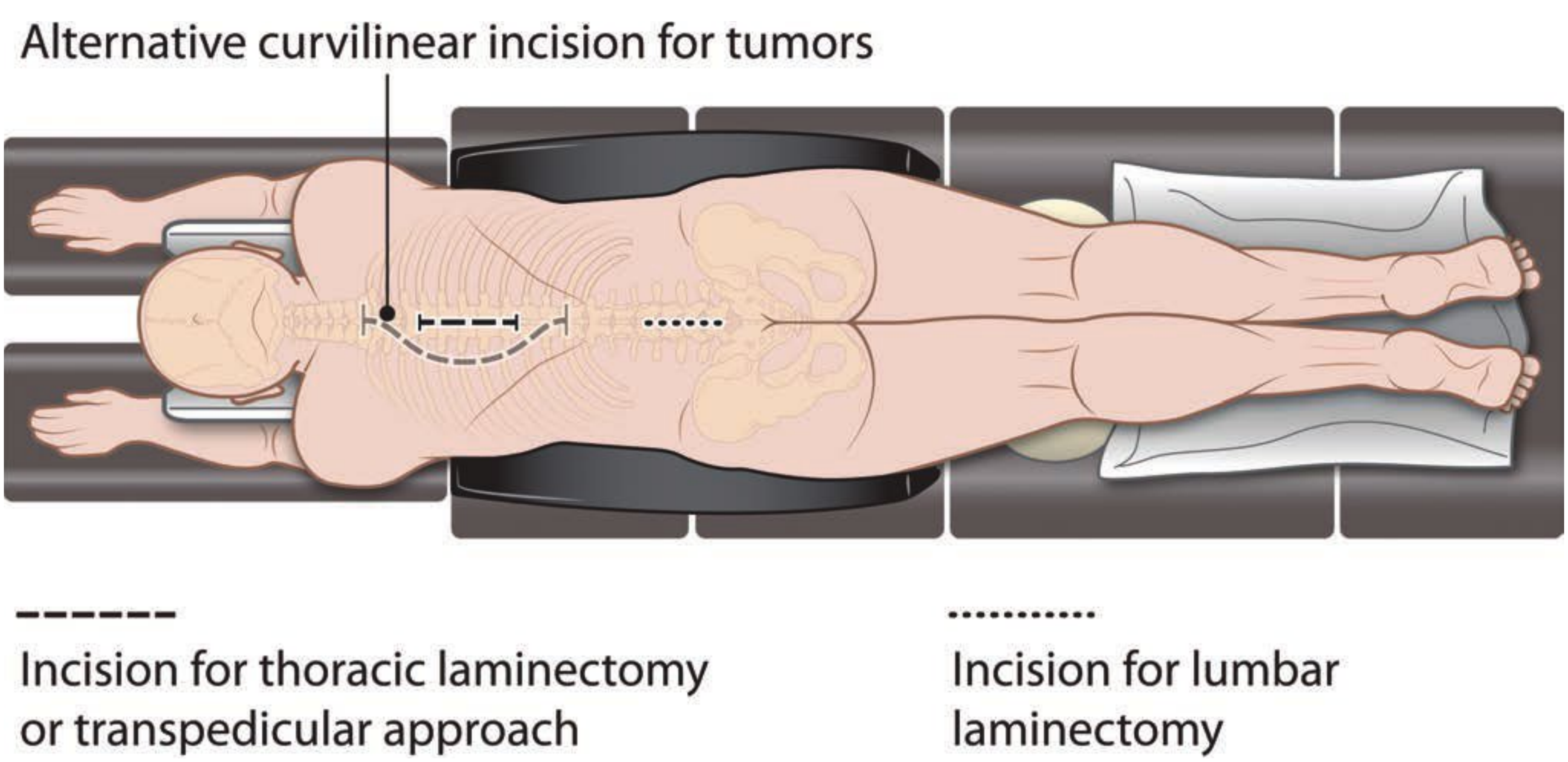
Operative Procedure

Positioning for Posterior and Posterolateral Procedures

Positioning and Incision (Fig. 17.4a, b)



a



b

Figure	Procedural Steps
Fig. 17.4	**(a) The patient is placed prone on a spinal table and/or Wilson frame (b) with an incision marked as diagrammed.**

Thoracic Laminectomy for Dorsal Spinal Epidural Hematoma

Laminectomy (Fig. 17.5)

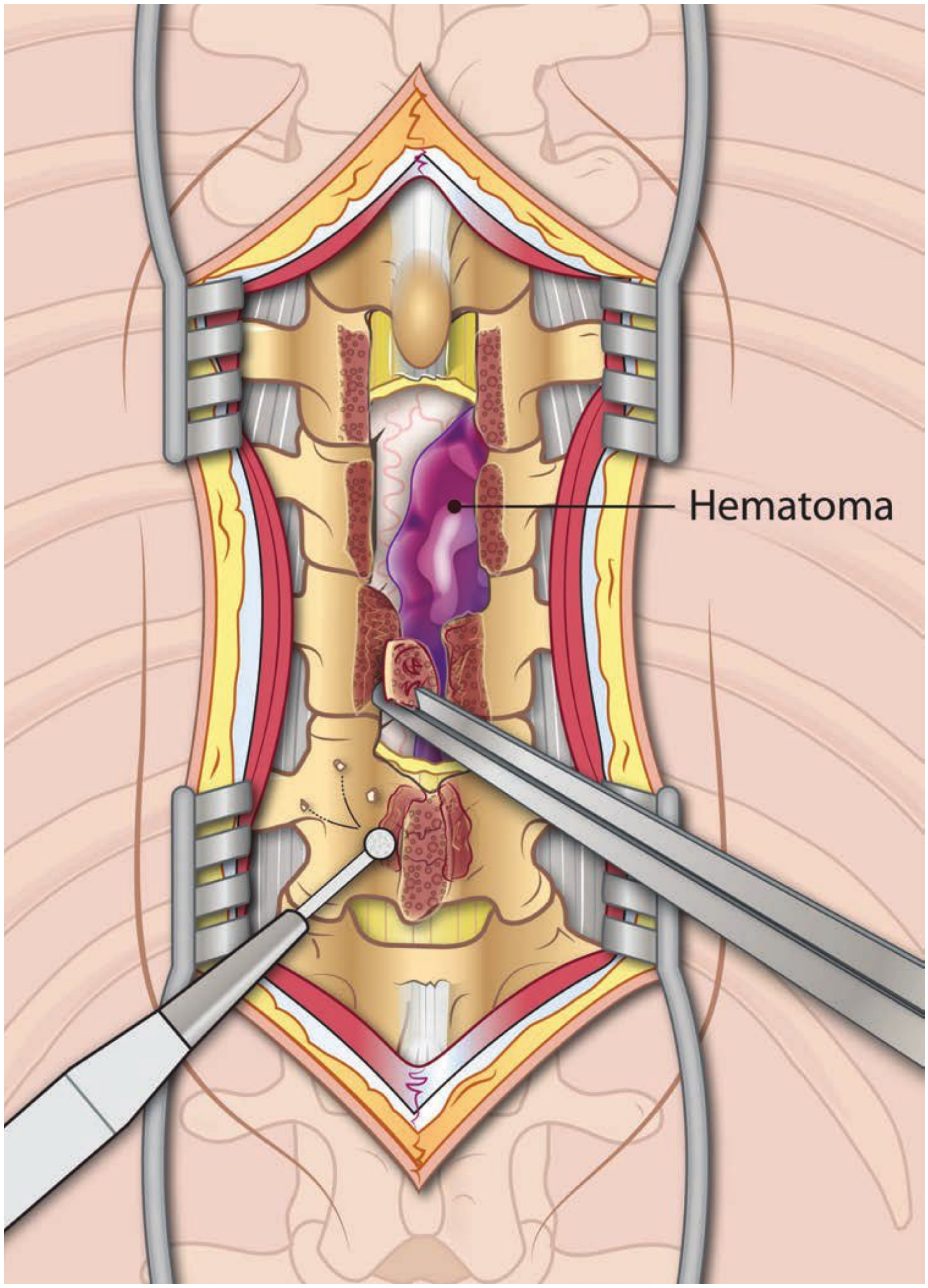


Figure	Procedural Steps
Fig. 17.5	**After incising the fascia and dissecting the muscle off of the spinous processes and laminae, the laminae are removed with a drill/Leksell rongeur exposing the epidural hematoma. It is important to remove as much of the laminae at consecutive levels until the superior and inferior limits of the hematoma have been reached.**

Hematoma Removal (Fig. 17.6)

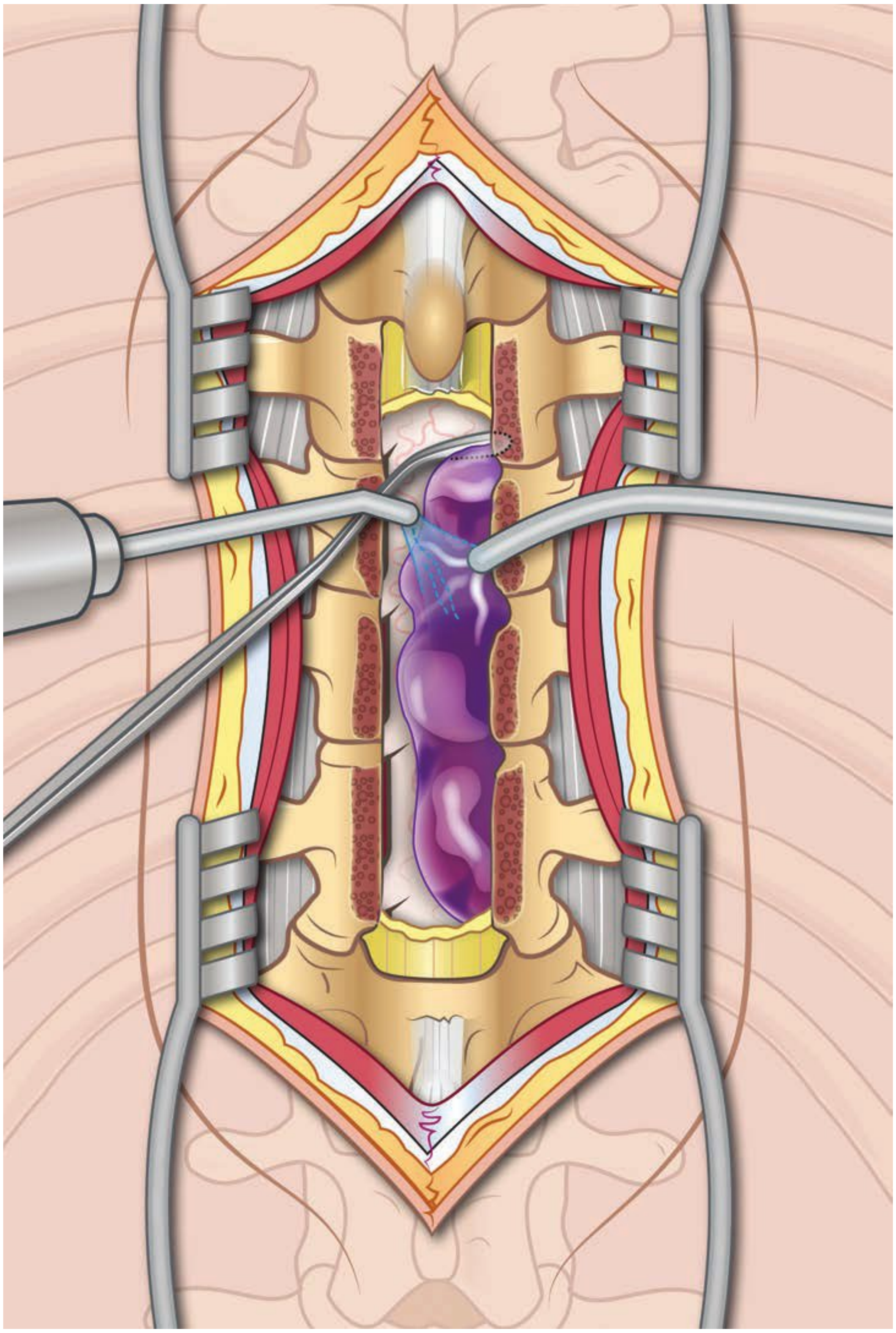


Figure	Procedural Steps
Fig. 17.6	**A Woodson or Penfield dissector is used in conjunction with suction to removed congealed hematoma taking care not to put undue pressure on the thecal sac and spinal cord. Irrigation is helpful in assisting hematoma removal.**

Lumbar Laminectomy for Epidural Abscess

Laminectomy (Fig. 17.7)

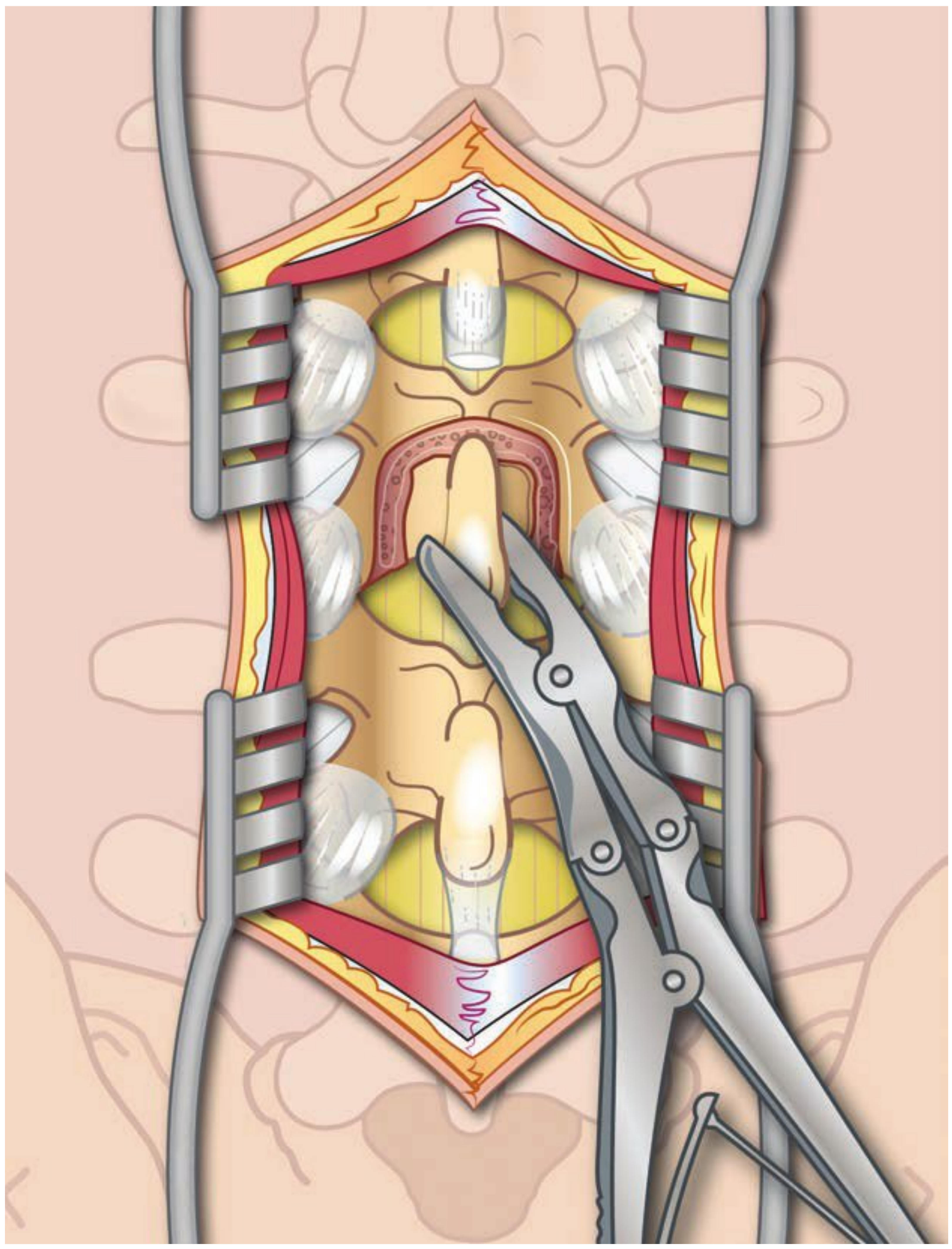


Figure	Procedural Steps
Fig. 17.7	**After incising the fascia and dissecting the muscle off of the spinous processes and laminae, the laminae are removed with a drill/Leksell rongeur and Kerrison rongeurs.**

Nerve Root Retraction and Abscess Removal (Fig. 17.8a, b)

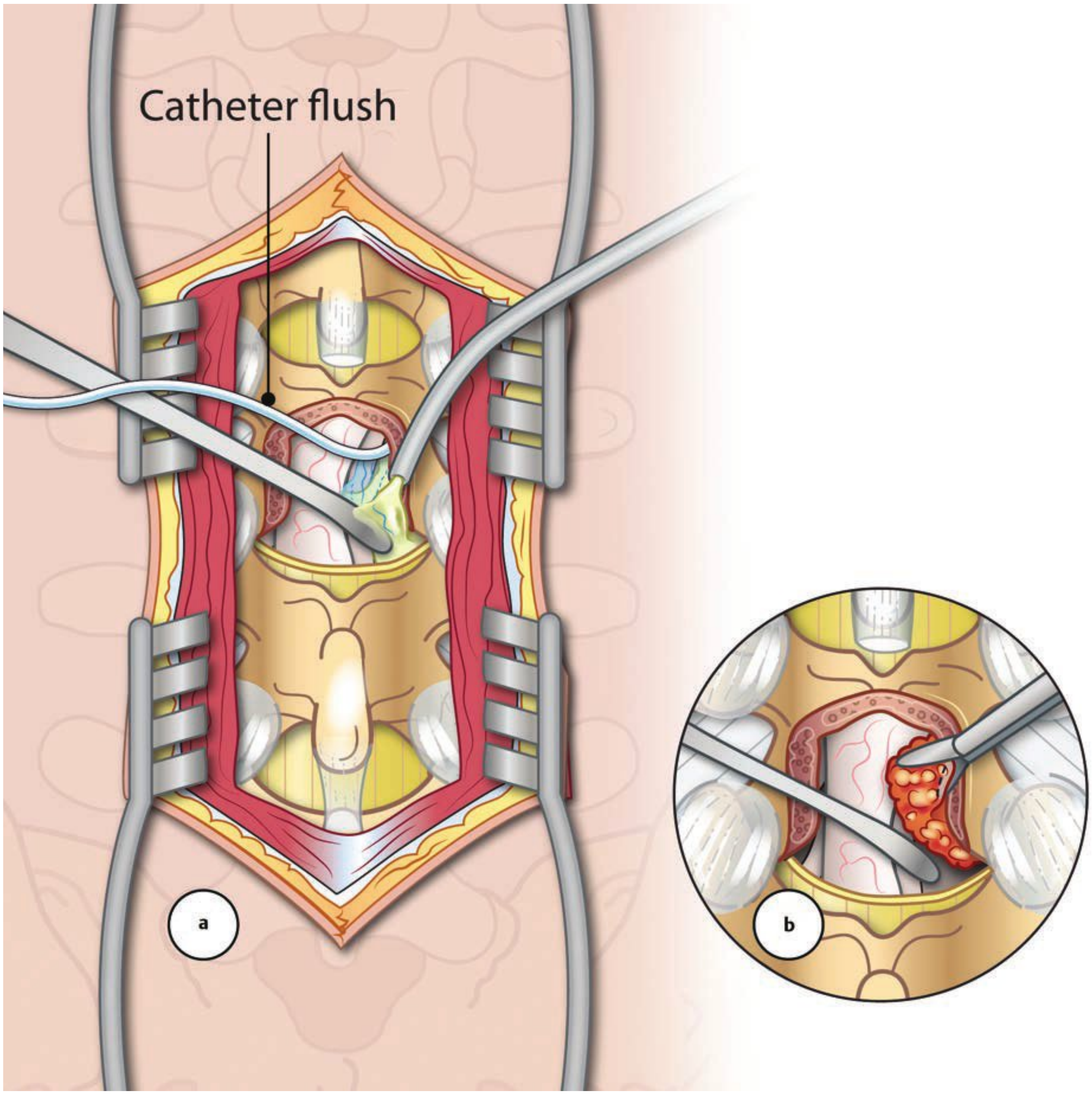


Figure	Procedural Steps	Pearls
Fig. 17.8	**For ventral and ventrolateral disease related to a diskitis or mycobacterium infection, the nerve root is retracted gently with a Penfield no. 4.** **(a) In the case of liquid purulent material, the abscess is evacuated with suction and a small catheter can be placed to flush out material from the epidural space ventrally and under adjacent laminae.** **(b) For chronic infections consisting of granulation tissue or granuloma, abnormal material is removed with small pituitary rongeurs, Woodson and Penfield dissectors, along with suction.**	• It is important to send multiple cultures for bacterial (anaerobic and aerobic), fungal, and acid fast bacilli in addition to pathology.

Transpedicular Approach for Metastatic Disease

Laminectomy (Fig. 17.9)

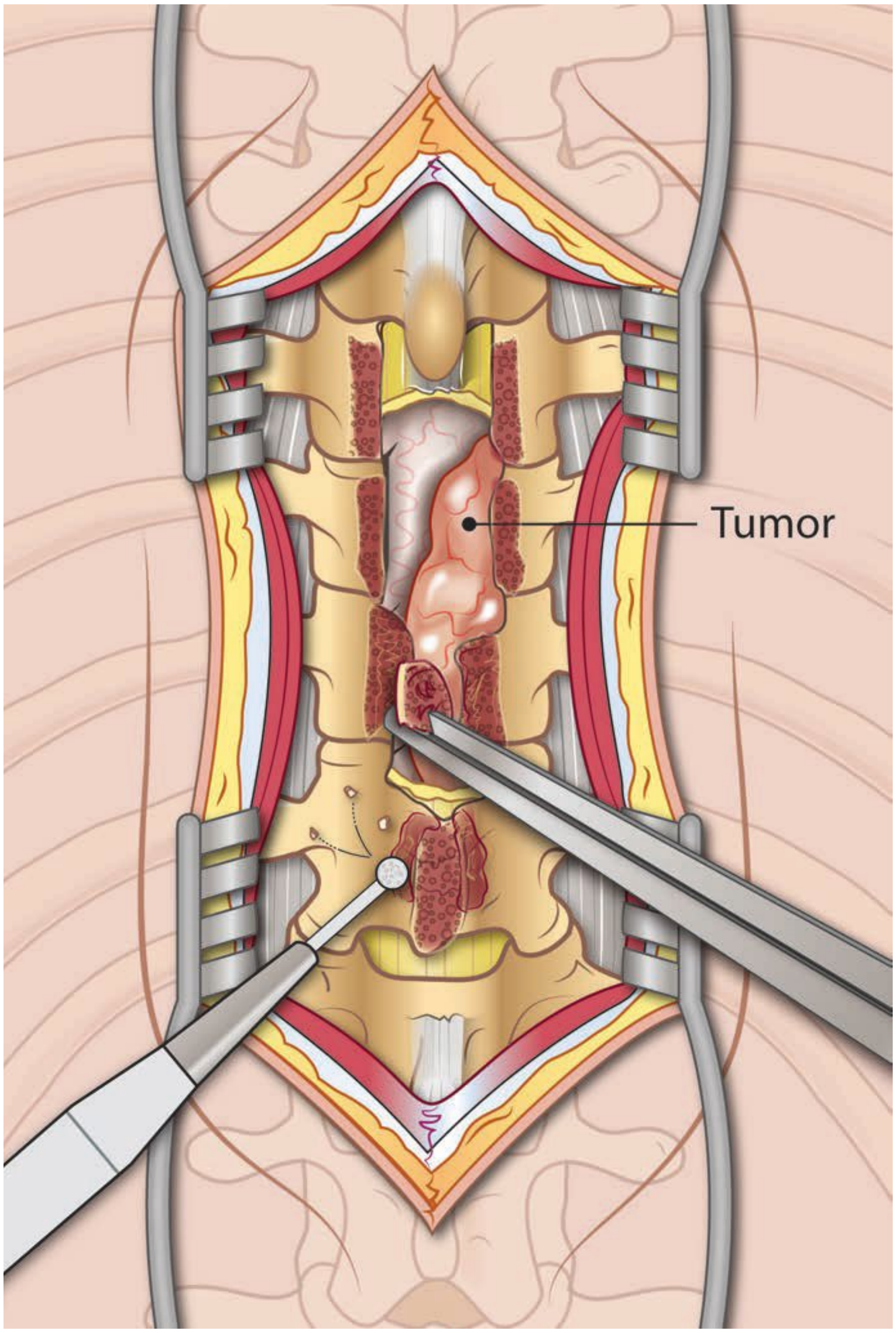


Figure	Procedural Steps
Fig. 17.9	**After incising the fascia and dissecting the muscle off of the spinous processes and laminae, the laminae are removed with a drill/Leksell rongeur exposing the epidural tumor. It is important to remove as much of the laminae at consecutive levels until the superior and inferior limits of the epidural mass have been reached.**

Pediculectomy (Fig. 17.10)

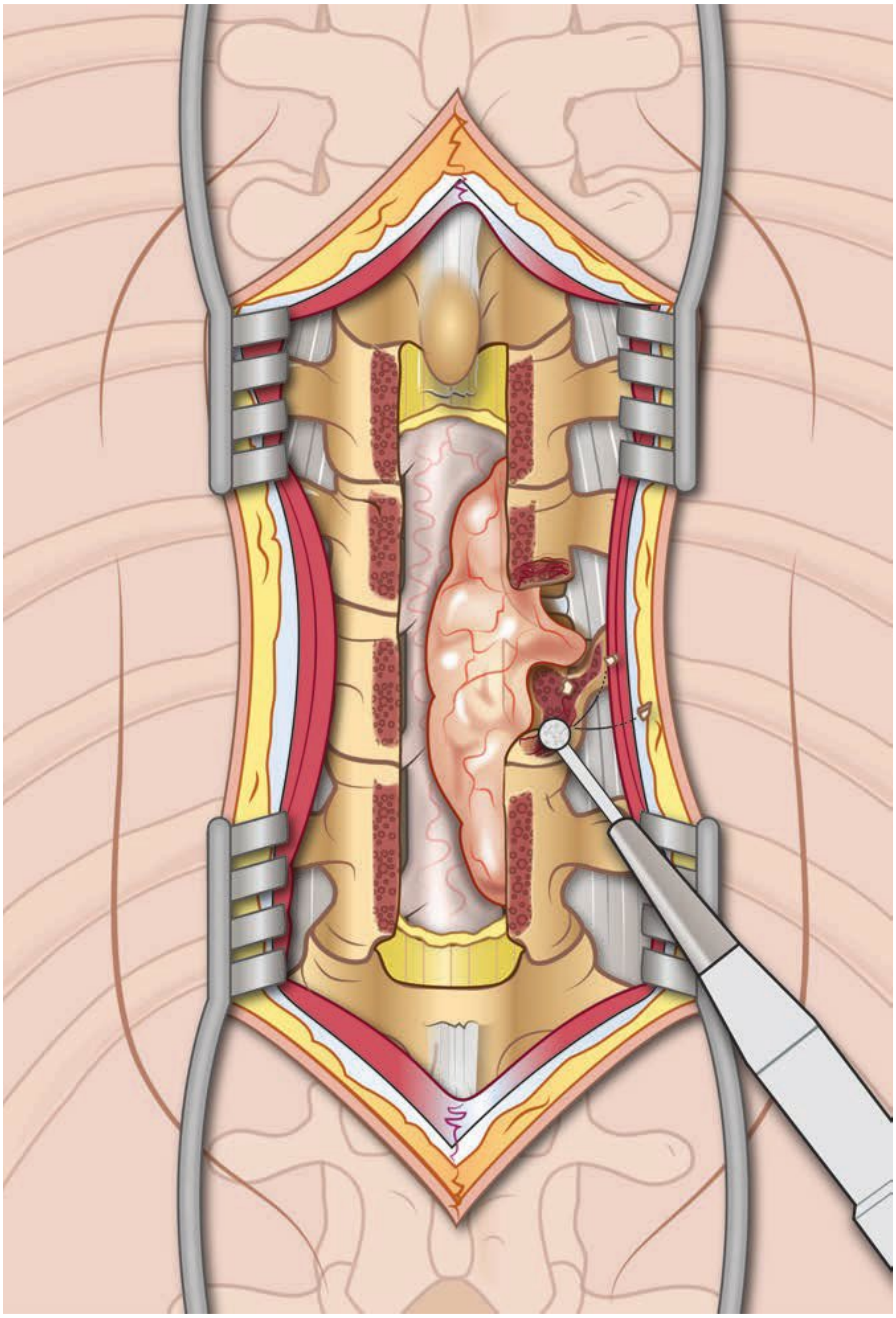


Figure	Procedural Steps	Pearls
Fig. 17.10	**If not already disrupted by tumor a bur is used to perform a partial facetectomy at the location of the pedicle and neural foramen. The pedicle is drilled down to the level of the posterior vertebral body. A Kerrison rongeur can be used to remove more of the facet to expose the neural foramen if tumor is occupying this area.**	• Many tumors arising from the vertebrae have eroded the pedicles. If there is lateral and ventral tumor without pedicle erosion, it will be necessary to drill the pedicle down to the posterior aspect of the vertebral body to remove tumor without retracting the thecal sac and spinal cord. Unilateral pediculectomy in the thoracic spine does not necessarily require stabilization, while bilateral pediculectomies do. • A costotransversectomy can be performed if substantial vertebral body erosion has occurred and instrumentation in planned to improve anterior column support (see Chapter 15).

Lateral and Ventral Tumor Removal (Fig. 17.11)

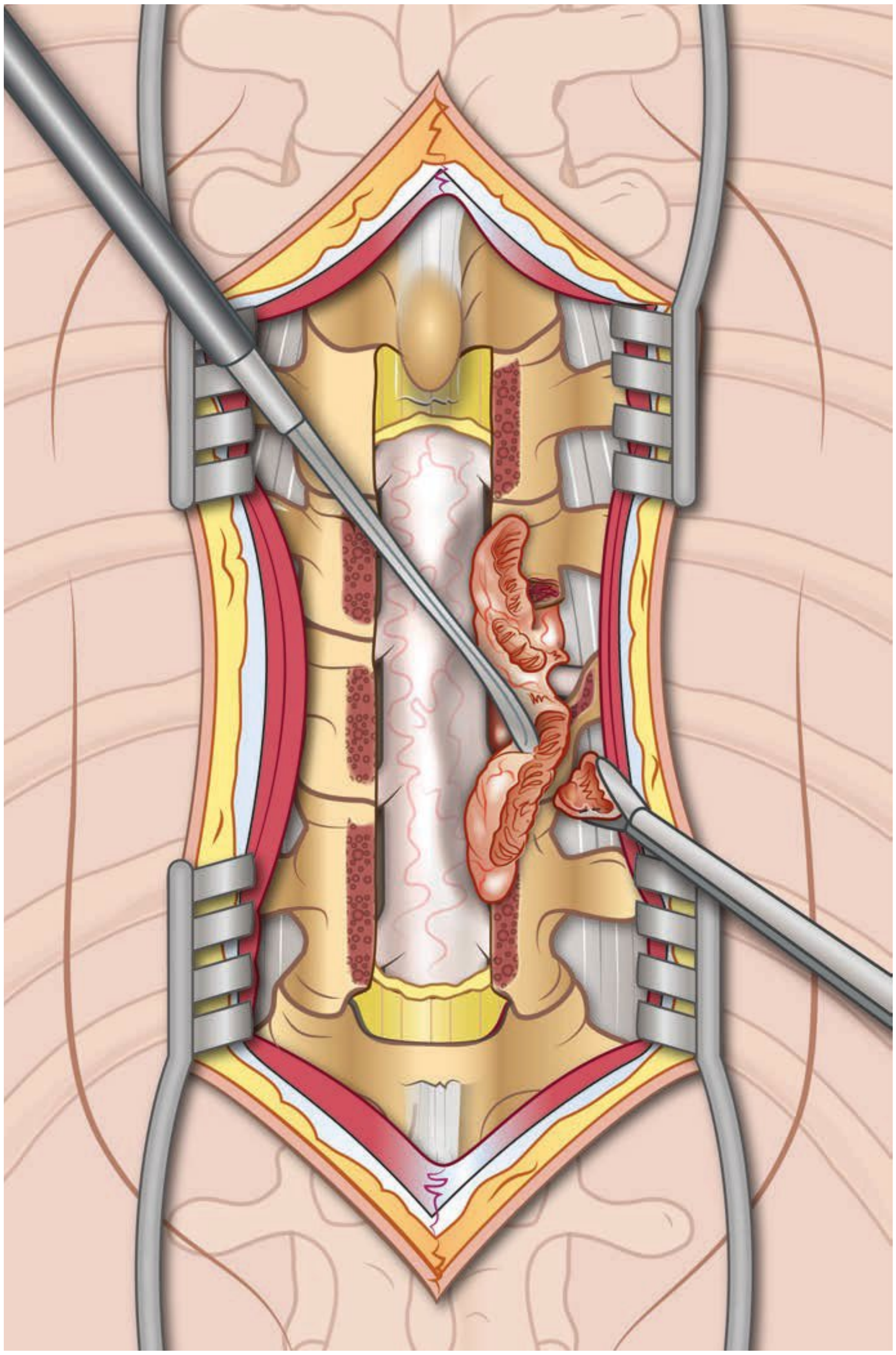


Figure	Procedural Steps
Fig. 17.11	**Without retracting the thecal sac and spinal cord, lateral and ventral tumor is removed with Penfield and Woodson dissectors. Down-going spinal curettes can be used to push ventral tumor away from the thecal sac. The tumor is collected by suction and small pituitary rongeurs.**

Closing

- The wounds are irrigated copiously with normal saline.
- All epidural bleeding should be coagulated and hemostatic material can be left,[8] as long as the hemostatic substance is not left in a way that will cause immediate or delayed (due to swelling of the material over time) spinal cord compression.
- A suction drainage device may be left in the subfacial plane in the postoperative period.
- The muscle and facial layers are closed with no. 0 absorbable suture. The facia is closed tightly with no gaps.

The subcutaneous layer is closed with 2–0 or 3–0 absorbable suture and the skin is closed with staples.

Postoperative Management

Monitoring

- Close neurologic monitoring should be performed in all cases after surgery.
- SEH: if a coagulopathy were present preoperatively, it should be followed with hematology laboratories and treated to normal values for at least 1 to 2 days afterward surgery. Treatment beyond that rarely has benefit, as the patient will revert to their normal state eventually.
- SEA: While single values of erythrocyte sedimentation rate (ESR)/C-reactive protein (CRP) are minimally informative, serial ESR and CRP levels can be trended to reflect the course of infection.

Medication

- SEA: Antibiotics are continued up to 12 weeks postoperatively, though the usual course is 4–6 weeks. Therapy should be initiated with IV antibiotics, and can be transitioned to oral antibiotics at a later time. As cultures yield a causative agent, coverage can be narrowed accordingly.
- MESCC: Chemotherapy is limited except for a few chemosensitive entities such as Ewing sarcoma and neuroblastoma. Depending on the extent of decompression, steroids may be continued or tapered.

Radiographic Imaging

- MESCC: Recurrence should be watched for via positron emission tomography (PET)/CT, MRI, or CT scan. Progressive spinal deformity may suggest either tumor recurrence or progression, or development of late radiation-induced osteonecrosis.

Adjuvant Treatments

- MESCC: Radiation therapy is usually an appropriate adjunct to treatment postoperatively after removal of epidural tumors.

Special Considerations

Spinal Epidural Hematoma

Spinal anesthesia is used for surgeries of the lower extremities, such as hip arthroplasty and amputations, and in obstetrics. Risk of an SEH is $< 1{:}150{,}000$ to 1:190,000 in this context. The primary predisposing factors are traumatic insertion and/or removal of the catheter and coagulopathy. However, given the high risk of deep vein thrombosis (DVT) in both hip arthroplasty and lower extremity amputations, current recommendations endorse initiation of therapeutic anticoagulation 2 hours after the spinal needle is inserted or epidural catheter is removed. Anticoagulation should be further delayed if there is a hemorrhage.[2]

Postoperative SEH surfaces as a particularly pertinent topic in the setting of postoperative DVT/pulmonary embolism prophylaxis. Postoperative SEH should be suspected in any patient who develops new neurologic deficits after surgery. Incidence across many studies is 1%or less. Preoperative coagulopathy is the most important risk factor. Other risk factors include age greater than 60; use of nonsteroidal anti-inflammatory drugs (NSAIDs); Rh1 blood group; greater than 5-level procedure; hemoglobin level less than 10; blood loss greater than 1 L; and international normalized ratio (INR) greater than 2.0 in the first 48 hours. Currently there is insufficient evidence to offer precise recommendations of when to start postoperative chemoprophylaxis for DVTs.[3]

Traumatic SEH has been associated with spinal fractures. In one series, approximately half of patients with a traumatic spinal fracture also suffered from an SEH. In this series, treatment focused exclusively on the fracture. The outcome in patients with neurologic deficits were equivalent in both the group with a traumatic SEH and the group without.[24]

Spinal Epidural Abscess

The underlying condition that predisposed the patient to developing a spinal abscess should be investigated, if not immediately known. While perfectly healthy patients can develop a spinal abscess without other risk factors, this is extremely rare and a search for a predisposing factor should be undertaken at the same time as the treatment itself. Antibiotics should be continued for several weeks after drainage, if undertaken, and the duration will depend on the infectious agent and local sensitivities. The inflammation surrounding the spinal cord from the infection can cause local thrombosis and ischemia, and the associated hypotension that can normally develop from any spinal cord injury or shock may worsen this effect. If the patient has any signs of hypotension, at least acutely, this should be managed, possibly in an intensive care environment, until the patient is stabilized or at least for the first 48 hours or so.

MESCC

Emerging technologies becoming increasingly relevant, especially for those who cannot tolerate surgery, include stereotactic radiosurgery, proton beam, radiofrequency ablation, and cryotherapy.

Minimally invasive surgical treatments may lower the bar for surgical intervention, especially if it facilitates reoperation or reimaging with less artifact If postoperative radiation is anticipated, incision placement may be modified in a manner that will minimize exposure to the field of radiation and maximize potential for wound healing.

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18 Treatment of Acute Cauda Equina Syndrome

Harel Deutsch

Introduction

Acute cauda equina syndrome is the sudden compression of the nerves in the lumbar cistern resulting in pain and neurologic impairment. The spinal cord ends at approximately the L1 to L2 levels and, therefore, cauda equina compression involves the nerve roots rather the spinal cord. Clinically it may not be possible to differentiate between a conus medullaris injury versus a cauda equina syndrome. Neurologic manifestations include bilateral leg weakness, loss of sensation, and bladder and bowel problems. True cauda equina syndrome is rare because the nerve roots are more resistant to compression than the spinal cord. Acute cauda equina syndrome therefore requires severe compression and a rapid onset of compression. Causes include an acute lumbar disk herniation or a lumbar fracture/dislocation. Chronic compression is an extremely rare cause of cauda equina symptoms. Treatment involves generally a wide lumbar laminectomy and removal of the compression. In cases where there is a fracture or dislocation, spinal reduction and instrumentation may be necessary. Other causes of cauda equina syndrome include hematomas, tumors, and infections such as epidural abscesses.

Indications

- Patients with acute cauda equina syndrome have leg weakness, decreased lower extremity sensation, and bladder retention. Imaging studies show severe lumbar acute compression. Patients also generally have severe lower back and bilateral leg pain.
- Some lumbar stenosis is a common finding on magnetic resonance imaging (MRI) scans. Cauda equina syndrome is not possible unless the stenosis is very severe. Additionally, most patients with very severe lumbar stenosis do not have cauda equina syndrome. For a cauda equina syndrome to occur there usually is an acute worsening of the baseline stenosis. Sometimes a small acute disk may be superimposed on chronic severe stenosis.
- Patients with acute cauda equina syndrome have urinary retention. Bladder catheterization after the patient tries to void allows documentation of the post void residual. A post void residual over 100 mL suggests a neurogenic bladder.
- Bowel function is not usually apparently disturbed in acute cauda equina syndrome. Patients may have severe constipation and impacted stool. Diarrhea or "loss of bowel" issues are *not* common findings in acute cauda equina syndrome.
- For patients with a traumatic lumbar fracture as the cause of an acute cauda equina syndrome, surgery may be required to address neurologic issues as well as spinal column stability.
- This chapter depicts decompression for an acutely herniated lumbar disk causing significant spinal canal compromise.

Preprocedure Considerations

Radiographic Imaging

- MRI is the preferred imaging study to evaluate for severe lumbar compression. T2-weighted MRI is excellent in showing the absence high intensity cerebrospinal fluid signal at the level of the compression (**Fig. 18.1**).
- If MRI in unavailable or patient factors preclude getting an MRI, then a computed tomography (CT) myelogram may demonstrate severe stenosis or a complete block to contrast flow at the level of compression.
- For patients with traumatic lumbar fractures, X-rays and CT scans are essential to evaluate alignment and fractures.

Medication

- Antibiotics are administered prior to incision.
- Updated guidelines released in 2013 recommend against the use of steroids in spinal cord injury. The guidelines conclude, "In summary, there is no consistent or compelling medical evidence of any class to justify the administration of MP [methylprednisolone[1,2]] for acute SCI [spinal cord injury]. Both consistent and compelling Class I, II, and III medical evidence exists suggesting that high-dose MP administration is associated with a variety of complications including infection, respiratory compromise, GI hemorrhage, and death. MP should not be routinely used in the treatment of patients with acute SCI."[3]

Foley Catheter Placement

- Patients may have significant urinary retention leading to hypotension because of bladder distension.

Operative Field Preparation

- Alcohol prep is performed before povidone iodine or chlorhexidine application.
- The incisions are marked and infiltrated with 1% lidocaine with epinephrine 1:100,000.

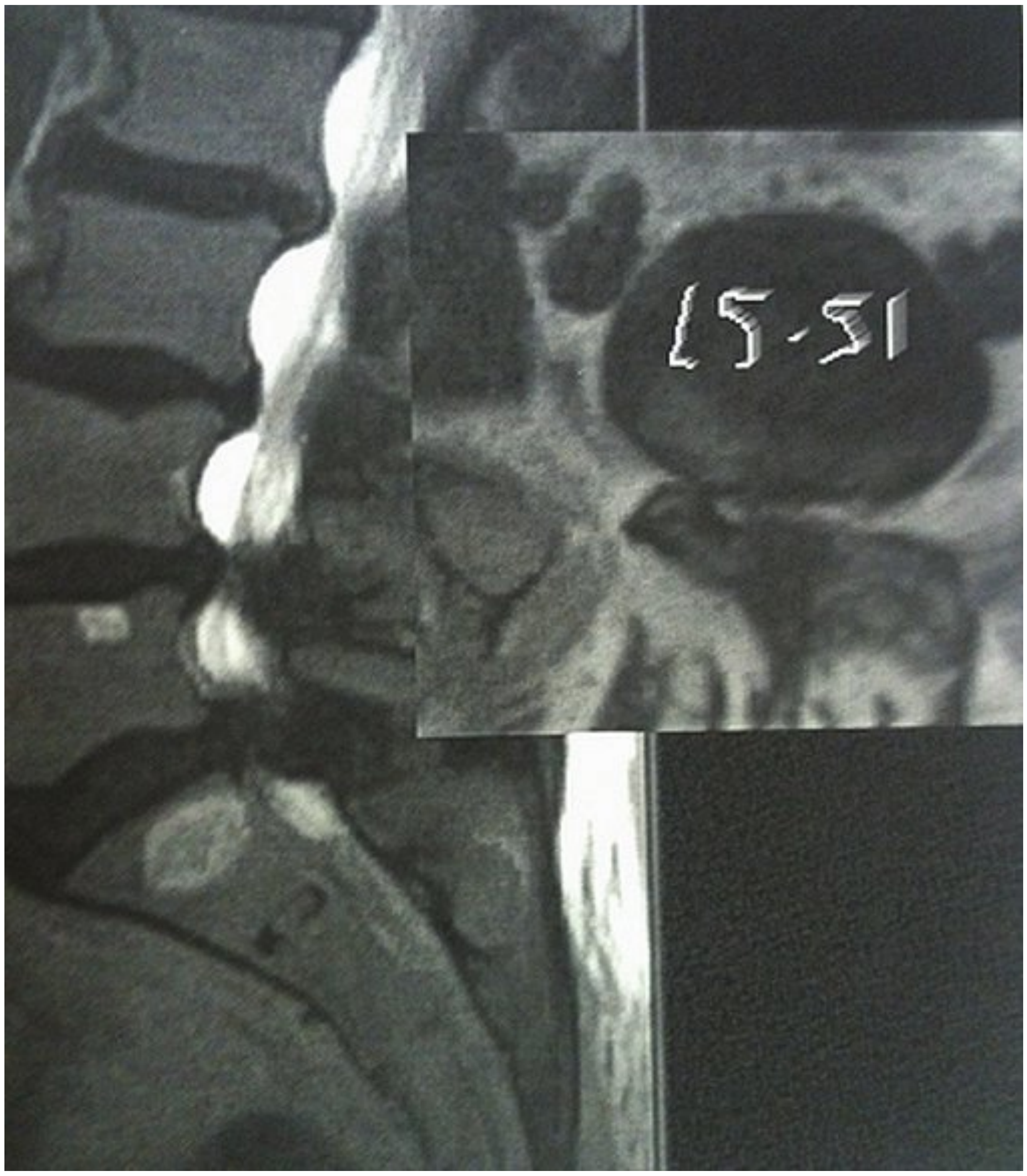

Fig. 18.1 Lumbar T2-weighted MRI sagittal and axial images with severe stenosis at L5-S1.

Operative Procedure

Positioning (Fig. 18.2)

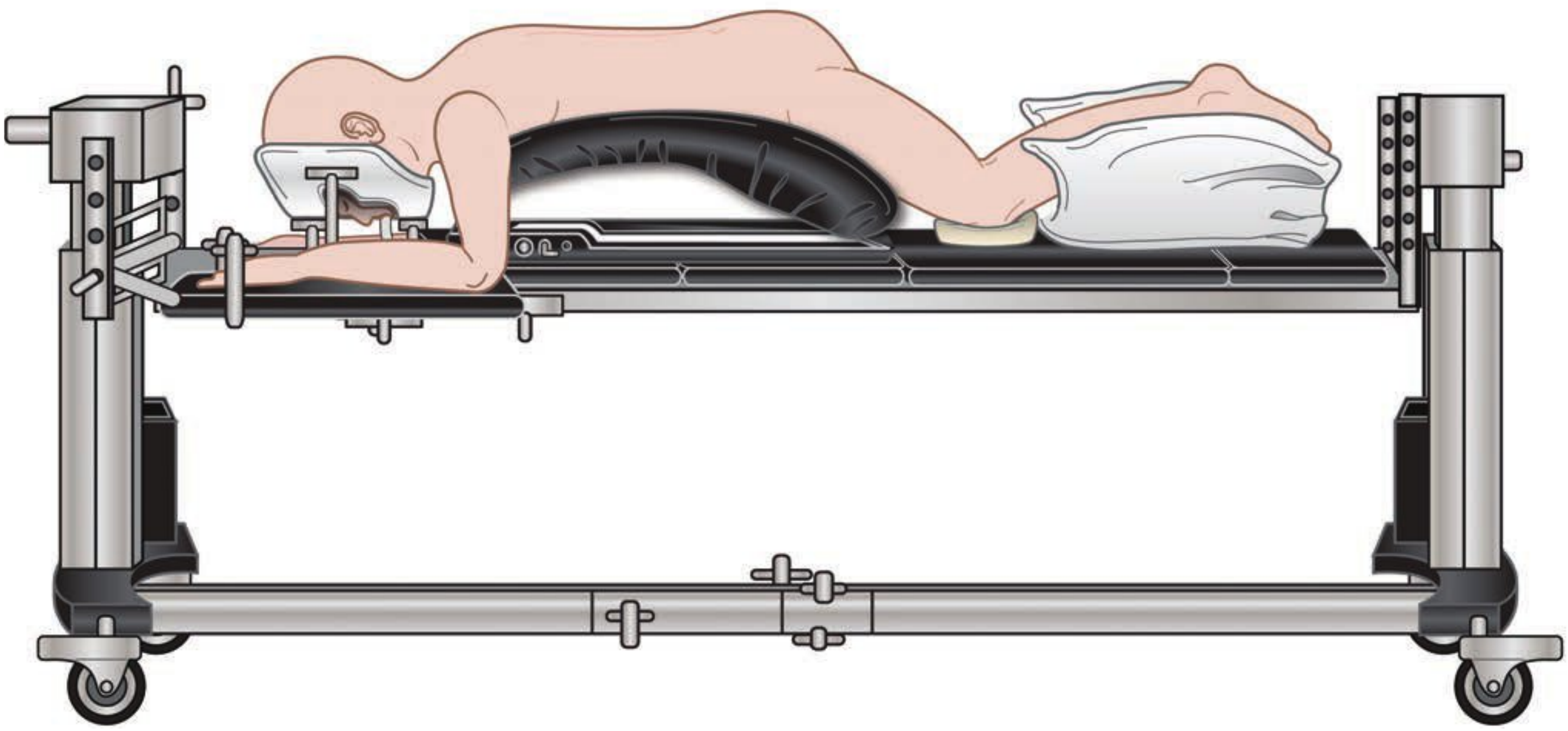

Figure	Procedural Steps	Pearls
Fig. 18.2	**Patient positioning. The patient is positioned prone. X-ray or fluoroscopy is used to localize the level and plan the incision.**	• There are several options for beds. Bolsters can be used for the chest. A Wilson frame allows for opening up of the lumbar spine. A spinal table with hip and chest pads avoids abdominal compression and may reduce bleeding due to venous congestion. In patients undergoing a fusion, a Wilson frame should be used carefully to avoid an iatrogenic flat back syndrome.

Skin Incision (Fig. 18.3)

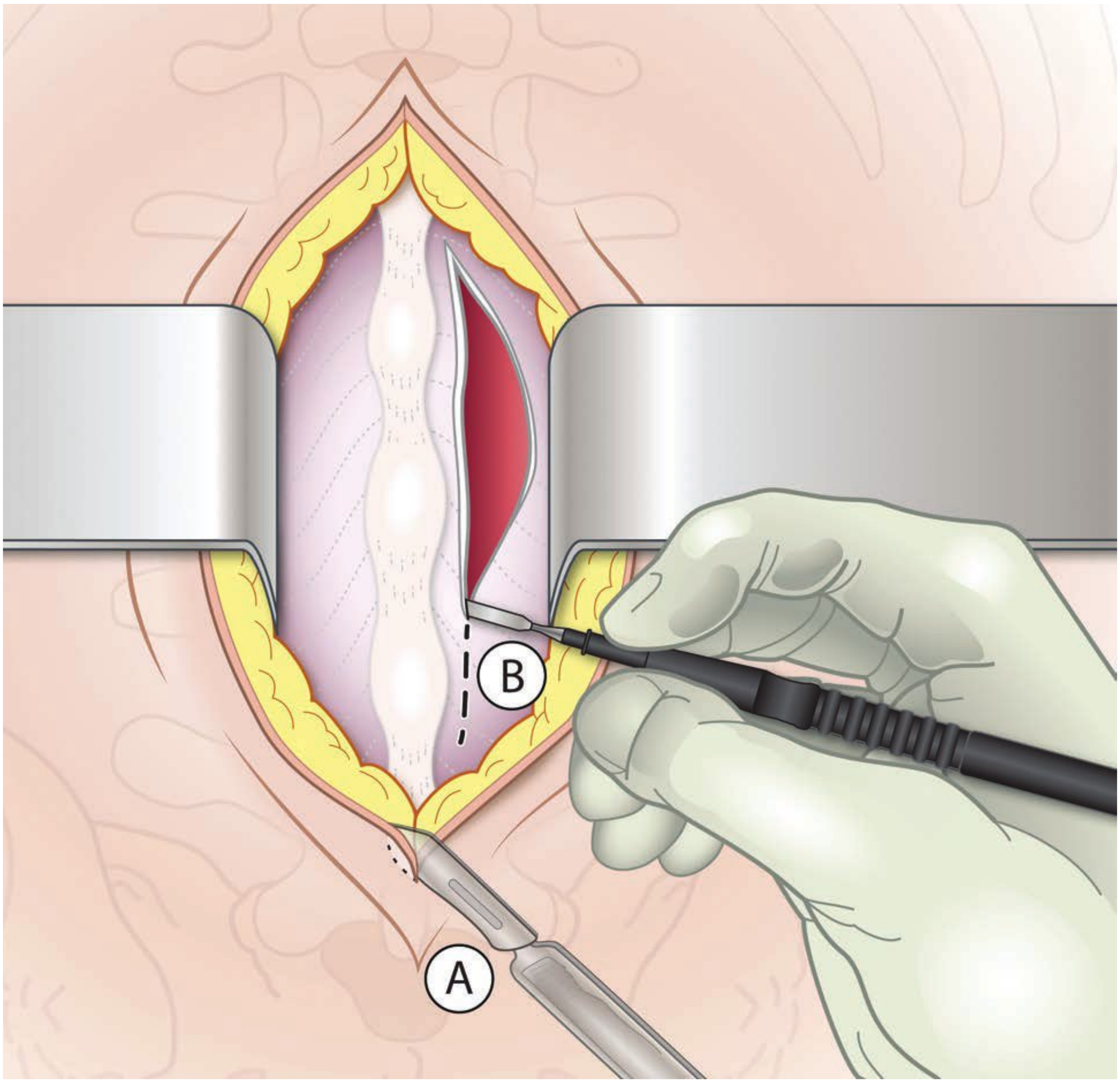

Figure	Procedural Steps
Fig. 18.3	**(a) The incision is made with a no. 10 blade and extends about 5 cm.** **(b) A monopolar is used to extend the incision through the posterior lumbar fascia.**

Subperiosteal Dissection (Fig. 18.4)

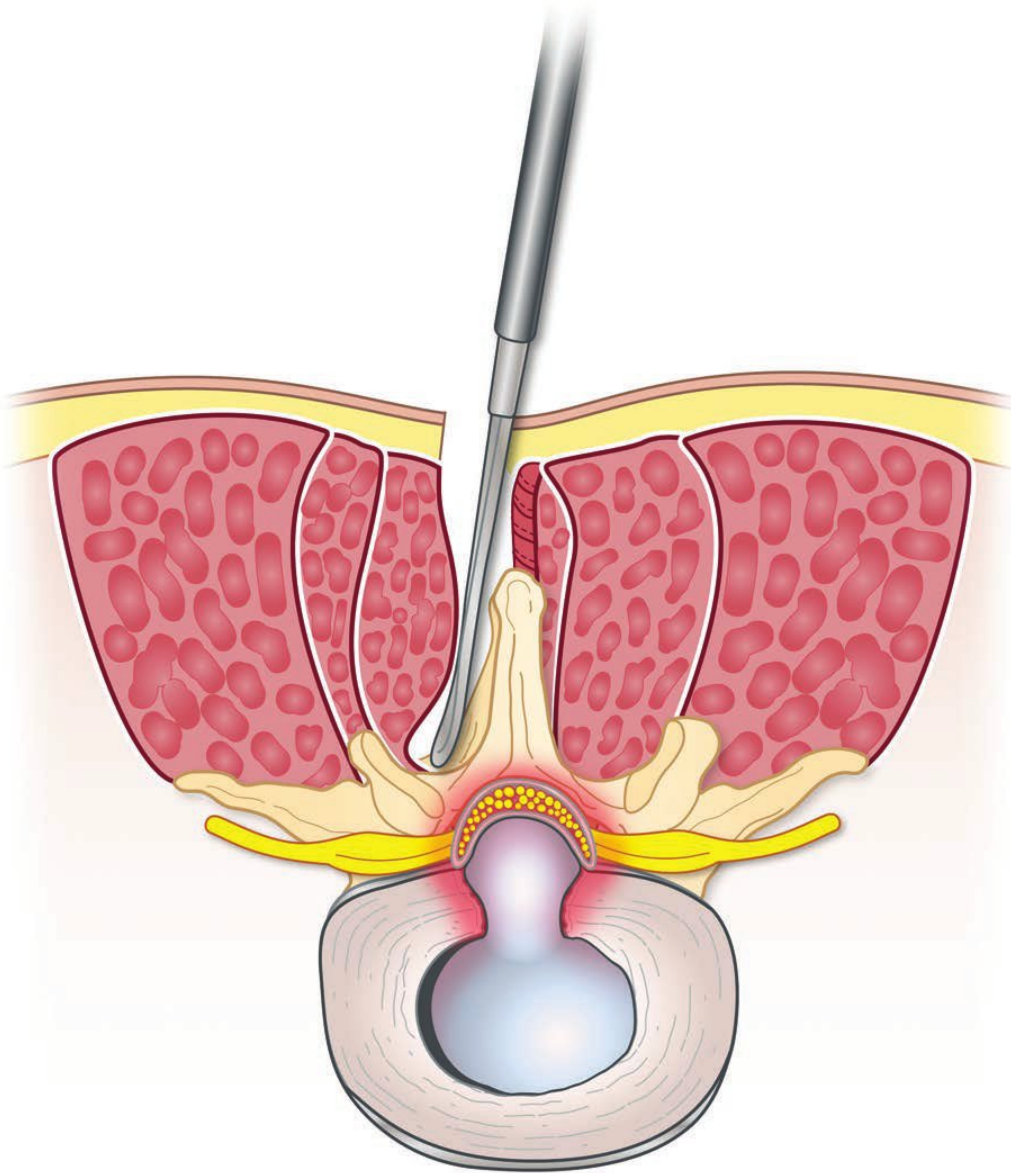

Figure	Procedural Steps	Pearls
Fig. 18.4	**The monopolar is used to strip the paraspinal muscles from the spinous process and lamina. The medial facet joint is exposed.**	• Staying in the subperiosteal space helps reduce bleeding. Constant bleeding from the muscle may interfere with subsequent steps. Preserving the facet capsule rather may prevent future facet arthropathy. Fluoroscopy or X-ray imaging is used to confirm the level.

Lumbar Laminectomy (Fig. 18.5)

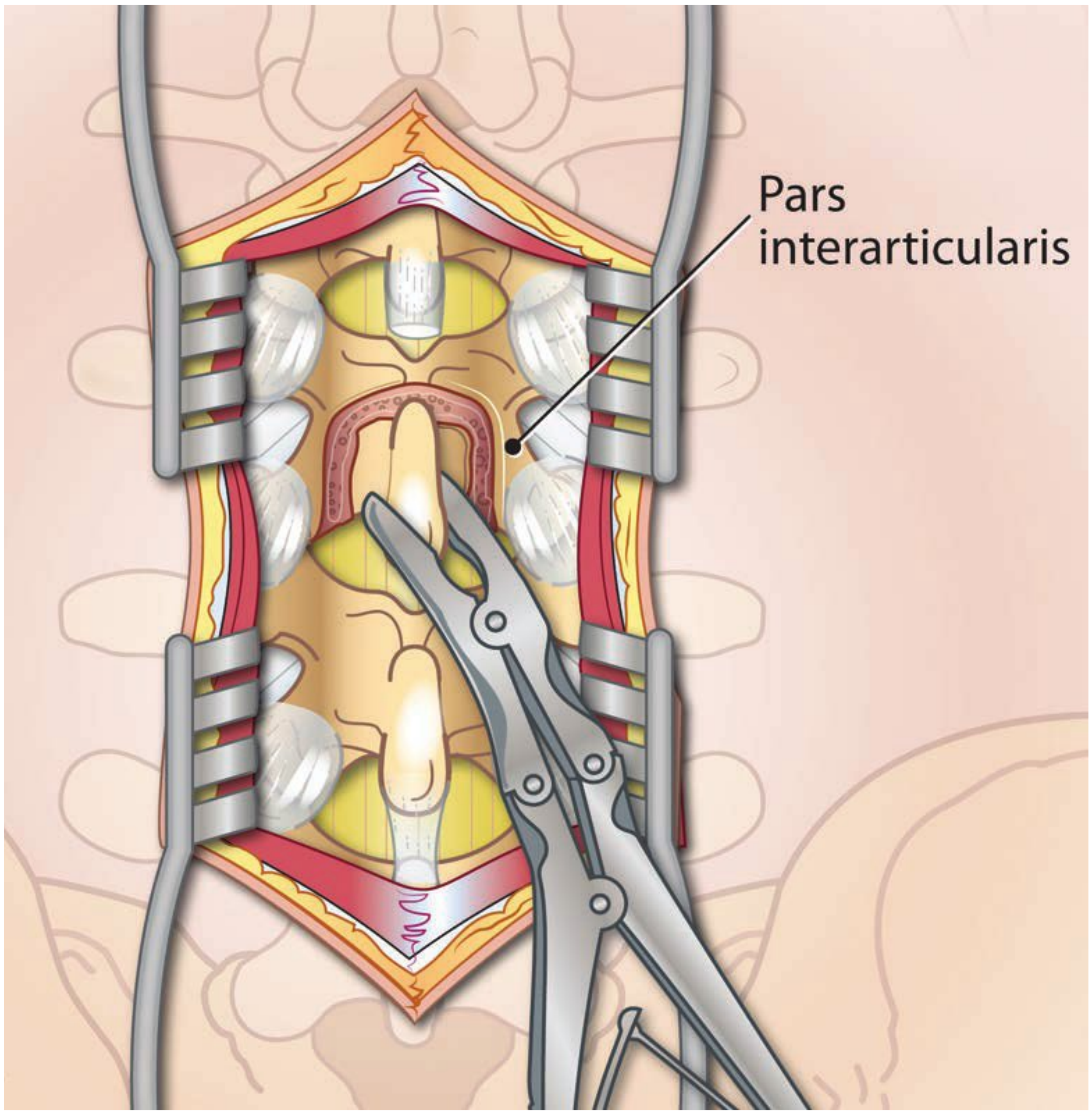

Figure	Procedural Steps	Pearls
Fig. 18.5	**The spinous process is removed and the lamina is removed using a high-speed drill, Kerrison, and/or Leksell rongeurs. A high-speed drill is helpful for performing a partial medial facetectomy.**	• The pars articularis is preserved to maintain lumbar stability.

Lumbar Diskectomy (Fig. 18.6a, b)

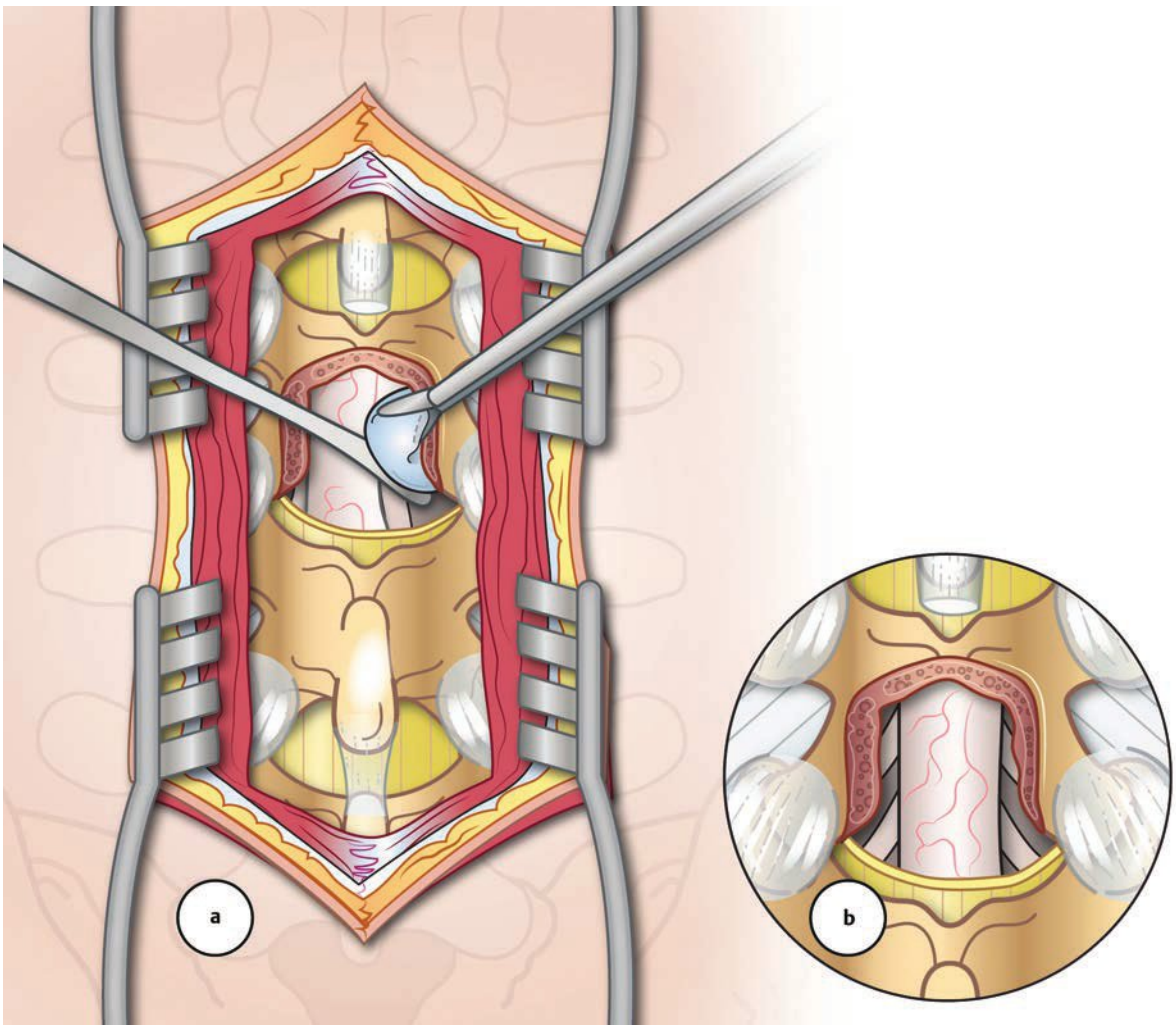

Figure	Procedural Steps	Pearls
Fig. 18.6	**(a) The dura is retracted and if there is a signif cant disk herniation component, the disk fragment is removed. The disk space is often incised and disk material removed with pituitary rongeurs under magnif cation. (b) The nerve root and thecal sac are inspected for any remaining fragments or compression.**	• With a large ventral disk herniation, dural retraction may be very difficult or impossible initially. More bone may need to be removed laterally. As the decompression progresses, dural retraction is easier.

Closing

Lumbar Incision

- The wound is heavily irrigated.
- A medium suction drainage device is placed deep and brought out through a separate skin incision.
- The posterior lumbar fascia is reapproximated using 0 absorbable suture in an interrupted fashion. Interrupted loose muscle sutures to obliterate dead space are optional.
- The subcutaneous tissue is closed using several interrupted 2-0 Vicryl sutures.
- The skin is closed with staples or a monofilament nylon suture.

Postoperative Management

Medication

- Two to three doses of prophylactic antibiotics in the immediate postoperative period are optional. Longer term antibiotics or antibiotics for drain management are discouraged.

Further Management

- Drains are removed when drainage is minimal (less than 50 mL per shift).
- Skin sutures or staples are removed after 2 weeks.

Special Considerations

Timing of Surgery

The timing of surgery and influence on outcome in cases of cauda equina surgery is the subject of multiple investigations.[4] The literature indicates outcome is more related to preoperative condition than the specific timing of intervention. Studies show people with complete urinary incontinence have a poor outcome and patients with a weak stream or decreased sensation having a better outcome. Shapiro et al reported an improvement for patients operated on within 48 hours[5] after reviewing 14 patients with cauda equina syndrome. All patients had bilateral sciatica and leg weakness. Of the 14 patients, 13 had urinary incontinence, 9 massive disk herniations, and 5 small disk herniations superimposed on stenosis. All patients were ambulatory. Shapiro found 7/10 patients with no incontinence had surgery within 48 hours. The four patients with incontinence after surgery all had surgery after 48 hours. Shapiro et al concluded surgery within 48 hours is warranted in cauda equina patients.

Tator et al used a survey to determine current practices in timing of surgery for spinal cord injury. Of the 585 cases they surveyed, 5.6% were cauda equina cases.[6] In general 23.5% of patients had surgery within 24 hours of injury. In another study, Tator et al found no improvement with acute surgery for spinal cord injury.[7] The cohort of 208 patients included some patients with cauda equina injury. In a review of the literature, Fehlings et al concluded animal studies show better outcome with early decompression for spinal cord injury.[8] The literature reviewed was mainly spinal cord injury data rather than cauda equina injuries. Fehlings et al concluded that early decompression within 24 hours is recommended for spinal cord injuries.[9] Gleave et al, Qureshi et al, and Olivero et al showed surgical timing did not affect patient outcome in cauda equina syndrome.[10–12] Rather, outcome was dependent on the patient's preoperative neurologic status. Cases of cauda equina syndrome should be treated expeditiously.[13] While absolute timing may not make a difference, earlier surgical interventions seems to prevent further deterioration.

Cauda equina syndrome injuries should be distinguishable from injuries to the conus medullaris. The conus medullaris is the terminal portion of the spinal cord and represents a central nervous system structure. Outcomes may be different with conus injuries.

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III Nontraumatic Emergencies

19 Removal of Spontaneous Intracerebral Hemorrhages

Justin Mascitelli, Yakov Gologorsky, and Joshua Bederson

Introduction

Spontaneous intracerebral hemorrhage (ICH) accounts for 10–30% of all strokes and is a significant cause of morbidity and mortality around the world. Although it is the second most common form of stroke after ischemic infarct, spontaneous ICH is the most deadly type of stroke with a 30-day mortality as high as 50% Unlike ischemic infarcts, spontaneous ICH usually progresses over minutes to hours often with worsening headache, nausea, vomiting, alterations of conscious, and deteriorating neurologic status. The most common location for a spontaneous ICH is deep (including the basal ganglia, thalamus, and internal capsule) followed by lobar, cerebellar, and brainstem. Rapid diagnosis and management is crucial as early deterioration is common within the first few hours after onset.[1,2]

Indications

Supratentorial ICH

- Precise indications for surgery are controversial[1–4] and should be based on the individual patient's neurologic condition, the size and location of the hematoma, the patient's age, and the family's wishes.
- The 2010 American Stroke Association/American Heart Association (ASA/AHA) guidelines recommend standard craniotomy for lobar clots greater than 30 mL and within 1 cm of surface.
- In general, factors that favor surgical management[5] include:
  - Lesions with marked mass effect, edema, or midline shift;
  - Lesions with symptoms that appear to be secondary to increased intracranial pressure (ICP) or mass effect;
  - Moderate clot volume;
  - Persistently elevated ICP despite maximal medical management;
  - Rapid neurologic deterioration;
  - Favorable locations: lobar, cerebellar, external capsule, nondominant hemisphere;
  - Young age;
  - Onset of symptoms less than 24 hours old.

Infratentorial ICH

- 2010 ASA/AHA indications for surgical evacuation of cerebellar ICH[1]
  - Patients who are deteriorating neurologically
  - Brainstem compression
  - Hydrocephalus from ventricular obstruction

Preprocedure Considerations

Radiographic Imaging

- Computed tomography (CT) can be obtained rapidly and clearly demonstrates high density blood within brain parenchyma. In addition, the ellipsoid method (diameter of the clot in each dimension: anteroposterior [AP], lateral [LAT], and height [HT]) can be used to calculate ICH volume and has prognostic significance.[6]
  - Ellipsoid volume 2 AP 3 LAT 3 HT / 2
- Magnetic resonance imaging (MRI) is not the initial diagnostic imaging modality of choice due to the time needed to complete the study as well as the complicated appearance of acute blood on MRI.[7]
- CT angiography (CTA) is recommended for all patients except those older than 45 years of age with preexisting hypertension and ICH in the thalamus, putamen, or cerebellum (**Fig. 19.1**).[8] CTA has lower yield for cerebellar ICH in comparison to supratentorial ICH.
- Preoperative imaging (**Fig. 19.2**).

Fig. 19.1 CTA demonstrating right cerebellar arteriovenous malformation with associated intracranial hemorrhage and intraventricular hemorrhage (IVH).

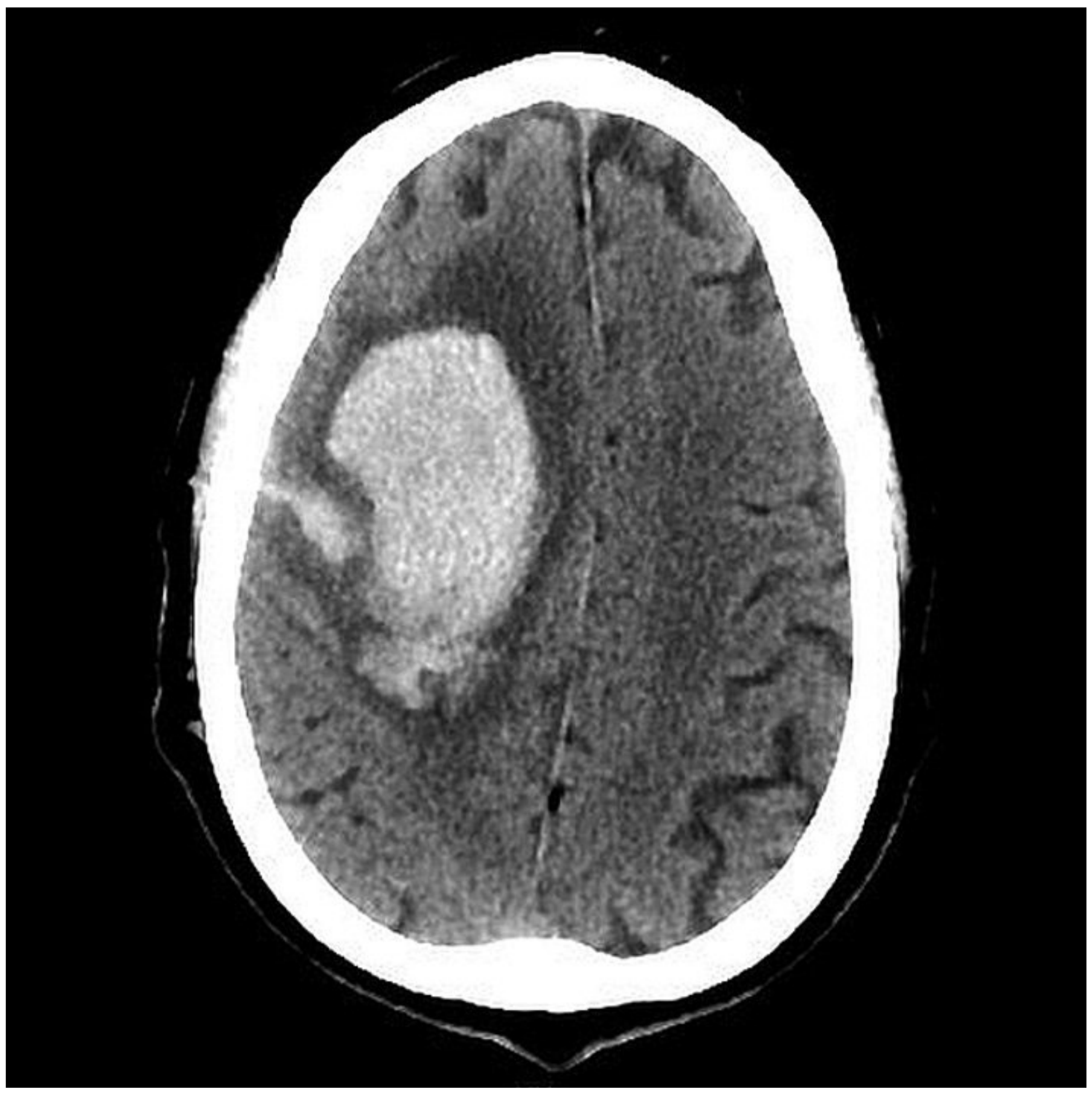


Fig. 19.2 Case example: frontal craniotomy. CT head demonstrating large right frontal intracranial hemorrhage with mild mass effect and midline shift and no hydrocephalus.

Initial Management and Medication[1,2]

- Initial monitoring should take place in an intensive care unit or other monitored setting.
- Blood pressure should be promptly but not over-aggressively controlled. In patients presenting with systolic blood pressure (SBP) of 160–220 mm Hg, the authors prefer nicardipine infusion with a goal SBP of 140–160 mm Hg.
- For patients with clinical seizures or electroencephalography (EEG) evidence of seizure activity, the authors prefer phenytoin. Although seizure prophylaxis is debated in the setting of ICH, the authors also prefer phenytoin for the prevention of early seizures in patients with lobar ICH.
- Glucose should be monitored and normoglycemia maintained.
- Platelet transfusion and factor replacement should be given to all patients with severe thrombocytopenia or coagulation factor deficiency, respectively. For patients with a coagulopathy, consideration should be given to giving protamine sulfate, vitamin K, fresh frozen plasma, cryoprecipitate, or other clotting factors. For patients with a history of antiplatelet medication use, the authors prefer desmopressin acetate alone for those undergoing conservative management and desmopressin plus platelet transfusion for those undergoing surgical management. Currently recombinant factor VIIa (rFVIIa) is not recommended given its thromboembolic risk.[9]
- Regarding the prevention of deep venous thrombosis and pulmonary embolism, all patients should have intermittent pneumatic compression, and pharmacological prophylaxis should be considered once cessation of bleeding has been documented.
- Treatment of elevated ICP should begin with simple measures such as head of bed elevation, analgesia, and sedation. More aggressive measures to reduce ICP include osmotic diuresis, cerebrospinal fluid (CSF) drainage, paralysis, hyperventilation, hypothermia, and barbiturate coma.
- Patients with obstructive hydrocephalus should undergo emergent placement of an external ventricular drain (EVD) in the intensive care unit prior to surgery. Alternatively, an EVD may be placed in the operating room at the time of surgery as long as this is done expeditiously.
- In the authors' experience, upward cerebellar herniation due to EVD over-drainage is extremely rare. Nonetheless, EVD drainage should be limited by setting a gradient no less than 10 cm H_2O prior to surgery.

Operative Field Preparation

- The exposed skin is sterilized with povidone iodine or chlorhexidine application.
- The incision is marked and infiltrated with 1%lidocaine with epinephrine 1:100,000.

Operative Procedure

Frontal Craniotomy[10]

Positioning and Skin Incision (Fig. 19.3)

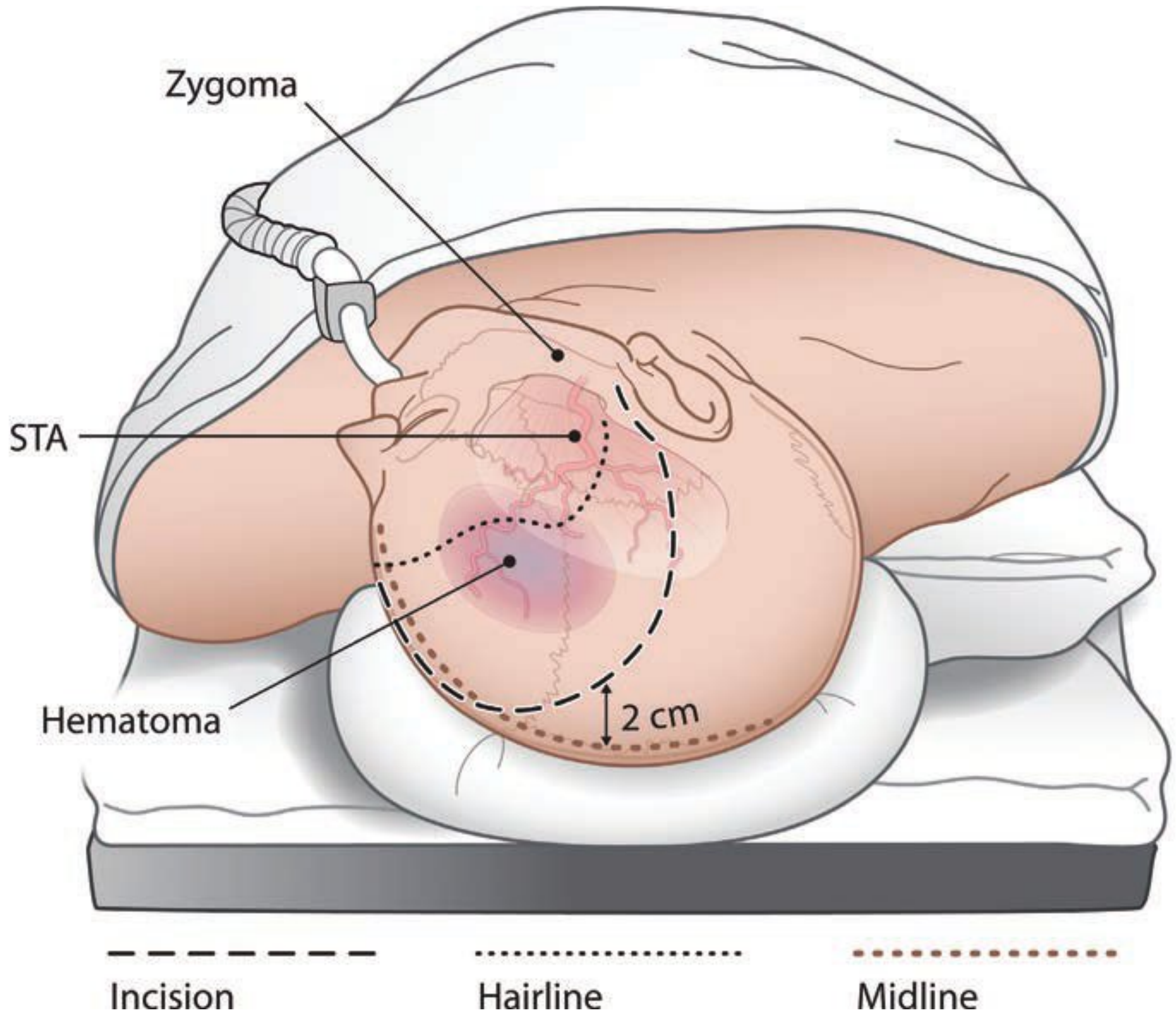


Figure	Procedural Steps	Pearls
Fig. 19.3	**The patient is placed supine on the operating table.** **The Mayfield skull clamp is placed with the single pin at the equator in contralateral frontal bone above the orbit and the paired pins placed at the equator in the ipsilateral occipital lobe.** **Alternatively, the patient's head may be placed on a horseshoe or a donut without a Mayfield clamp.** **The head is rotated as far as possible to the contralateral side without obstructing the airway or venous drainage.** **The superficial temporal artery (STA) should be palpated at the level of the zygoma and the vertical limb of the incision should be placed between the artery and the tragus.** **The incision begins at the zygoma and then curves posteriorly to the parietal eminence and upward from the auricle to reach 2 cm from the midline.** **The incision is then carried forward to the frontal region and curved across the midline just behind the hairline.**	• A frontal craniotomy is described here. Of course, the exact craniotomy should always be tailored to the location of the ICH. • Sufficient time should be devoted for ICH localization before the incision is marked. The patient's head position should be correlated with the CT scan. It is often helpful to draw the planned craniotomy on the scalp. • If time permits, a volumetric CT scan may be obtained and intraoperative navigation may be used for precise localization of the ICH. • When applying the Mayfield clamp, the frontal sinus and mastoid air cells should be avoided. • Care should be taken to avoid the frontal branch of facial nerve that originates just below the root of the zygoma and travels in the superficial temporal facia to the orbital rim.[11] • Care should also be taken when dissecting adjacent to the auricle to not violate the external auditory canal.

Subcutaneous Dissection (Fig. 19.4)

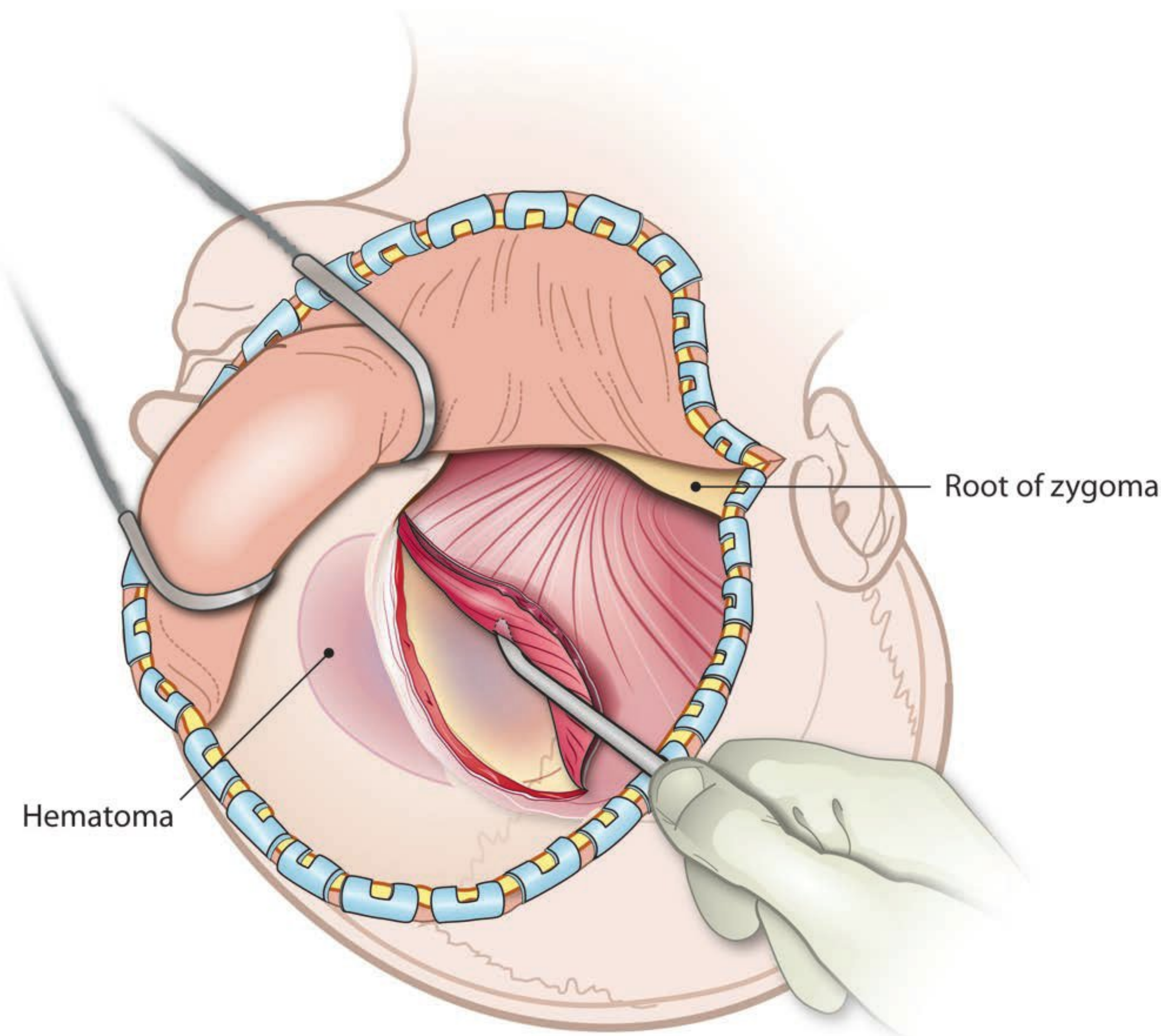


Figure	Procedural Steps	Pearls
Fig. 19.4	**The skull is then exposed by incising the temporalis muscle posteriorly and superiorly and elevating the muscle anteriorly and inferiorly with a periosteal elevator.** **The approach of Spetzler and Lee[12] involves leaving a cuff of temporalis superiorly that can be used during the closure.**	• Use of electrocautery to elevate the temporalis muscle may result in injury to the trigeminal nerve motor fibers. Mechanical elevation with a periosteal elevator is preferred.

Craniotomy (Fig. 19.5)

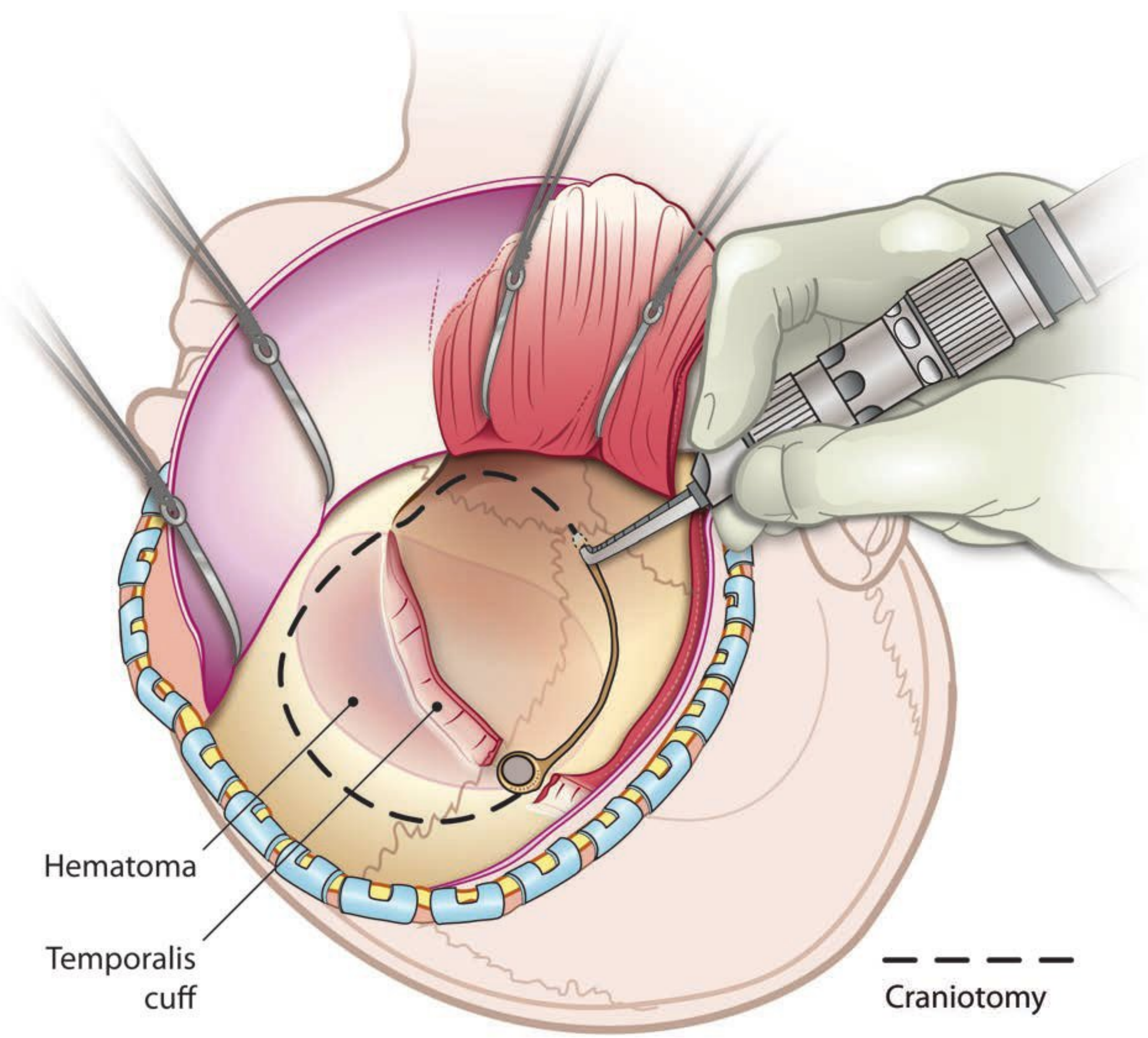


Figure	Procedural Steps	Pearls
Fig. 19.5	**The craniotomy should be started with a single bur hole, the location of which is tailored to the planned craniotomy (in this case, it is placed at the posterior superior temporal line).** **The craniotomy is then widened using the craniotome.** **A high speed drill can be used to flatten the orbital roof and remove the inner table of the frontal bone if needed.**	• It is helpful to again re-correlate with the CT scan prior to making the craniotomy. • While drilling the inner table of the frontal bone, care should be taken not to enter the orbit or frontal sinus. If this were to occur, the orbit can be packed with oxidized cellulose and the sinus with muscle/fascia. • If the temporal air cells are entered, they should be thoroughly waxed.

Dural Opening (Fig. 19.6)

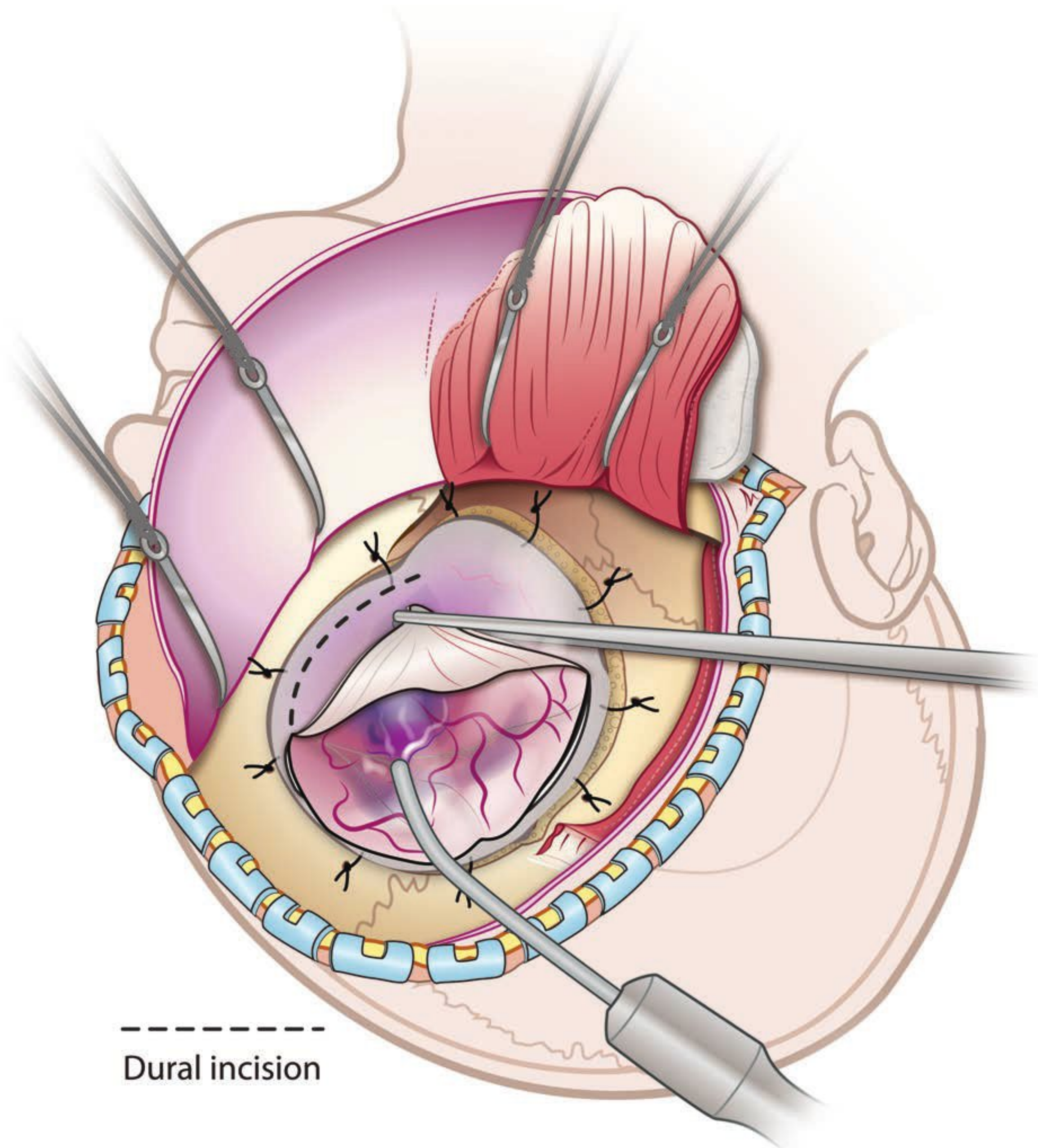
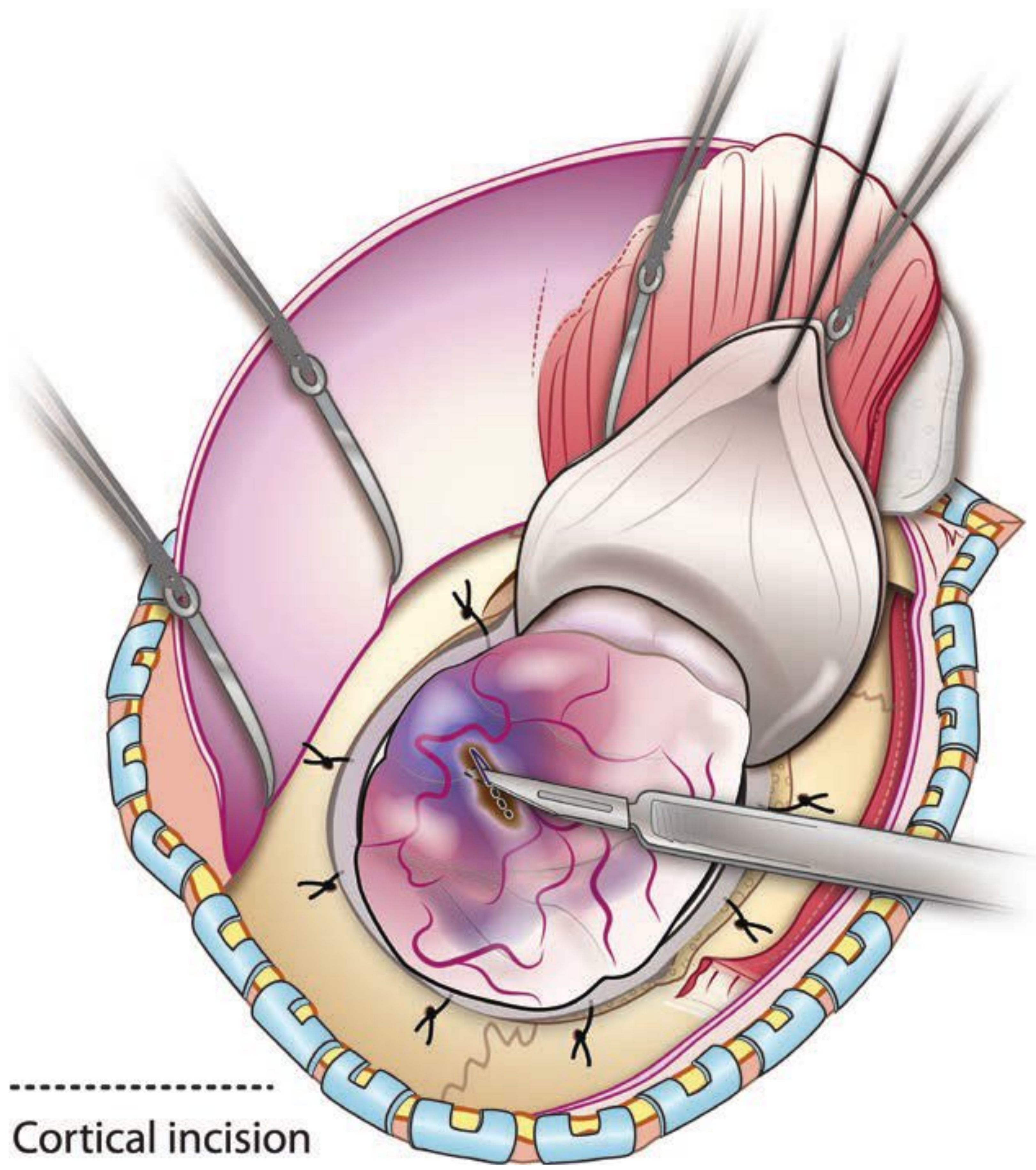
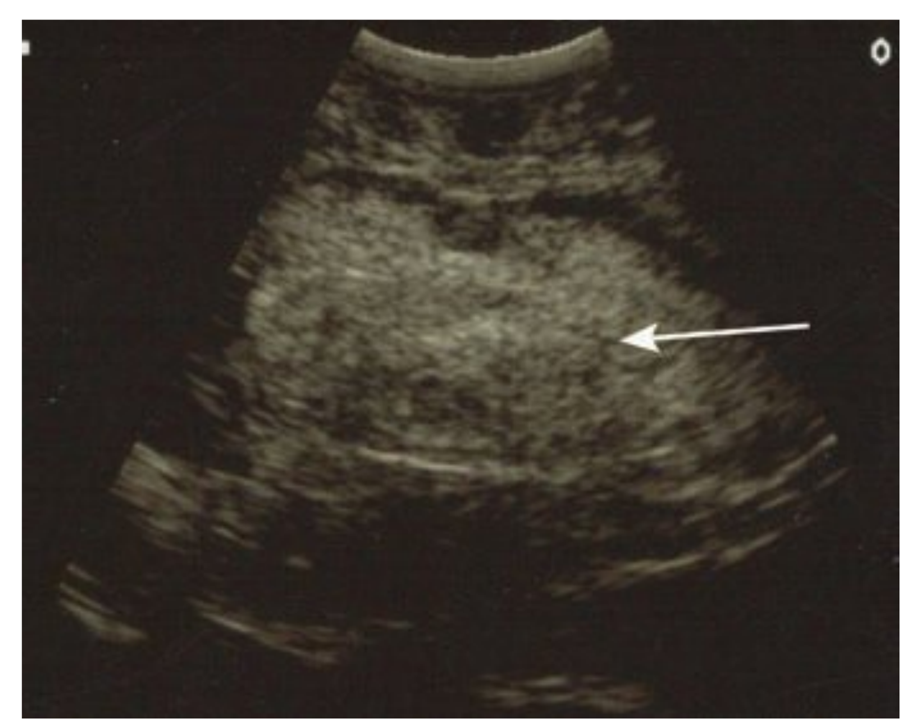


Figure	Procedural Steps	Pearls
Fig. 19.6	**Before opening the dura, tack up sutures should be placed along the entire craniotomy to prevent postoperative epidural hematoma formation.** **There are many fashions in which the dura may be opened. The authors prefer a C-shaped opening with the dura reflected anterior/inferiorly in the same direction as the scalp/muscle.**	• Placement of dural tack ups may be delayed until after ICH evacuation if the patient is actively herniating and immediate ICH evacuation is necessary.

Hematoma Evacuation (1)[13] (Fig. 19.7a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 19.7	**(a) A corticotomy is then performed where the hematoma comes closest to the surface (a).** **Bipolar cautery should be used along the planned cortical incision to prevent bleeding.** **The cortical incision is then made using a no. 11 blade.**	• Eloquent tissue should be avoided when choosing the location for the corticotomy. • Intraoperative ultrasound may be used if the ICH does not come to the cortical surface. (**b**) Intraoperative ultrasound image of a large frontal basal ganglia hematoma (arrow).

Hematoma Evacuation (2) (Fig. 19.8)

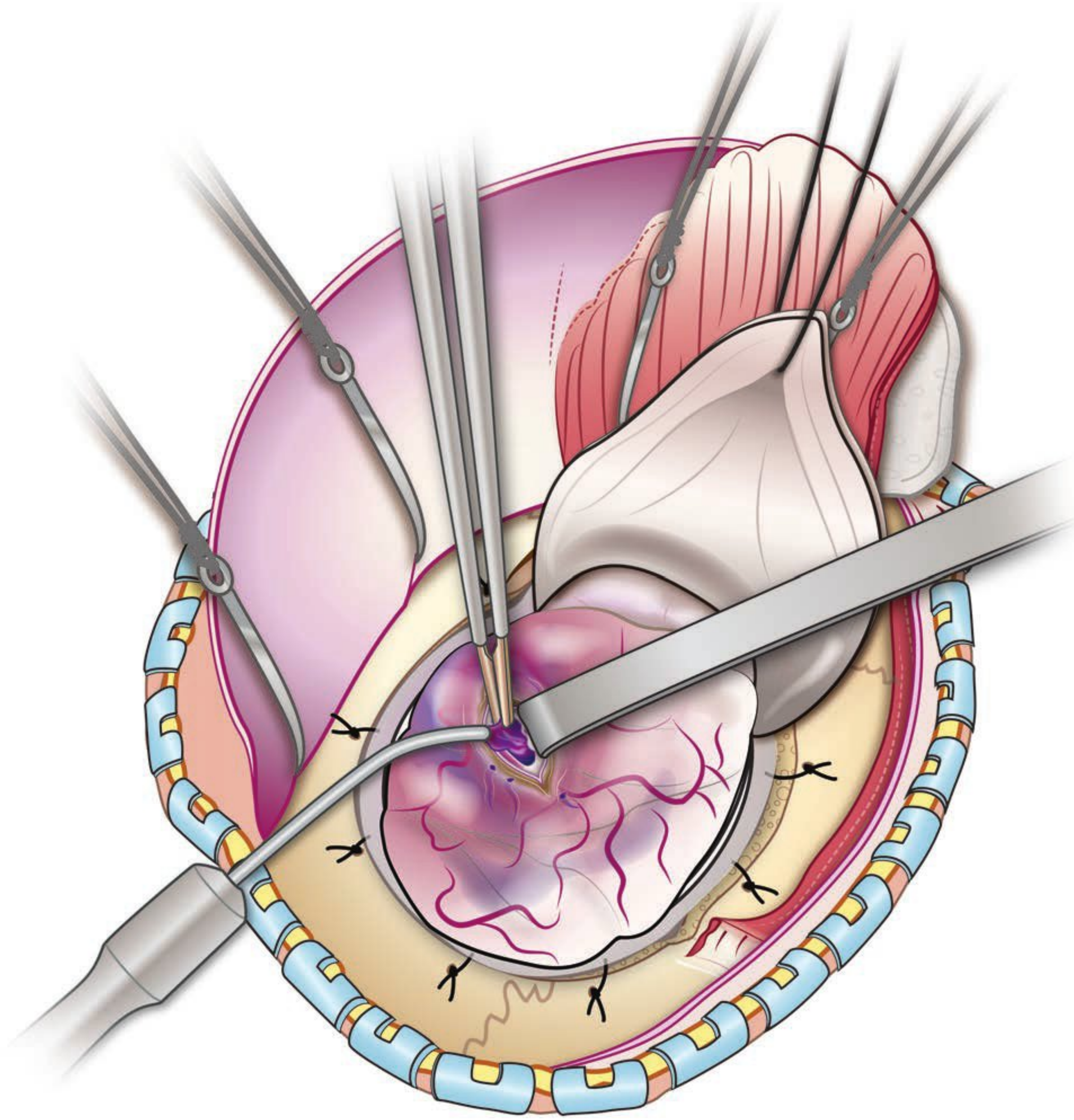
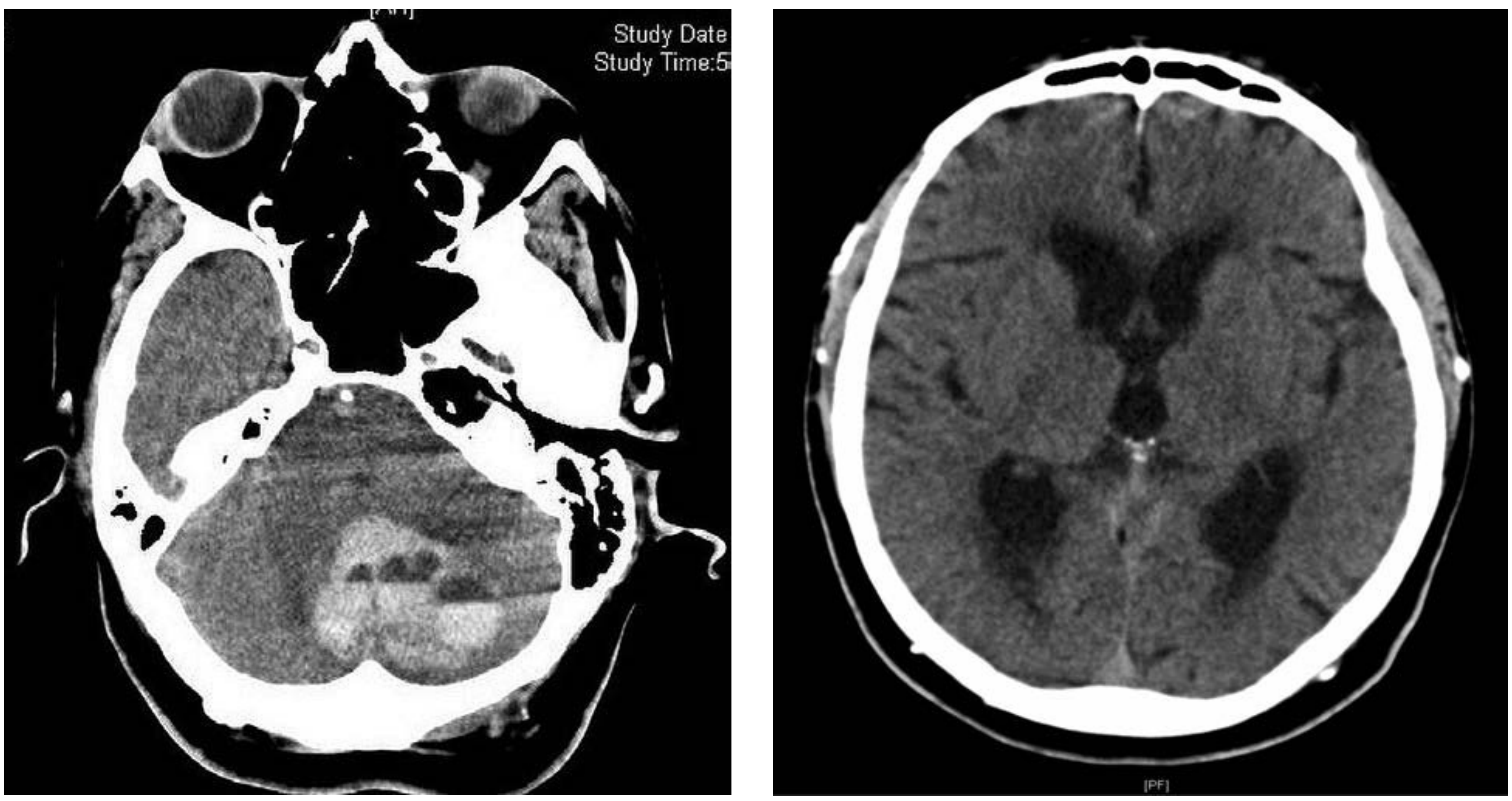


Figure	Procedural Steps	Pearls
Fig. 19.8	**A malleable can be used to gently retract the cortical opening.** **The hematoma is then evacuated from within the cavity. The center of the hematoma is evacuated first followed by the peripheral blood.** **Bipolar cautery is used to stop bleeding from the cavity walls. Gelatin sponge and oxidized cellulose available in various forms may also be used for final hemostasis.**	• Self-retaining retractors are not advised as they can damage normal parenchyma. • The operating microscope may be used for this part of the case for increased illumination and magnification, if needed. • Special attention should be paid for small tumors, cryptic arteriovenous malformations (AVMs), and cavernous angiomas.

Closing

- Once adequate hemostasis has been achieved, the dura is closed using running or interrupted 4-0 braided nylon sutures (the dura may be left open if increased ICP is a potential concern).
- The bone flap is placed and secured with plates and screws (the bone plate may be marsupialized in the abdomen if increased ICP is a potential concern).
- The wound is copiously irrigated.
- A medium suction drainage device is placed in the subgaleal plane.
- The temporalis muscle is reapproximated with 2-0 braided absorbable sutures.
- The galea is approximated with 3-0 braided absorbable suture in an inverted, interrupted fashion.
- The skin is closed with 3-0 nylon suture in a running fashion or staples.

Midline Suboccipital Craniectomy10 (Fig. 19.9a, b)



a b

Fig. 19.9a, b Case example: midline suboccipital craniectomy. (**a**) Large cerebellar intracranial hemorrhage causing effacement of the fourth ventricle and brainstem compression. (**b**) Hydrocephalus secondary to fourth ventricular compression.

Positioning (Fig. 19.10)

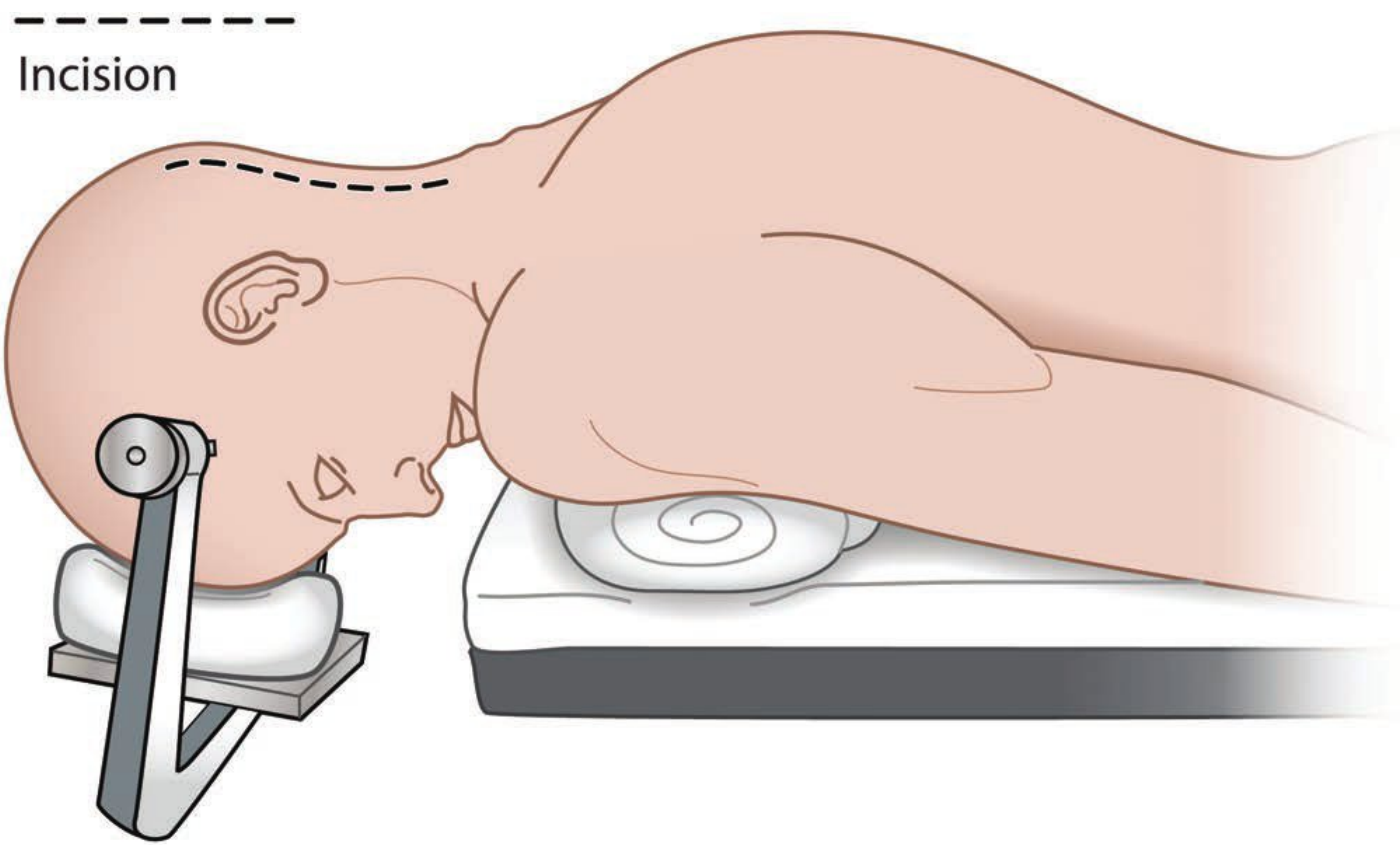


Figure	Procedural Steps	Pearls
Fig. 19.10	**The head is fixed in a Mayfield skull clamp with the single pin on the linea temporalis anterior to one external auditory meatus (EAM) and the paired pins on the opposite linea temporalis (one pin over the EAM and one pin anterior to the EAM).** **The patient is placed in the prone position on the operating table on bolsters.** **The head should be in flexion with as much distraction as possible.**	• The midline suboccipital craniectomy is described here. The lateral suboccipital craniectomy can also be used for more lateral cerebellar ICHs. • Care should be taken to not hyperflex the neck and compromise the airway as well as to inspect and pad all pressure points. • If not done already, an EVD should be placed first. Once it has been secured, the patient should be turned to the prone position for the craniectomy.

Skin Incision and Subcutaneous Dissection (Fig. 19.11)

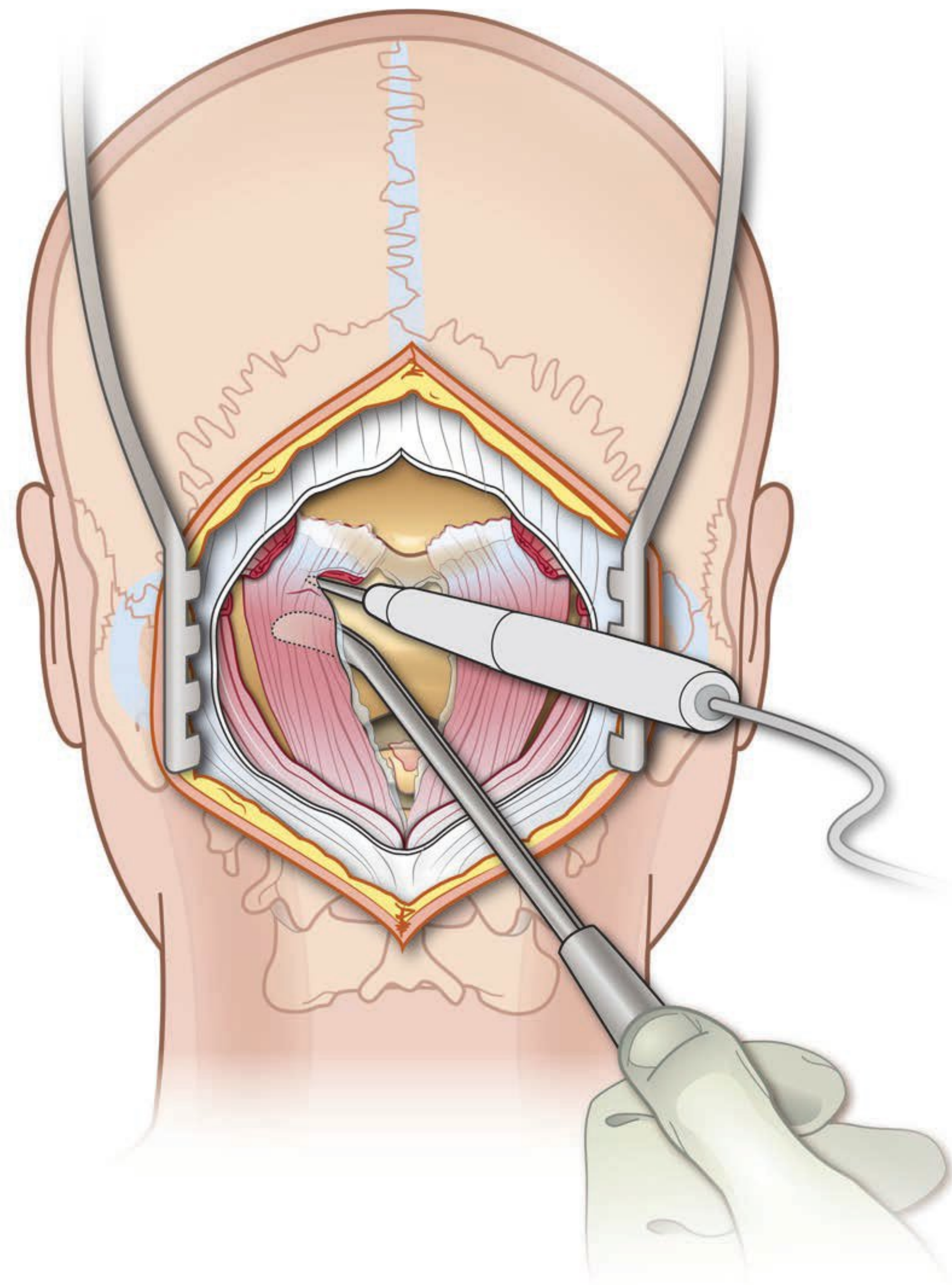
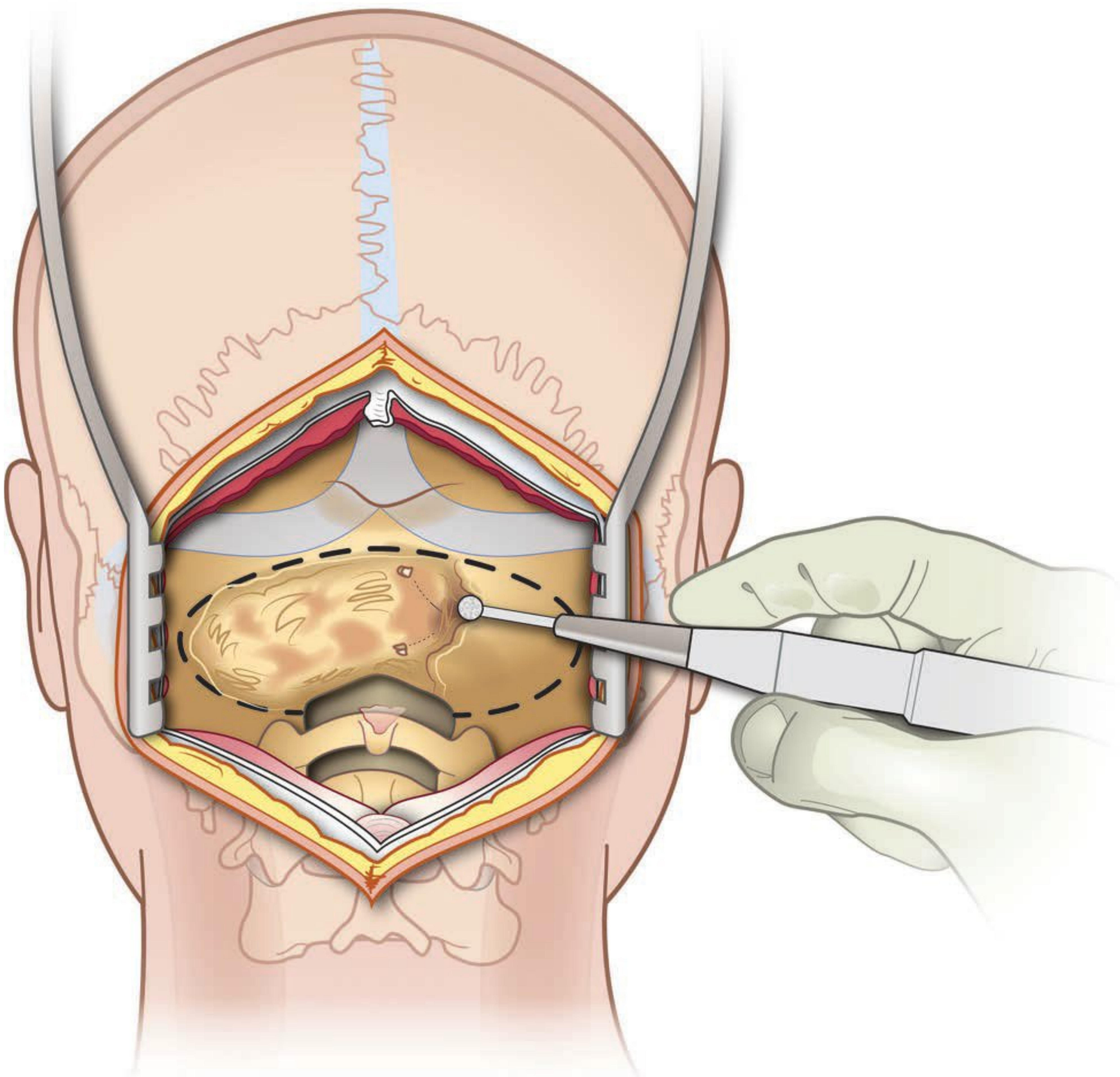


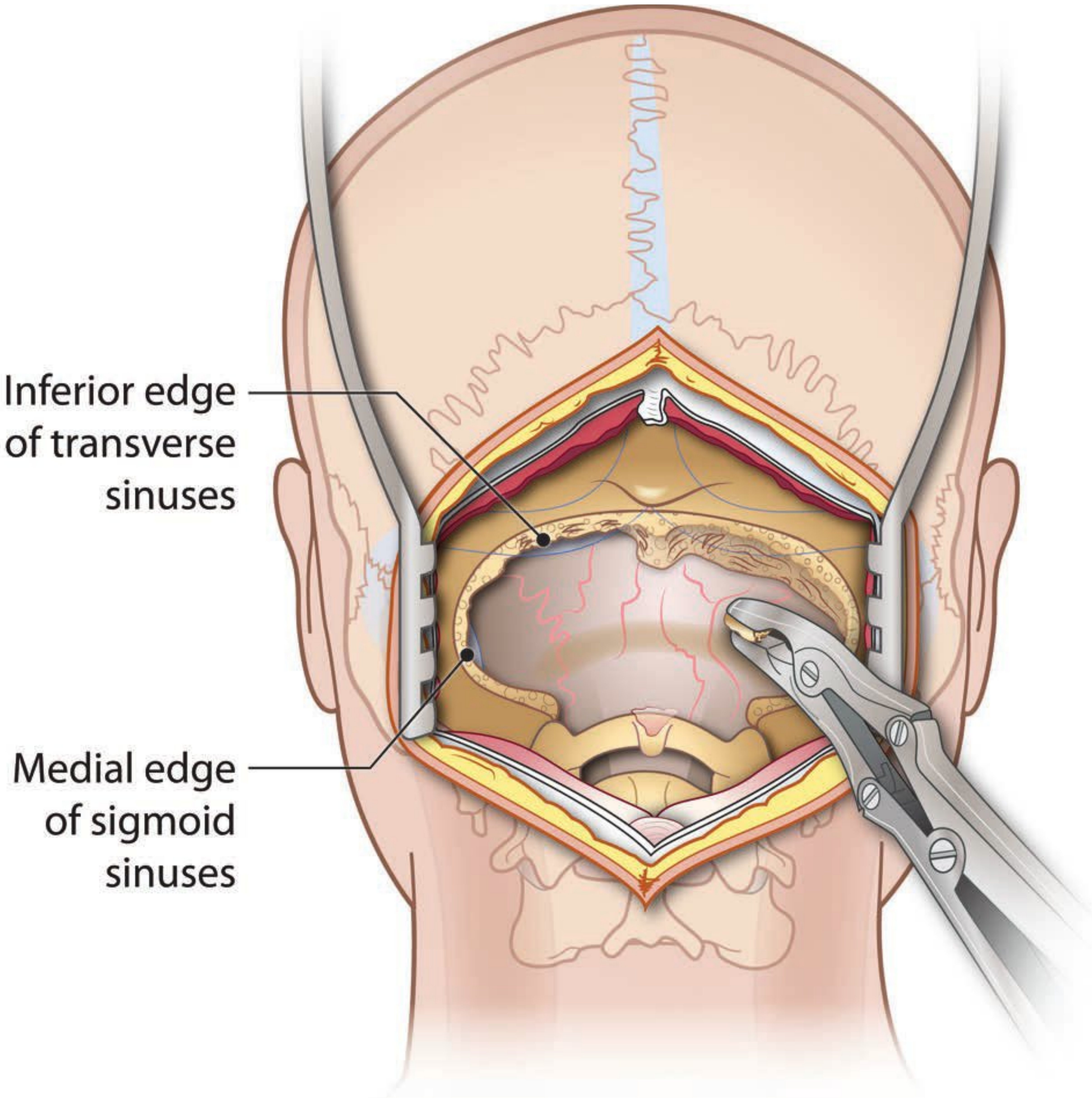
Figure	Procedural Steps	Pearls
Fig. 19.11	**A linear midline skin incision is made from the inion to the upper cervical vertebrae.** **The subcutaneous musculature is divided along the midline raphe. The muscle is reflected laterally.**	• The inferior extent of the incision should be determined by the size of the planned craniectomy and need for C1 or C2 laminectomy. • The midline raphe is avascular and blood loss can be minimized by remaining along that plane.

Craniectomy (Fig. 19.12a, b)



a

Figure	Procedural Steps	Pearls
Fig. 19.12	**The craniectomy is made from just below the inion/torcula and carried downward toward the foramen magnum.** **There are a number of ways to perform the craniectomy; (a) the authors prefer to thin the bone with a high speed drill and then (b) complete the bone removal with rongeurs and punches.**	• The location and size of the lesion will determine the extent of the craniectomy; occasionally the posterior arch of C1 will need to be removed.


Inferior edge
of transverse
sinuses
Medial edge
of sigmoid
sinuses

b

Dural Opening and Hematoma Evacuation (Fig. 19.13)

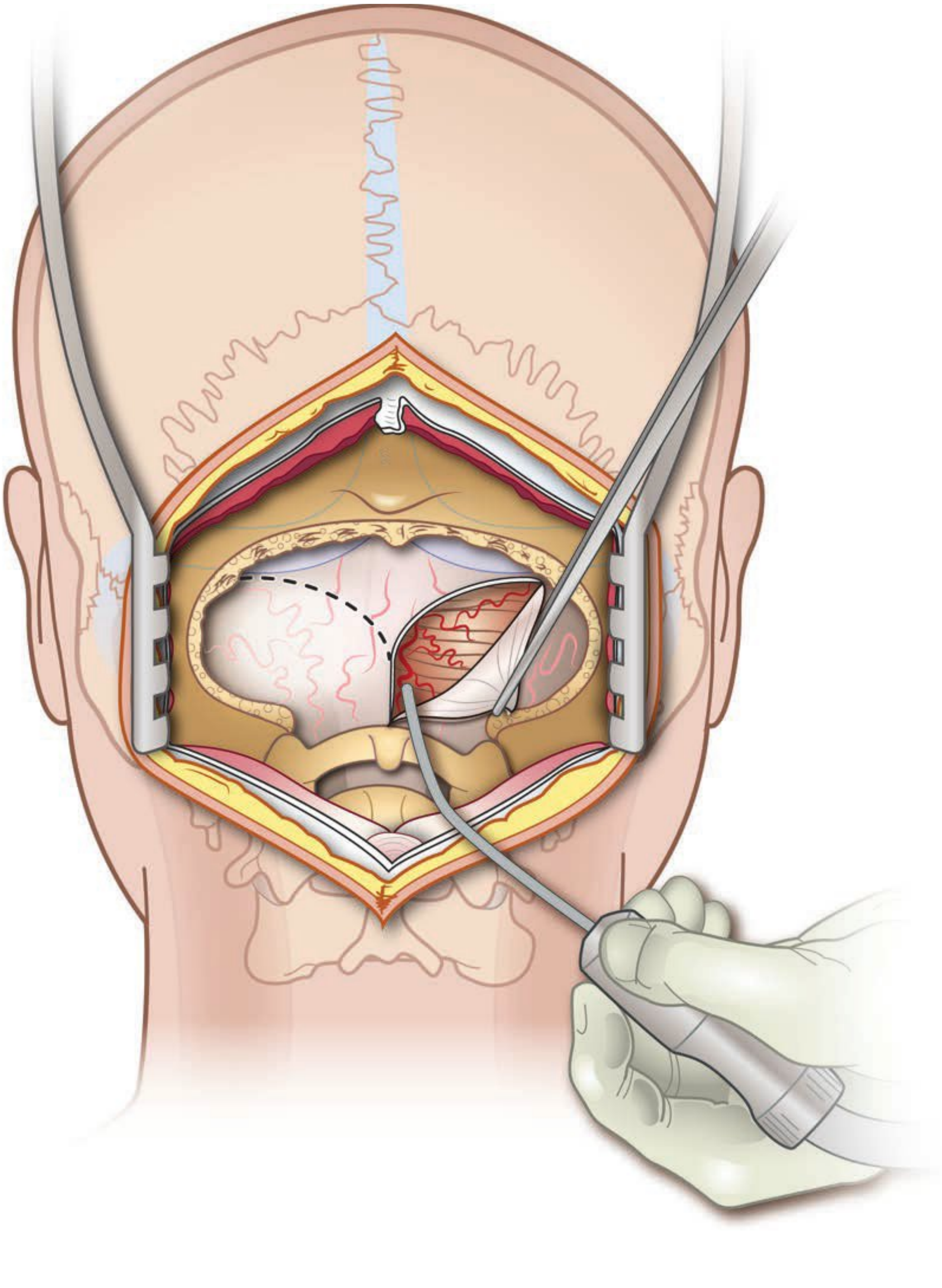


Figure	Procedural Steps
Fig. 19.13	**There are a number of ways to perform the dural opening; the authors prefer a Y-shaped opening with the superior dural flap reflected over the transverse sinus.**

Hematoma Evacuation (Fig. 19.14)

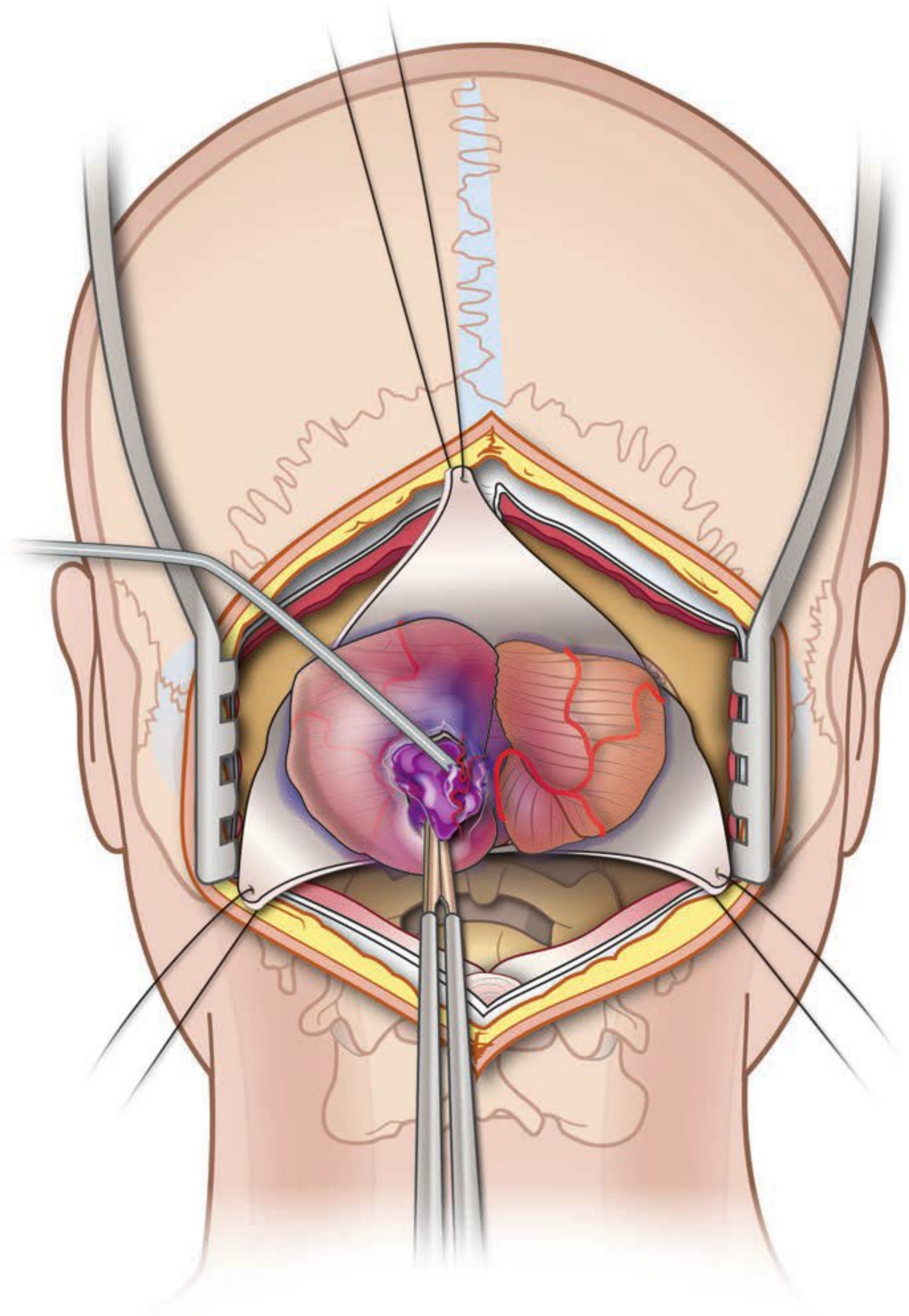


Figure	Procedural Steps	Pearls
Fig. 19.14	**A cerebellar hematoma should be evacuated using the same techniques as a supratentorial hematoma.**	• If the cerebellum is noted to be significantly swollen or irritated, consideration should be given to resection of a portion of the cerebellar hemisphere.

Closing

- Once adequate hemostasis has been achieved, the dura is closed using running or interrupted 4-0 braided nylon sutures (Valsalva maneuver should be used to assure a watertight dural closure).
- If the cerebellum is swollen, consideration should be given to a dural patch graft.
- The wound is heavily irrigated.
- A medium suction drainage device is placed in the epidural/subfacial plane.
- The muscle and fascia should be approximated in layers using 2-0 braided absorbable suture (again, a watertight fascial closure should be obtained to prevent CSF leakage through the wound).
- The dermis is approximated with 3-0 braided absorbable suture in an inverted, interrupted fashion.
- The skin is closed with 3-0 nylon suture in a running fashion or staples.

Postoperative Management[5]

- Patients should be monitored in an intensive care unit.
- Complete postoperative labs should be obtained and the patient should be kept NPO (nothing by mouth).
- A CT scan of the head should be obtained to evaluate the decompression and ventricular size (**Figs. 19.15** and **19.16**).
- It is optional to give two to three doses of prophylactic antibiotics in the immediate postoperative period.
- Specifically for cerebellar ICH
  - During the postoperative evaluation, check for respiratory rate and patter, hypertension, and evidence of CSF leak.
  - Consider keeping patient intubated for 24 to 48 hours as a precautionary measure as respiratory arrest can occur suddenly.
  - Hypertension should be avoided.
  - Postoperative edema or hematoma are complications that can be seen in the immediate postoperative period and be rapidly fatal.
  - Standard EVD management should be used and is not described in detail here.
- Drains should be removed on postoperative day 1 or 2.
- Sutures or staples should be removed 1 to 2 weeks after surgery depending on surgeon preference.

Fig. 19.15 Postoperative CT following evacuation of right frontal hematoma shown in Fig. 19.2.

Special Considerations

Other Surgical Considerations

In addition to standard craniotomy, more minimally invasive techniques have been considered including endoscopic aspiration and stereotactic infusion of thrombolytics into the clot cavity. Endoscopic aspiration via a single bur hole has been shown to improve outcome.[14] Although infusion of thrombolytics has been shown to reduce clot burden and risk of death, rebleeding is a greater concern and functional outcome is not necessarily improved.[15] Both minimally invasive techniques are still under investigation. Currently there is too little data to comment on the role of decompressive hemicraniectomy as a treatment option for spontaneous ICH although it has been shown to be beneficial for deep ICH in animal models.[16] Surgical timing remains controversial as well as the definition of "early surgery." Currently there is no clear evidence that there is a benefit from either ultra early or delayed evacuation. In fact, ultra early craniotomy has been associated with recurrent bleeding.[1]

Arteriovenous Malformation-Associated ICH

Spontaneous ICH can be secondary to AVM, aneurysm, or venous angioma rupture. AVM hemorrhage produces ICH in 82% of cases and less commonly intraventricular hemorrhage (IVH), subarachnoid hemorrhage (SAH), or subdural hemorrhage (SDH). AVM resection is generally an elective procedure. Many recommend, if possible, delaying AVM surgery weeks to months after hemorrhage thus allowing the patient to stabilize and the clot to liquefy.[17–19] It has been suggested that if an AVM associated ICH is managed operatively, the hematoma should be addressed first as well as aggressive management of intraoperative ICP[20] and that the AVM should only be addressed at the same time if it is superficial with easily elucidated anatomy.[21]

As a caution, if AVM bleeding occurs, hemostasis in these cases can be extremely difficult. Gentle and prolonged tamponade is often very helpful and hemostatic adjuncts such as gelatin sponge or powder are important tools. Occasionally persistent bleeding and can be mitigated with induced hypotension. Cerebral perfusion pressure (CPP) should always be kept in mind, however, especially in patients with elevated ICP.

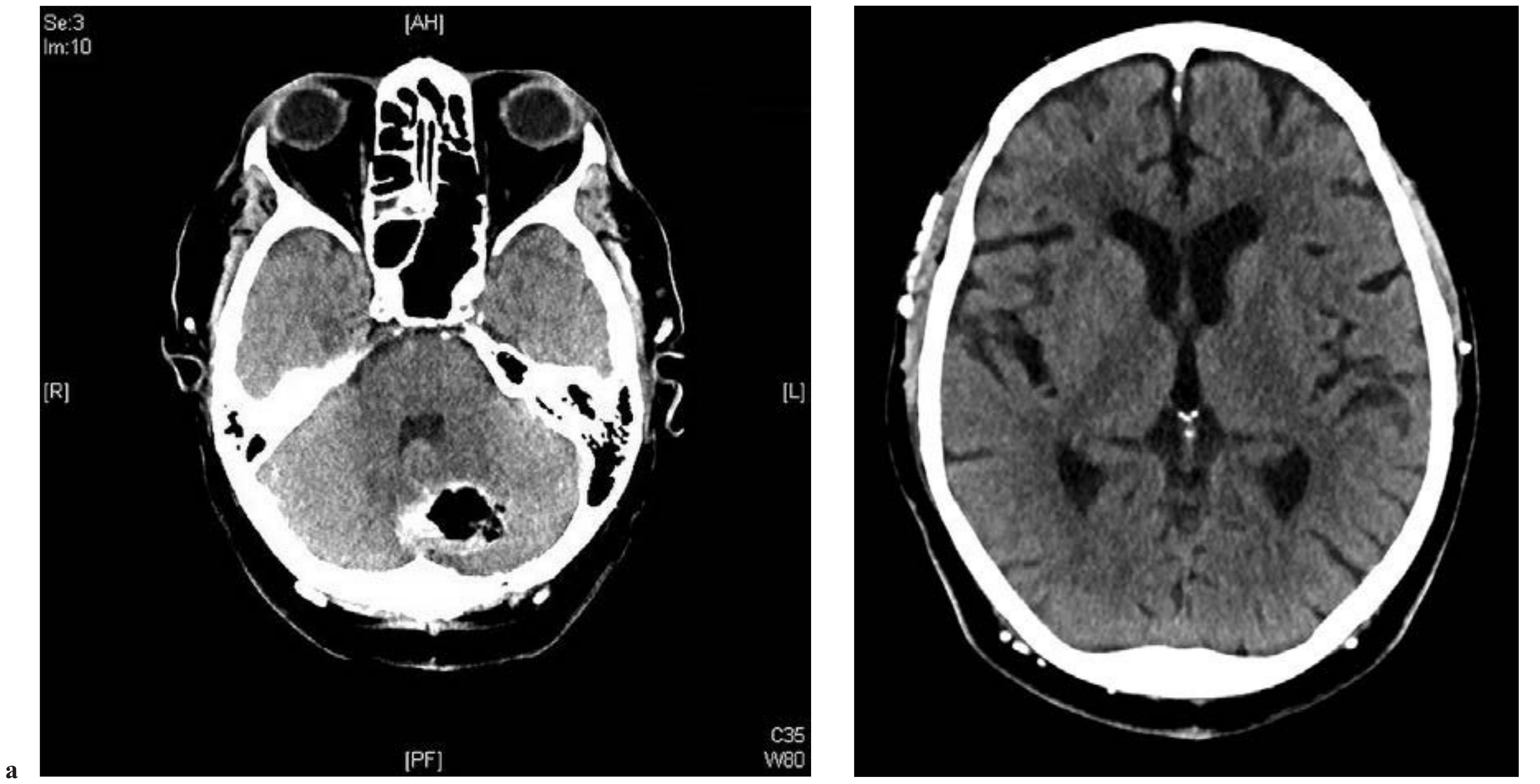


Fig. 19.16a, b (**a**) Postoperative CT following evacuation of cerebellar hematoma shown in Fig. 19.9. (**b**) Hydrocephalus has also improved (without an EVD in this particular case).

Rarely, AVM re-rupture during ICH removal leads to bleeding that cannot be controlled with the above mentioned maneuvers. In these desperate circumstances, urgent resection of the AVM may be the only life-saving measure available to the surgeon. If AVM resection is undertaken at the time of hemorrhage, the basic tenets of AVM surgery should still be maintained: wide exposure, occlusion of large feeding arteries first, circumferential dissection of the AVM nidus, systematic separation of the AVM from white matter, and preservation of draining veins until the end of the procedure.[19] Whenever blood loss is significant enough to require major infusion of fluids and transfusion of packed red blood cells, consideration should be given to replenishing fresh frozen plasma, platelets, and other clotting factors to avoid a dilutional coagulopathy.

Aneurysmal ICH

Aneurysm rupture typically results in SAH but can also produce ICH and usually involves aneurysms distal to the circle of Willis such as the middle cerebral artery (MCA) or aneurysms that have become adherent to the brain. Patients with aneurysmal ICH in general have poorer outcomes due to mass effect and increased ICP.[22] Unlike the treatment for AVM associated ICH, ultra early hematoma evacuation and aneurysm clipping in patients with poor clinical grade has been advocated for aneurysmal ICH.[23] There is a much greater importance in securing the aneurysm given the propensity for and devastating consequences of aneurysm re-rupture. Although catheter angiography is the gold standard for aneurysm diagnosis and preoperative evaluation, some advocate operating based on CTA alone as the delay could lead to worse outcome.[24] If time permits, however, consideration should be given to preoperative angiography and coil embolization to protect the aneurysm from re-rupture and, in turn, allow for a much safer ICH evacuation.[25] If preoperative embolization is not an option due to time constraints, the surgeon should be fully prepared to clip the aneurysm.

Prior to entering or evacuating the ICH, the operating room and personnel should be prepared for potential aneurysm rupture. Ideally, a discussion of the following steps should occur before the skin incision is even made. The operating microscope should be draped and ready. A full selection of temporary and permanent clips should be open on the surgical field. The anesthesiologist should be prepared to adjust blood pressure rapidly. At least two (possibly three) large suctions should be prepared and ready. Once the hematoma is entered, a conservative evacuation is warranted. Particular care should be taken near the bottom of the ICH (near the aneurysm) to avoid undue manipulation. If rupture occurs, suction and precise tamponade are performed while proximal arterial control is obtained. The aneurysm anatomy is defined surgically and the aneurysm neck is reconstructed. After clipping and ICH evacuation, the patient should have immediate angiography, ideally in the operating room. Finally, a third reasonable option includes craniectomy without ICH evacuation to immediately address ICP followed by immediate coil embolization.

External Ventricular Drainage

Placement of an EVD should be considered in all patients with IVH especially those with blood in the third ventricle, the cerebral aqueduct, or fourth ventricle. Generally, the EVD should be placed in the lateral ventricle contralateral to the hemorrhage to avoid clogging the catheter. Although intraventricular tissue plasminogen activator (rt-PA) may help lyse clot and maintain catheter patency,[26] it is still considered investigational and should not be used if there is a suspected vascular lesion. Importantly, ventricular drainage alone is not an acceptable treatment for cerebellar hemorrhage with associated hydrocephalus. These patients should undergo surgical decompression.[1]

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20 Surgery for Acute Intracranial Infection

P. B. Raksin

Introduction

Space-occupying intracranial infection may arise via contiguous spread from adjacent structures, through hematogenous dissemination, following operative neurosurgical procedures, or after head trauma. The same structural elements that define the various intracranial compartments—epidural, subdural, parenchymal, and ventricular—also dictate the pathways for spread of infection across those natural barriers. Management typically involves a combination of medical and surgical modalities.

Epidural Abscess

Infection within the space between the inner table of the calvarium and dura occurs most commonly as a complication of paranasal sinusitis, orbital cellulitis, mastoiditis, or chronic otitis media. It may also occur following traumatic fracture of the calvarium or following craniotomy. Rarely, epidural abscess may follow from fetal scalp monitoring or the application of halo pins to the skull.[1] Clinical presentation is often insidious. Headache may be accompanied by a relative paucity of other symptoms unless mass effect is present or the infectious process extends to the subdural space as well. Periorbital edema occurs in conjunction with bone osteomyelitis or orbital cellulitis. (Pott's puffy tumor is the historical term applied to the clinical finding of forehead soft tissue swelling due to the presence of subgaleal fluid.[2]) An infectious nidus adjacent to the petrous apex may present as Gradenigo syndrome. Streptococci (*Streptococcus milleri* group) predominate, though posttraumatic and postcraniotomy infections are more commonly associated with staphylococci.[3]

Subdural Empyema

Infection within the potential space between dura and arachnoid mater arises either from the spread of infection via valveless emissary veins (in association with thrombophlebitis) or via extension of an osteomyelitis of the skull with an accompanying epidural abscess. Other predisposing conditions include skull trauma, infection of a preexisting subdural hematoma, or prior neurosurgical procedure. A small number are metastatic (often from a pulmonary source). Subdural empyema may also occur in up to 10% of infants with bacterial meningitis, presumably as the result of infection of a previously sterile subdural effusion.[4] Fever is present in most cases. Headache and vomiting are typical early findings. These symptoms may be accompanied by confusion, seizure, and focal neurologic deficits (most commonly hemiparesis). Neurologic decline may be rapid following symptom onset. On the other hand, postsurgical subdural empyema may present in a delayed fashion—up to 8 weeks following initial intervention.[3] A less fulminant course may be seen with prior antimicrobial therapy, as well as in the setting of metastatic spread to the subdural space or infection of an existing subdural hematoma. Bacterial isolates are similar to those found in epidural abscess cases. Polymicrobial infection is common. The incidence of culture-negative (27–29% in one series) cases is greater in subdural empyema[5]; this may reflect the fastidious nature of many anaerobic organisms.

Intracerebral Abscess

Focal, encapsulated infection within the brain tissue may be single or multifocal. A single abscess typically arises by direct extension of a paranasal sinus, mastoid, or middle ear infection; a solitary focus may also arise following penetrating trauma. Multifocal disease more commonly results from hematogenous dissemination of primary cardiac, pulmonary, periodontal, abdominal, or dermatologic infection. Less than 50% of patients will present with the classic triad of headache, fever, and focal neurologic deficit.[6] In fact, patients may present with headache or nausea alone. Fever, when present, is typically low-grade; a temperature of greater than 101.5° F (38.6° C) should raise suspicion for a systemic infection. Focal neurologic symptoms reflect the location of the pathology. Hemiparesis is common.[7] New onset of meningismus, associated with sudden neurologic worsening, may indicate rupture into the ventricular space. Mortality in such cases is high.[8] Isolated pathogens are predominantly bacterial, commonly polymicrobial, and reflect the site of origin. Streptococci are isolated in up to 70% of cases. *Bacteroides* and *Prevotella* are present in 20–40% of cases and often occur in mixed culture. *Staphylococcus aureus* is present in 10–15% of brain abscesses—usually posttrauma or in the setting of endocarditis—and is usually monomicrobial. Enteric Gram-negative bacilli are present in up to 22–33% of cases, often in association with otic foci, bacteremia, or prior neurosurgical procedure.[9] Diagnostic considerations must be expanded in cases of immunocompromise. Gram-negative organisms and fungal isolates are common in cases of neutrophil deficiency, while *Listeria*, *Nocardia*, *Cryptococcus*, and *Toxoplasma* are encountered in the setting of T-cell deficiency.

Indications

The indications for surgical intervention are dictated by size, anatomic location, and accessibility, as well as by known or presumed pathogen. In all cases, surgical intervention must be coupled with appropriate intravenous (and, in certain cases, intrathecal) antimicrobial therapy.

Epidural Abscess

Most cases require open neurosurgical debridement. Bur hole drainage generally is ineffective given the tenacity of the purulent material; however, in select cases where a very small collection is present, trial bur hole drainage may be attempted. The participation of Otolaryngology may be necessary for simultaneous debridement of the affected sinus(es).

Subdural Empyema

The vast majority of cases require open neurosurgical debridement. More limited bur hole drainage may be considered in cases of parafalcine empyema, critically ill patients in septic shock, and children presenting with empyema secondary to meningitis.[10] Repeated drainage and/or conversion to craniotomy may be necessary in such cases.

Intracerebral Abscess

Several factors dictate the indications for and extent of neurosurgical intervention. Primary considerations include the maturity of the capsule, size, and location. Britt and Enzmann sought to define stages in the maturation of the abscess capsule.[11] Cortical inflammation—or, cerebritis—alone is not a surgical disease. Demarcation of an abscess cavity with respect to the surrounding parenchyma begins about 10 days after the onset of infection. The capsule wall, however, remains thin and discontinuous at this time. Abscesses may be amenable to cannulation and drainage—without attempted resection of the wall—during this early encapsulation phase. This strategy may also be appropriate in the setting of a more mature lesion in a less accessible location. With further maturity comes greater collagen deposition and, consequently, a capsule more consistent with that of a metastatic lesion. Consideration may be given to drainage—with resection of capsule—in the case of a mature and accessible lesion. This is generally feasible after ~ 2 weeks.

The size of the lesion also may influence treatment strategies. It has been suggested that abscesses of a certain size (1.7 cm or less) may be treated by medication alone, whereas lesions of greater than 2.5 cm rarely resolve without surgical intervention.[9,12]

Medical therapy alone may be considered in cases of multifocal disease, lesions in eloquent areas, concomitant meningitis, coexistent hydrocephalus where shunt placement risks contamination, or where medical contraindications to invasive intervention may exist.[13]

In a patient with documented bacteremia and a positive culture, consideration may be given to a trial of systemic antimicrobial therapy, provided the chosen agent(s) offers good central nervous system penetration. If the diagnosis is in question and/or there is a question of a polymicrobial infection in an immunocompromised host, consideration should be given to early biopsy to permit tailoring of medical therapy.

Preprocedure Considerations

Radiographic Imaging

- CT head pre- and post-contrast will provide basic information regarding lesion location, the degree of associated edema/mass effect, and bony involvement. Cerebritis will appear as a nonspecific region of hypodensity. A more mature abscess will demonstrate ring-enhancement with associated perilesional edema. CT of the sinuses (with coronal and sagittal reconstructions) may be a necessary adjunct if contiguous extension is suspected.
- MRI brain pre- and post-gadolinium may provide additional information to assist diagnosis and therapeutic interventions. MRI may define the stage of abscess or cerebritis. In cases of epidural or subdural empyema, magnetic resonance venography (MRV) will define the extent of sinus thrombosis, if present. Magnetic resonance diffusion images are useful in diagnosing subdural empyema, which often shows hyperintense signal indicating diffusion restriction.[14]
- Magnetic resonance spectroscopy or positron emission tomography may help distinguish an infectious from a neoplastic process.
- Lumbar puncture generally is not necessary and, when a mass lesion is present, may be contraindicated. Given physical separation from the subarachnoid space, cerebrospinal fluid should be sterile (perhaps with nonspecific inflammatory changes) in the setting of epidural empyema.
- Blood cultures should be drawn (preferably prior to initiation of antimicrobial therapy).
- In the setting of bacteremia, an echocardiogram is indicated to exclude endocarditis as the etiology for intracranial infection.
- HIV testing should be undertaken as the spectrum of infectious pathology (and the approach to treatment) in the immunocompromised population may differ.
- A chest X-ray should be completed. A purified protein derivative skin test should be placed if tuberculosis is suspected.
- A panoramic X-ray may define an odontologic etiology for intracranial infection.
- Preoperative imaging (**Fig 20.1a–f**).

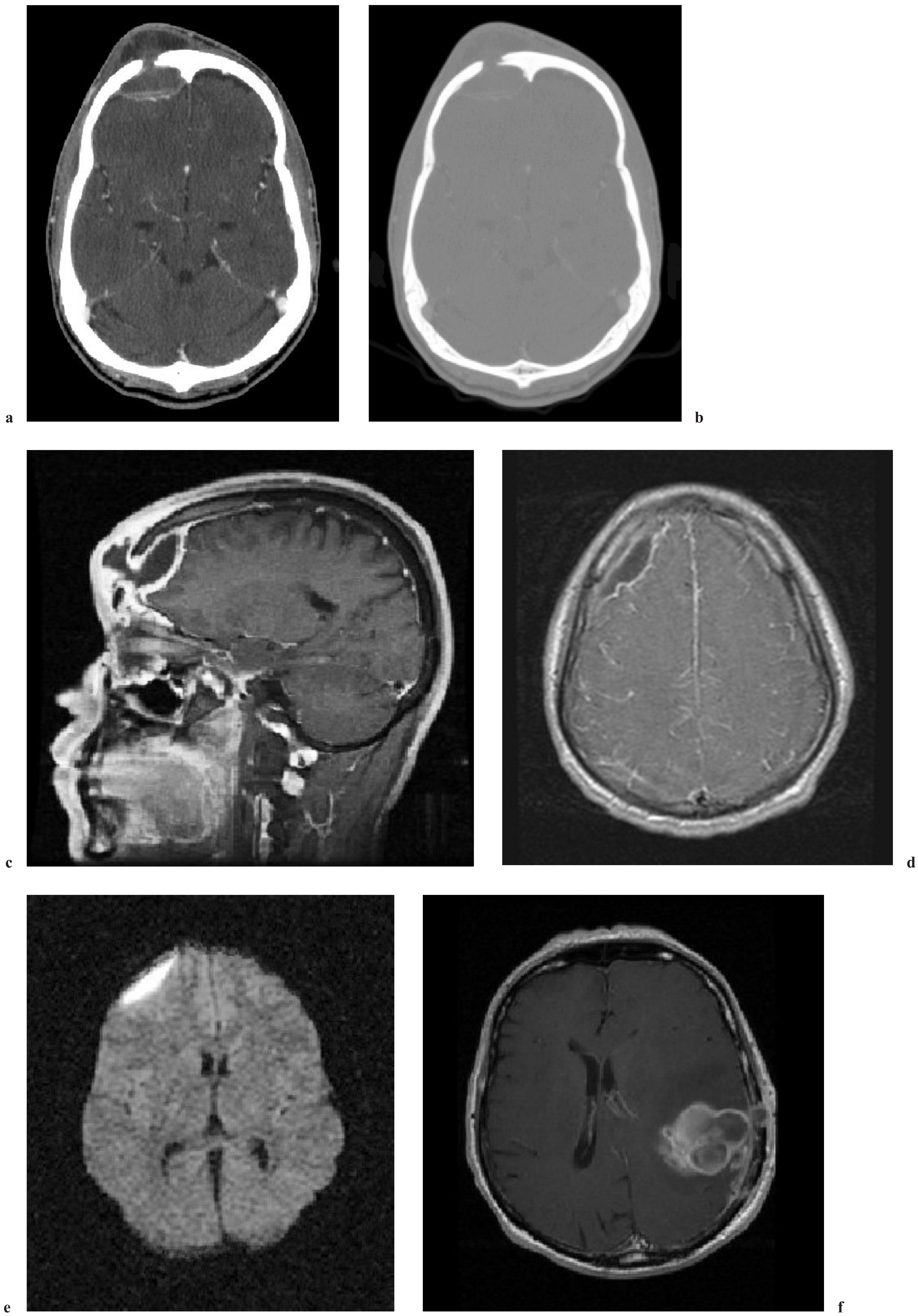


Fig 20.1a–f Axial CT (**a**) soft tissue and (**b**) bone windows, as well as (**c**) sagittal MRI post-gadolinium T1-weighted image demonstrating a Pott's puffy tumor. Note the extracranial soft tissue collection in communication with the epidural space, via the frontal air sinus. (**d**) Axial MRI post-gadolinium T1-weighted image demonstrating a right frontal subdural empyema. (**e**) The diffusion-weighted imaging sequence, in this setting, demonstrates hyperintense signal, indicating diffusion restriction. (**f**) Axial MRI post-gadolinium T1-weighted image demonstrating an intracerebral abscess with loculations and peripheral enhancement, extending to the local meninges.

Medication

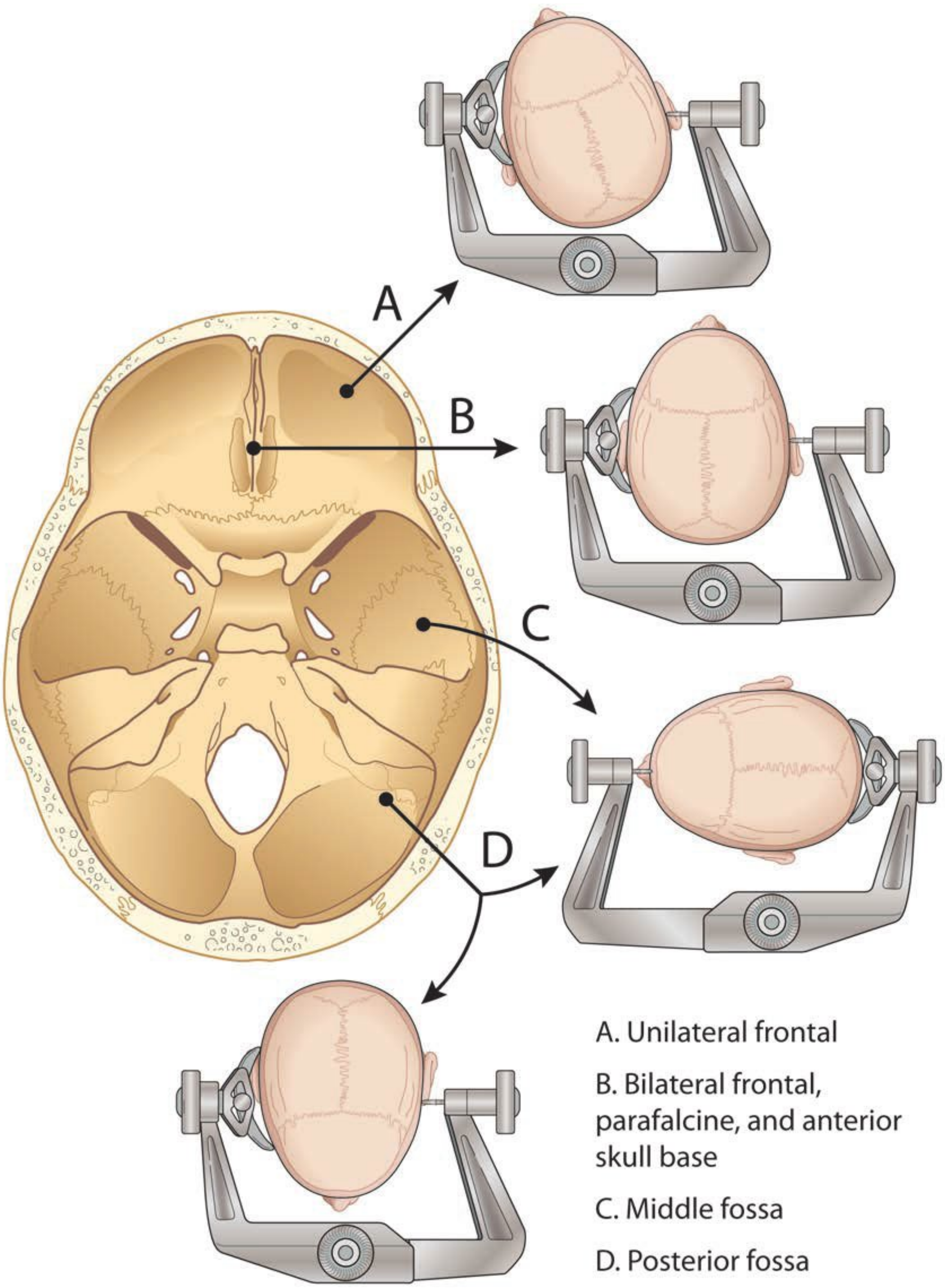
- Empiric, broad-spectrum antimicrobial therapy should be initiated at the time of presentation. The source, and therefore likely pathogens, should be considered. The author prefers a regimen of vancomycin, ceftriaxone (cefepime if a nosocomial infection is suspected), and metronidazole, bearing in mind that the specific clinical circumstances of a given case may dictate modification of this regimen and/or the addition of antifungal or antituberculous coverage.
- In cases where the pathogen is known, targeted antimicrobial therapy is the goal.
- Corticosteroid therapy may be considered on an individual case basis for management of accompanying vasogenic edema. While the use of corticosteroids has been shown to be of some benefit in the setting of meningitis,[15] there exists no similar established role for steroids in the primary medical management of abscess.
- Seizures are common in the setting of intracranial infection. Antiepileptic drug prophylaxis should be initiated upon presentation.

Operative Field Preparation

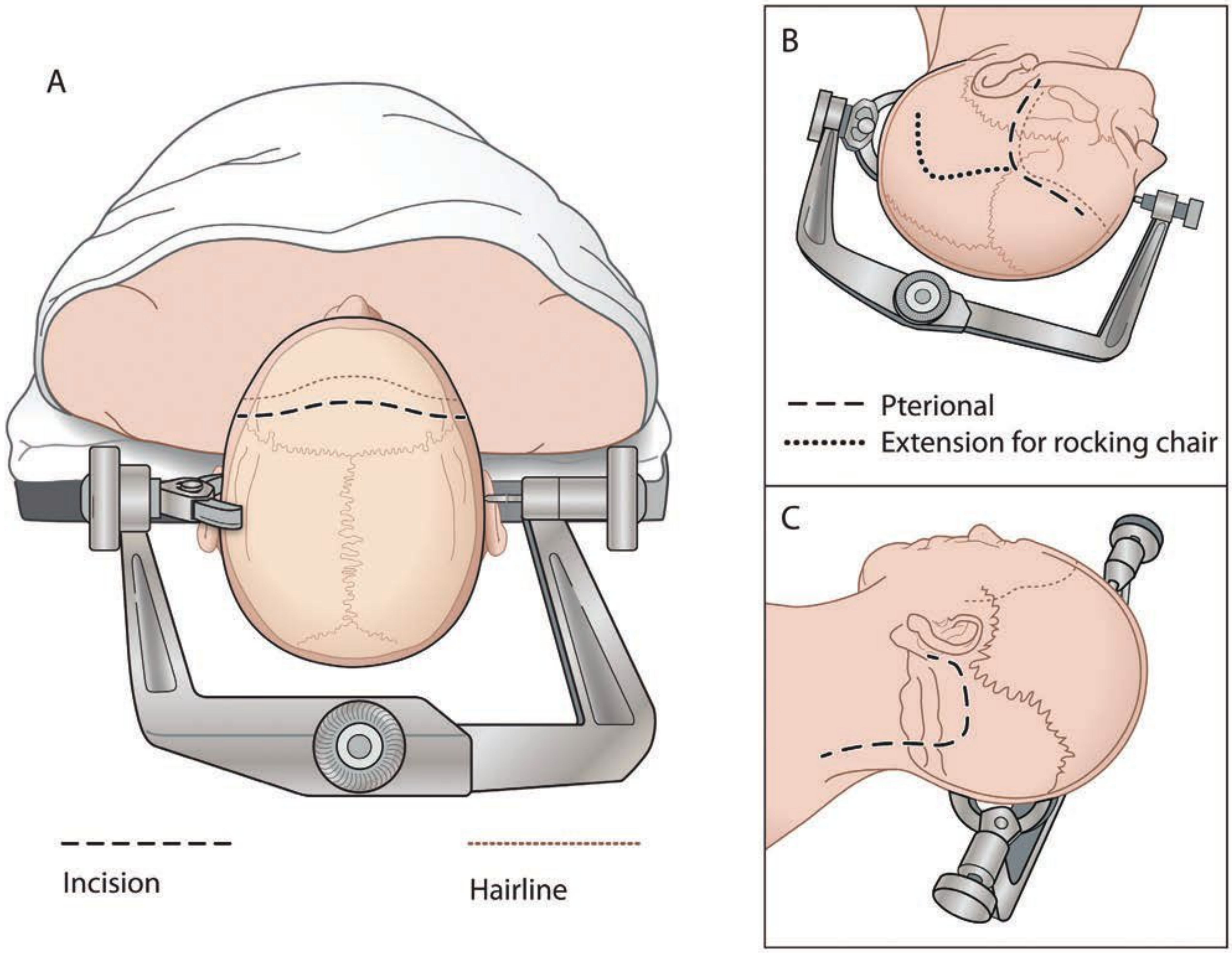
- The hair is cropped (not shaved) with an electric razor at the planned surgical site.
- The skin is prepared initially with alcohol, followed either with a standard povidone iodine or chlorhexidine scrub.
- The planned incision site is infiltrated with 1% lidocaine with 1:100,000 epinephrine.

Operative Procedure

Positioning (Fig. 20.2a, b)



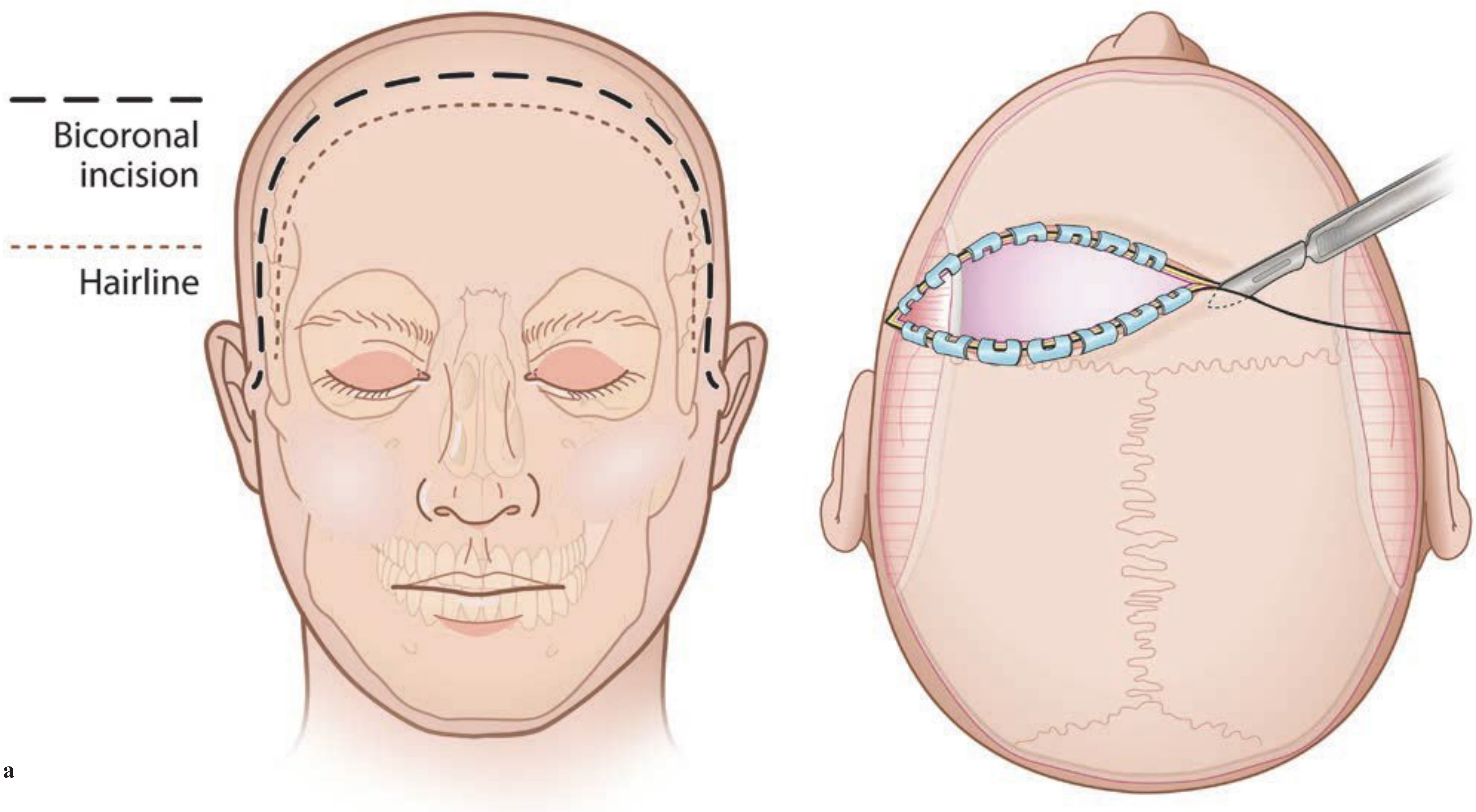
a



b

Figure	Procedural Steps	Pearls
Fig. 20.2	**(a) Patient positioning will depend upon the ultimate surgical target. In the majority of cases, a supine position—with varying degrees of head turn—will be appropriate. Posterior fossa pathology may be approached in the prone position. The head should be clamped in three-point pin fixation. All pressure points should be padded.** **(b) The surgical target will dictate the planned incision. (A) For pathology involving the frontal lobes, anterior skull base, and/or anterior falx, a bicoronal incision is appropriate. (B) For temporal lobe pathology, a pterional or rocking chair-type incision is appropriate. (C) Posterior fossa, petrous-associated pathology may be approached via a paramedian linear or hockey stick incision. For simplicity, the subsequent steps will assume a bicoronal approach.**	• Infectious processes arising in the frontal sinus often extend contiguously to the frontal lobe. Mastoid-related processes generally track to the adjacent temporal fossa or posterior fossa.

Incision (Fig. 20.3a, b)



a

b

Figure	Procedural Steps
Fig. 20.3	**(a) An incision is planned extending from tragus to tragus, just posterior to the hair line.** **(b) A no. 10 blade is used to initiate the skin opening. The incision initially is carried down to the level of pericranium centrally and temporalis fascia laterally. Hemostatic scalp clips are applied to the skin edges. The scalp flap is reflected forward until the orbital rim and root of zygoma are palpable bilaterally.**

Pericranial Flap Harvest (Fig. 20.4)

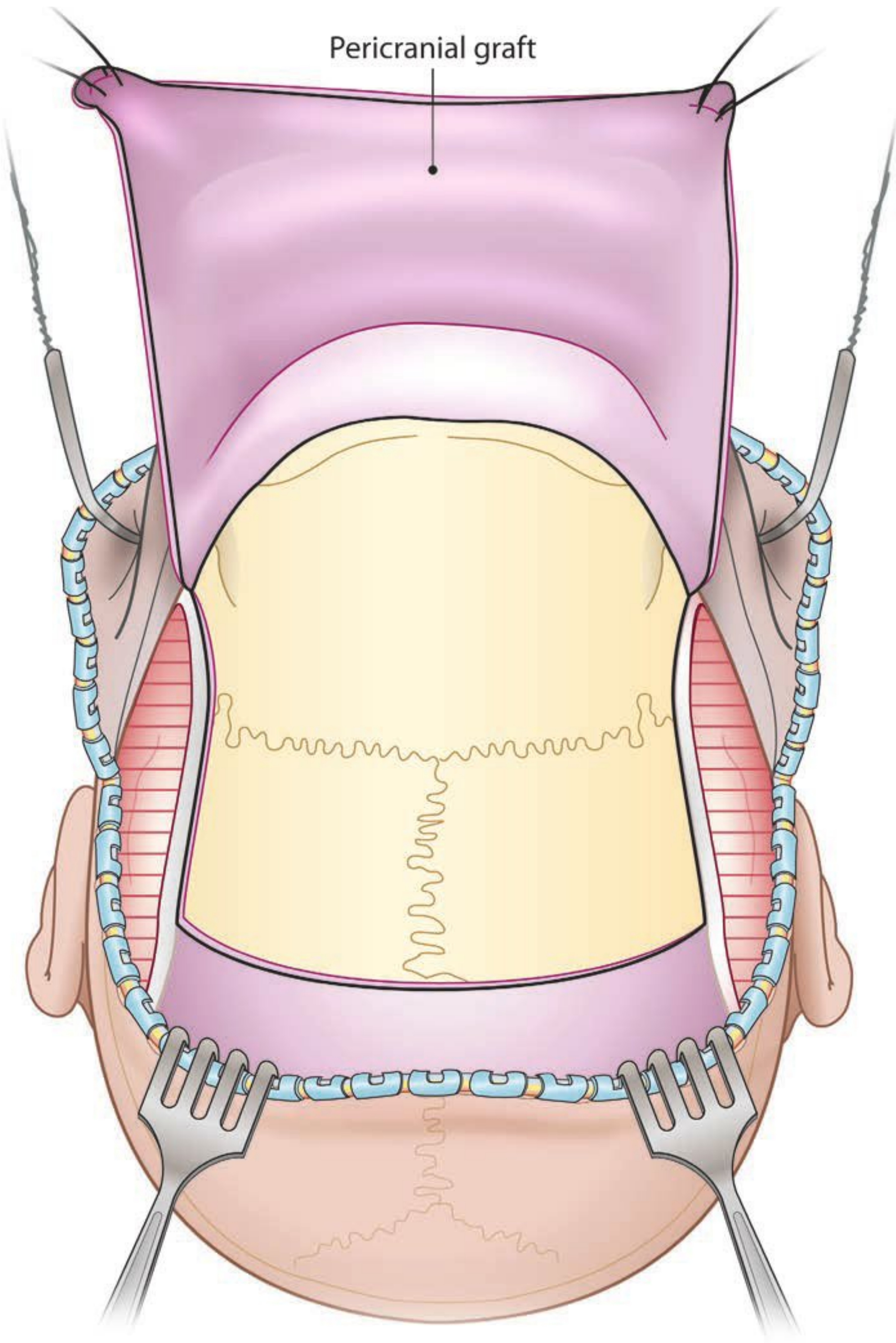


Figure	Procedural Steps
Fig. 20.4	**A no. 15 blade is used to open the pericranium bilaterally just superior and parallel to superior temporal line; a third, transverse cut is made at the level of coronal suture. A periosteal elevator is used to advance the flap forward to the level of the superior orbital rim. The vascularized flap is wrapped in a saline moistened sponge and secured temporarily with 4-0 braided nylon sutures under minimal tension.**

Division of the Temporalis and Bur Holes (Fig. 20.5)

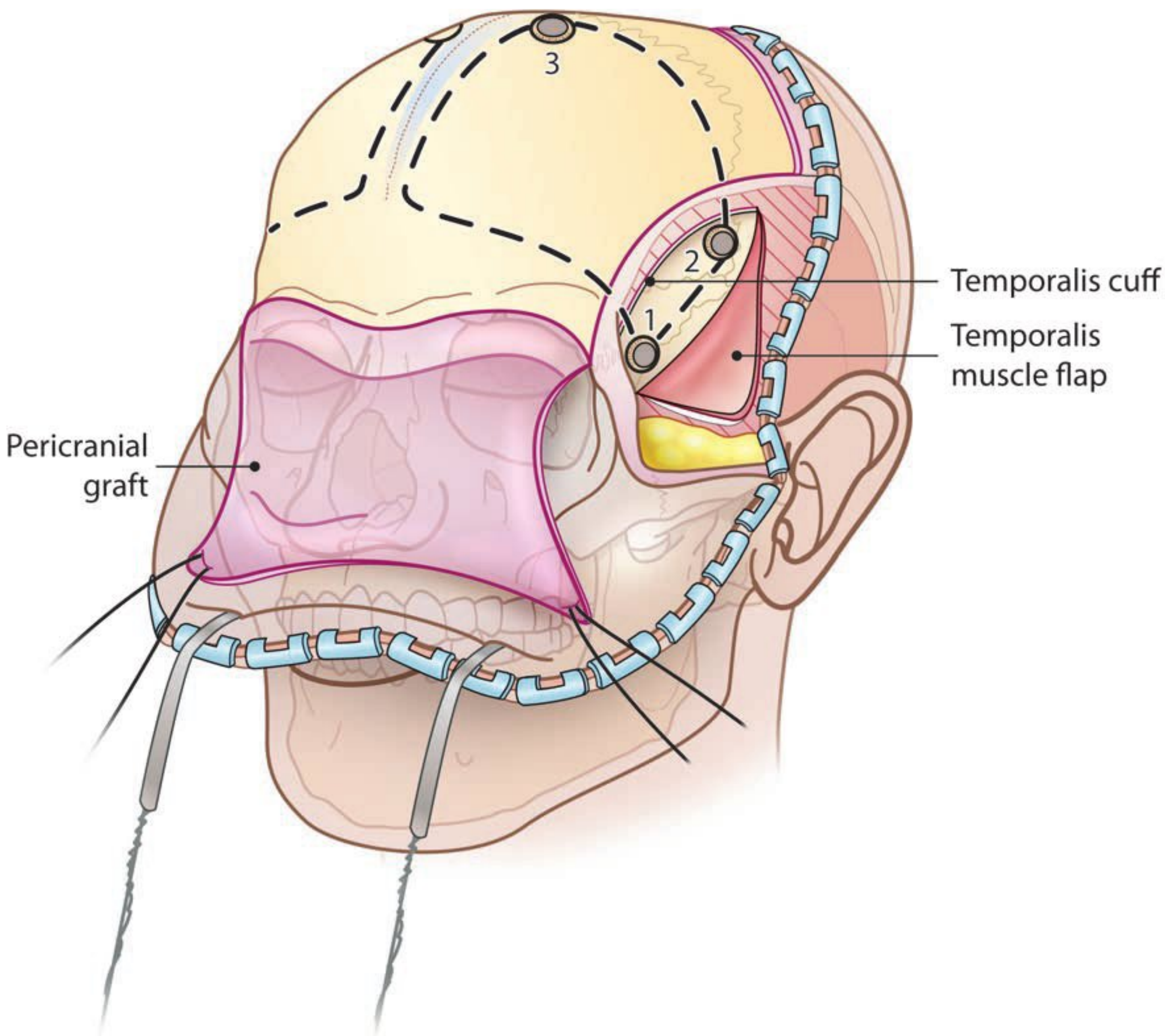


Figure	Procedural Steps	Pearls
Fig. 20.5	**Division of the temporalis muscle and fascia generally is not necessary for an approach to the frontal lobe/frontal air sinus. The author does create a cuff in the fascia and muscle just inferior and parallel to superior temporal line, allowing for placement of bur holes at the key hole and most posteriorly, at the level of the coronal suture.** **The position of the bone flap, too, will depend on the location of the target pathology. A rectangular frontal bone flap will address frontal lobe and unilateral frontal sinus pathology. If pathology is present along the bilateral falx, a mirror image bone flap may be necessary over the contralateral frontal lobe, leaving a strip of bone along the midline sagittal sinus.** **For a unilateral frontal bone flap, holes may be placed with a high speed drill at three points: (1) the keyhole, (2) at the level of coronal suture and just inferior to superior temporal line, and (3) just anterior to coronal suture and lateral to midline. Bone wax is applied to the bony edges. A Penfield no. 3 is used to strip the dural attachments from the undersurface of the calvarium between each set of bur holes.**	• If access to the temporal fossa is necessary, an additional vertical opening can be made from the midpoint of the cuff to the root of zygoma (creating a T). The resultant flaps may be reflected anteriorly and posteriorly, respectively. • The strategic placement of two bur holes and subsequent flushing of the epidural space with antibiotic irrigation between the holes may be considered in the case of a very small epidural collection.

Elevation of the Bone Flap (Fig. 20.6)

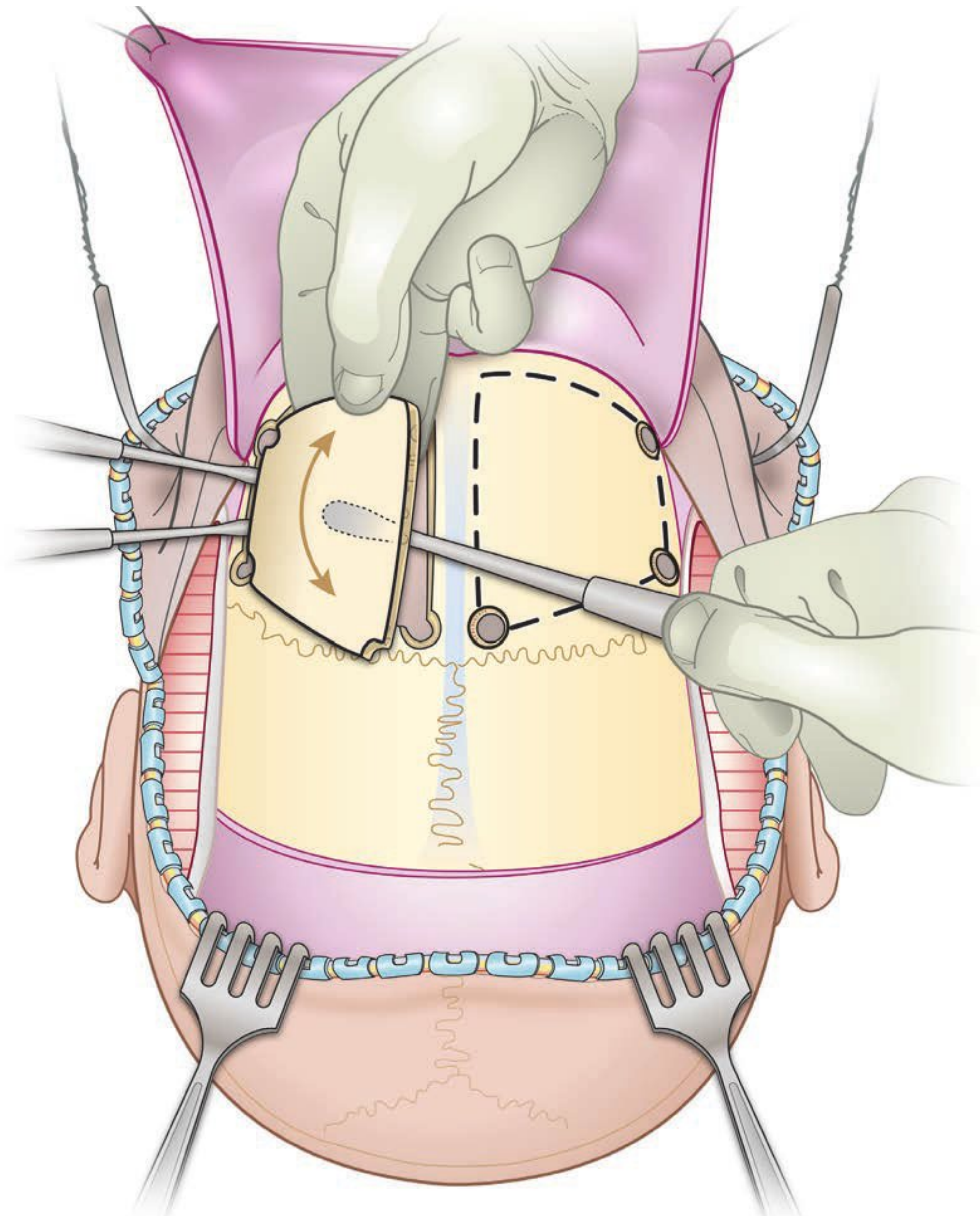


Figure	Procedural Steps
Fig. 20.6	**The craniotome is used to create a roughly rectangular bone flap. A periosteal elevator or Penfield no. 3 is used to elevate the bone flap away from the underlying dura. The dural surface is irrigated with saline. Hemostasis is attained with bipolar electrocautery. Bleeding attributable to the midline sinus may be controlled with fibrillar hemostatic material and/or gelatin foam soaked in thrombin. Epidural tacking stitches may be used to augment these techniques. If epidural abscess is present, proceed to the next step. If not, proceed to "Dural Opening and Addressing Subdural Empyema" (Fig. 20.8).**

Addressing Epidural Abscess (Fig. 20.7)

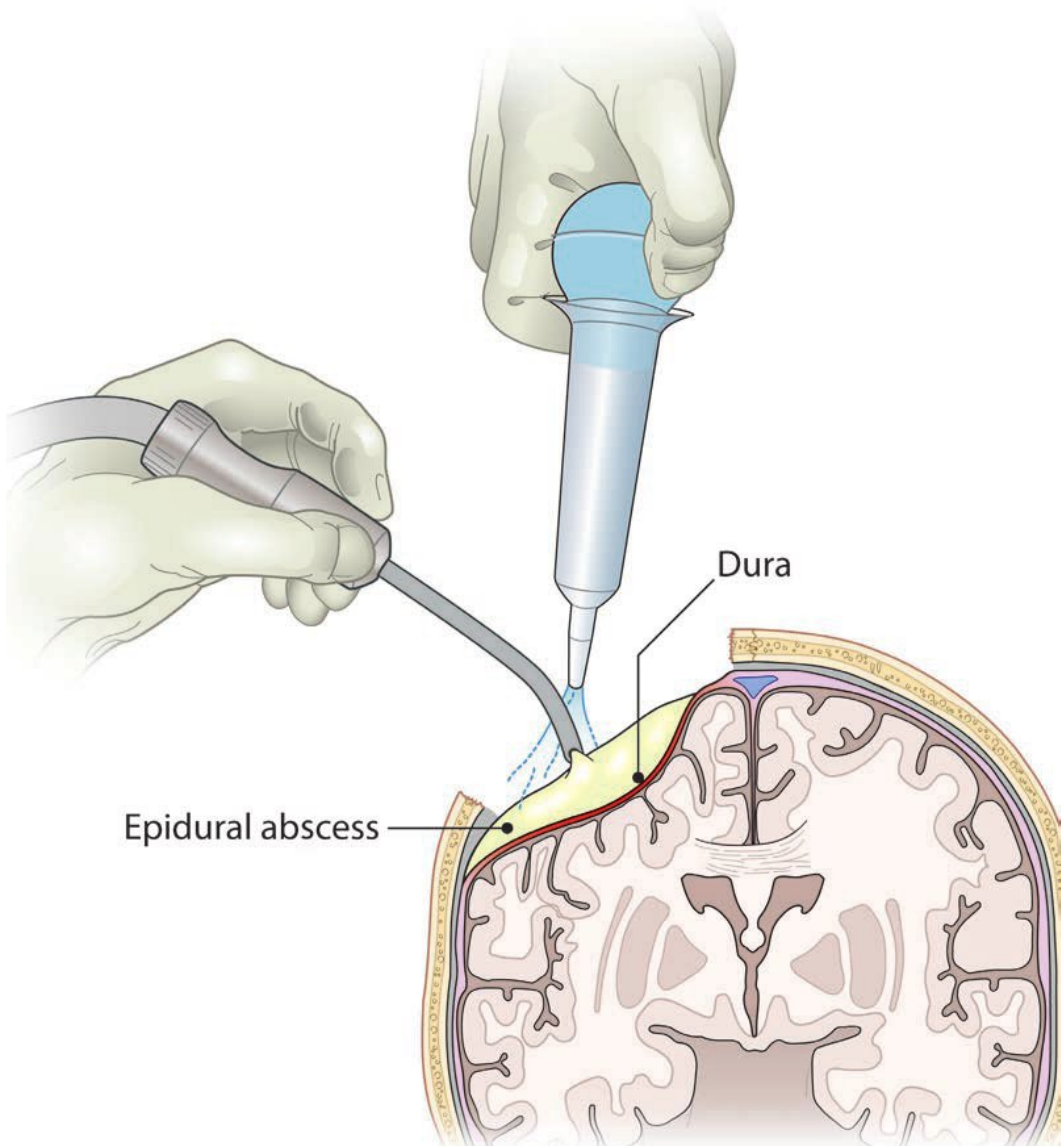


Figure	Procedural Steps	Pearls
Fig. 20.7	**Epidural abscess, if present, will be evident immediately upon elevation of the bone flap (if not at the time of bur hole placement). Direct communication with an adjacent air sinus and/or the orbit may be observed via gross erosion of bone. Liquid purulent material may be captured in a suction trap. Often, there is a friable, inflammatory pannus adherent to the dural surface. A Penfield no. 2 or Oberhill periosteal may be used (gently) to scrape this layer away from the underlying dura. A drain may be left in the epidural space and brought out through one of the posterior bur holes to a skin exit site, posterior to the scalp incision. Here, the drain is secured with a 3-0 nylon stitch. If no deeper infection is suspected, proceed to "Dural Closure and Cranialization of Frontal Sinus" (Fig. 20.11).**	• Specimens should be obtained for stat Gram stain, aerobic, anaerobic, acid-fast bacilli, and fungal culture. Where feasible, collect tissue and/or fluid as the diagnostic yield may exceed that of swabs alone. • Great care must be taken to avoid perforating otherwise intact dura. Bleeding is best controlled with bipolar electrocautery. The epidural space should be irrigated with large volumes of antibiotic solution. • The dura should be inspected but not opened unless there is a strong suspicion for a subdural component to the infectious process. Intentional or unintentional breach of the dura may result in seeding the deeper compartments with infection.

Dural Opening (Fig. 20.8)

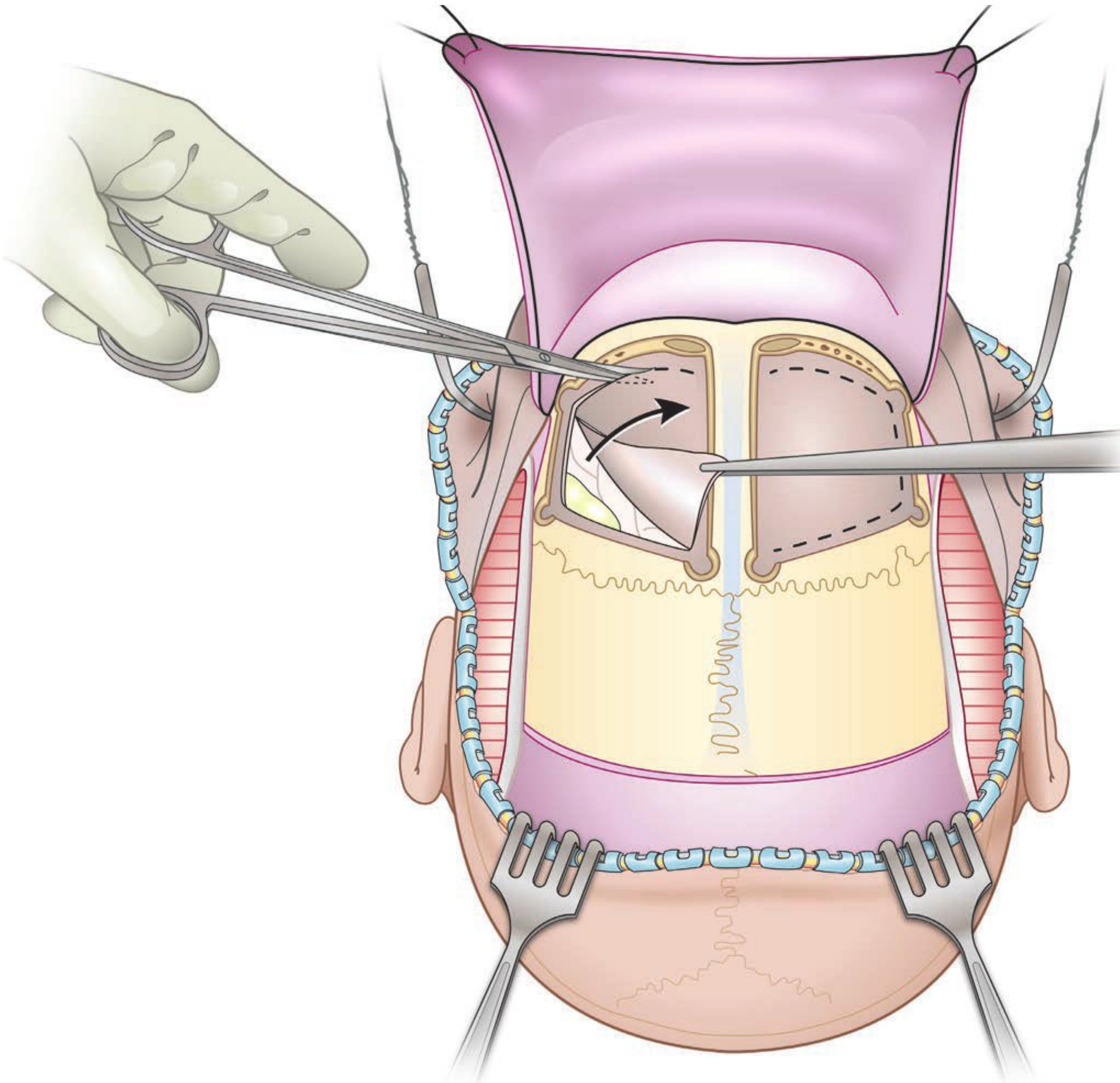


Figure	Procedural Steps
Fig. 20.8	**The dural opening will depend on the position of the bony defect. In the setting of a frontal craniotomy, a no. 15 blade is used to initiate a trap door–type opening that may be flapped toward the midline sagittal sinus. A mirror image opening is made if a bifrontal craniotomy is present.**

Addressing Subdural Empyema (Fig. 20.9)

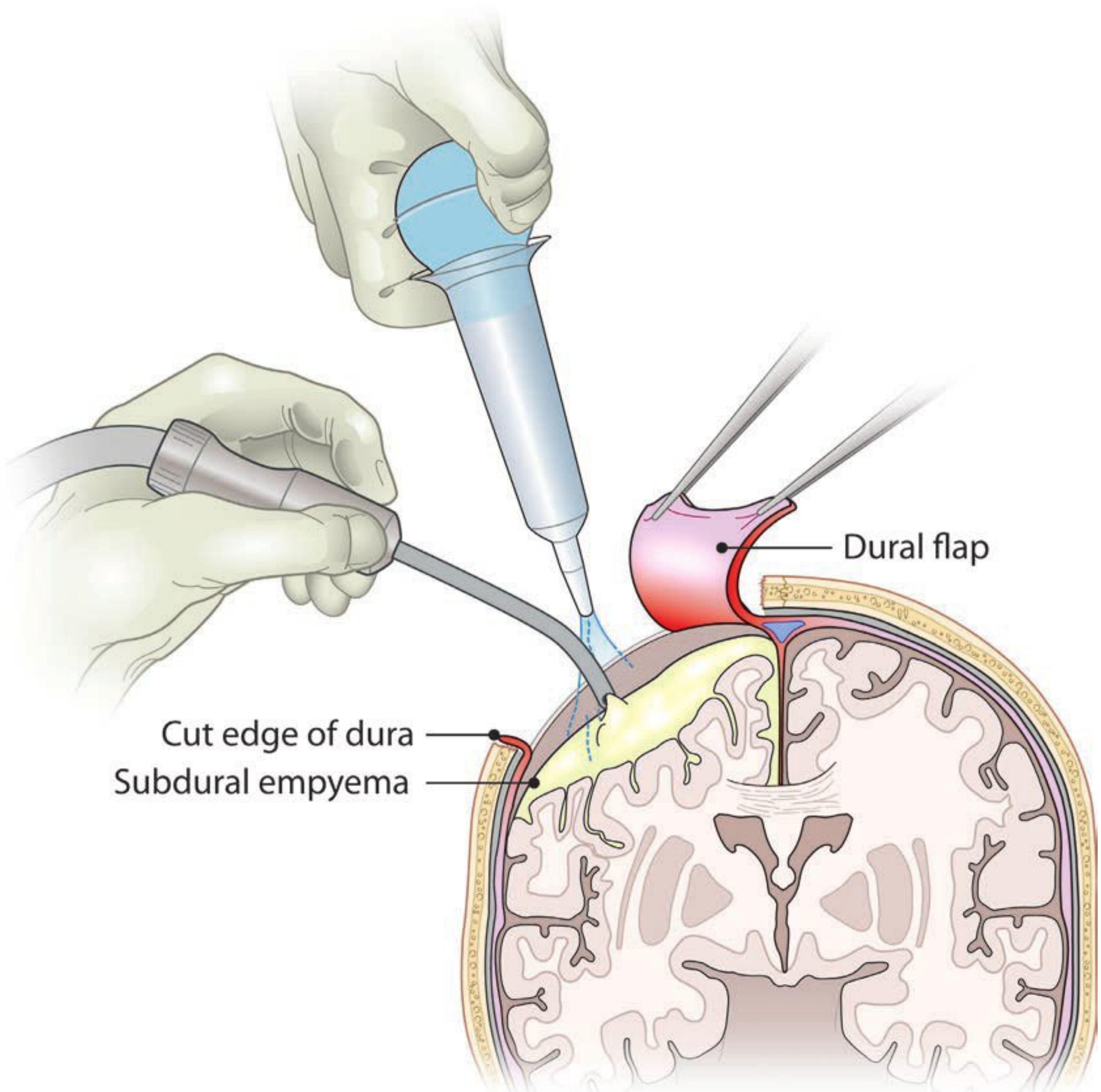


Figure	Procedural Steps	Pearls
Fig. 20.9	**Subdural empyema, if present, will be visualized upon elevation of the dural flap. Once again, liquid purulent material may be collected in a suction trap. Gentle retraction of the frontal pole will permit access to the frontal floor. Gentle depression/retraction of the superior frontal gyrus will permit access to the falx. The subdural space should be explored in all directions under direct visualization and irrigated with antibiotic solution to flush out any remaining purulent material. An inflammatory pannus may be adherent to the pia. If no deeper infection is suspected, proceed to "Dural Closure and Cranialization of Frontal Sinus" (Fig. 20.11).**	• The development of brain swelling must be anticipated upon evacuation of subdural empyema. If subdural empyema is suspected, a large bone flap should be planned. Likewise, the dura may be opened initially via multiple linear radiations from a central point. In cases of parafalcine empyema, Nathoo advocates an initial drainage via parasagittal craniectomy—prior to craniotomy—to help prevent acute, massive swelling.[16] • The exudative membrane should not be disturbed as attempted debridement may result in cortical injury and/or hemorrhage.

Approaching Intraparenchymal Abscess—Open Craniotomy (Fig. 20.10)

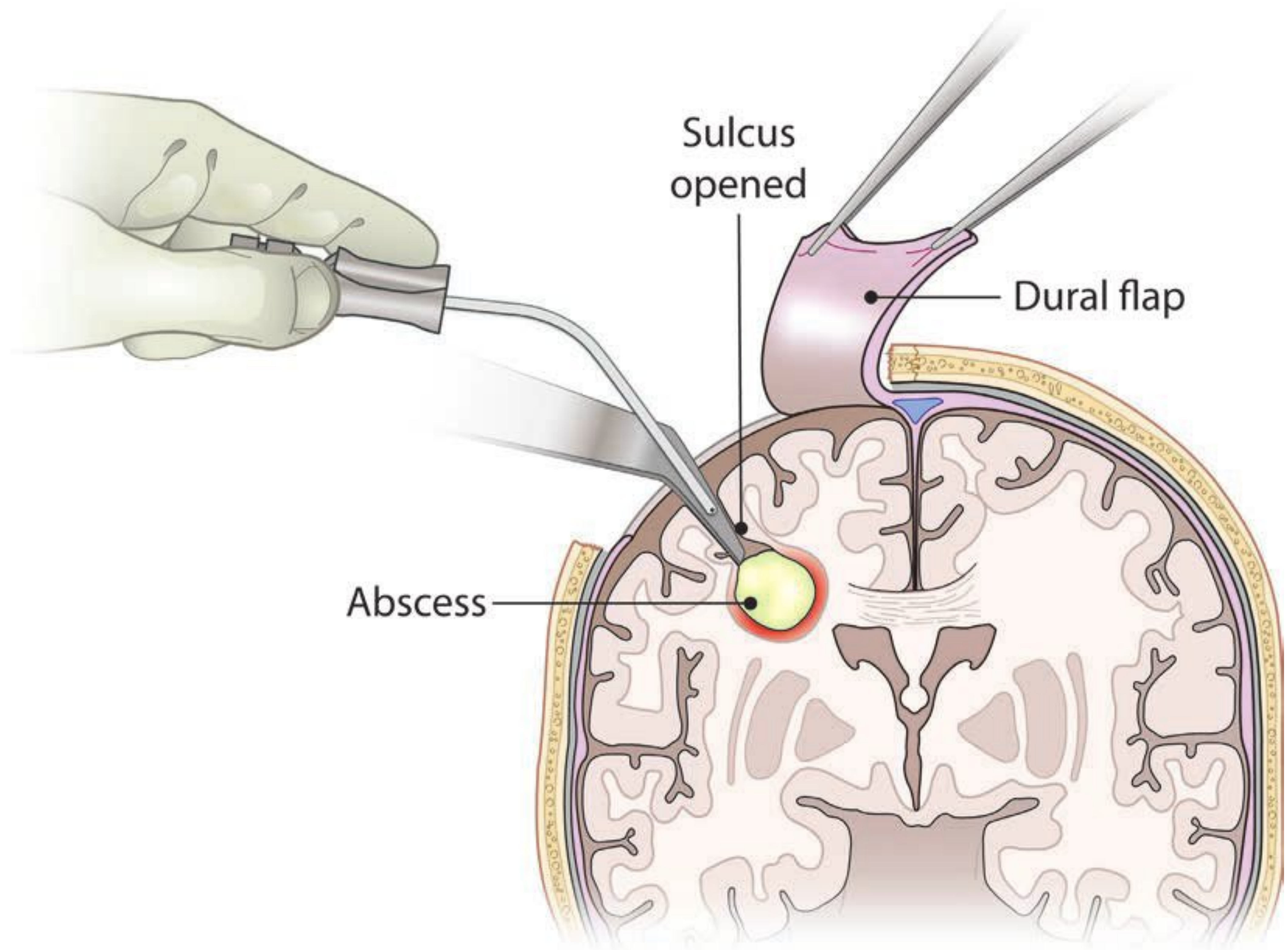


Figure	Procedural Steps	Pearls
Fig. 20.10	**To approach an intraparenchymal abscess, the sulcus overlying the abscess is opened; the abscess cavity typically lies at the base of the sulcus. A blunt brain needle may be introduced under ultrasound or image guidance into the abscess cavity for immediate drainage. The blunt needle may be exchanged for an external ventricular drain catheter, allowing for continued drainage and/or instillation of antibiotic agents. The capsule may be dissected away from the surrounding white matter. The capsular plane is followed circumferentially until the lesion has been "shelled out." The site then is irrigated with antibiotic solution and hemostasis attained with bipolar electrocautery as well as various hemostatic agents.**	• An open approach is indicated for an easily accessible lesion with a well-developed capsule, in a noneloquent area. Abscesses secondary to fungal infection and/or foreign body may be medically refractory. • If the abscess is not visible along the cortical surface, ultrasound or image guidance may be used to determine the best trajectory for approach. • The surrounding tissue is often friable and bleeds easily. • Particular care must be taken with periventricular lesions where the capsule wall may be thinner. Consideration should be given to aspiration alone, given the risk of intraventricular rupture with attempted resection.

Dural Closure and Cranialization of Frontal Sinus (Fig. 20.11)

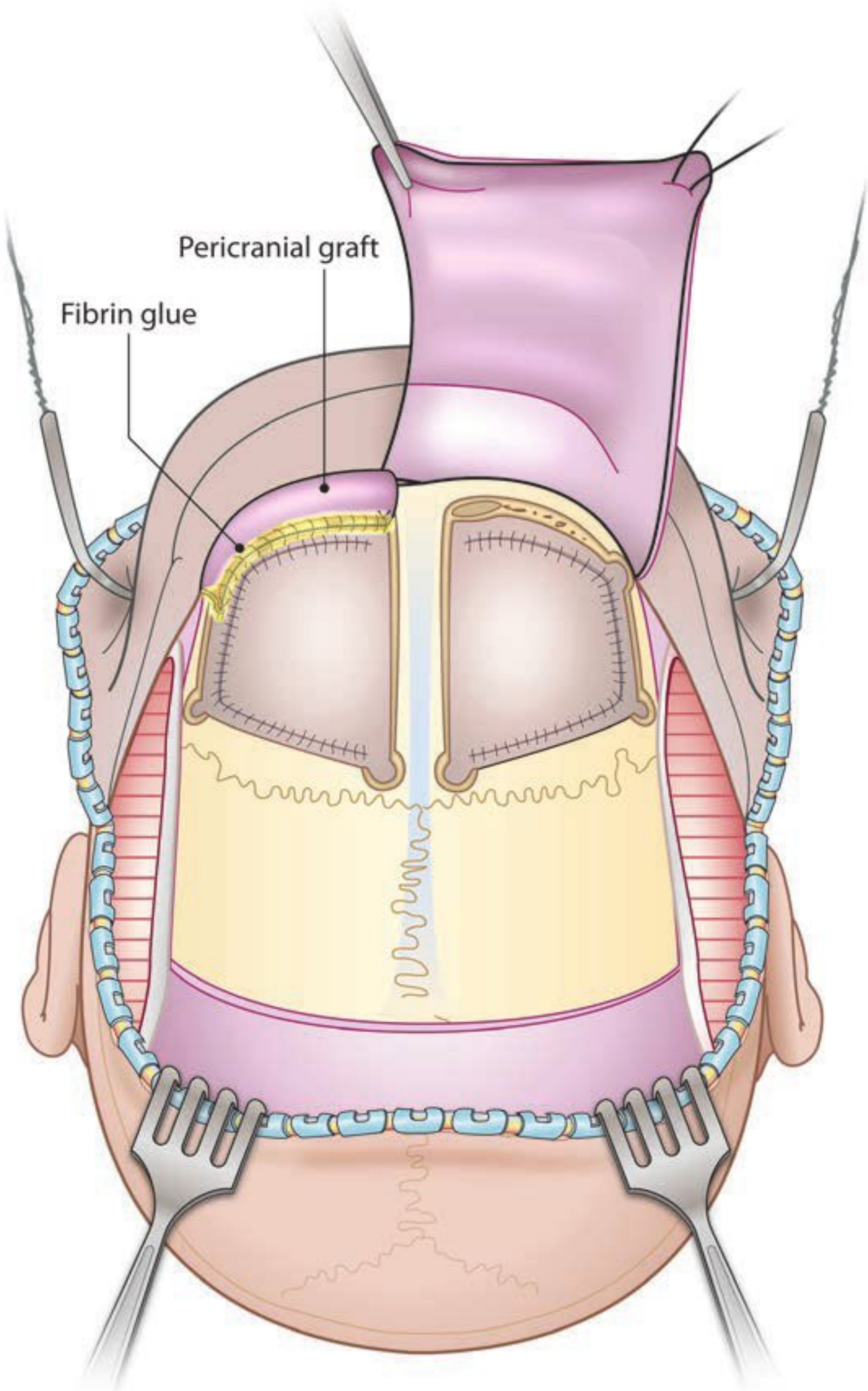
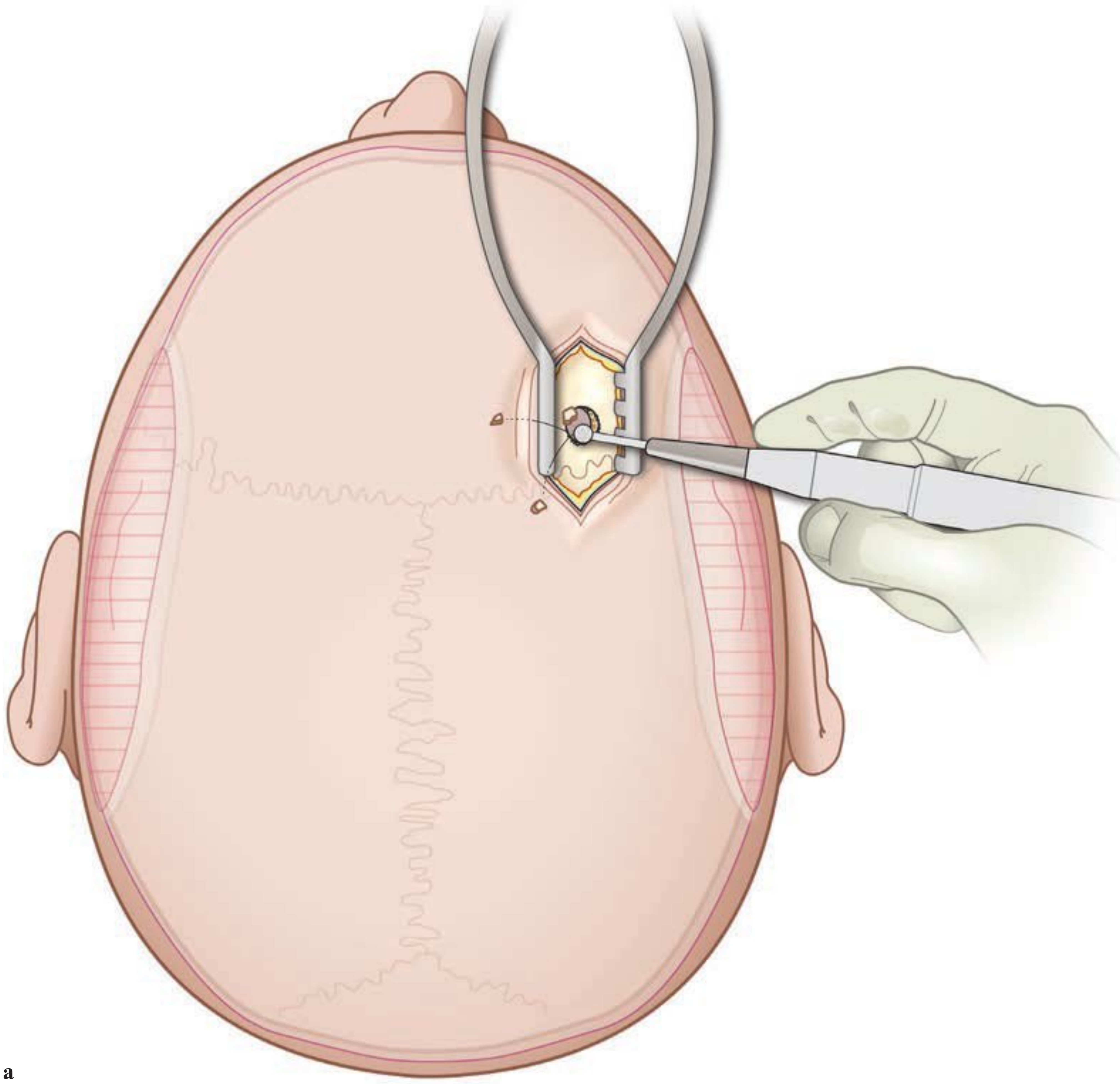


Figure	Procedural Steps	Pearls
Fig. 20.11	**If feasible, primary closure may be accomplished with interrupted 4-0 braided nylon stitches. If grafting is necessary, it is preferable to incorporate autologous materials in the setting of infection. Pericranium, temporalis fascia, or fascia lata (the latter requiring the foresight to prepare the lateral thigh preoperatively) are good options.** **In cases of contiguous extension of infection from the frontal air sinus to the epidural and/or subdural space, it is necessary to cranialize the frontal sinus prior to closure. The dura should be dissected from the roof of the orbit and posterior wall of the frontal sinus (if not already done by the abscess itself). The posterior table should be drilled flushed with the frontal fossa floor. Mucosa should be stripped from the sinus and the inner surface of the sinus, in turn, decorticated with a diamond bur. The sinus then is packed. The nasofrontal duct is obliterated. The previously harvested, vascularized pericranial flap then is folded down over the sinus opening and secured to the native dura at multiple points with 4-0 braided nylon stitches. A layer of fibrin glue is applied to the suture line.**	• Primary dural closure may not be feasible in the setting of malignant cerebral edema. Autologous graft material may be tacked loosely at the edges to accommodate swelling. In extreme circumstances, a large piece of dural substitute material may be laid over the dural defect. • The author uses dry pieces of gelatin sponge coated with bacitracin powder for packing of the frontal sinus. Alternately, adipose tissue (from a peripheral site) or muscle (temporalis) may be used. • See Chapter 27 for additional discussion of techniques for frontal sinus reconstruction.

Approaching Intraparenchymal Abscess—Stereotactic (Fig. 20.12a–c)



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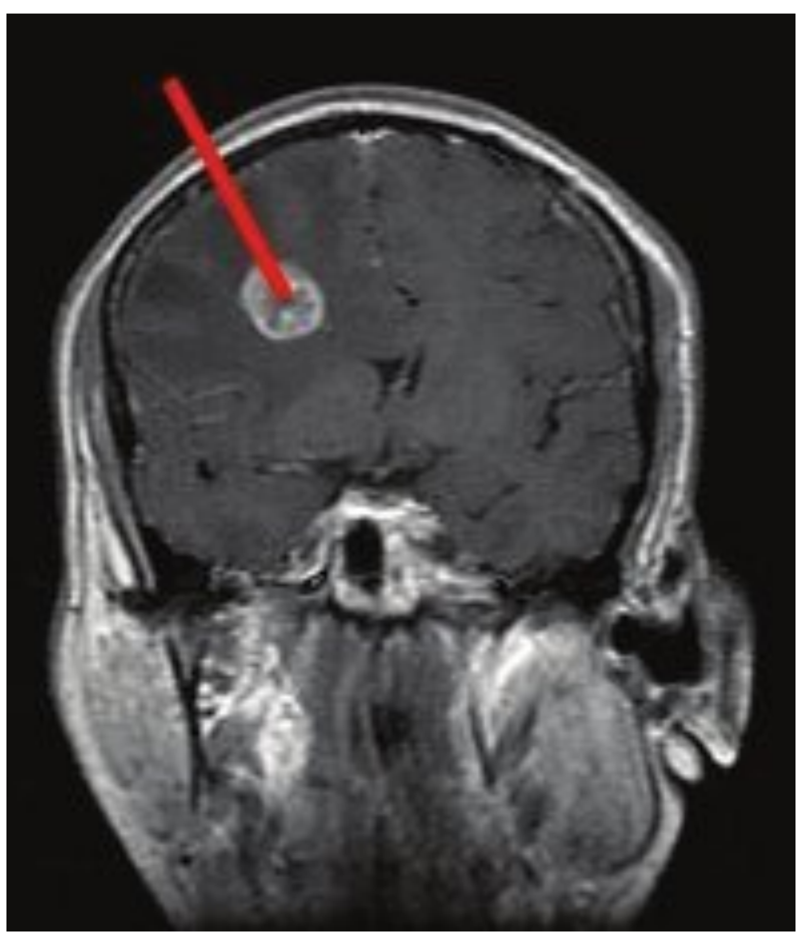

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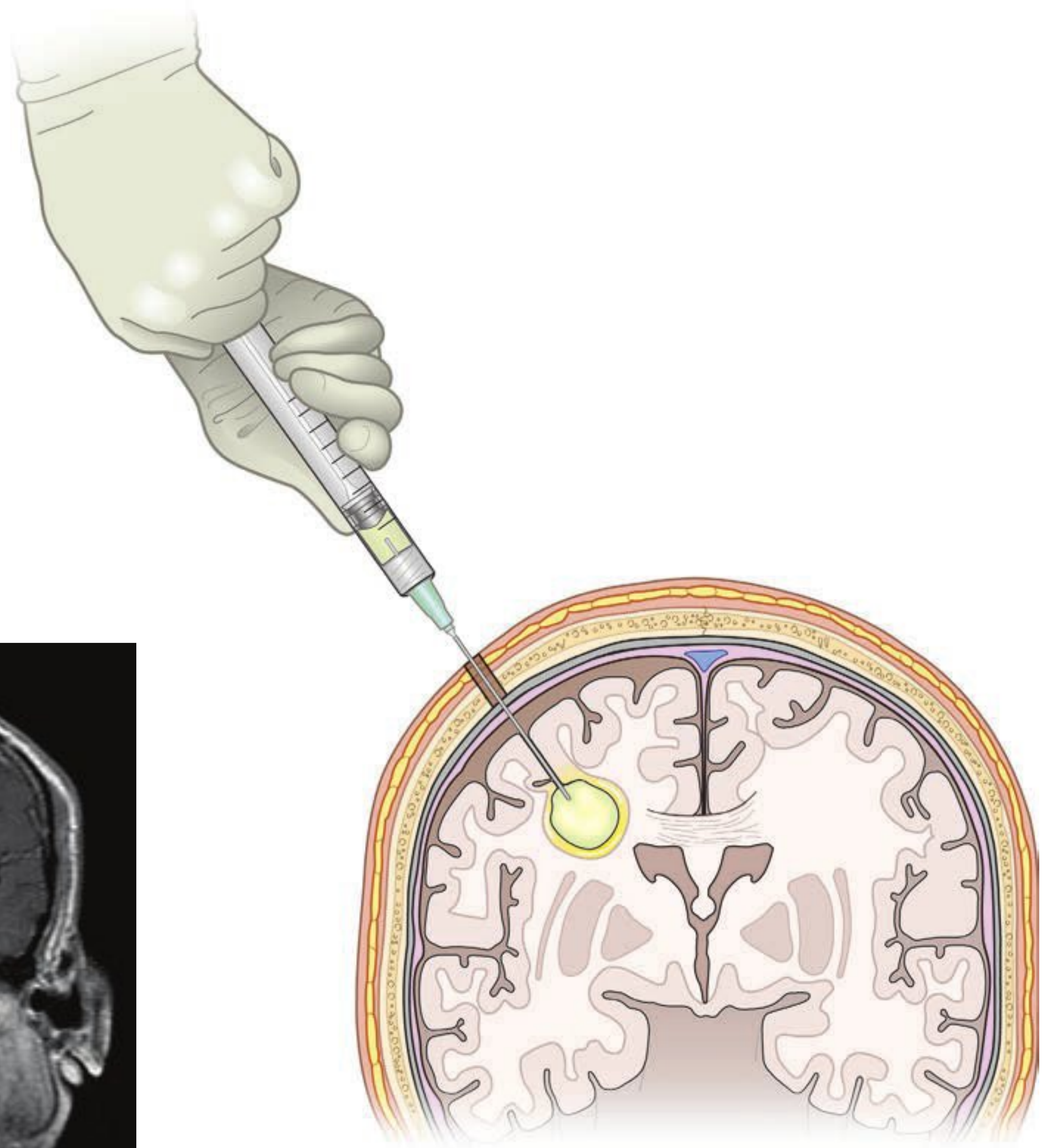


c

Figure	Procedural Steps	Pearls
Fig. 20.12	**(a) Using framed or frameless stereotaxy, a small skin opening is planned to allow for access to the abscess cavity along a defined trajectory. A single bur hole is placed at the planned entry site. The underlying dura is coagulated with bipolar electrocautery and opened in a cruciate fashion with a no. 11 blade. The dural leaflets again are coagulated. The underlying arachnoid-pia is coagulated and opened sharply. (b) Frameless stereotactic planning for needle aspiration of a right frontal deep intraparenchymal abscess. (c) An external ventricular drain or blunt brain needle is passed along the predetermined image guidance trajectory until the abscess cavity is entered. Liquid purulent material is collected by gravity drainage and gentle aspiration. The catheter may be irrigated gently, taking care that the amount of fluid entering is observed to drain by gravity. The catheter may be left in place and brought out to a skin exit site, remote from the scalp incision. Here, the drain is secured with a 3-0 nylon stitch. The bur hole site is irrigated with antibiotic solution. The scalp is closed in two layers (see Closing).**	• A stereotactic approach is indicated for aspiration of less mature lesions, deep lesions, and lesions adjacent to eloquent areas. • If image guidance is not available, ultrasound may be used in conjunction with a slightly larger bony opening. • Multiple lesions or multiple loculations within an abscess may require multiple entry points for aspiration. • Passage of a needle through thickened leptomeninges, without opening of the arachnoid-pia, may result in subdural bleeding as cortex is pushed away from the calvarium. • The “best” trajectory is defined as the shortest route to the pathology that bypasses eloquent areas and vital structures.

Closing

- If there is radiographic and/or gross evidence of osteomyelitis involving the bone flap, it should not be reimplanted.
- Likewise, if malignant cerebral edema is present, the bone flap should not be reimplanted.
- In other circumstances, the bone flap may be reapproximated using a plate and screw system.
- The incision site is irrigated with antibiotic solution.
- Hemostasis is attained with a combination of bipolar electrocautery and hemostatic agent(s) of choice. Epidural tacking stitches are placed circumferentially around the craniotomy defect with 4-0 braided nylon suture.
- A no. 7 Jackson-Pratt drain is laid in the subgaleal space and brought out to a skin exit site just posterior to the scalp incision. Here, the drain is secured with a 3-0 nylon stitch.
- The temporalis cuff is reapproximated with 0-absorbable braided suture interrupted stitches.
- The scalp flap is released from retraction. Hemostatic scalp clips are removed from the skin edges and hemostasis attained, where necessary, with bipolar electrocautery.
- The galea and subcutaneous tissue are reapproximated with 0-absorbable braided suture inverted stitches.
- The skin is closed with a running 3-0 nylon stitch or staples.

Postoperative Management

Monitoring

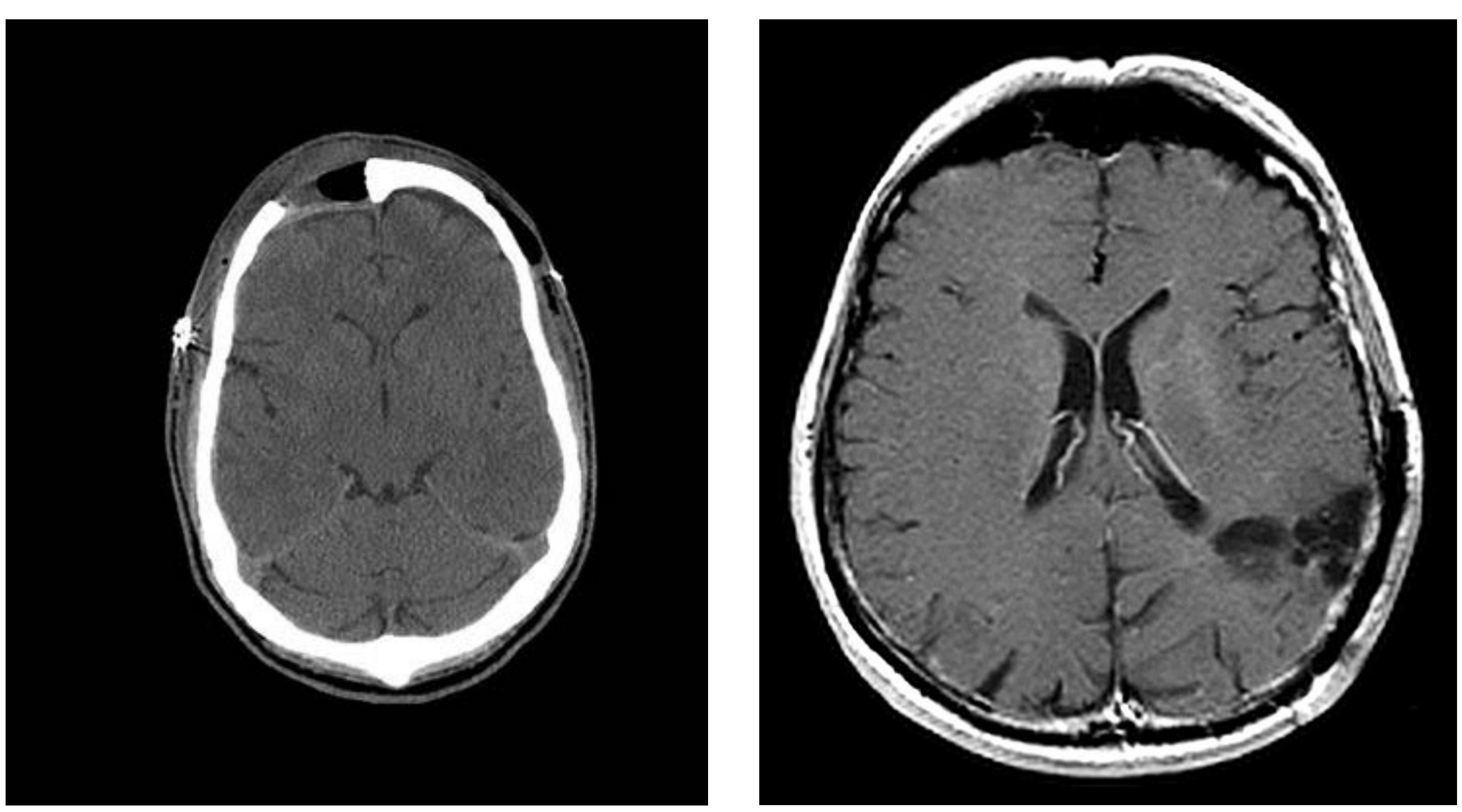
- Patients should be monitored in the intensive care unit setting following operative intervention.
- The use of invasive neurologic monitors (intraparenchymal or intraventricular) is appropriate for patients in whom serial neurologic exam is not feasible.
- The output of epidural and/or subdural drains, if present, should be monitored. Drain removal may be considered when outputs become minimal and/or serial imaging demonstrates resolution of the targeted collection.

Medication

- Empiric, broad-spectrum antimicrobial therapy should be continued pending culture results and then narrowed accordingly to provide targeted therapy for the identified pathogen(s). Generally, a 4- to 6-week course of intravenous antimicrobial therapy is prescribed. Some advocate a 6- to 8-week course for intracerebral abscess.[16] Longer-term therapy may be indicated for select organisms (e.g., *Mycobacterium tuberculosis*).
- Steroid therapy should be tapered rapidly in accordance with evolving clinical exam and evidence of resolving edema/mass effect per serial imaging.
- Antiepileptic drug (AED) prophylaxis should be continued in cases where documented seizure activity is present. Otherwise, AEDs may be tapered off in the postoperative period.
- Patients with evidence of increased intracranial pressure may require additional medical therapies for management.

Radiographic Imaging

- Early postprocedure CT imaging is indicated to assess the efficacy of debridement as well as to rule out hemorrhage, ischemia, and hydrocephalus. Imaging should be repeated at intervals during the immediate postoperative course as neurologic status warrants.
- MRI may be used for longer-term follow-up, bearing in mind that MRI enhancement may persist for months despite clinical improvement and appropriate antimicrobial therapy. MRI may be employed for more detailed characterization of structural pathology in the acute setting, as well as for serial tracking of response to therapy (bearing in mind that radiographic change often lags behind clinical improvement).
- Postoperative imaging (**Fig. 20.13a, b**). A CT scan is obtained in the immediate postoperative period for interval assessment



a b

Fig. 20.13a, b (**a**) Non-contrast CT scan demonstrating local craniectomy and debridement of epidural abscess for the patient depicted in Fig. 20.1a–c. (**b**) Post-gadolinium T1-weighted axial image demonstrating resolution of intracerebral abscess and associated meningeal enhancement for the patient depicted in Fig. 20.1f.

of mass effect, edema pattern, and ventricular size, as well as to exclude hemorrhage.

Further Management

- Reaccumulation of epidural, subdural, and intraparenchymal collections may occur. Patients may require multiple operative interventions for debridement.
- In the setting of intraventricular rupture of an abscess, placement of an external ventricular drain is appropriate to permit continuous drainage of cerebrospinal fluid, as well as intrathecal administration of antimicrobial therapy.

Special Considerations

- If infection arises from the sinuses or mastoid process, simultaneous management of the infectious pathology by Otolaryngology may be indicated. Otolaryngology should be involved in the preoperative planning for such cases.
- Formal Infectious Diseases consultation is appropriate to guide antimicrobial therapy.
- Suppurative intracranial thrombophlebitis is a feared complication of central nervous system infection. Suppurative thrombophlebitis may begin within the veins or venous sinuses or may occur after infection of the paranasal sinuses, middle ear, mastoid, or oropharynx. MRI of the brain, with MRV, is the test of choice. A 3 to 4 week course of intravenous antimicrobial therapy is recommended. The use of anticoagulation in this setting is controversial.[17] It is also important to note that relapse may occur within 6 weeks—after apparent clinical resolution—and abscess formation has been reported up to 8 months later.[18]

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21 Ventricular Shunt Malfunction

Sergey Abeshaus, Samuel R. Browd, and Richard G. Ellenbogen

Introduction

A ventricular shunt (VS) malfunction is a common neurosurgical emergency. In fact, a shunt revision is one of the most common procedures a neurosurgeon may perform. It is estimated that up to 50% of shunts may fail within 2 years. Despite its apparent simplicity, a shunt revision requires meticulous attention to detail and vigilance in diagnosis and management to ensure the patient is treated in a timely and adequate manner. The workup and surgical treatment of a VS malfunction is fraught with risks and complications even in the most experienced hands. In the United States, shunt revision costs are high, perhaps over $1 billion a year. The human costs are staggering. Common causes of shunt malfunction include mechanical failure (obstruction, disconnection, or migration), hardware failure (valve), infection, functional (underdrainage or overdrainage), or a combination of these aforementioned issues.[1,2]

A typical clinical presentation of an acute VS malfunction includes drowsiness, severe headaches, and vomiting.[3] However, the presentation may be quite diverse, from rapid to slow/subtle and chronic. The common signs and symptoms may be as modest and inconspicuous as deterioration in school performance, irritability, increase in head circumference over the 95th percentile, increased lethargy or sleep, clumsiness, chronic malaise, chronic fever, abdominal pain, or swelling around the shunt tract. More impressive presentations include seizure, cranial nerve paresis (III, IV, or VI), decrease in visual acuity, paralysis of upward gaze, papilledema, weakness or paralysis, stupor, coma, or change in vital signs (decreased pulse or increased mean arterial pressure).

Obtaining meticulous information from a patient or his/her caregiver or the medical records about the type of shunt implanted and previous shunt failure presentation is important. Previous imaging, especially when done during symptom-free period, is vital in surgical decision making. Knowledge of the type of shunt and information about the setting, date, and specifics of previous operations may influence treatment strategy in complex cases. However, these details may often be incomplete. It is important to note that a shunt can malfunction without causing an obvious change in ventricular size, in part, due to poor compliance of the brain. However, the intracranial pressure (ICP) can be elevated and only the history from the patient or family member, symptoms, or exam may be helpful. In those patients whose scans may not change during a typical shunt malfunction, it is imperative to listen to the history provided by a knowledgeable caregiver who can accurately compare this presentation with that of a previous shunt malfunction. Failure to do so may be catastrophic.

The steps in working up a ventricular shunt malfunction:

1. Obtain information about the underlying etiology of hydrocephalus treated by initial shunt placement. In our experience, over 90% of patients have hydrocephalus from intraventricular hemorrhage (IVH) of prematurity, infection, trauma, tumor, normal pressure hydrocephalus (NPH), past hemorrhage, aqueductal stenosis, or congenital etiology (myelomeningocele, craniofacial, or genetic). In about 10% of patients the etiology is unclear. This history may be especially important in cases of aqueductal stenosis, in which a patient may undergo an endoscopic third ventriculostomy (ETV), instead of a shunt revision.
2. Determine the type of the VS. The most common are ventriculoperitoneal, ventriculoatrial, and ventriculopleural shunts; type of valve (maker, model, fixed pressure or adjustable [need to verify last pressure setting]); side of the shunt implantation; and date and type of recent interventions on shunt system. There are a variety of shunt valves currently available at the market (please refer http://www.pedsneurosurgery.org/education.asp for further information).

Indications

- Clinical symptoms of shunt malfunction such as those listed in the introduction
- Radiological symptoms of shunt malfunction with ventricular dilatation
- Positive cerebrospinal fluid (CSF) cultures, positive evidence of microorganism or elevated white count consistent with infection, and other possible clinical scenarios described elsewhere[1,2]
- Discontinuity in shunt tubing or dislodgement of tubing from ventricle or abdomen (VP), pleura (Vpleural), or heart (VA)
- Exposure of shunt tubing
- Shunt exploration without ventriculomegaly in patient who has poor compliance of brain, and presents with signs and symptoms of increased intracranial pressure
- Slit-ventricle with intermittent shunt malfunction
- Desire to convert shunt patient into a shunt-free patient by an ETV, in the face of a shunt obstruction

There is a simplified algorithm for decision making in ventricular shunt malfunction in **Fig. 21.1**.

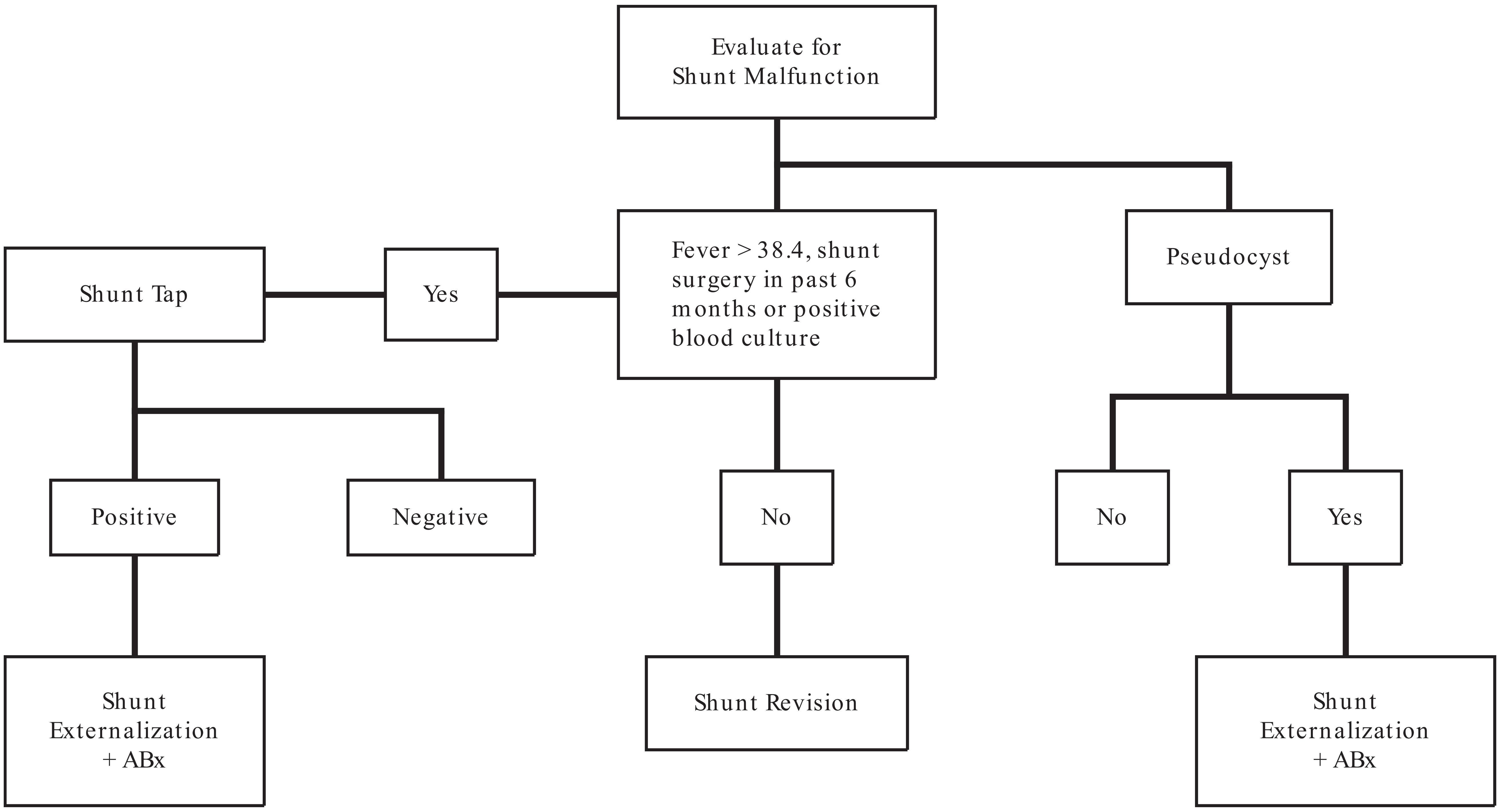


Fig. 21.1 Simplified algorithm for decision making in ventricular shunt malfunction.

Preprocedure Considerations

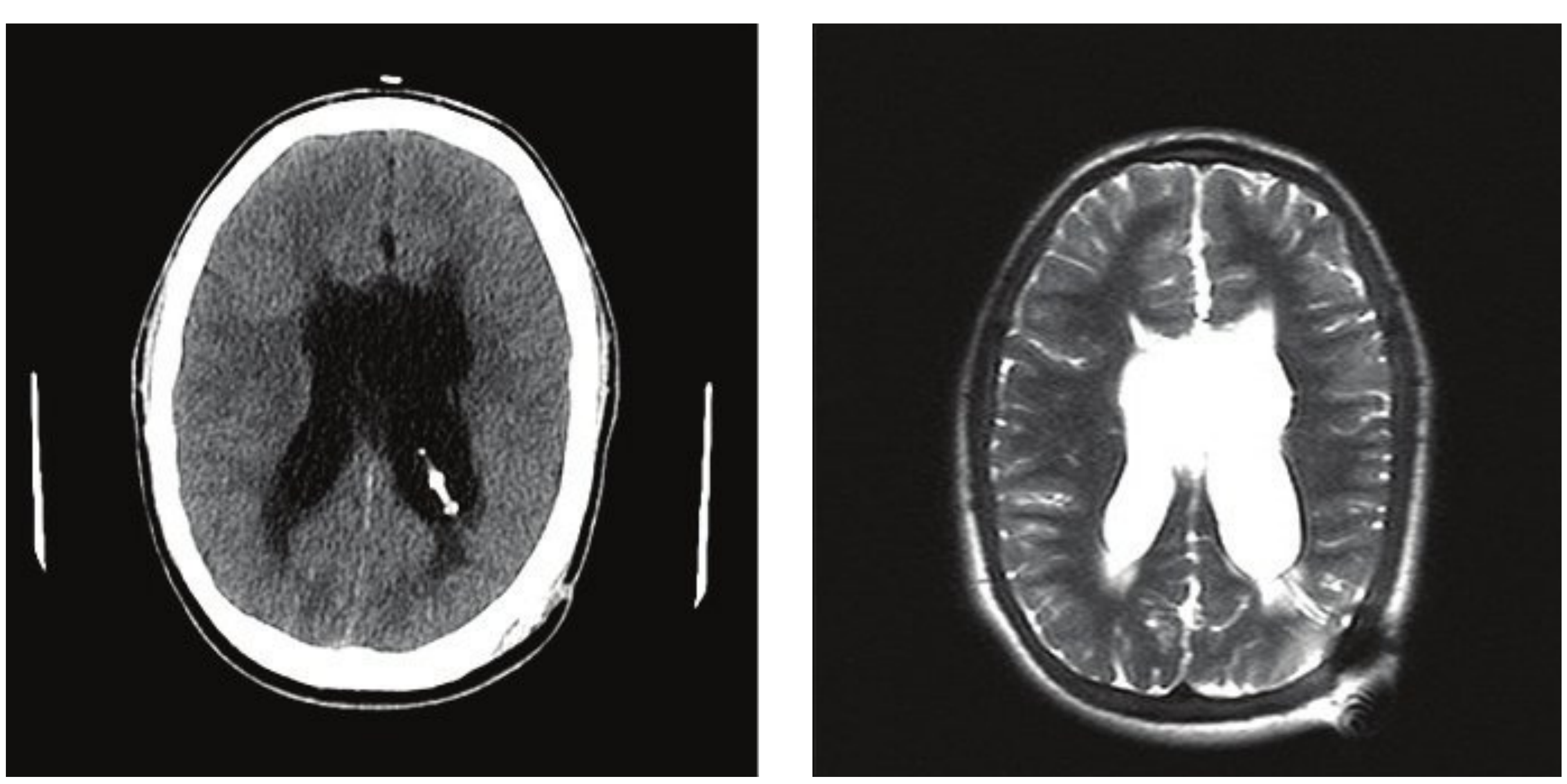
Radiographic Imaging

- Head computed tomography (CT; may be combined with fiducial markers for navigation) (**Fig. 21.2a**).
- Rapid sequence brain magnetic resonance imaging (MRI; Haste T2 protocol)[4] (**Fig. 21.2b**)—fast, generally no need for anesthesia/sedation. The rationale for using a fast T2-weighted abbreviated MRI exam is to avoid the radiation risk from cumulative CT scans.
- Shunt series—X-ray: Head and neck anteroposterior (AP) and lateral (**Fig. 21.3a, b**), chest AP and lateral, abdomen and pelvis AP (**Fig. 21.3c**) and lateral. Abdomen and pelvis radiography is not necessary in case of ventriculoatrial or ventriculopleural shunt evaluation.[5]
- Shuntogram (radionuclide) provides some information regarding opening pressure and shunt flow. Radionuclide shuntogram should be considered in patients whose history, CT scan, or exam is not definitive and shunt flow characteristics need to be evaluated to decide whether or not to operate. A radionuclide study should not delay revision in the setting of an acute, obvious malfunction.

Diagnostic Procedures

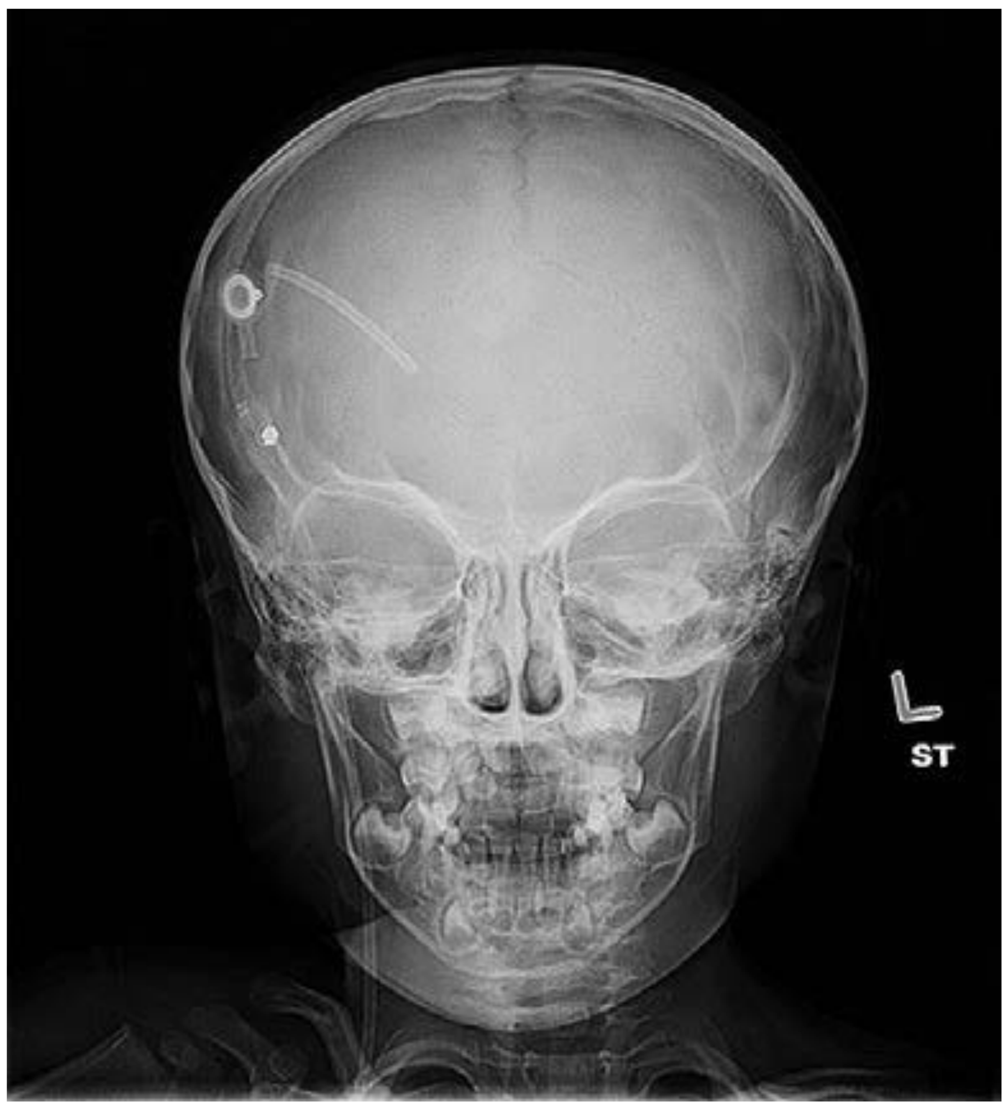
- Shunt tap—if the fever is greater than 101° F or there is a positive blood culture in last 48 hours and/or shunt system inter-

a



b

Fig. 21.2a, b Preoperative imaging of shunt malfunction of the same patient. **(a)** Head CT and **(b)** brain MR (Haste T2 protocol).



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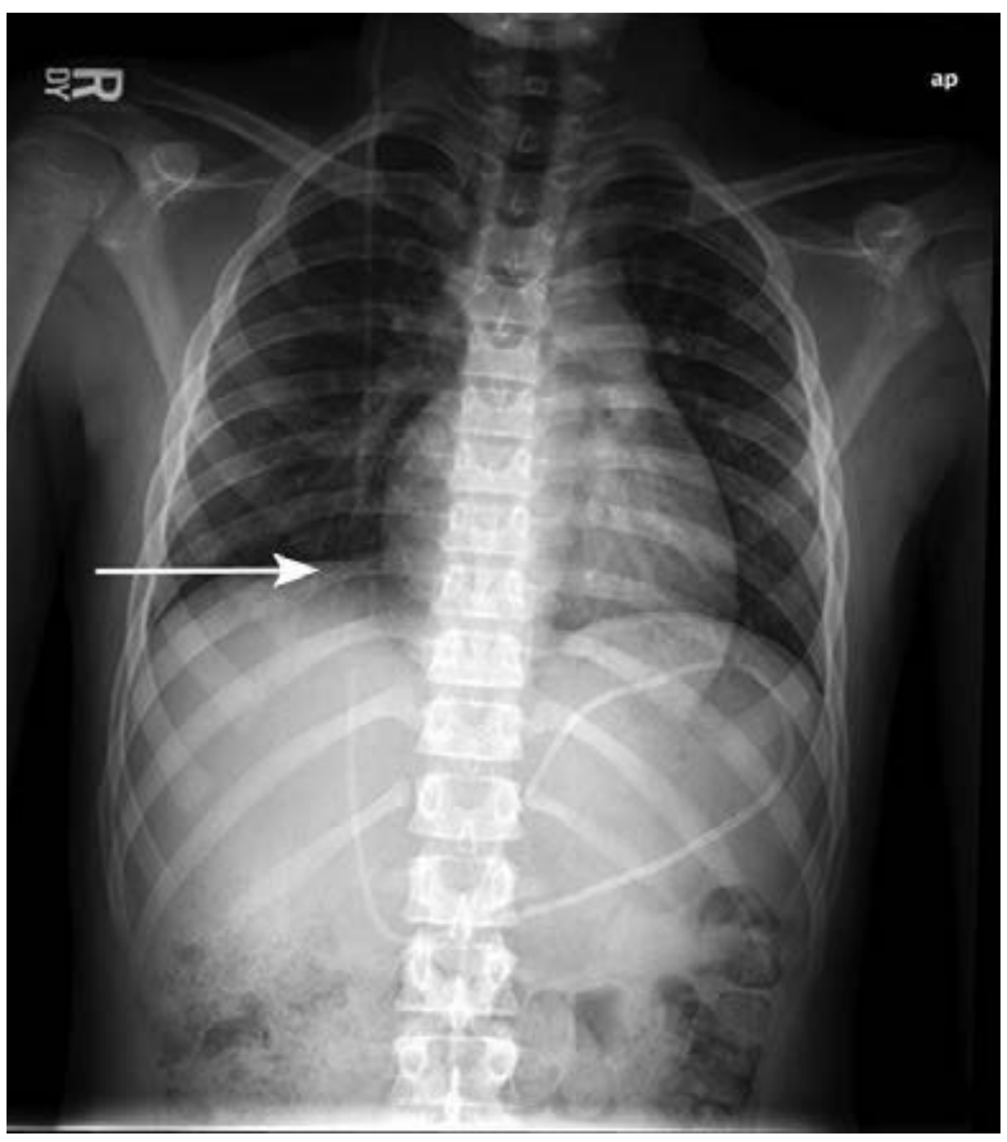


c

Fig. 21.3a–c Shunt series. (**a**) Anteroposterior (AP) and (**b**) lateral skull showing ventricular catheter disconnection. (**c**) AP abdomen showing distal catheter disconnection (arrow).

vention within 6–12 months, proceed with shunt tap prior to revision. Over 95%of all shunt infections occur within 1 year of the last shunt instrumentation, with the majority of them occurring within 3 months.

Medication

Antibiotics

- Any new shunt placement or revision: two doses of cefazolin or any late generation cephalosporin; first dose is administered during anesthesia induction (45 minutes to 1 hour prior to the incision) and the second dose after the surgery within 8 hours. Some surgeons cover the patients with antibiotics for 24 hours; however, the evidence mostly supports a single preoperative dose prior to skin incision. Consider vancomycin 1 hour in advance of surgery in methicillin-resistant *Staphylococcus aureus*–colonized patients.
- Shunt infection: tap shunt, then immediately begin triple antibiotics (ceftriaxone, vancomycin, and metronidazole in community-acquired and imipenem/cilastin instead of ceftriaxone in hospital-acquired infection).[6]

Operative Field Preparation

Preparation is done according to following the Hydrocephalus Clinical Research Network (HCRN) protocol adopted for Seattle Children's Hospital (**Fig. 21.4**).[7]

Position the patient with the head away from the door. Wide exposure is important. Hair is removed with clippers. Preliminarily prepare the skin with chlorhexidine soap, then isopropyl alcohol, to remove any dirt or debris and allow to dry. Mark the incision.

Previous incisions on the scalp may be extended to get appropriate exposure of ventricular catheter and shunt valve (consider vascular supply to scalp so as not to devascularize the scalp flap). We use 2%chlorhexidine gluconate/70%isopropyl alcohol solution preparation for the surgical field and wait 3 minutes or longer to dry. Double gloves are advised. Drape with antimicrobial incise film and ensure isolation of potential infection sources (tracheostomy, gastrostomy tube, etc.).

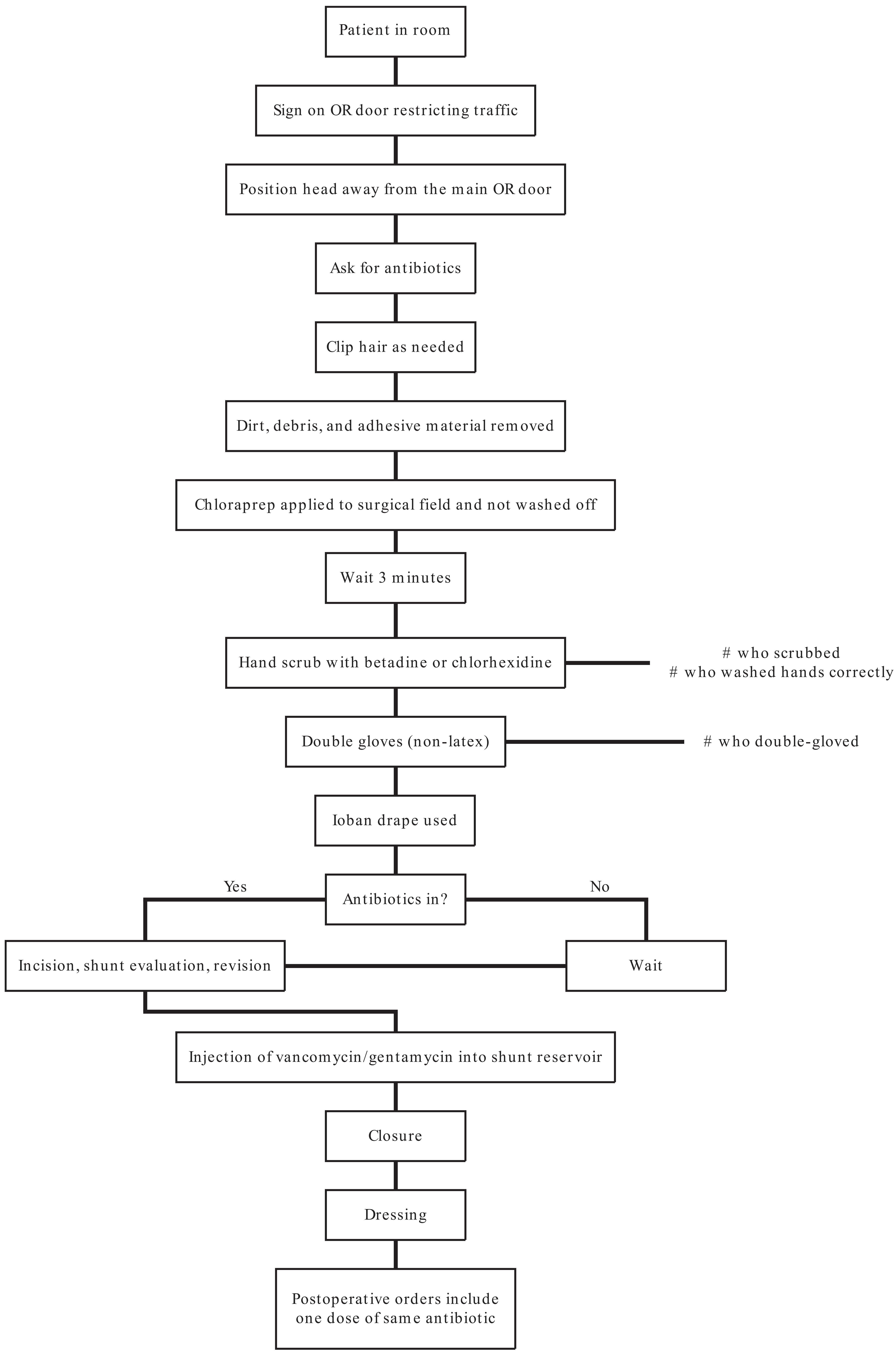


Fig. 21.4 HCRN protocol[7]/Seattle Children's Hospital (SCH) protocol.

Operative Procedure

Shunt Revision

Positioning and Preparation (Fig. 21.5)

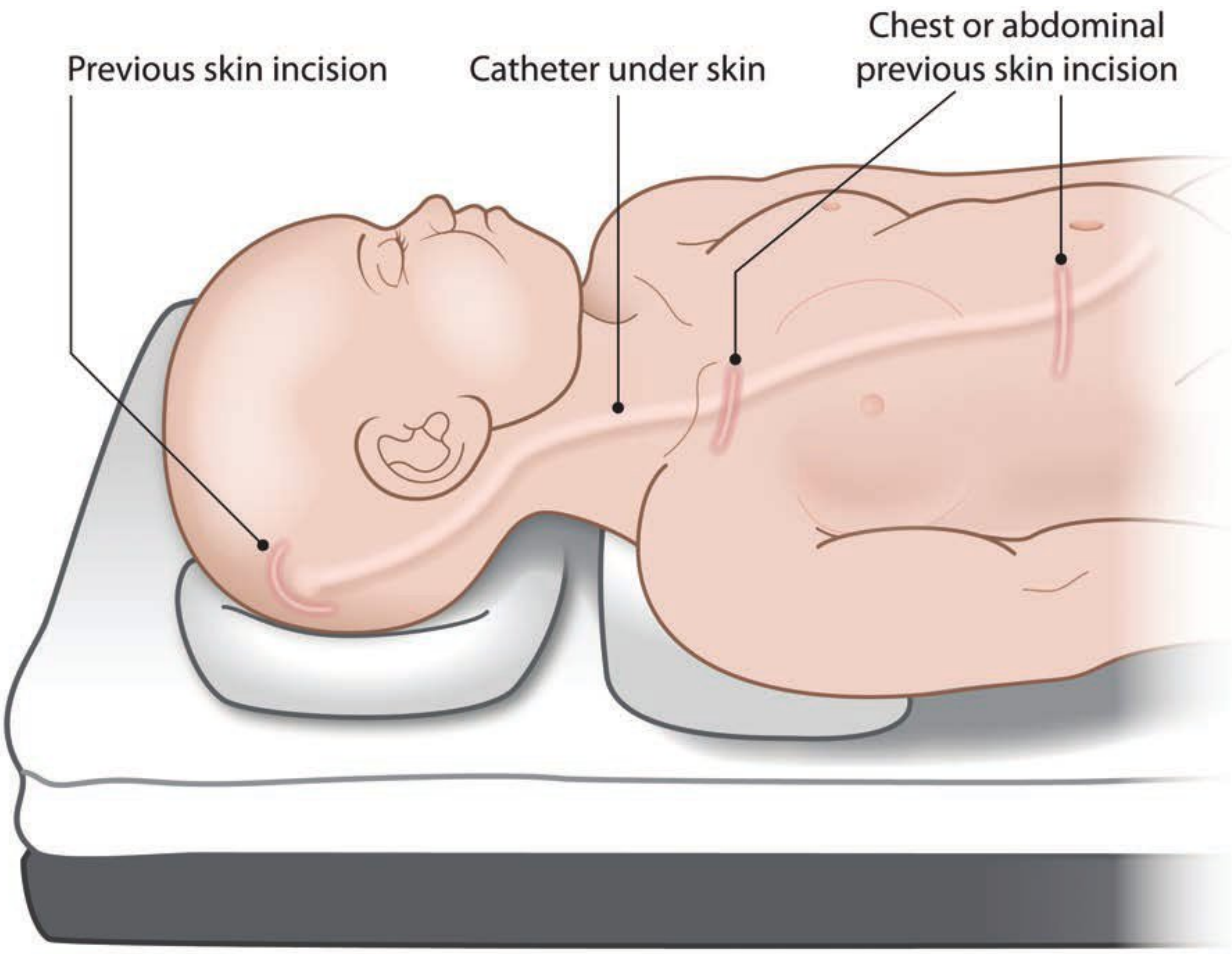
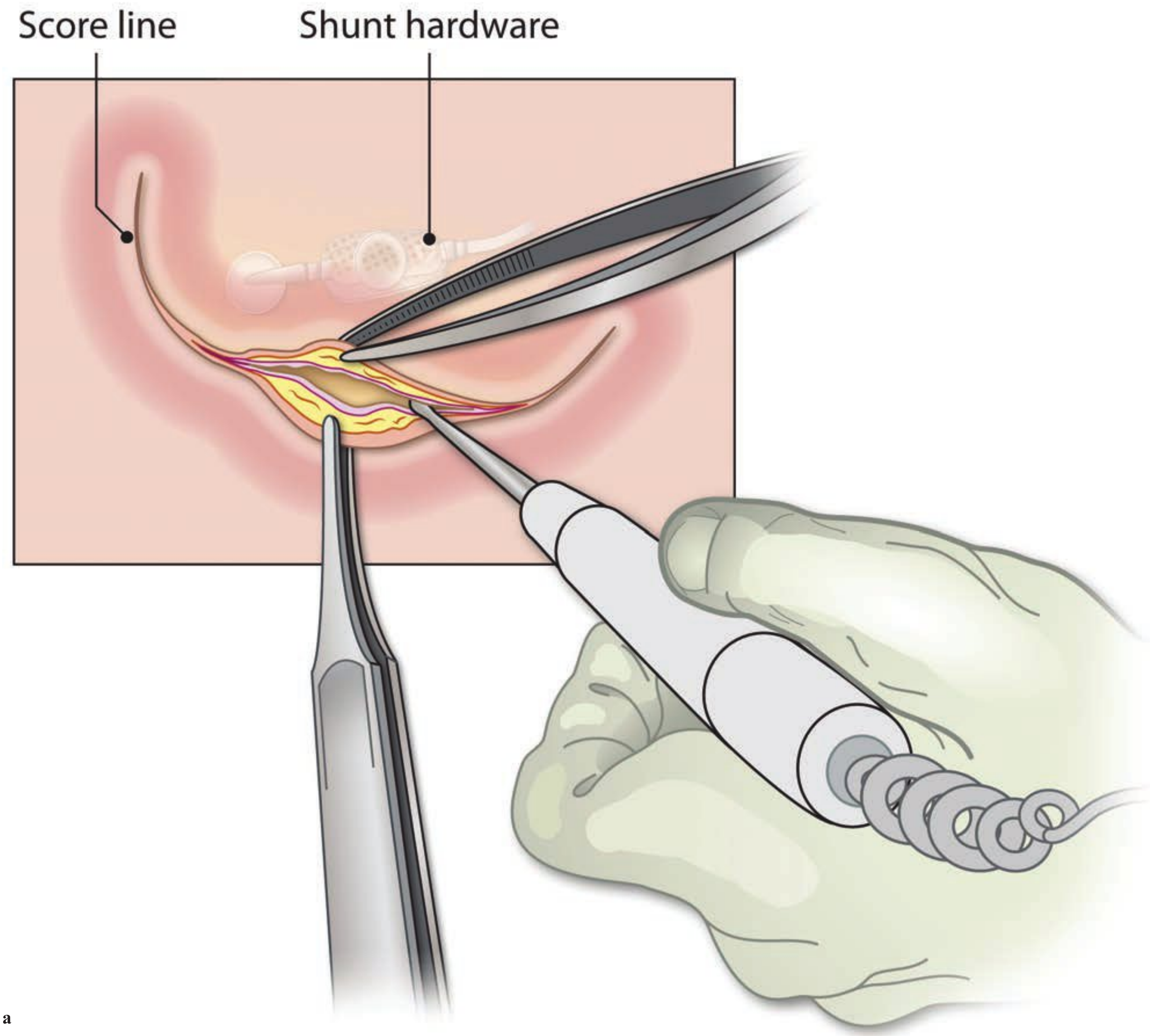


Figure	Procedural Steps	Pearls
Fig. 21.5	**The patient is placed supine with the head on a gel donut, head mildly rotated away from valve site for adequate exposure of operative field. A gel roll is placed under the shoulders to extend and maintain the appropriate plane for tunneling. Ensure appropriate foam or gel padding to reduce pressure sore risk at every pressure point.** **Always expose widely so that all parts of the shunt and tract (abdomen for the VPS, chest for ventriculoatrial or ventriculopleural shunt) are covered. In noninfected cases, incisions are infiltrated with 1%lidocaine with epinephrine 1:100,000.**	• Sometimes in complex patients wound preparation and draping may be challenging, such as those patients with chemotherapy catheters or gastrostomy tubes. • It is important to change gloves before making the incision.

Skin Incision and Wound Dissection (Fig. 21.6a, b)



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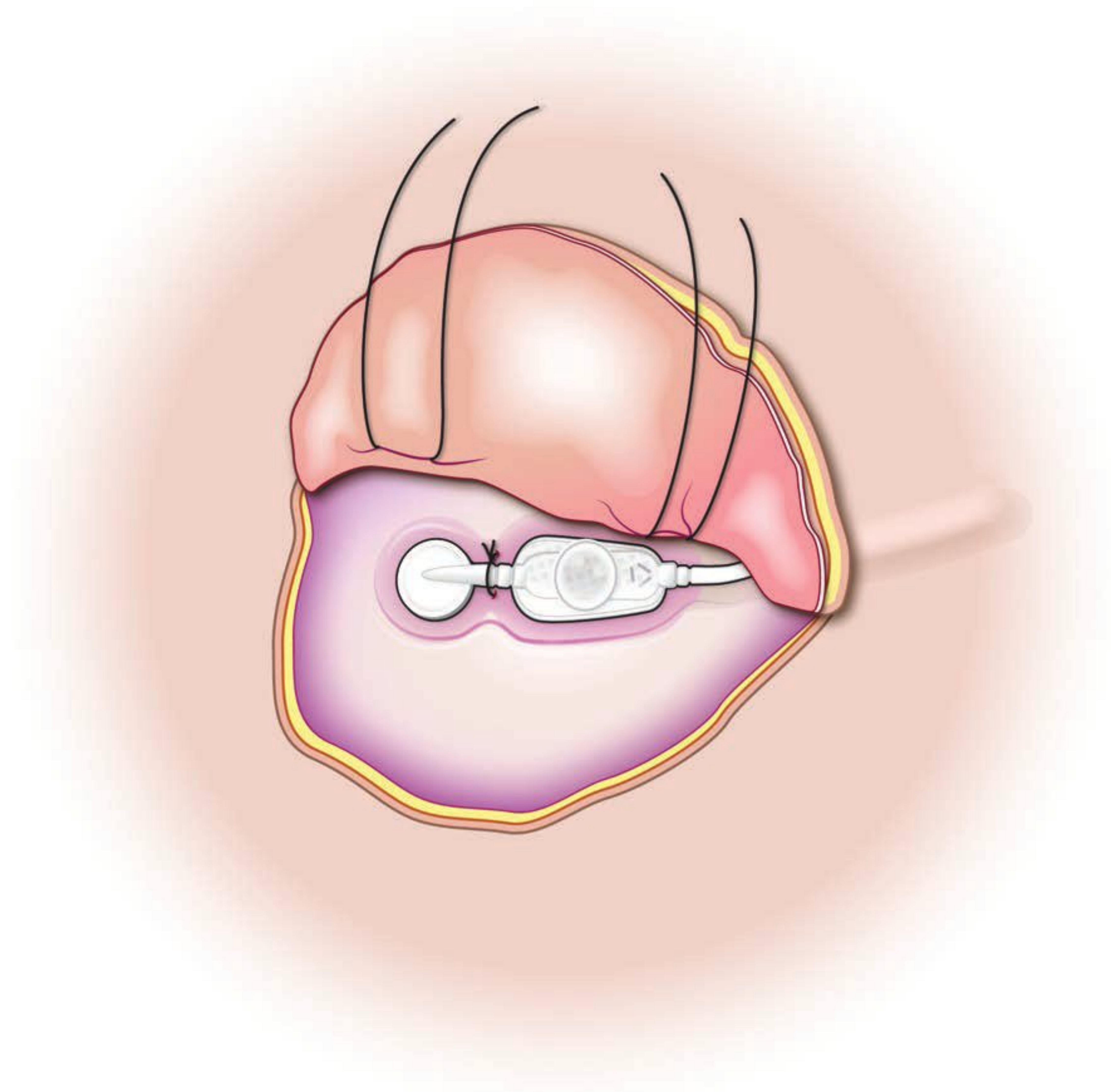


b

Figure	Procedural Steps	Pearls
Fig. 21.6	**Evaluate ventricular catheter skull entry site and valve location based on review of imaging, palpation, and navigation assistance. (a) An incision is made with a no. 10 or no. 15 blade often through a preexisting incision with extension along the valve for appropriate exposure of distal part of the valve. The incision should not be over the hardware to avoid wound breakdown. After we score the skin with a blade, we use Bovie electrocautery down to and around the shunt hardware because it does not cause harm to the valve or tubing. (b) The careful dissection of soft tissue in the galeal-pericranial plane to preserve pericranium and appropriate exposure of both ventricular catheter and valve is performed. Wound edges are retracted carefully with Weitlaner retractor(s) or retraction sutures. Wound hemostasis is obtained with monopolar or bipolar electrocautery.**	• We use the needle tip monopolar electrocautery. • One can utilize a custom tailored skin incision or curvilinear incision to provide adequate scalp coverage and release tension from the wound. In patients with a compromised scalp, the surgeon may need to perform a Z-plasty—a rotational flap or score the galeal layer to ensure adequate scalp coverage over the tubing without tension.

Evaluation of Ventricular Catheter Reservoir (Fig. 21.7)

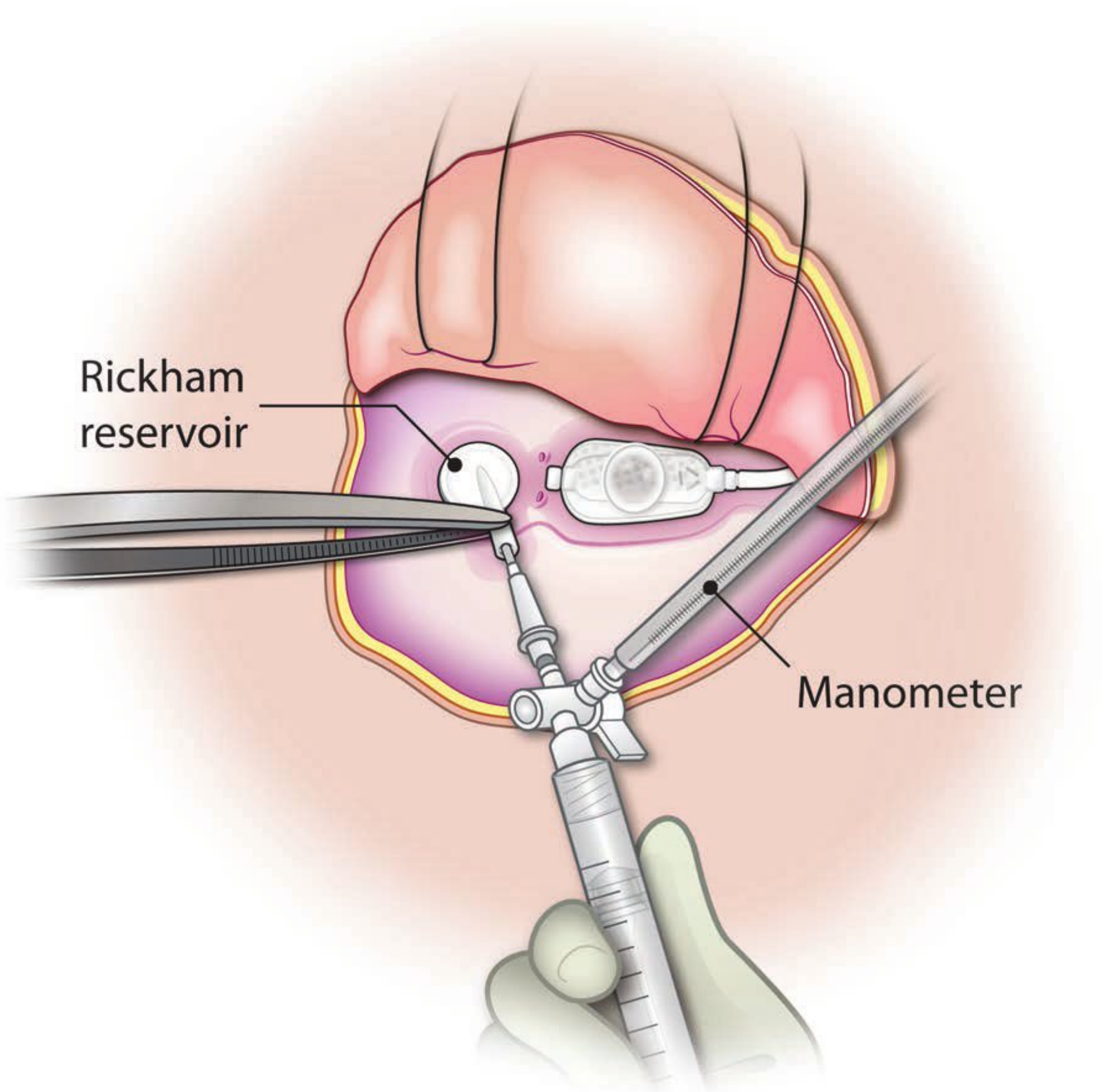


Figure	Procedural Steps	Pearls
Fig. 21.7	**Carefully disconnect the ventricular catheter from the valve and assess CSF flow. If no flow, the catheter is replaced. If partial flow, connect the ventricular catheter to a manometer and obtain the opening pressure. If there is partial obstruction, so identified due to high ICP or no pulsatility in the CSF fluid column then proceed with catheter revision.** **When extant, the side arm of the Rickham reservoir and valve are carefully dissected free. Disconnect the side arm of the Rickham reservoir from the valve to assess CSF flow. Use above algorithm for revision if no/reduced flow.**	• It is important to avoid pulling the Rickham reservoir/ventricular catheter out (if adherent) to reduce risk of intraventricular bleeding.

Revision of Ventricular Catheter (Fig. 21.8)

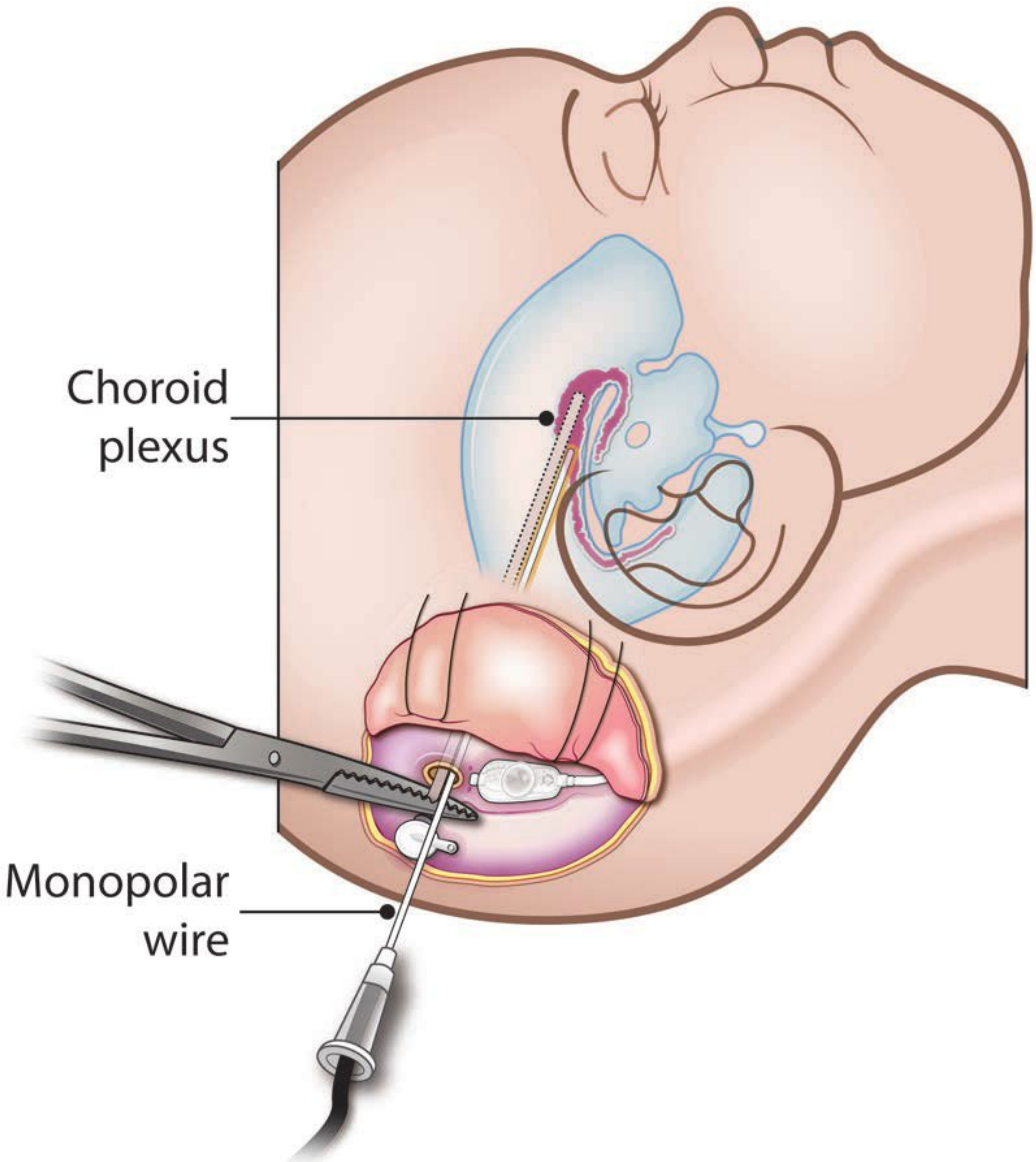


Figure	Procedural Steps
Fig. 21.8	**During catheter revision, if the ventricular catheter is adherent to the choroid plexus in the ventricle, a monopolar wire is used to release the catheter. It takes careful monopolar coagulation, gentle manipulation, or twisting of the catheter until a burst of CSF signals the release of the catheter. We use a Jake clamp to hold the catheter during this maneuver.[8] If there is intraventricular blood, gently irrigate the ventricle via barbotage with normal saline or lactated Ringer's until it clears.**

Placement of Ventricular Catheter (Fig. 21.9)

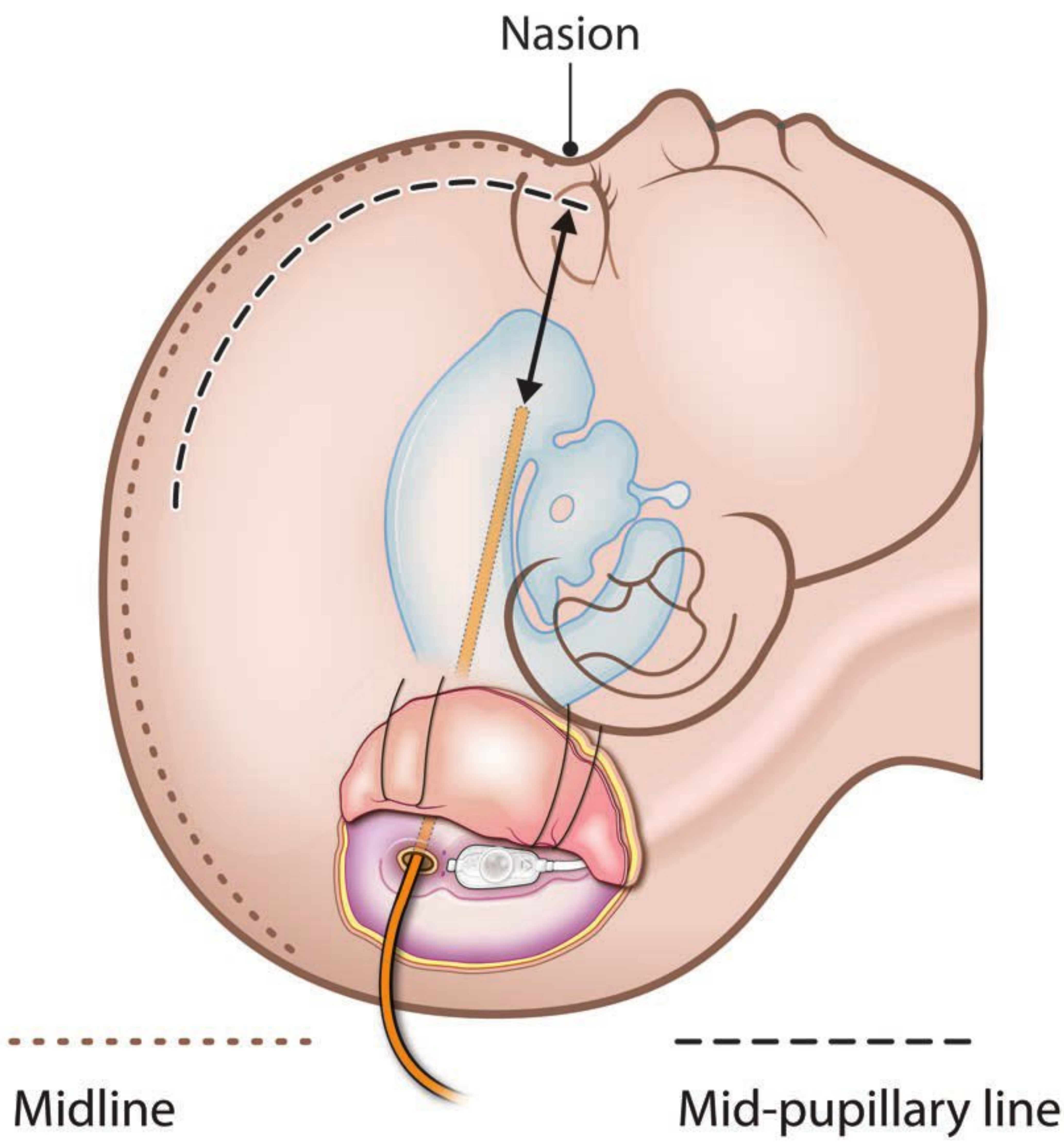


Figure	Procedural Steps	Pearls
Fig. 21.9	**After removal of the old ventricular catheter, a new antibiotic impregnated or dotted ventricular[9] catheter is placed with the catheter tip just anterior to ipsilateral foramen of Monro. We utilize stereotactic navigation to assist placement.[10] Alternatively, one can use anatomic landmarks, such as the mid-pupillary line and nasion, with the catheter insertion and trajectory perpendicular to the skull.**	• Place a gloved finger in the hole immediately after removal of a ventricular catheter to prevent the CSF from leaking out which might reduce or shift the ventricle size thereby making catheter insertion challenging. Consider using intrathecal antibiotics according to HCRN protocol if the catheter is not antibiotic impregnated.

Evaluation of Valve and Distal Catheter (Fig. 21.10)

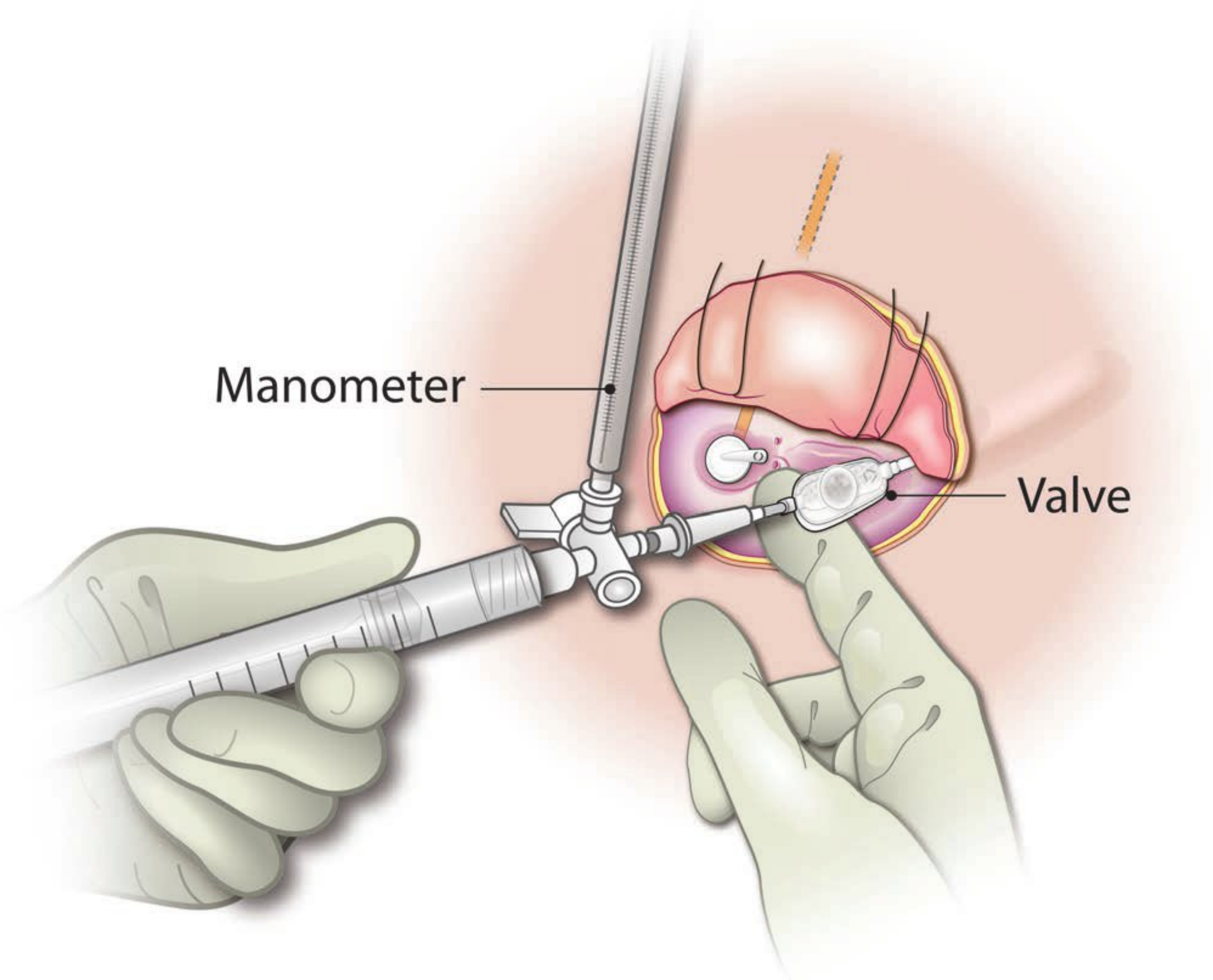


Figure	Procedural Steps	Pearls
Fig. 21.10	**Following revision of the ventricular catheter (or if it is found to be functioning and not revised), a manometer is connected to the proximal part of the valve to test distal run-off. If the pressure is appropriate according to the performance characteristics of the valve, then the proximal catheter is reconnected to the valve and secured with a 2-0 silk tie. If the pressure is higher than inspected, the valve is disconnected from distal tubing and the distal tubing is evaluated again with a manometer. The expected pressure is usually less than 5 cm H_2O. If found to be functional, the distal catheter is flushed with 1–2 mLof normal saline and the presumed compromised valve is replaced with a new one. The connections to the proximal and distal catheters are secured with 2-0 silk ligatures. If the distal catheter is obstructed, it is removed by gently pulling out as one piece through the cranial incision. If the distal catheter is adherent, the abdominal incision will need to be opened in an attempt to free the catheter. In rare cases when total removal of shunt in one piece is not possible, the abdominal incision is opened to remove the rest of the distal catheter.**	• While reconnecting the parts of the shunt, it is important to ensure that there is no airlock in any part of the tubing including the valve.

Revision of Distal Catheter (Figs. 21.11 to 21.15)

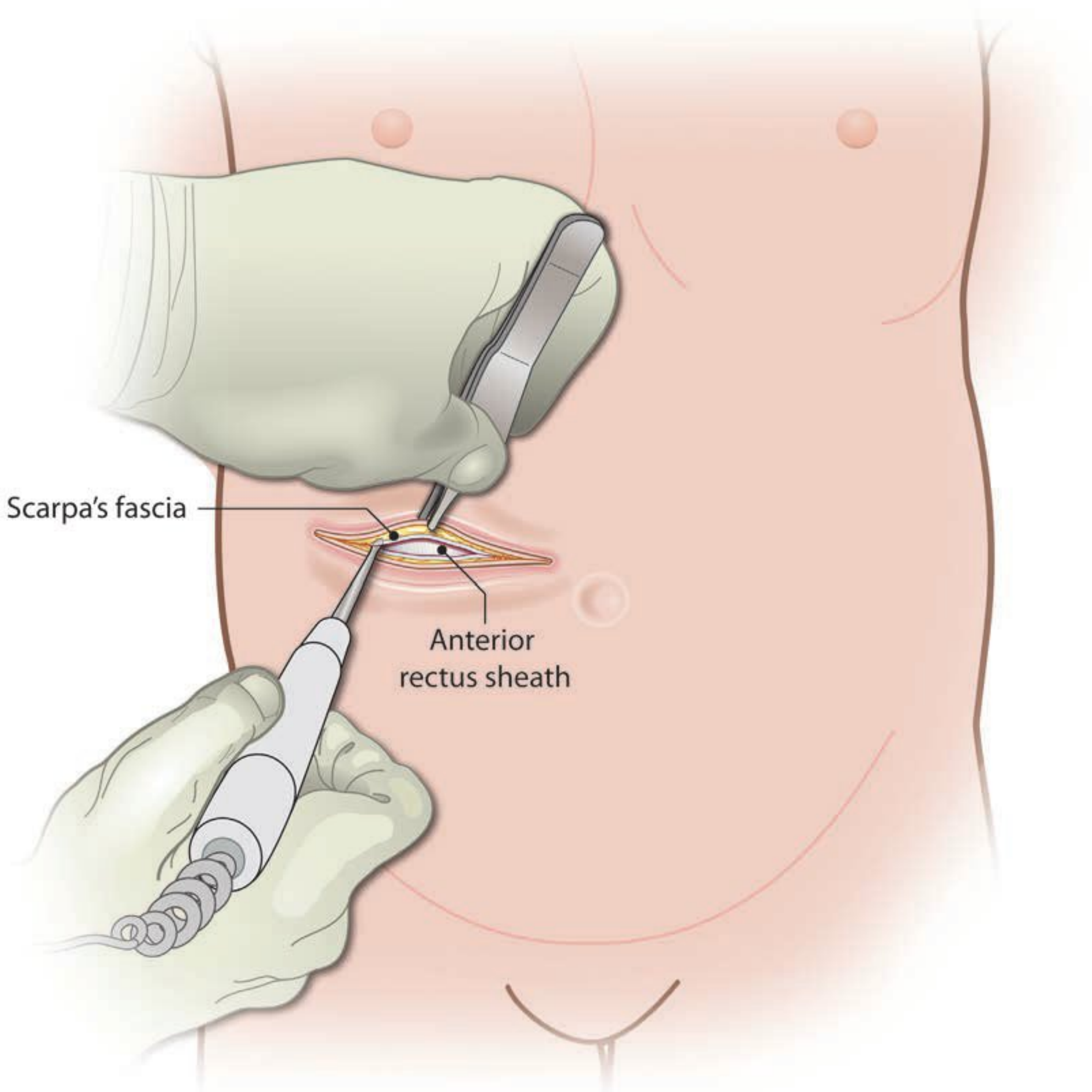


Figure	Procedural Steps	Pearls
Fig. 21.11	**Subcostal approach: After removal of the distal (peritoneal) catheter, a superficial abdominal skin (linear) incision (usually at the site of the previous incision) is made by a no. 15 blade or needle tip cautery. The incision size depends on the patient's age and body mass index. The incision is usually 10–20 mm in length but is tailored to the patient's particular anatomic features. The surgeon holds the skin edges gently distracted so that the incision can be extended through the subcutaneous fat layer and deep membranous layer (Scarpa's fascia) down to the anterior rectus sheath.**	• There are several ways to replace the distal catheter in cases of obstruction. Either a small abdominal opening, blunt abdominal trochar, or laparoscopic technique are performed.[11,12] For obese patients, we prefer a laparoscopic approach. For an open approach, some surgeons prefer a sub-xiphoid, vertical midline incision, while others prefer a right-sided subcostal lateral incision. Both general approaches work well as long as the surgeon is familiar with the anatomy in the abdomen. • We usually use the preexisting incision. The goal is to avoid multiple parallel incisions if possible.

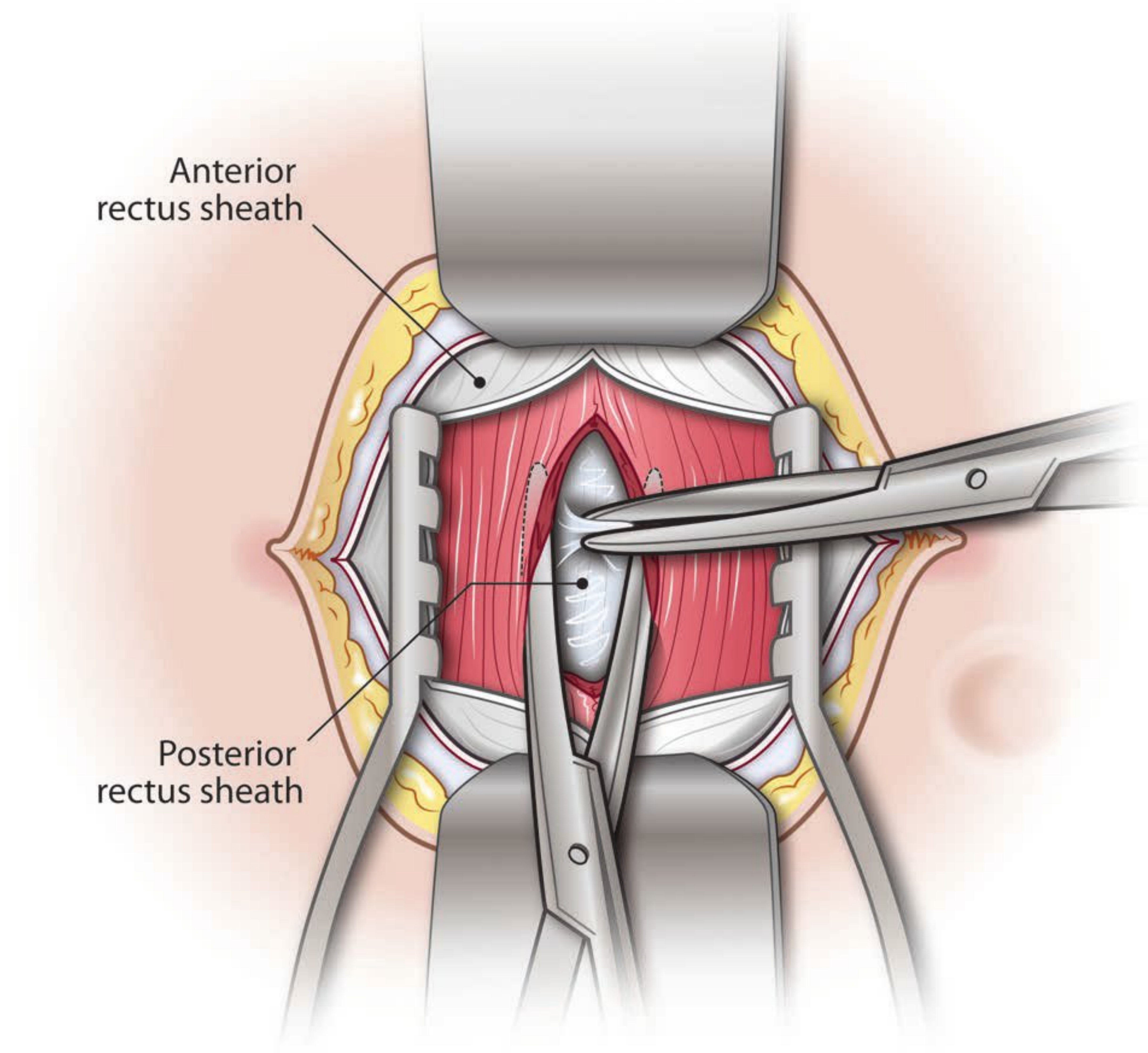


Figure	Procedural Steps
Fig. 21.12	The anterior rectus sheath is opened along the tissue fibers and the rectus muscle is identified. Straight clamps are used to separate along the muscle fibers. A self-retaining retractor is placed to keep the anatomic layers spread. The posterior rectus sheath can be gently elevated with an atraumatic toothed forceps and sharply opened with no. 15 blade or cautery. The incision may be extended with curved Metzenbaum scissors. After advancement of the retractor, the transversalis fascia is opened often revealing extraperitoneal fat.

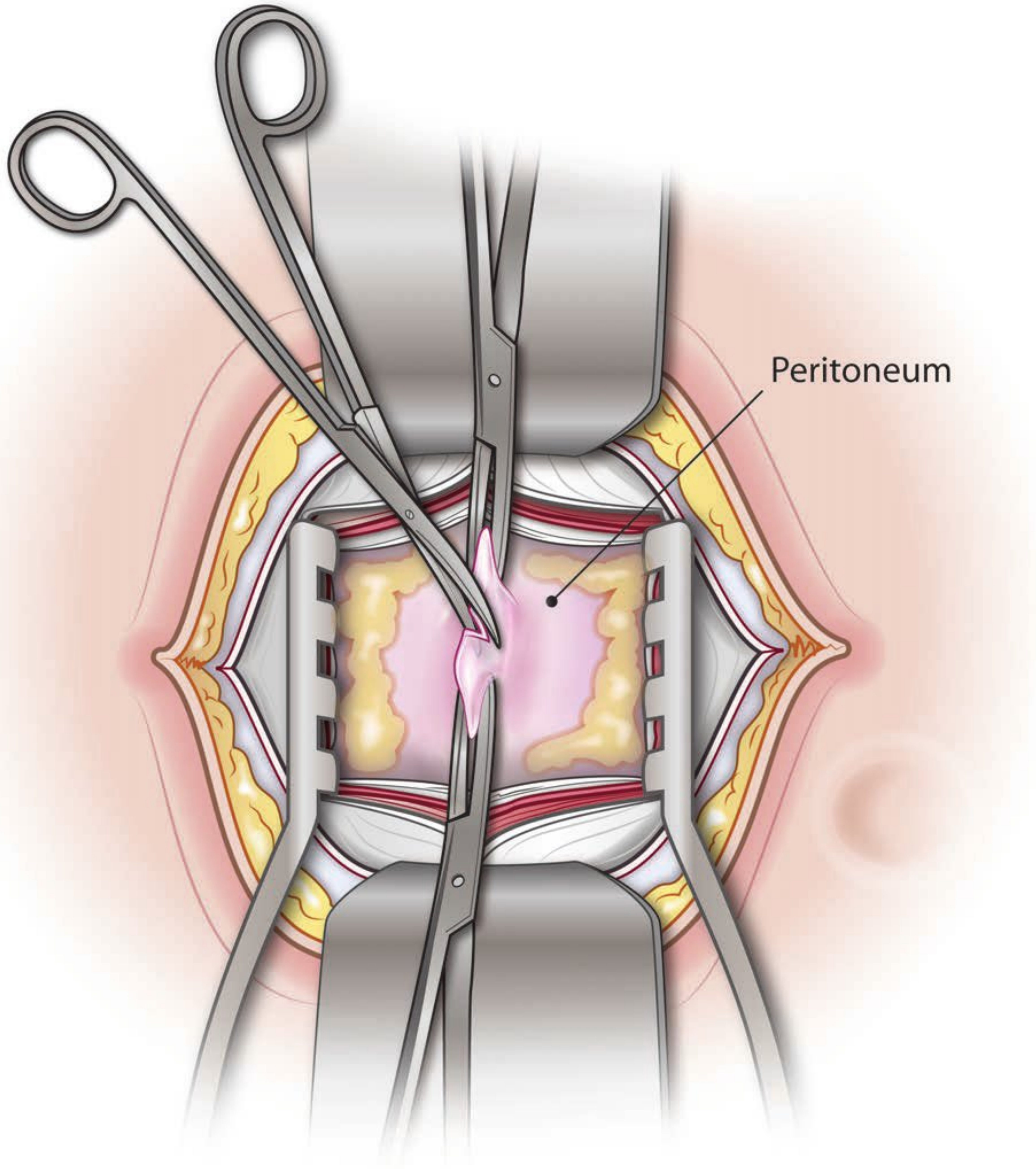


Figure	Procedural Steps	Pearls
Fig. 21.13	**The peritoneum is identified and elevated as between two Halsted mosquito clamps to avoid trapping the viscus below. Delicate scissors are used to create a small 5–7 mm incision into the peritoneum**	• A Penfield no. 4 dissector is gently introduced into the peritoneal cavity to confirm entrance into this space. If the Penfield no. 4 does not pass with ease, it is possible to be in a pre-peritoneal space. Once can often see bowel or liver to confirm presence in the peritoneal cavity.

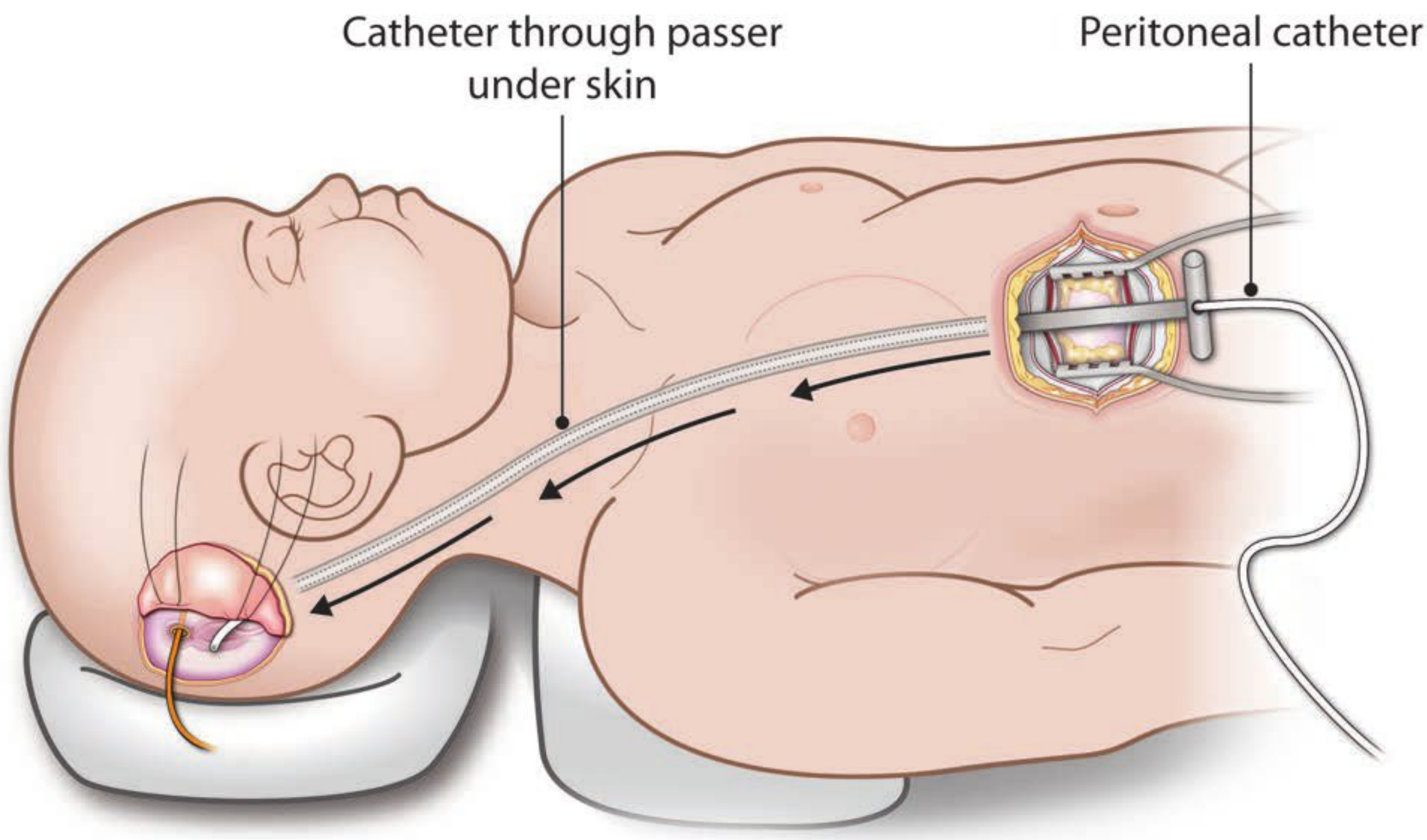


Figure	Procedural Steps	Pearls
Fig. 21.14	**The peritoneal catheter is tunneled subcutaneously through a passer and connected to the valve with a 2-0 silk tie.** **The direction of tunneling is of surgeon preference. We prefer the tunneling from the peritoneal end toward the cranial direction in the majority of patients unless it is safer to tunnel from the cranial direction toward the peritoneum. There is no proven benefit to either tunneling technique.**	• There are many tricks to passing a shunt through the subcutaneous track. One technique is to pass the shunt through the hollow end of the shunt passer while saline is irrigated through the tube from the other end. Another technique includes using a heavy 72-inch 2-silk ligature at the end of the shunt passer and pulling the silk through the subcutaneous track. The new tubing is tied to the silk ligature and pulled through the subcutaneous track as the silk is pulled toward the surgeon. Alternatively, a silk ligature could be placed on the old distal tubing and pulled through the subcutaneous track. The new tubing is tied to the end of the silk ligature and it is pulled toward the surgeon with the new tubing which is then laid in its new position. The proximal catheter/reservoir and valve can subsequently be sutured to the tubing.

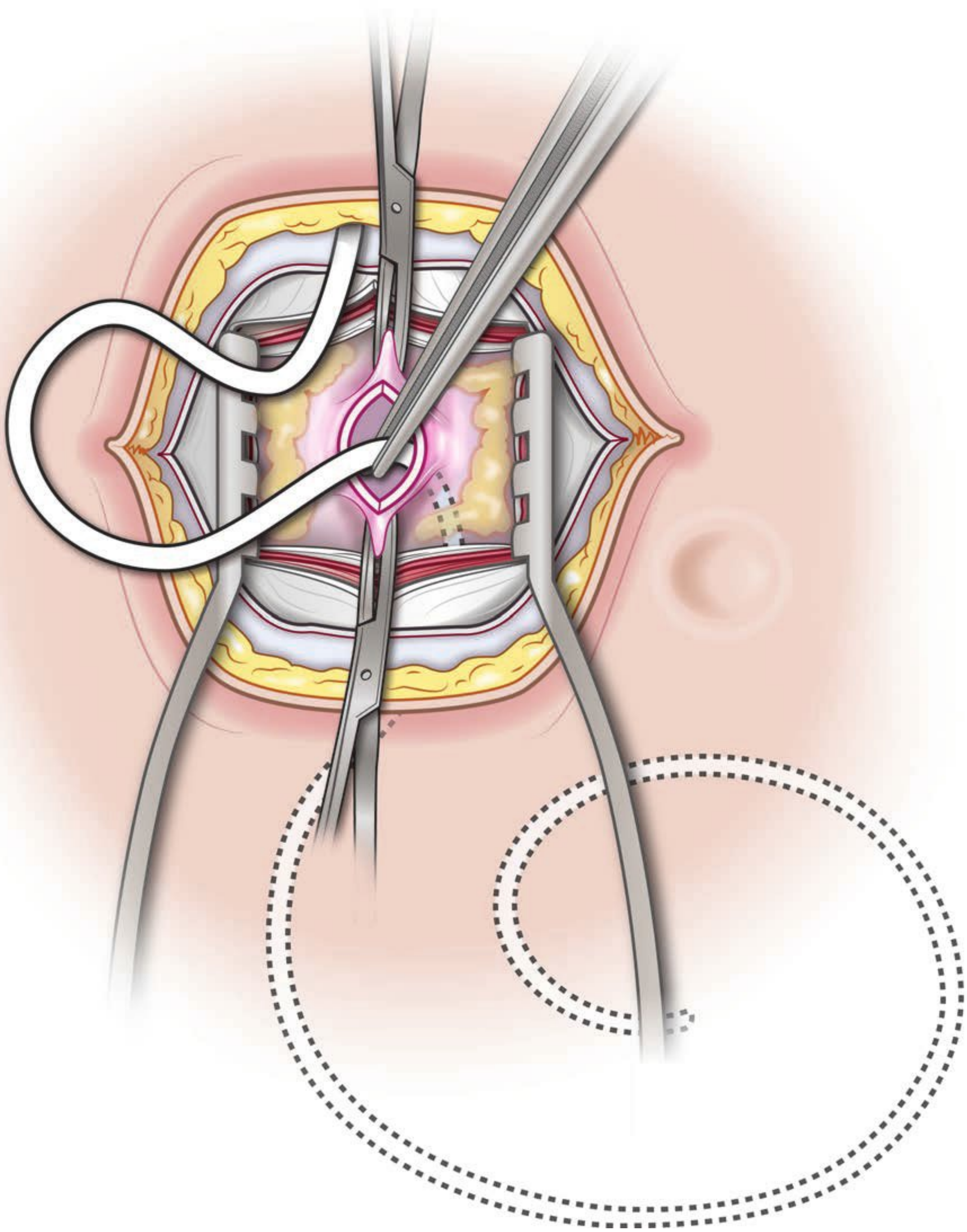


Figure	Procedural Steps	Pearls
Fig. 21.15	**After CSF flow is observed, the distal catheter is inserted into the peritoneal cavity with two smooth forceps (Adson or bayonet). The peritoneum is closed with absorbable suture maintaining the shunt tubing in the peritoneum and away from the suture loops.**	• The catheter should smoothly slide into the peritoneum. If it forms a tight coil or is ejected, it is possible to be pre-peritoneal or trapped in adhesions.

Placement: Ventricular Catheter and Tunneling for External Drainage (Fig. 21.16)

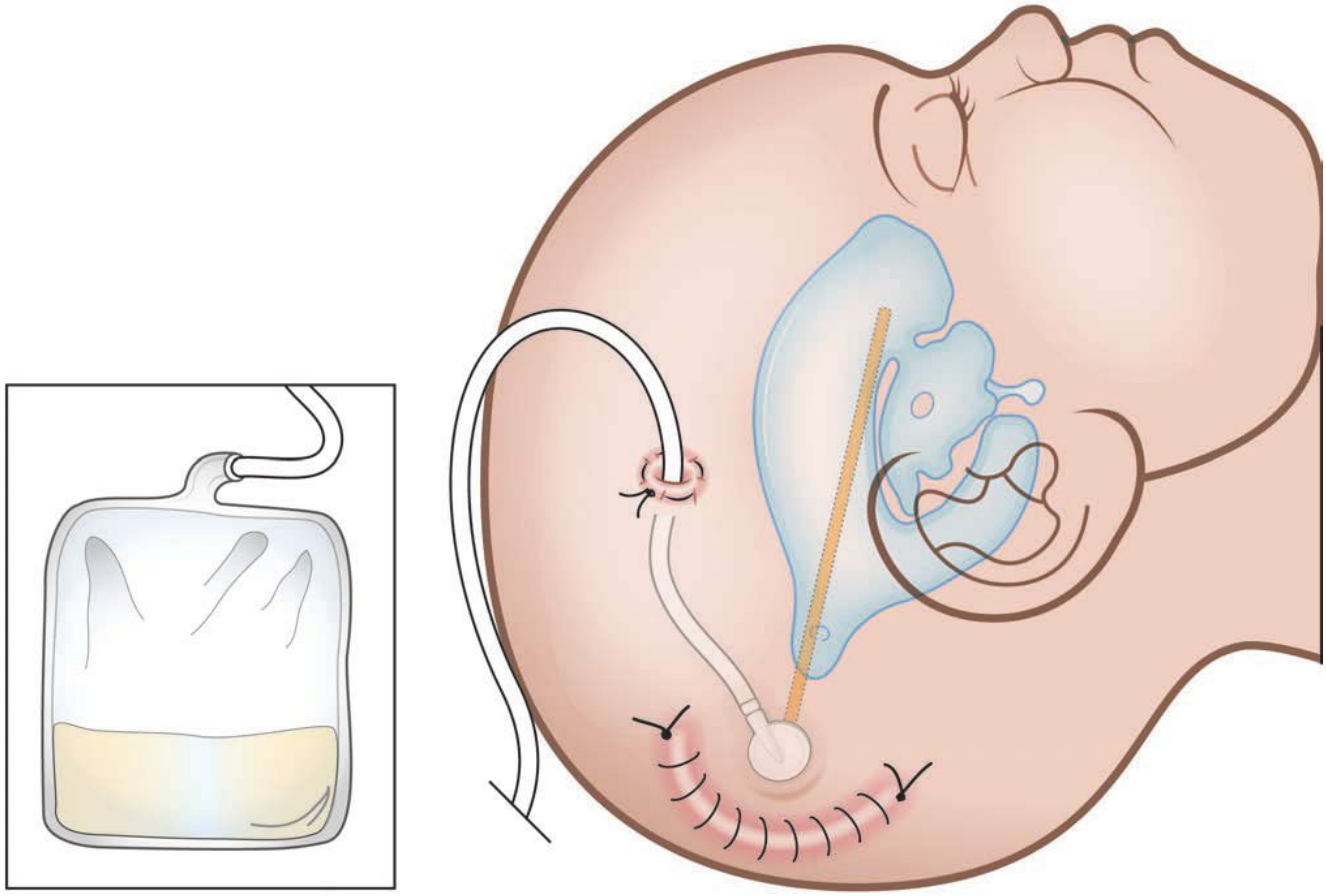
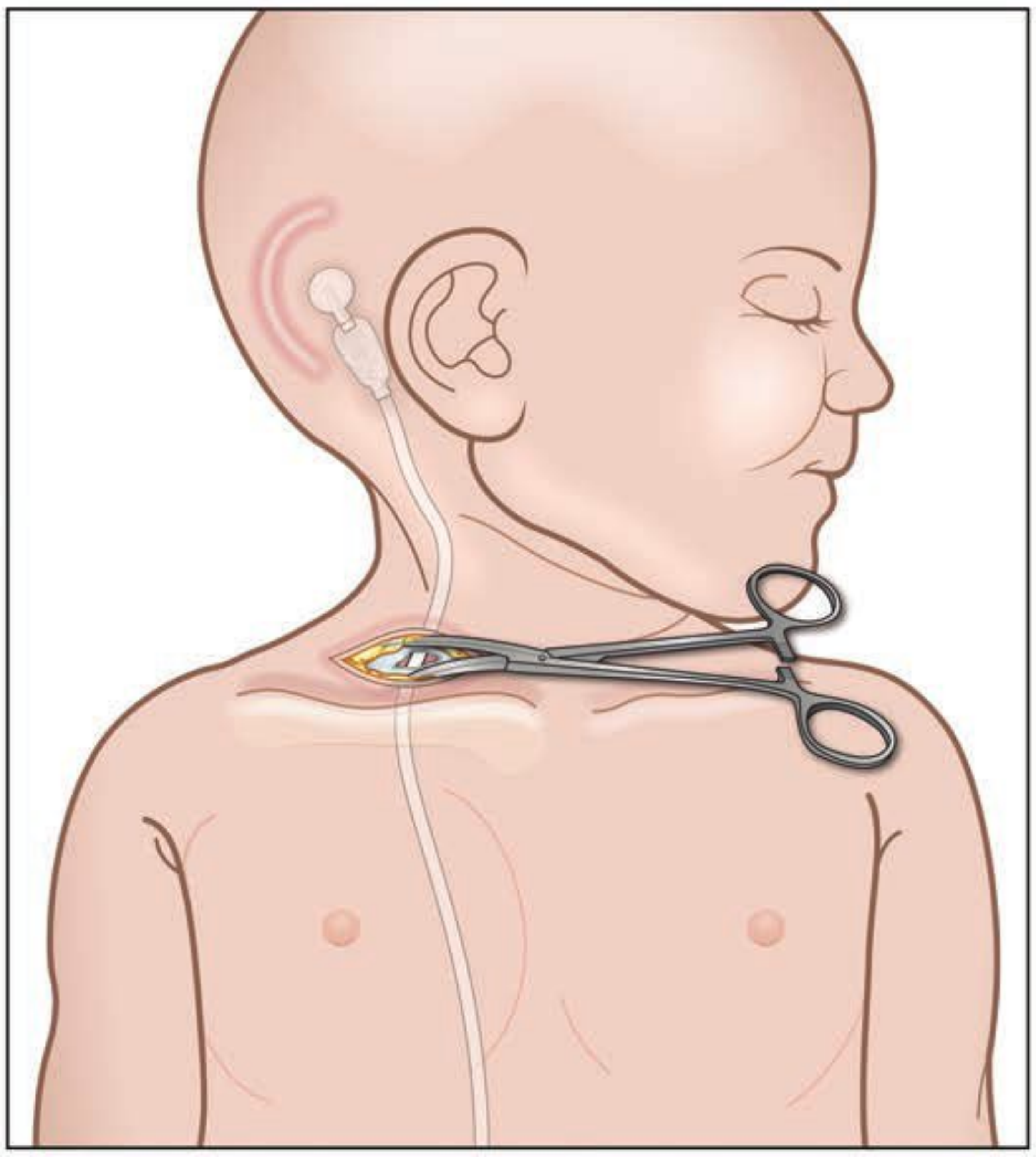


Figure	Procedural Steps	Pearls
Fig. 21.16	**If circumstances require removal of an entire shunt system with continued need for ventricular drainage, then an external drain is placed. Placement of antibiotic-impregnated ventricular catheter[9] occurs with ideal placement of the tip anterior to the ipsilateral foramen Monro. We typically utilize stereotactic navigation or alternatively use anatomic landmarks.** **The distal end of the tubing is then tunneled subcutaneously utilizing a trocar to an exit site at least 5 cm from the edge of incision. The exiting tubing is securely fixed with a purse string stitch to prevent CSF leak and connected to sterile external CSF collection bag** (inset)**.**	• Prevent CSF from leaking to improve likelihood of cannulating the ventricle.

Closing

- After appropriate irrigation wounds are closed in a multilayered fashion. We use absorbable braided suture sutures for subcutaneous and absorbable monofilament sutures for skin closure. Current sutures are antibiotic impregnated.
- If the wound is of questionable integrity, we utilize nylon sutures for closure.
- The abdominal wound is also closed in a layered fashion: transversalis fascia, anterior and posterior rectus sheaths, Scarpa's fascia, and the skin. Meticulous attention is paid throughout the closing to match up the anatomic layers and avoid kinking or injuring the shunt tubing.
- Glue is placed on the skin surface after subcuticular closure.

Externalizing the Distal Catheter (Fig. 21.17)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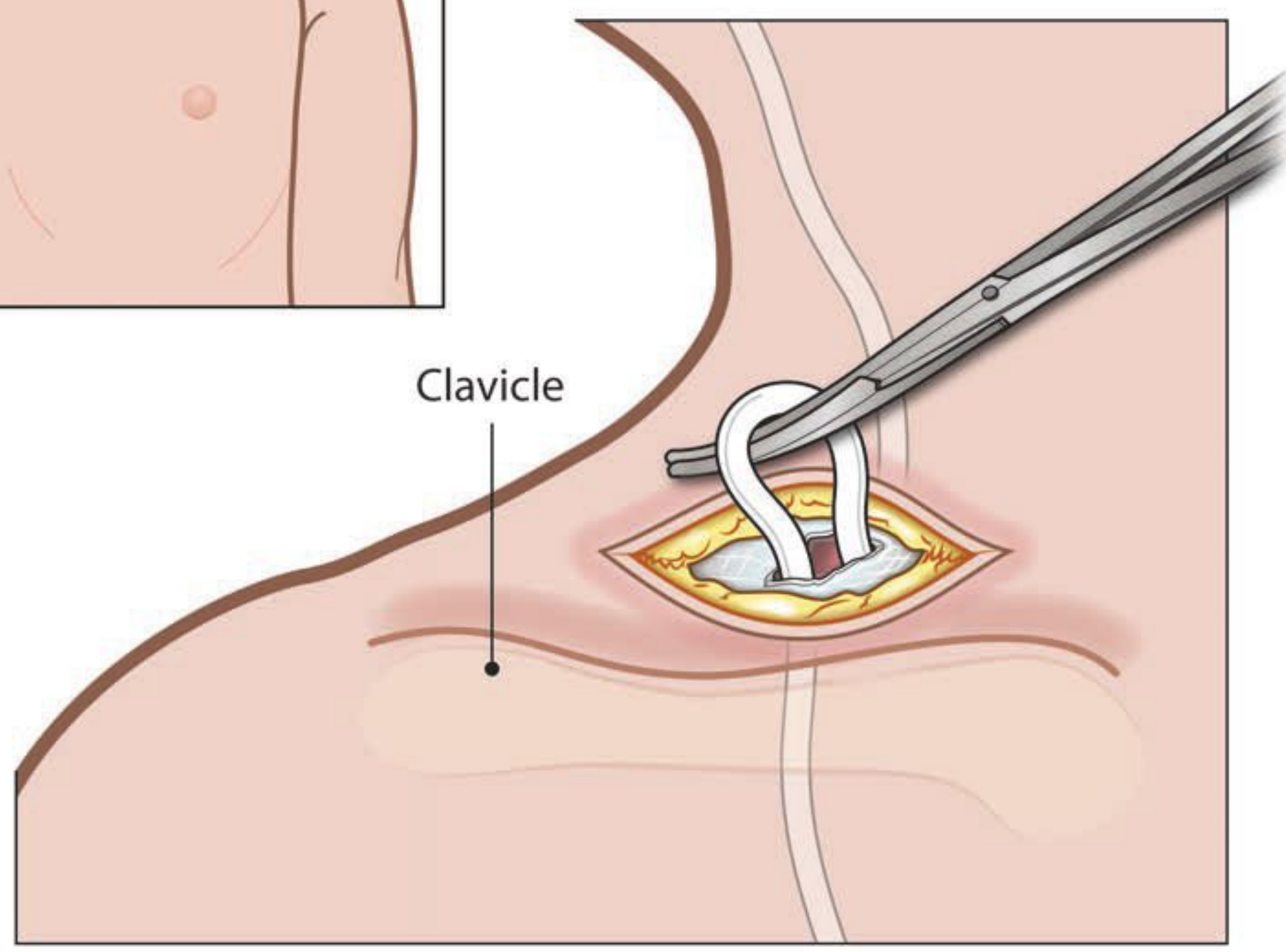

b

Figure	Procedural Steps	Pearls
Fig. 21.17	**(a) A small incision (1 cm) is marked at a level near the clavicle and made with a no. 10 blade through the epidermis. Use monopolar cautery to dissect down to the subcutaneous fat. Use blunt dissection with small hemostat to find the catheter. Typically, a connective tissue sheath may need to be incised with cautery to isolate the tubing. (b) The distal part of the tubing is then externalized through the clavicular incision.**	• One may use ultrasound to assist with tube localization if it is not easily palpable. In cases of pseudocyst the distal tubing may be used to drain the cyst, and the cyst fluid should be sent for stat Gram stain and culture. Propionibacterium is a common cause of pseudocyst but may take 2 weeks for a positive culture to grow.

Wound Closure (Fig. 21.18)

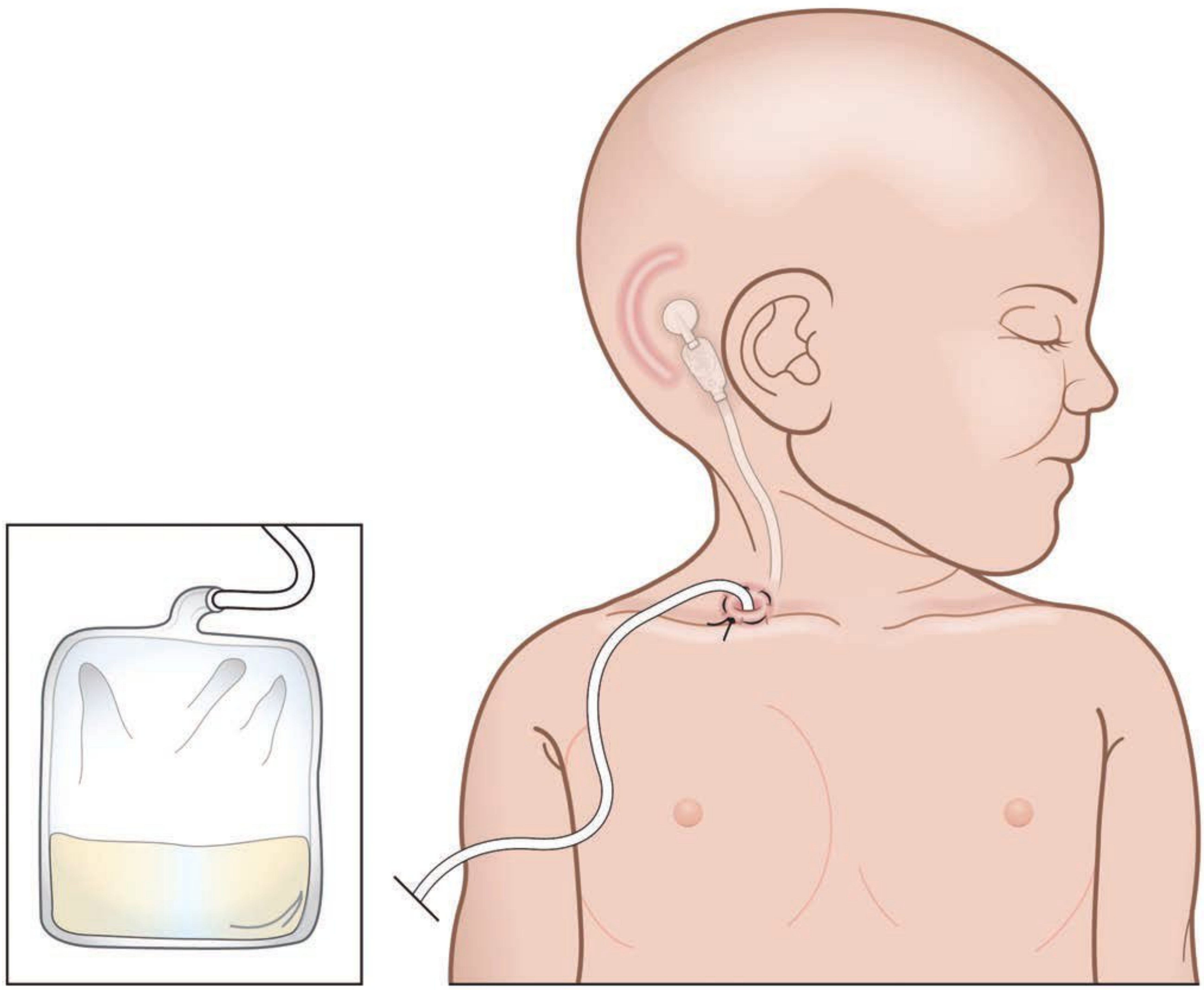

Figure	Procedural Steps	Pearls
Fig. 21.18	**A nylon purse string suture is used at tubing exit site and the catheter is connected to a sterile, external CSF collection bag** (inset)**.**	• Make sure that purse string suture is not to tight and allows CSF passage.

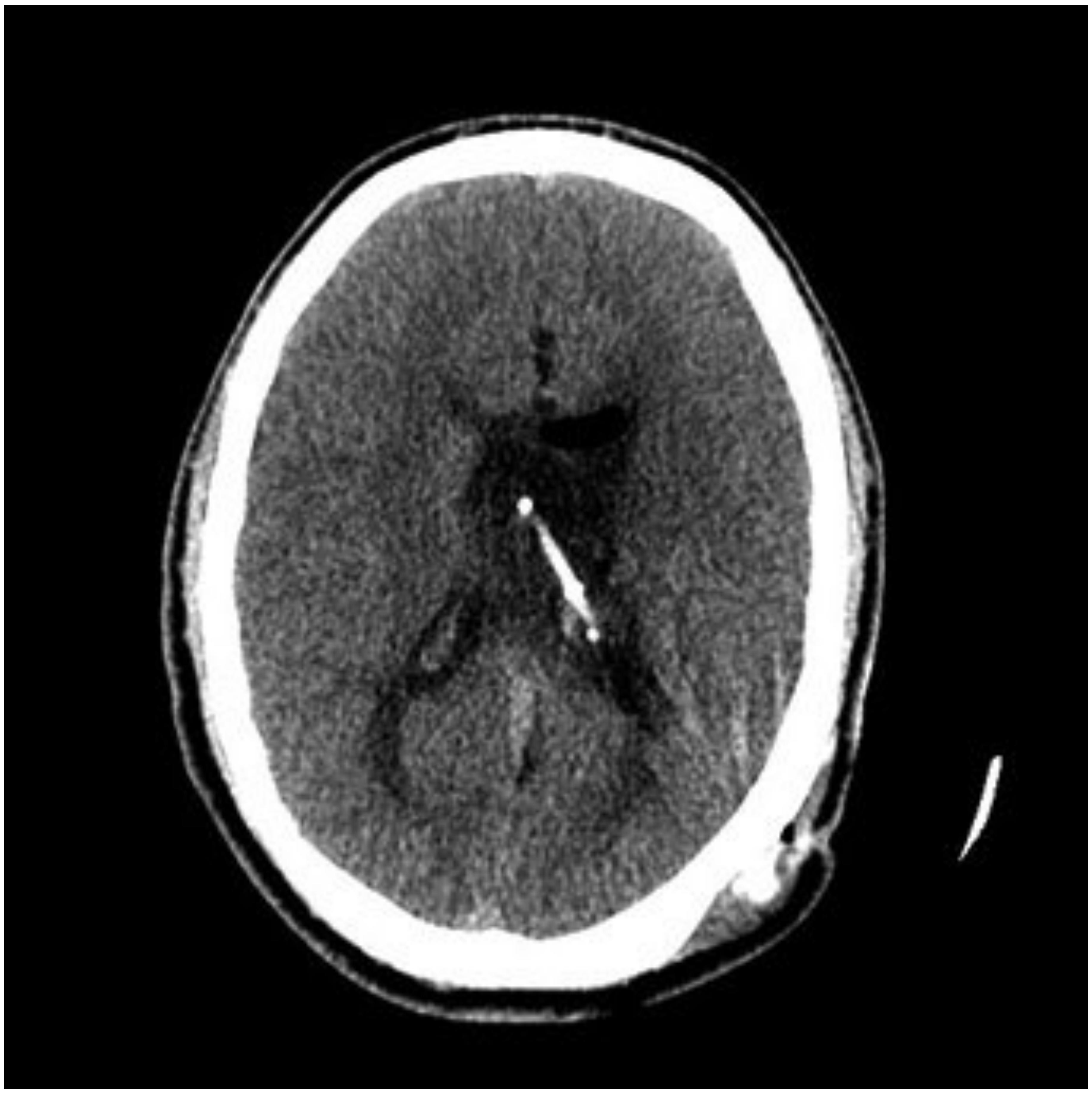

Fig. 21.19 Postoperative CT scan of same patient depicted in Fig. 21.2 after shunt revision.

Postoperative Management

Practice patterns vary: we routinely obtain an immediate postoperative CT if the ventricular catheter is revised. The immediate postop CT serves as a baseline for the follow up (**Fig. 21.19**). A shunt series consisting of plain radiographs is reasonable after most procedures to ensure proper placement of shunt and as a baseline assessment for comparison in follow-up should problems arise.

The usual length of stay in the hospital is 24–72 hours depending on complexity of the case and clinical condition of the patient. Typical follow-up occurs at 2 weeks for a wound checkup then at 6 weeks with repeat imaging, typically a rapid sequence MRI.

Special Considerations

In pediatric patients we typically follow-up at yearly intervals with or without imaging, depending on symptoms. If the patient is well, no imaging may be needed except at surveillance scan intervals of 1–5 years. We obtain a shunt series to ensure no catheter disconnections are seen and to follow the length of the distal catheter after the last shunt insertion. If the patient goes through a rapid growth period or if there is any swelling in the shunt track, another surveillance shunt series may be appropriate.

Programmable shunts need to be reprogrammed and the valve setting confirmed following exposure to the high magnetic field of an MRI.

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22 Pituitary Apoplexy

Kalmon D. Post and Soriaya Motivala

Introduction

Pituitary apoplexy is a neurosurgical emergency in which prompt intervention may halt and even reverse associated neurologic deficits and possible mortality. The condition results from hemorrhage or necrosis of a pituitary tumor. It has been found to occur in 0.6 to 10.5% of all pituitary adenomas.[1]

In 1950, Brougham was the first to describe the clinical and pathologic findings of five patients who presented with changes in mental status, headaches, meningismus, and ocular disturbances.[2] Since then, there has been extensive interest in the entity as well as considerable debate on what the term *pituitary apoplexy* encompasses. In fact, there have been reports of silent pituitary apoplexy.[3] Mohr estimated the incidence of asymptomatic hemorrhages in pituitary adenomas to be 9.9% as opposed to 0.6% that presented with clinical findings.[4] Furthermore, Onesti described five patients with subclinical pituitary apoplexy, that is, a clinically silent yet extensive hemorrhage into a pituitary adenoma.[5]

With such a broad interpretation in the literature it is increasingly helpful to define the diagnosis of pituitary apoplexy by clinical parameters that include the sudden onset of headache, meningismus, visual impairment, and occulomotor abnormalities in varying combinations along with radiologic evidence of hemorrhage in or sudden expansion of a pituitary adenoma.

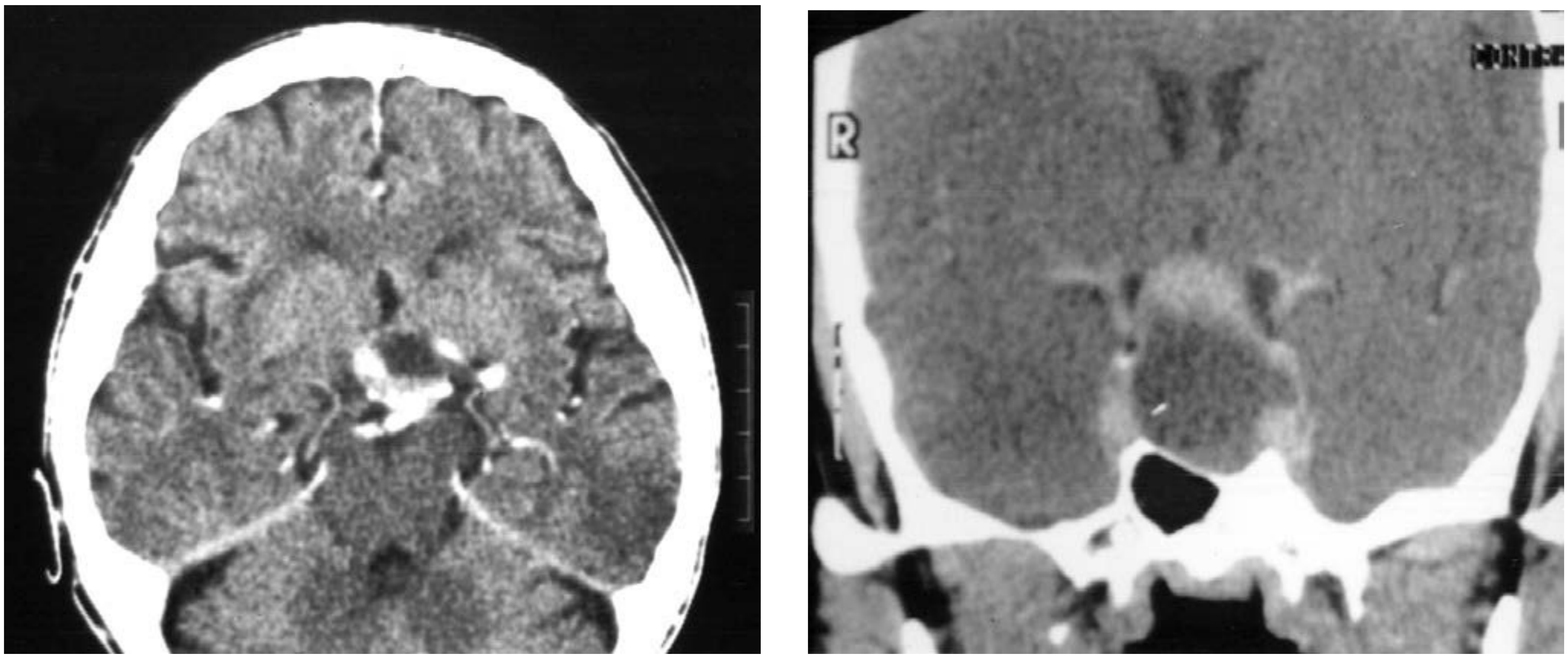
Indications

- Diagnosis of apoplexy requires evidence of hemorrhage or rapid expansion on either computed tomography (CT) or magnetic resonance imaging (MRI) within a preexisting adenoma as well as clinical correlation.
- Patients often present with sudden onset of headache, meningismus, disturbances of mental status, and ocular findings that can range from ophthalmoplegia and visual field defects to monocular or binocular blindness.
- Bacterial and viral meningitis, intracerebral hematoma, optic neuritis, brainstem infarction, temporal arteritis, encephalitis, transtentorial herniation, cavernous sinus thrombosis, and migraine may all in one form or another mimic an acute pituitary vascular accident.[1,6]
- The most important entity that must be considered and excluded is an aneurysmal subarachnoid hemorrhage.[7,8]
- A ruptured Rathke's cleft cyst, though rare, may also mimic pituitary apoplexy.[9,10]
- Initial medical stabilization with intravenous fluid and steroids is required in all cases to correct the profound hypoadrenalism that may result.
- Transsphenoidal resection is considered for those with continued neurologic deficit after initial conservative therapy, and immediately for those with loss of acuity and/or fields.[6]
- While ophthalmoplegia has been shown to correct as frequently with conservative management as with surgical intervention,[11–13] surgical resection offers the most hope of improving visual field and acuity deficits. Many studies have suggested that decompression within 1 week may offer the best chance of visual recovery.[11,14] Others have shown improvement with decompression months after initial visual loss.[15]

Preprocedure Considerations

Radiographic Imaging

- CT without contrast is most valuable the first 2 days of hemorrhage (**Fig. 22.1**).
- After 48 hours, MRI is more sensitive, as it can better delineate older blood from tumor and areas of necrosis from cystic changes (**Fig. 22.2**). The MRI is also helpful in estimating the age and time course of the hemorrhage. Hemorrhages less than 7 days will appear hypo- to isointense on T1- and T2-weighted images. During the second week a hyperintense signal can be found bordering the hematoma. By the second week increasing hyperintensity will be seen throughout the hematoma on both T1- and T2-weighted images.
- If clinically warranted, an angiogram or magnetic resonance angiogram (MRA) should be obtained if neither CT nor MRI is able to rule out a concomitant aneurysm.
- MRI will also best demonstrate the extension of the tumor or hemorrhage into the suprasellar space as well as chiasmal compression and cavernous sinus extension. Furthermore, the intracarotid distance can be delineated in order to avoid injury during surgical resection.



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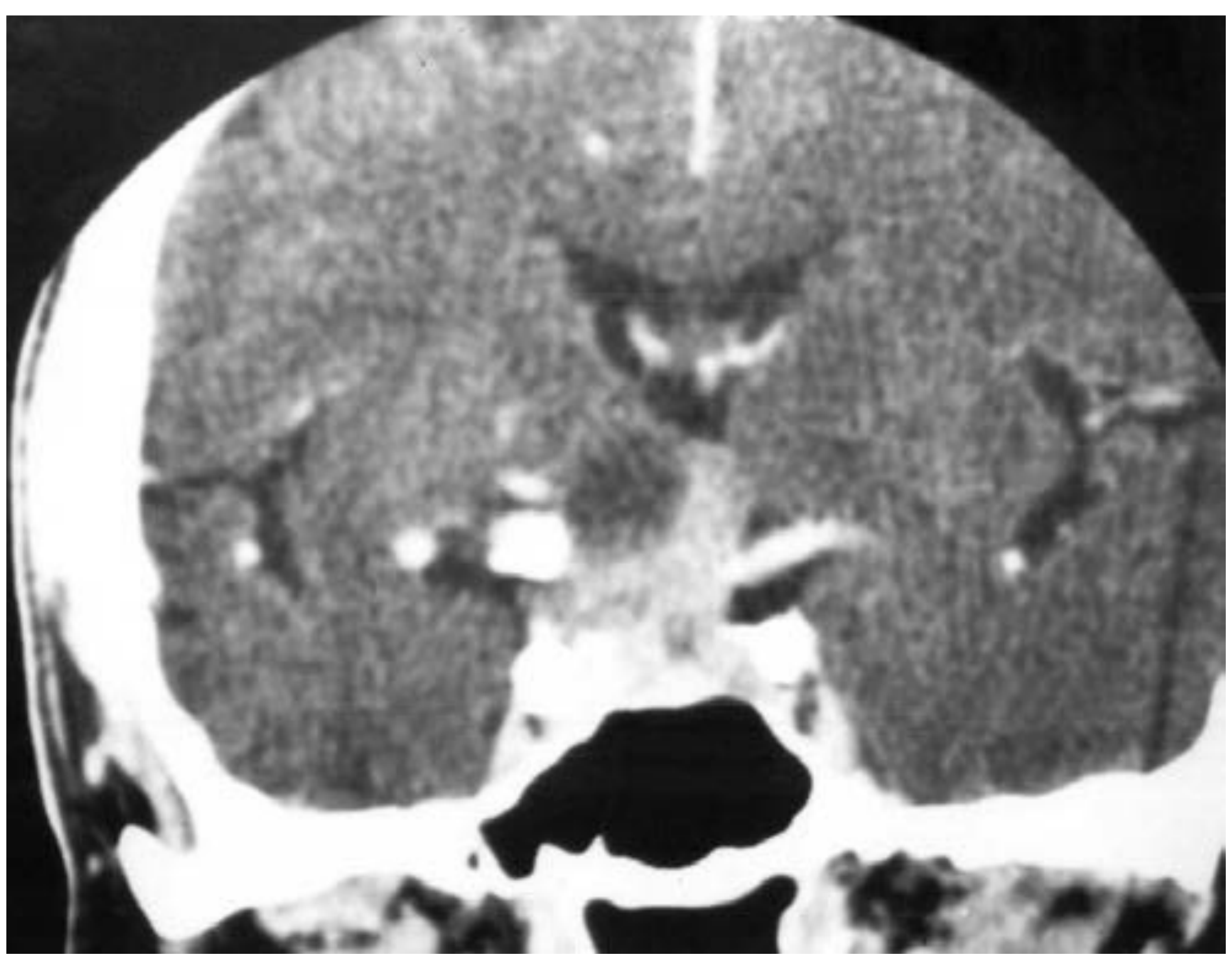
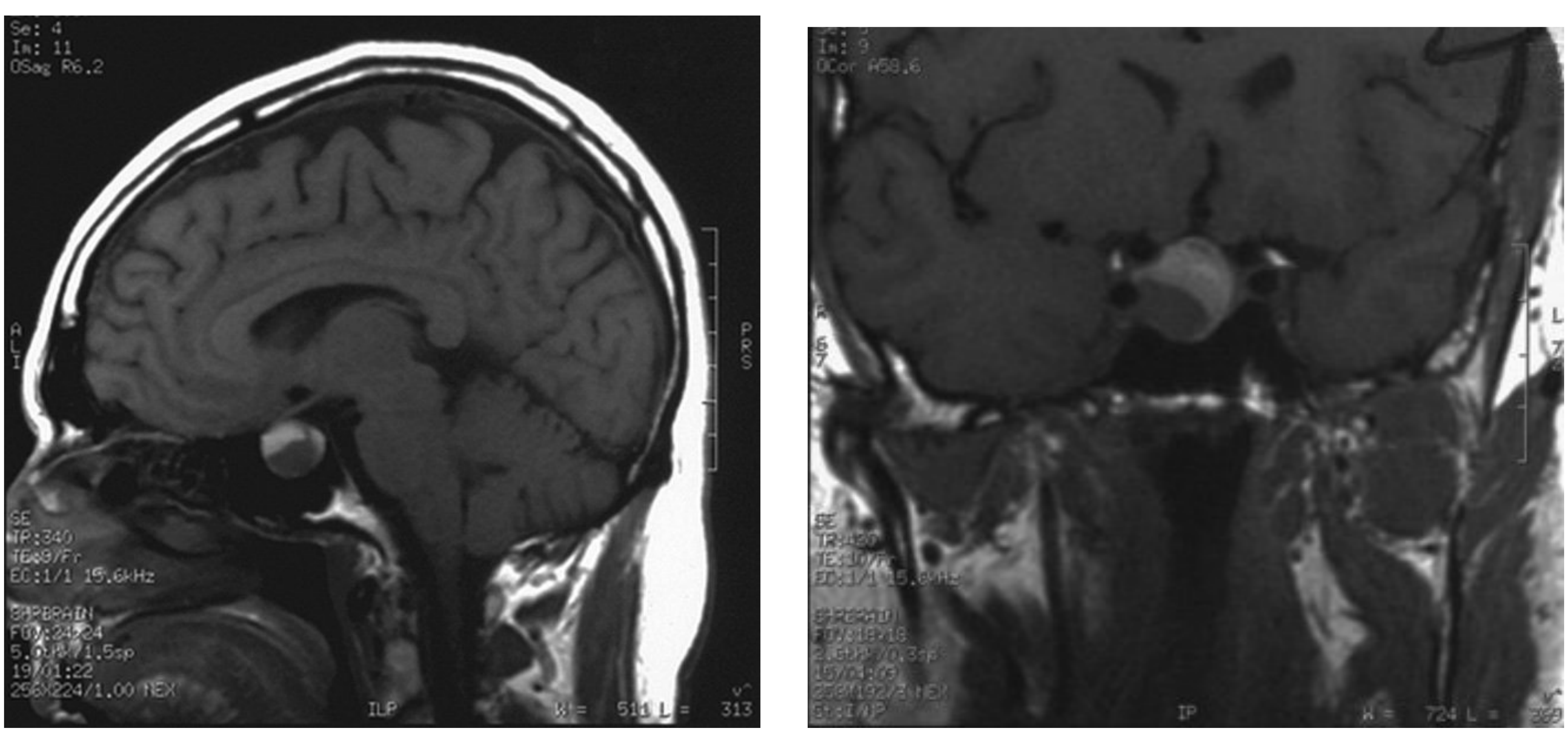


c

Fig. 22.1a–c **(a)** Axial and **(b, c)** coronal CT scans showing hemorrhagic cavity with fluid-fluid level and surrounding enhancing sellar lesion.



a b

Fig. 22.2a, b **(a)** T1-weighted sagittal and **(b)** coronal MRI demonstrating a sellar mass of heterogeneous signal intensity, with suprasellar extension of increased signal intensity consistent with acute hemorrhage.

Medication

- It is our practice to give dexamethasone 16 mg/day prior to surgery and to taper to a slightly supraphysiologic level postoperatively.
- Furthermore, it is our practice to send a full endocrine panel at this time as a baseline.
- Thirty minutes prior to initial incision, 1.5 g of cefuroxime is given (if the patient has no reported allergies to penicillin; otherwise, vancomycin and gentamicin are preferred). Antibiotics are continued postoperatively while the nasal packings are in place.

Operative Field Preparation

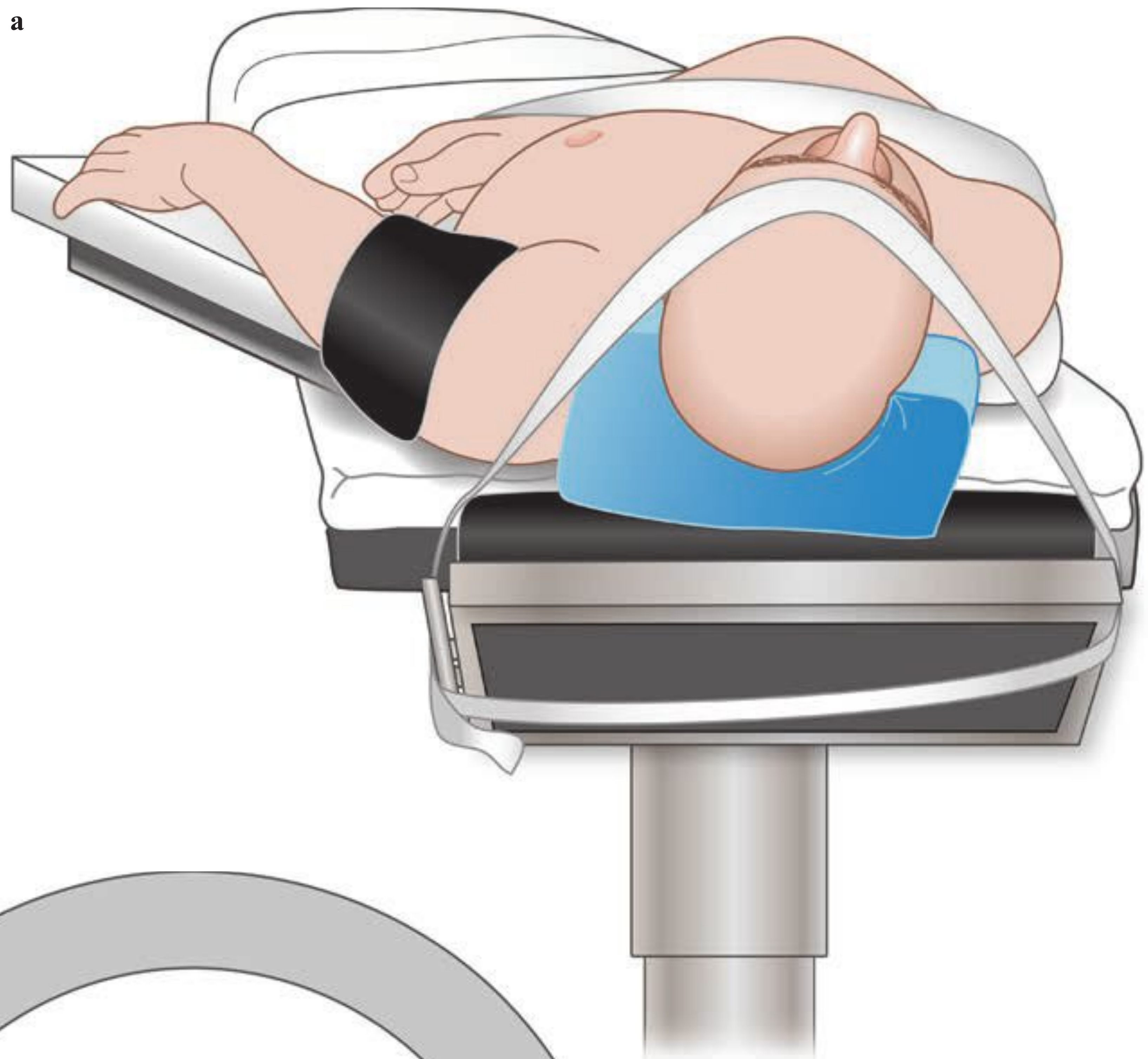
- After intubation the patient's eyelids are gently taped shut and betadine is applied over the nares, cheeks, and upper lip.
- Betadine-dipped swabs are used to clean the inside of both nostrils as well as under the upper lip (for possible sublabial approach should it become required).
- The right abdomen is prepped sterilely with a separate tray of betadine for possible fat graft.
- Fluoroscopy or image-guided navigation are employed throughout the case to determine appropriate trajectory in a midline plane.

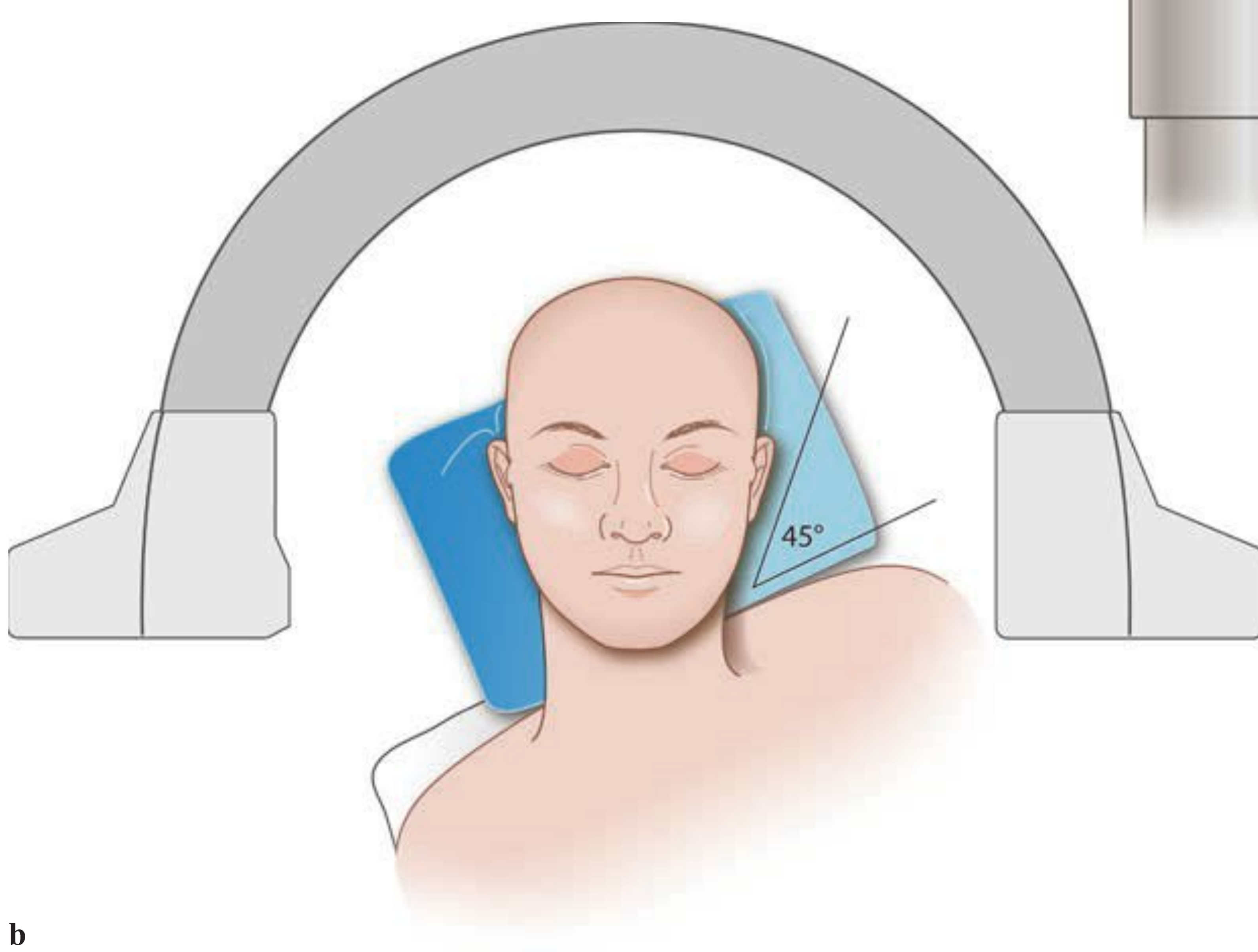
Operative Procedure

Microscopic Pituitary Tumor Resection

Positioning and Fluoroscopy (Fig. 22.3a, b)

a





b

Figure	Procedural Steps	Pearls
Fig. 22.3	**Patient is placed on far right edge of table in supine position. Right arm is bent 90 degrees and secured across chest with padding and tape.** **(a) Head is placed on a foam "holder" with right ear tilted 45 degrees in relation to right shoulder. Head of bed is flexed just slightly such that the chest does not interfere with use of instruments.** **(b) Fluoroscopy is positioned at the head of the bed to obtain lateral view of the sella.**	• Patient is positioned to allow for ease of trajectory to the sella. • If used, image guidance systems should be set up to allow ease of viewing while surgeon is in operative position.

Fluoroscopy Imaging (Fig. 22.4)

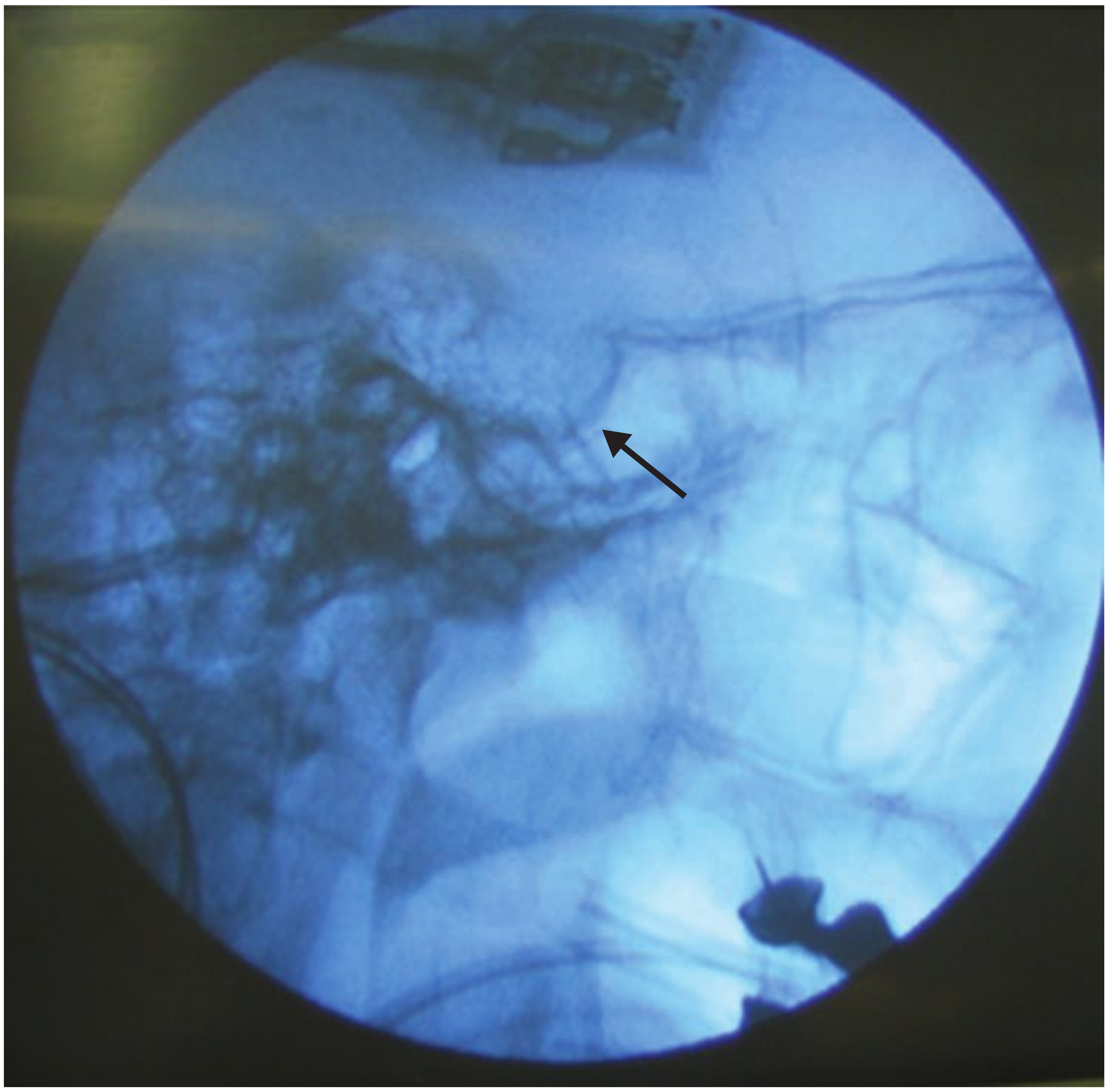
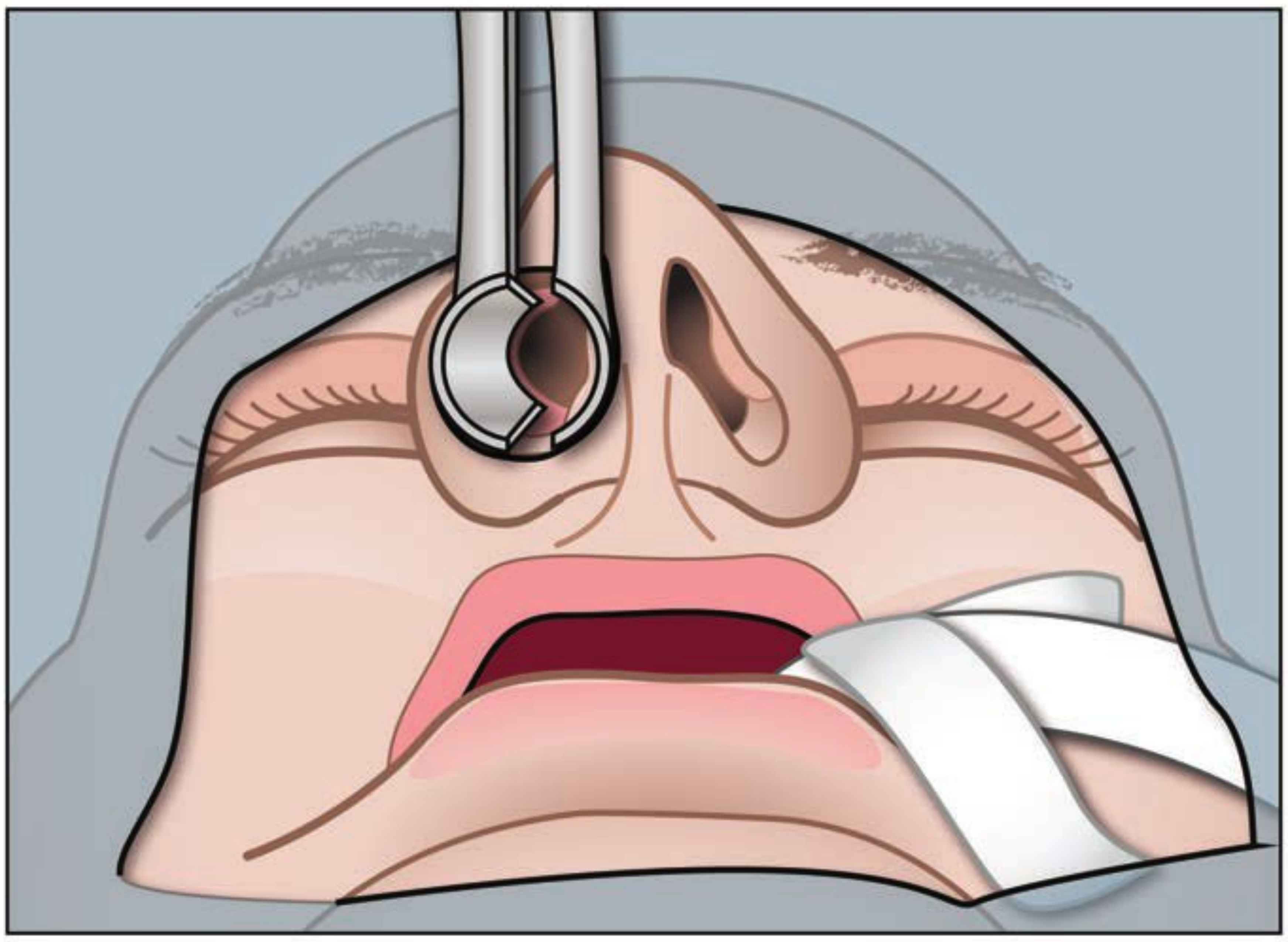


Figure	Procedural Steps
Fig. 22.4	**Initial lateral skull fluoroscopic images are obtained to evaluate trajectory to the sella.**

Draping and Operating Microscope (Fig. 22.5a, b)



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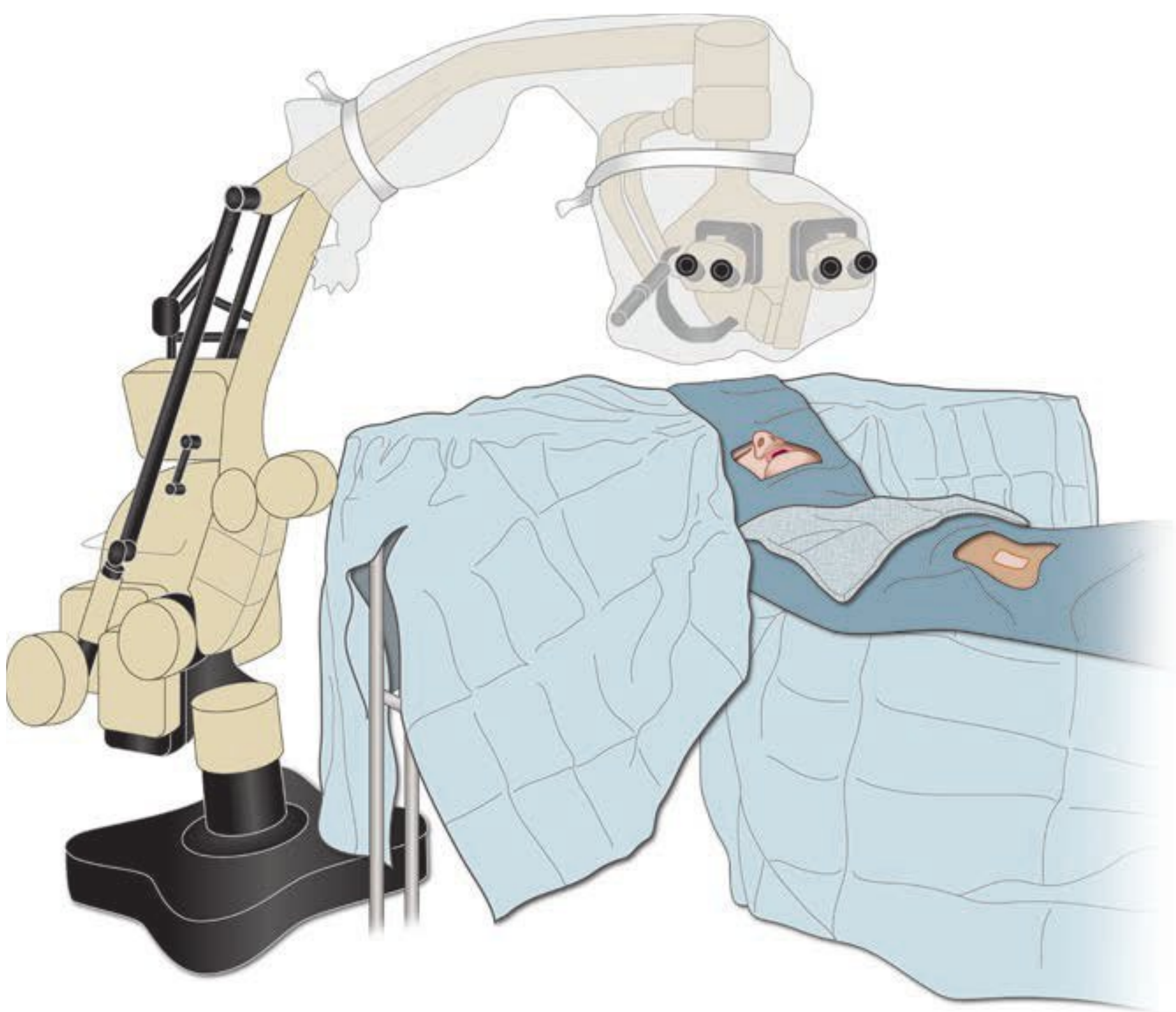
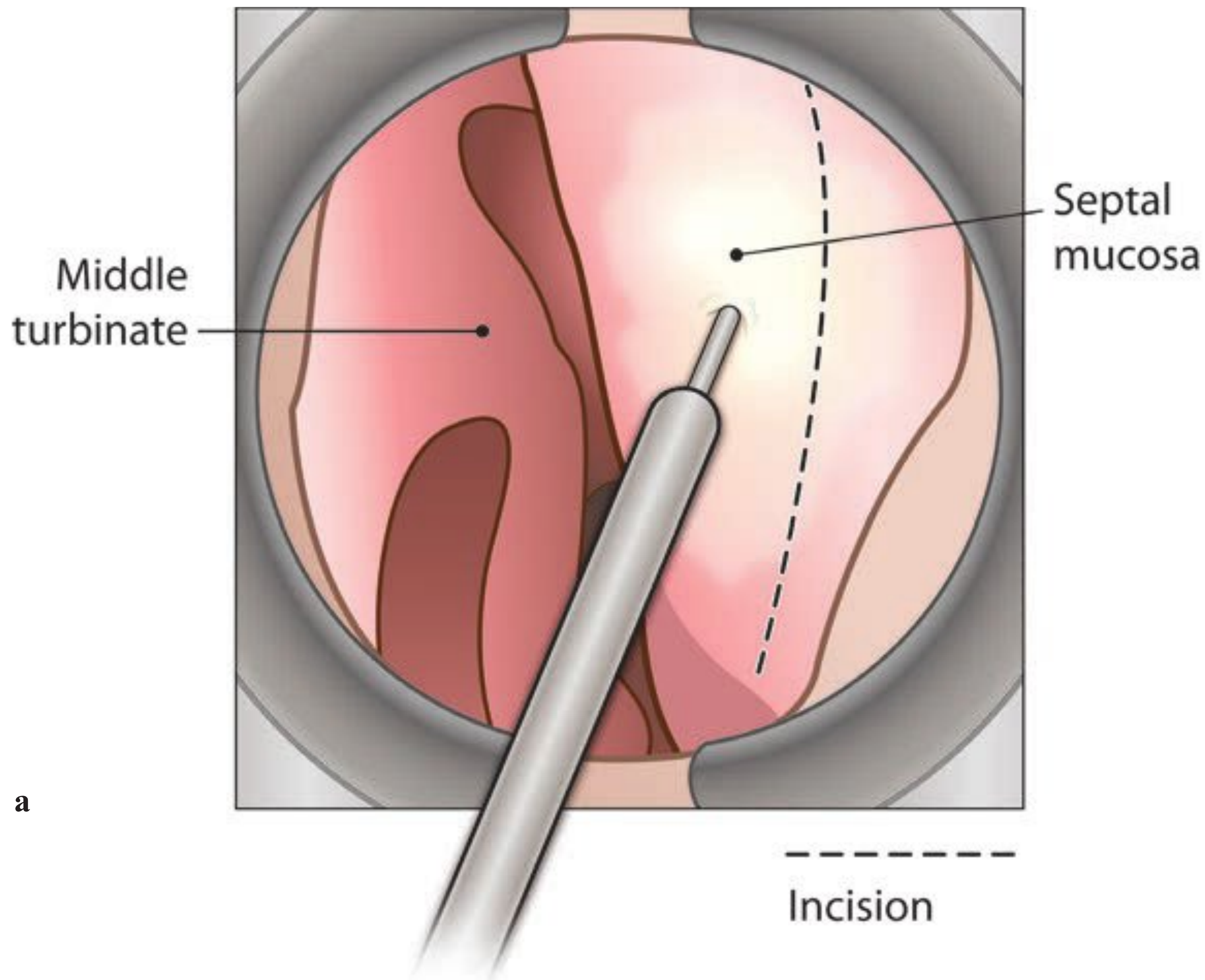


b

Figure	Procedural Steps	Pearls
Fig. 22.5	**(a) Surgical fields of the nasal passages and the right lower abdominal quadrant are prepped and draped in a sterile fashion. (b) The operating microscope is sterilely draped and positioned for optimal view through the right nasal passage.**	• Abdominal fat graft may become required if cerebrospinal fluid is encountered during resection (see **Fig 22.12**). • When operating through the right nostril, the observer is positioned to the left.

Mucosal Flap (Fig. 22.6a, b)



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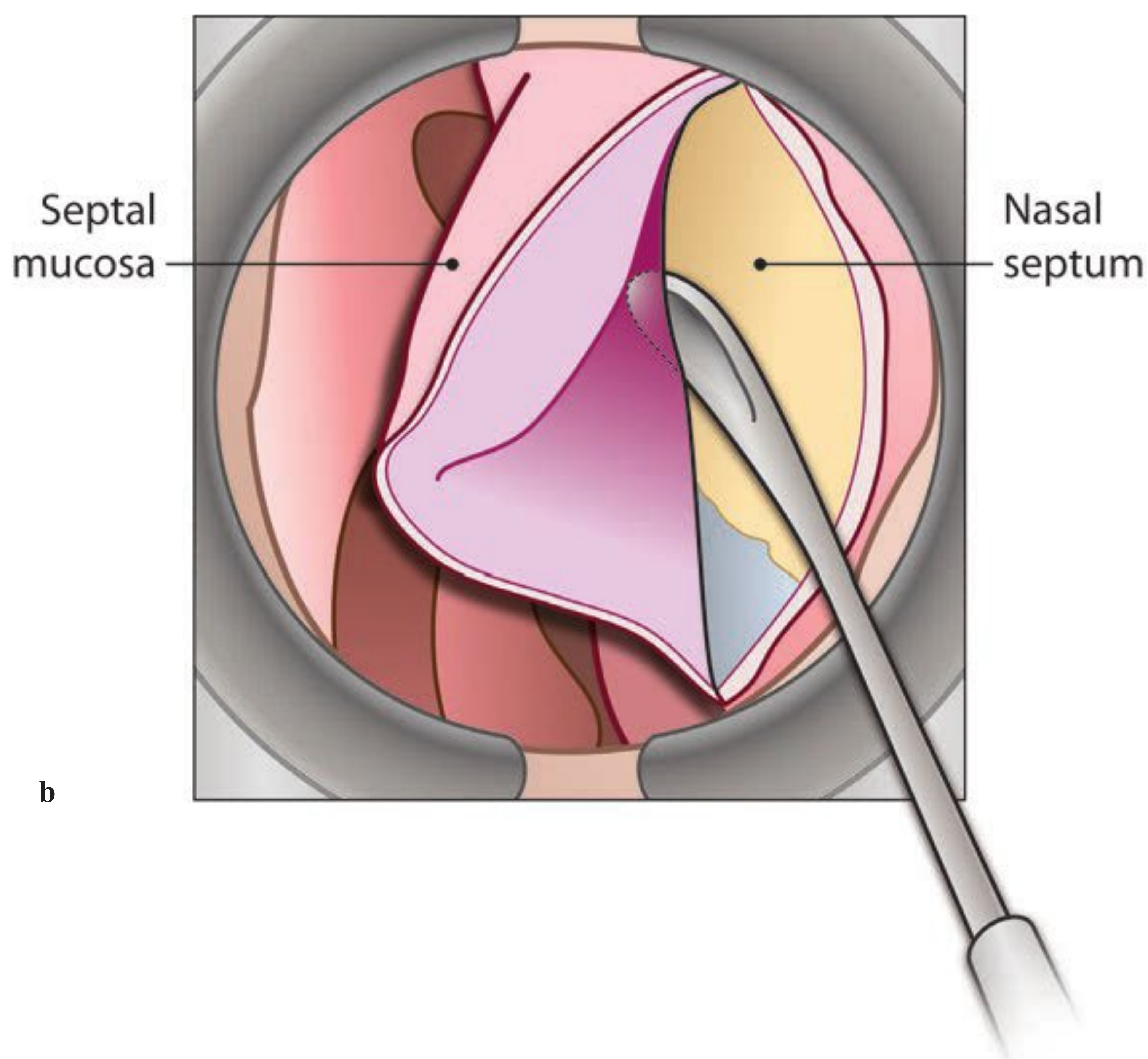


b

Figure	Procedural Steps	Pearls
Fig. 22.6	**(a) Using a handheld speculum as well as fluoroscopy/image guidance to direct the dissection toward the sella, the nasal mucosa is identified in the midline and 1–2 mL of lidocaine with epinephrine 1:100,000 are injected between the mucosa and bony nasal septum. This causes the mucosa to blanche and separate from the septum.** **(b) A no. 15 blade is then used to make a linear incision in the mucosa and the mucosa is dissected off the septum using a Freer instrument.**	• Trajectory to the sella usually follows the middle turbinate.

Identification of the Sphenoid Bone (Fig. 22.7a, b)

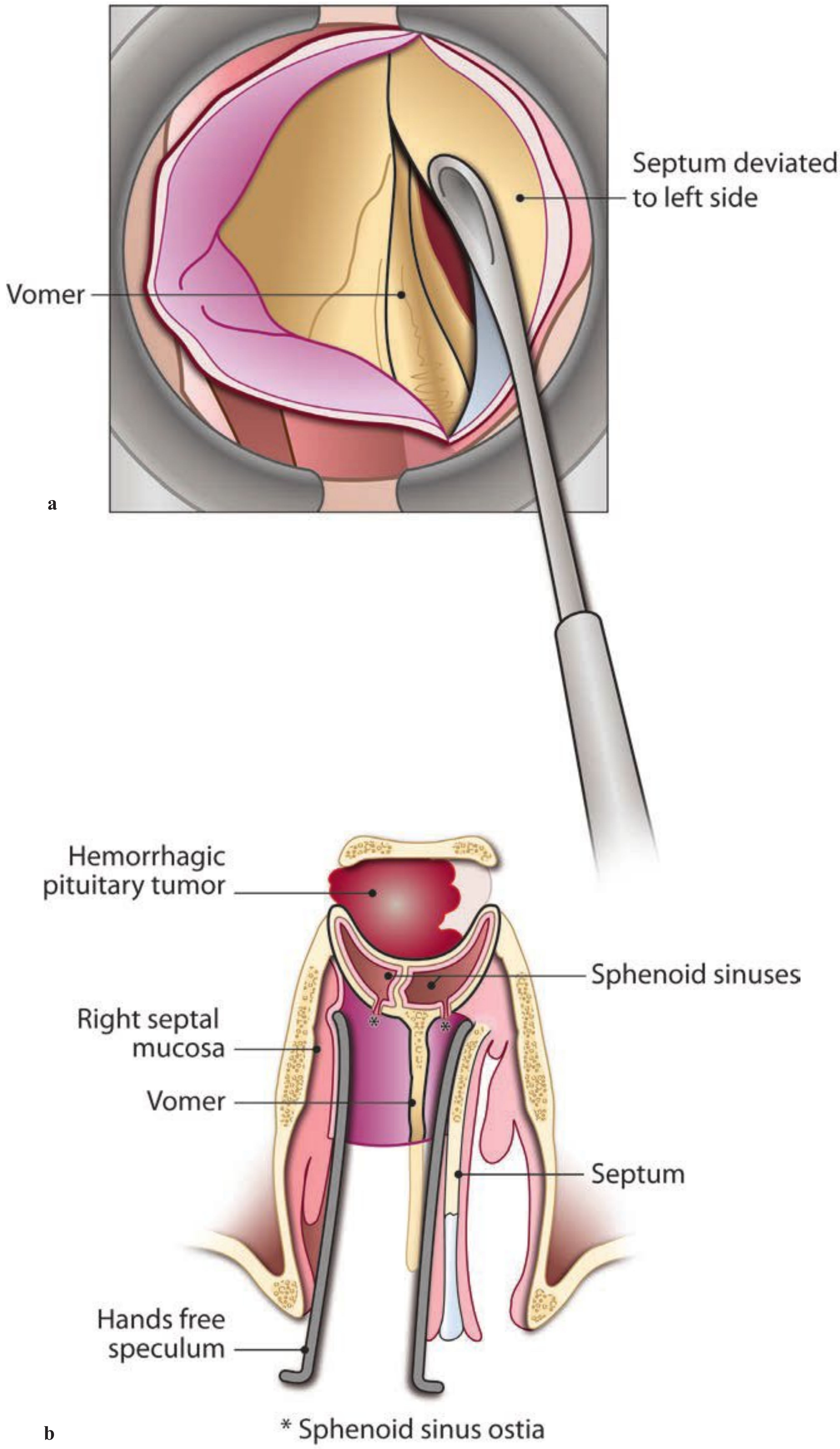
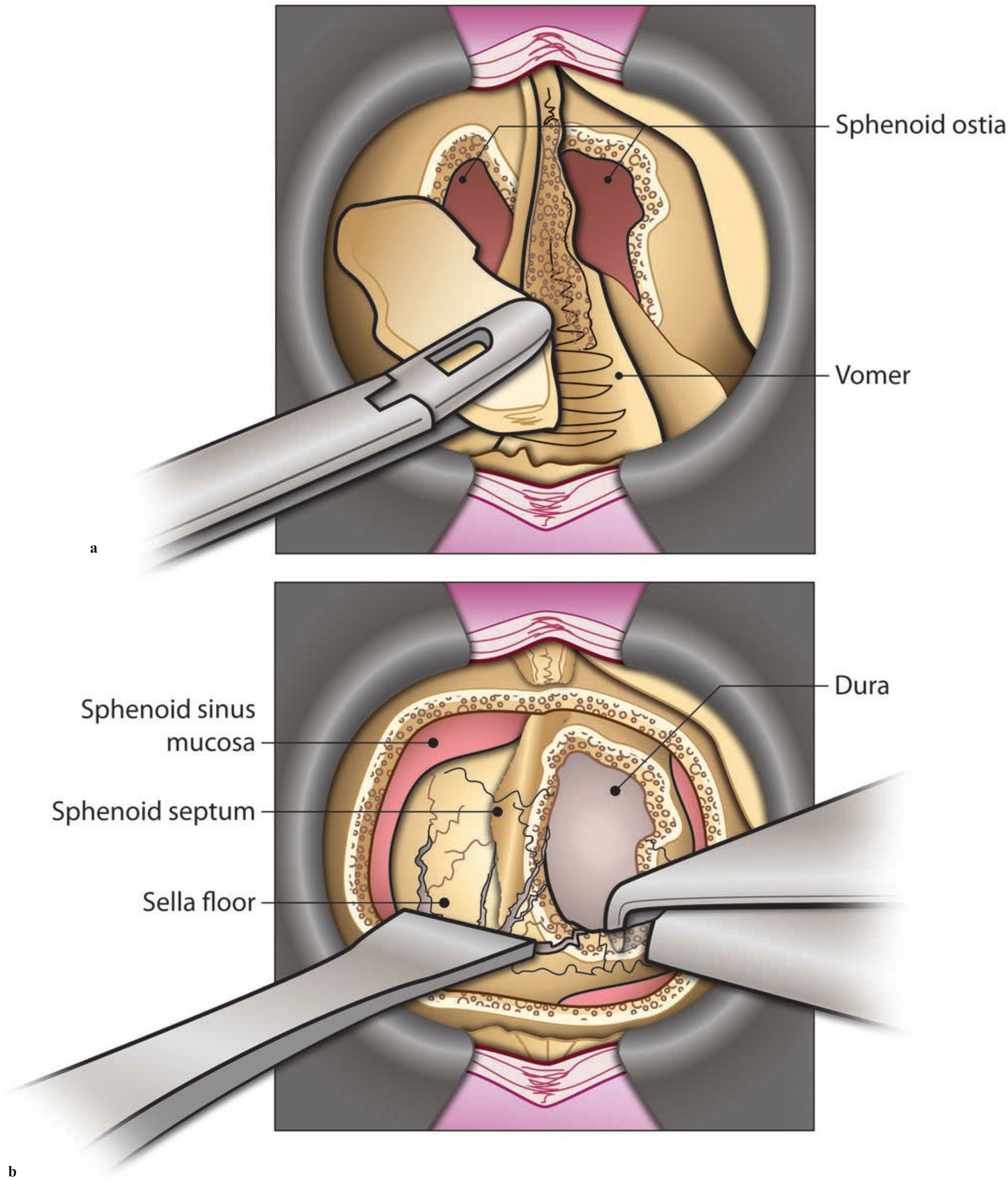
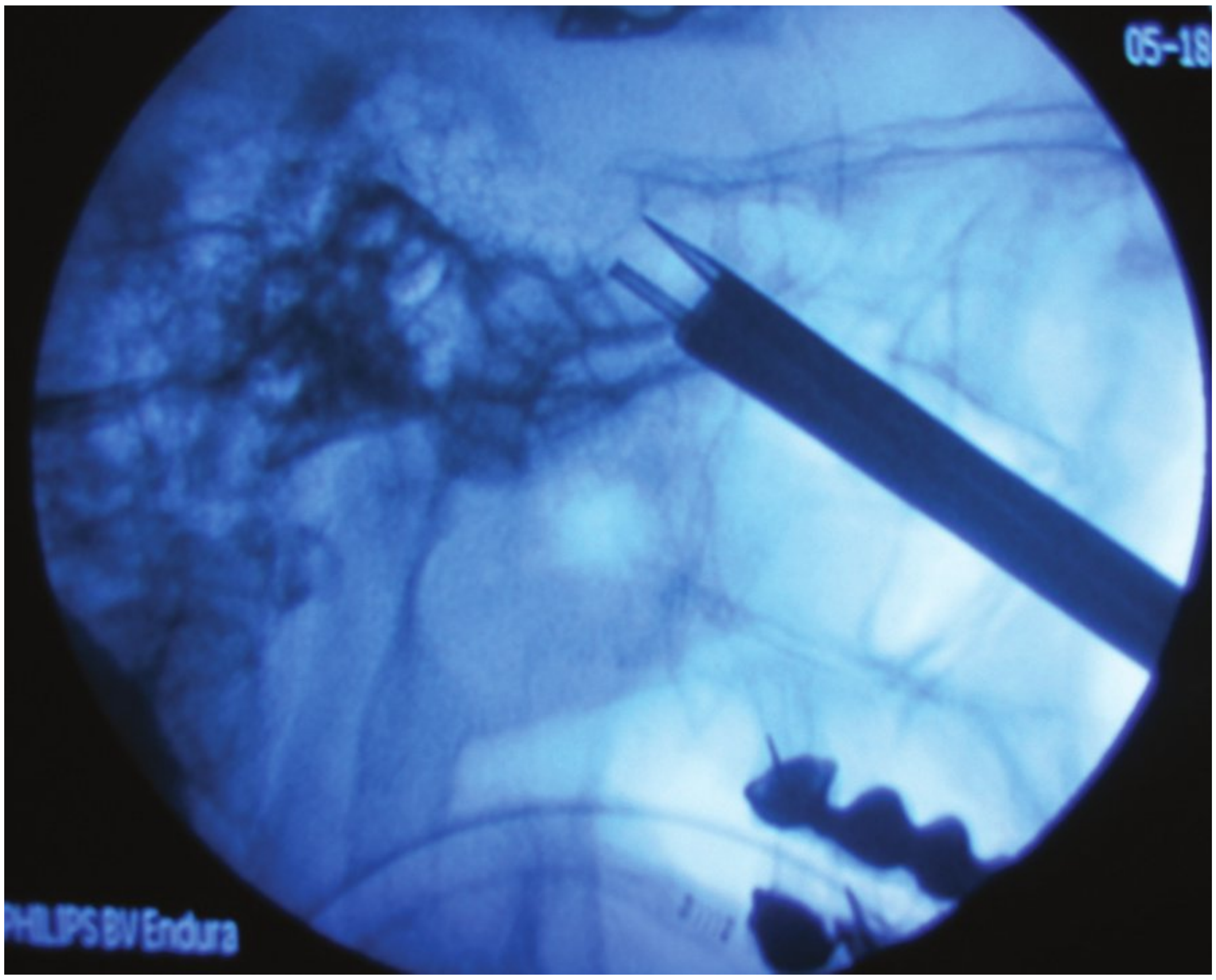


Figure	Procedural Steps
Fig. 22.7a, b	**(a) The septum is the deviated to the patient's left and the keel-shaped vomer of the sphenoid is exposed.** **(b) A hands free speculum is then placed with one blade on either side of the vomer.**

Exposure of the Sella (Fig. 22.8a–c)





c

Figure	Procedural Steps	Pearls
Fig. 22.8	**(a) A combination of rongeurs and pituitary instruments are used to remove the vomer, enlarging the bilateral ostia into the sphenoid sinus. The sphenoid sinus mucosa is moved aside.** **(b) A small osteotome and mallet is used to fracture the sella floor, and then Kerrison rongeurs are used to remove it.** **(c) Lateral fluoroscopy image depicting the trajectory of the speculum with instruments marking the superior and inferior limits of the sella turcica.**	• The removed bone is saved for later use at closure. • It is important to note that sphenoid sinus septations are not usually midline; the vomer marks the midline. • Fluoroscopy or image guidance allows the surgeon to be certain of being midline at this juncture.

Dural Incision and Pituitary Tumor Resection (Fig. 22.9)

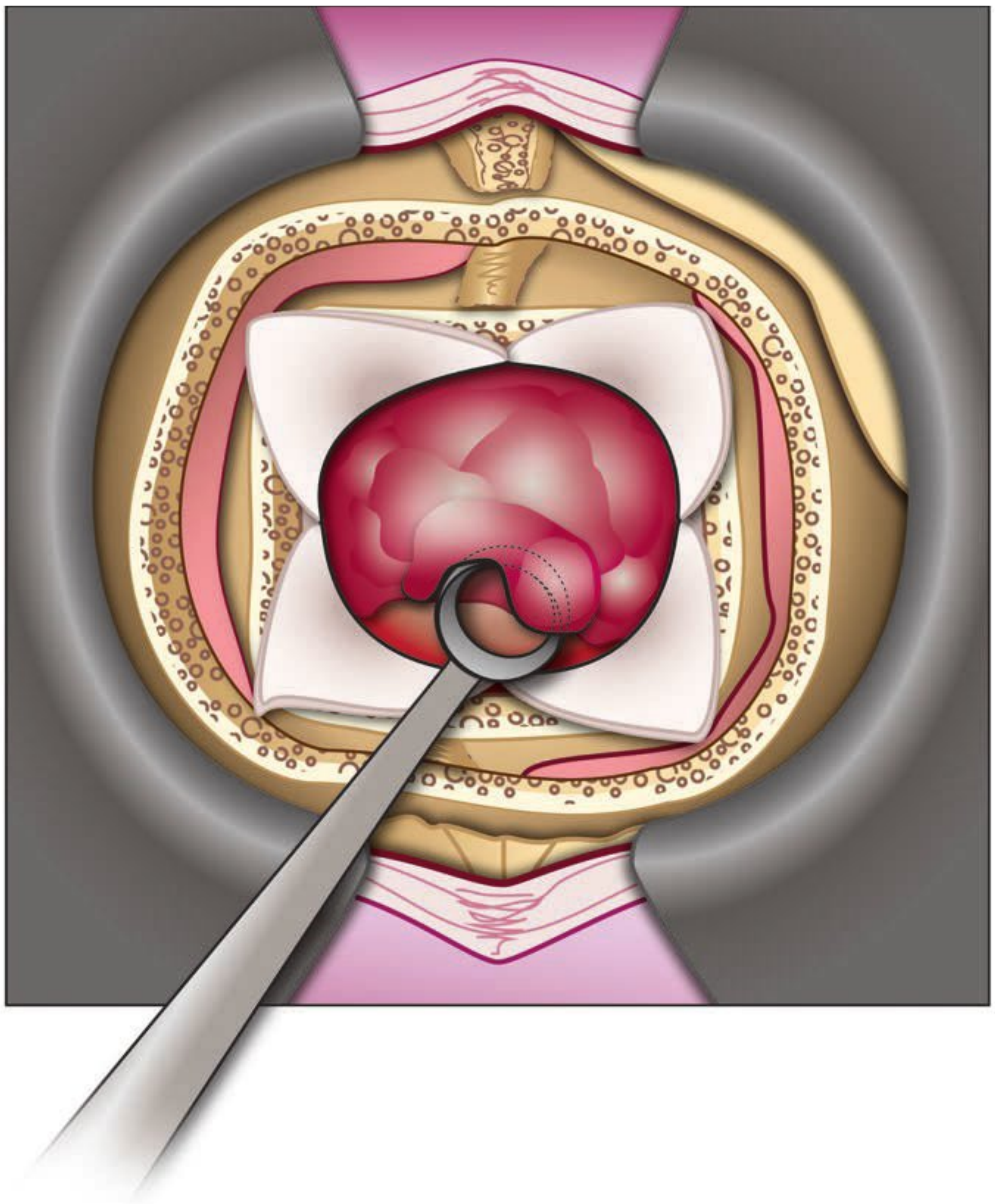


Figure	Procedural Steps	Pearls
Fig. 22.9	**The dura, now exposed, is then incised using a no. 15 blade in a cruciate fashion. Ring curettes of various sizes are then used to remove the infarcted hemorrhagic tumor in a stepwise fashion inferiorly then laterally to the limits of the cavernous sinus and finally superiorly.**	• Resection in the superior plane is left until the end to avoid the descent of arachnoid into the operative field, making further resection difficult.

Reconstruction of the Sella Floor (Fig. 22.10)

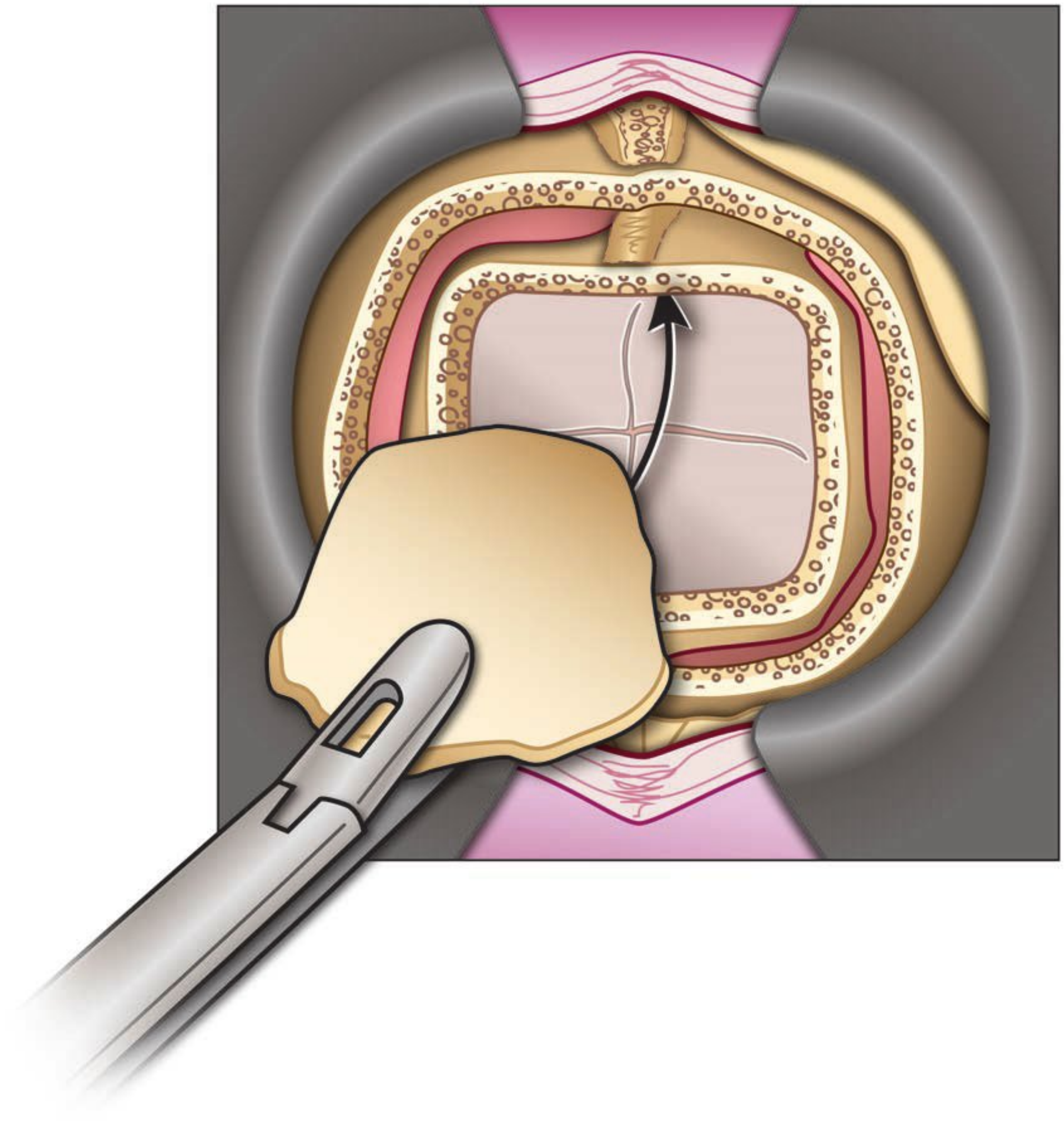


Figure	Procedural Steps	Pearls
Fig. 22.10	**After irrigation the previously removed bone fragments are placed to reconstruct the sellar floor.**	• If CSF is seen, a piece of subcutaneous fat harvested from the abdomen is packed in the sella and sphenoid sinus (see **Fig. 22.12** for graft harvesting).

Hemostasis and Closure (Fig. 22.11)

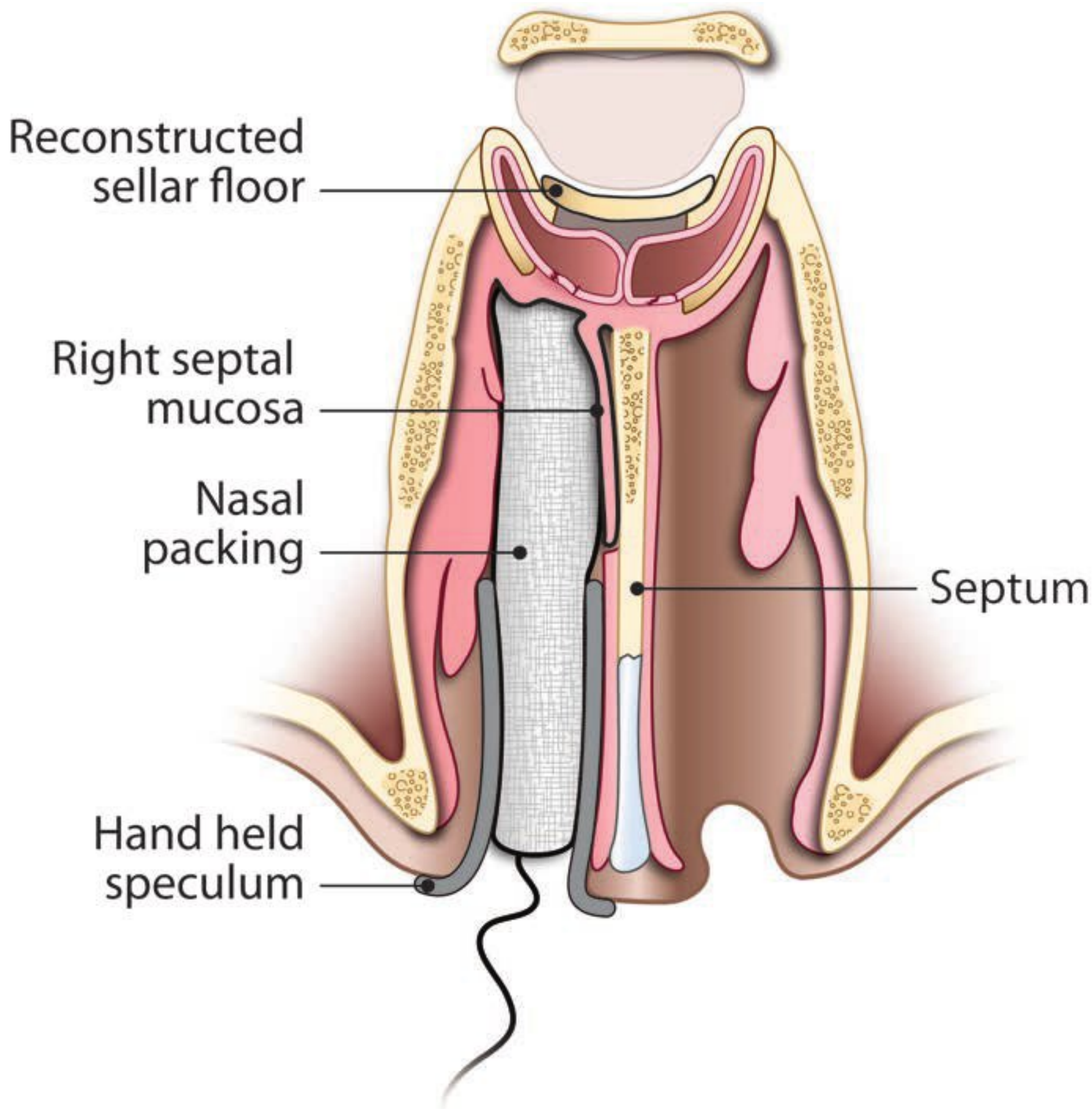


Figure	Procedural Steps	Pearls
Fig. 22.11	**Hemostasis is secured and the retractor is removed. Using a handheld speculum, a nasal tampon is placed in the right nares to ensure that the mucosal flap is flush with the nasal septum.**	• Right-sided nasal packing is almost always placed; however, left nasal packing is placed only if CSF was seen or if bleeding was appreciated.

Abdominal Fat Graft (Fig. 22.12)

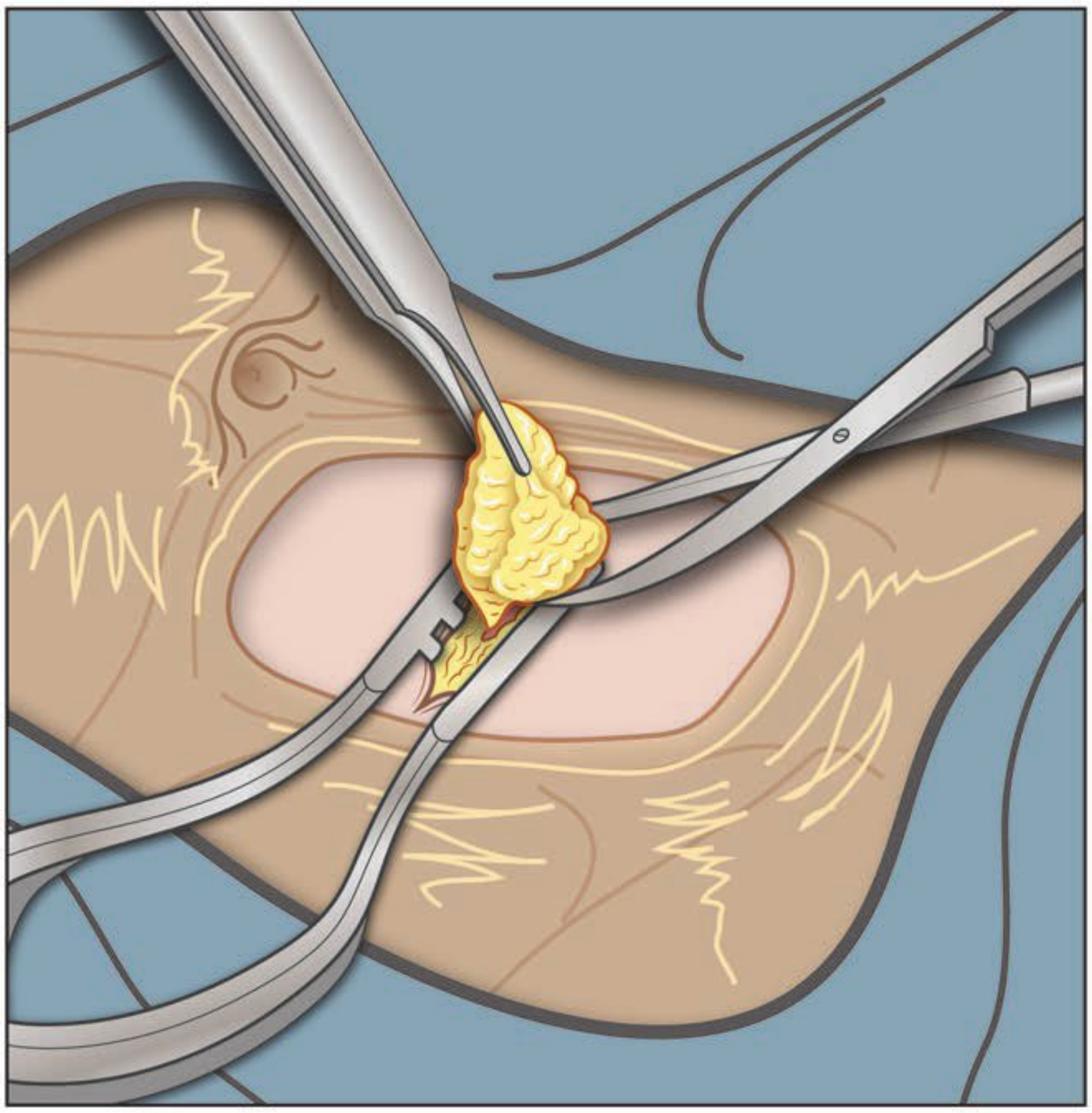


Figure	Procedural Steps	Pearls
Fig. 22.12	**If necessary an abdominal fat graft is harvested by making a small linear incision in the right lower quadrant and removing a quarter-sized piece of subcutaneous fat. The incision is then closed with 3-0 inverted absorbable braided sutures and subcuticular absorbable monofilament closure.**	• It is important not to contaminate the abdomen with any instruments that have been placed in the nose.

Postoperative Management

- Dexamethasone or hydrocortisone is continued in the immediate postoperative period.
- If a left sided packing was placed it is removed that evening.
- The patient is monitored for any signs of addisonian crisis as well as diabetes insipidus. To that end strict measurements of intake and output are taken as well as daily sodium and osmolality levels. Should the patient have more than 200 mL/hr of urine output over the course of 3 consecutive hours repeat sodium level is drawn and if it is elevated, desmopressin acetate therapy is initiated.
- Postoperative day 2 the right packing is removed and the patient is discharged if they continue to be stable.
- Endocrine labs are sent as outpatient to assess the level of pituitary function.
- Neurosurgical, endocrine, and ophthalmology follow-up is provided.

Special Considerations

- It is our preference to use the operating microscope for the transsphenoidal approach; however, transsphenoidal endoscopy is also often used to provide wider exposure. Surgeon comfort level should dictate which technique is used.
- Craniotomy is reserved for patients with a nonaerated sphenoid sinus, a small sella with a large suprasellar mass, a tight diaphragma sellae with a dumbbell-shaped mass, or an associated intracerebral hematoma.[5,16]

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IV Emergency Operations in Combat

23 Combat Cranial Operations

Leon E. Moores

Introduction

This chapter covers the procedure for a large hemicraniectomy following severe penetrating combat trauma with massive soft tissue involvement. Similar operative principles apply for less severe penetrating wounds, as well as for hemicraniectomy for blunt trauma. Where blunt trauma is concerned, the most significant divergence involves preoperative decision making. We have tended throughout recent conflict to be quite aggressive with surgical intervention for both blunt and penetrating trauma. Long-term outcome studies are pending, but initial experience justifies continuing this aggressive approach in our patient population.[1,2]

Comparisons between civilian and combat cranial trauma may be difficult because of the service members' very young average age and high overall level of fitness, the nearly immediate availability of basic and advanced life support care, and extraordinarily robust resources on the battlefield and within close proximity of wounding. Additionally, combat injuries are notable for massive soft tissue/bone/brain injury, gross contamination (often with aggressive organisms), concurrent injuries to face/neck/extremities/trunk, and extended patient transfers. Evacuation to facilities in Germany and, then, onward to national military medical centers in Bethesda, Maryland, consists of two flights of more than 6 hours duration without in-flight neurosurgical capability.[3]

However, the major goals of surgery in both situations are removal of contaminants (including devitalized tissue), brainstem decompression, hemostasis, skull base reconstruction (with obliteration of air-filled sinuses), dural coverage, soft tissue coverage, and stabilization for transport with appropriate monitoring in place and functioning.

Indications

- Severe penetrating trauma.
- Blunt trauma with significant mass effect from hemispheric swelling or hematoma.
- Absence of major disruption of midline deep cerebral nuclei in the region of the sella (zona fatalis). Disruption of the zona fatalis—typically associated with Glasgow Coma Scale (GCS) 3—is a relative contraindication to operative intervention.[4]
- In the combat setting, low GCS score (, 5) is not necessarily a contraindication to surgical intervention. Additionally, pupillary asymmetry or dilation may be the result of traumatic iridoplegia or chemical irritation. The overall clinical picture and wounding history must be taken into account before making a decision to categorize a patient as expectant. Because of the differences in patient population as outlined, this indication may not fully translate into civilian practice.

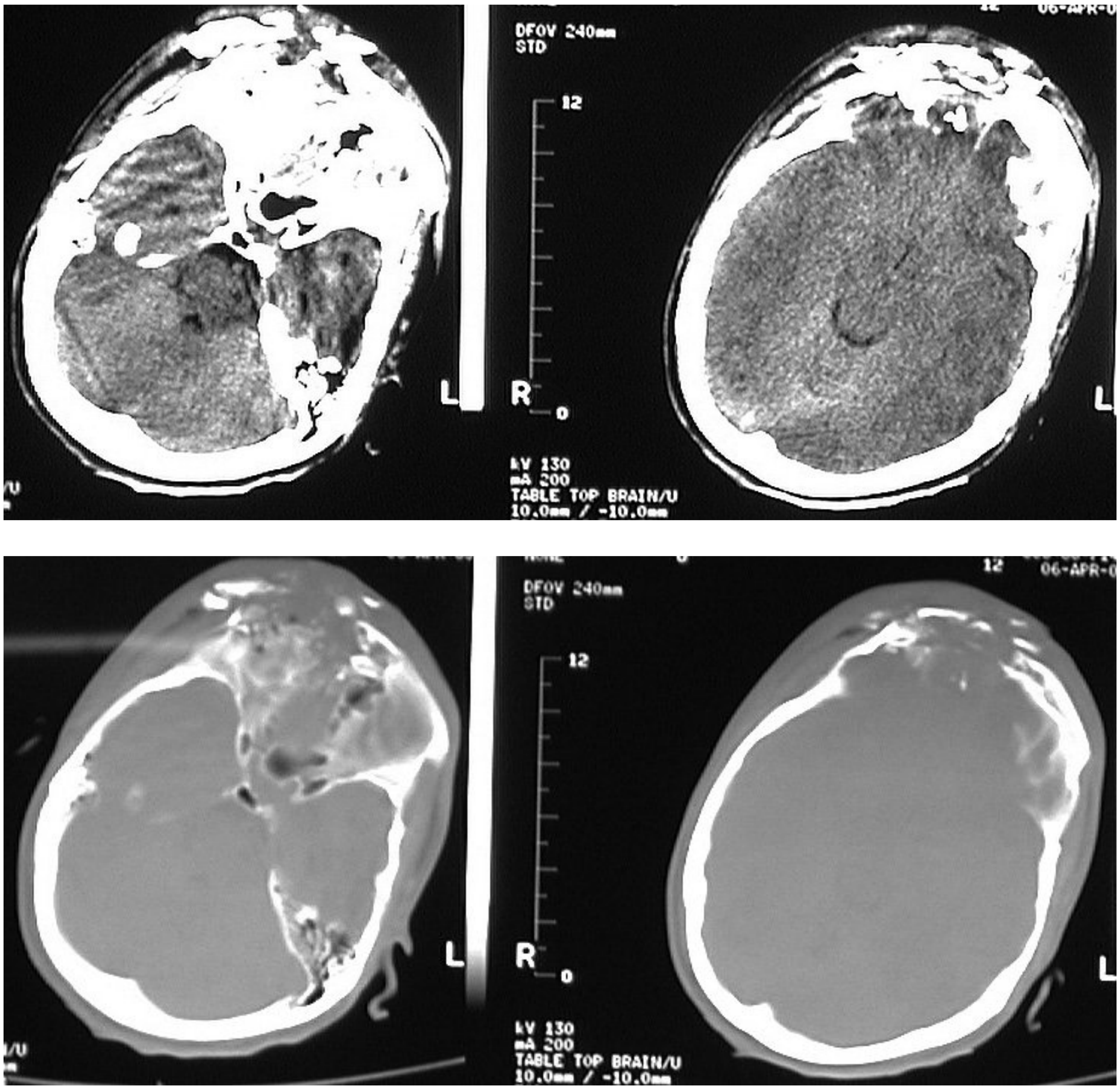
Preprocedure Considerations

Consultation/Teamwork

Successful management of patients severely wounded in combat operations is truly a multidisciplinary effort. Multiple surgical specialists are often involved—in addition to efforts from anesthesiology, nursing, and laboratory/blood bank. A single patient may present with an extremity amputation, an abdominal penetration, exposed brain, a partially enucleated globe, and severe soft tissue/bone loss involving the maxilla, requiring simultaneous evaluation and surgical management by five specialists. Constant communication and coordination is required among all members of the team.

Radiographic Imaging

- Computed tomography (CT) scan is routinely available at the medical facilities in theater where neurosurgical capability is present.
- Angiography is not routinely available and requires the presence of both specialized equipment and a trained neurointerventionalist. Where angiographic capability is available in theater, it has proven useful in the management of penetrating trauma of the neck and head. Upon arrival to the United States, angiography is often performed—whether blunt or penetrating mechanism—due to the increased incidence of vasospasm associated with blast-related trauma, even in the absence of cranial penetration.[5]
- Preoperative imaging (**Fig. 23.1a, b**).



a

b

Fig. 23.1a, b CT (**a**) brain and (**b**) bone images of a frontotemporoparietal IED injury demonstrating typical massive soft tissue swelling, air-filled sinus disruption, intracranial fragments, and epidural hematoma. These are actual hardcopy images from in-theater CT scan operating under extreme weather and force protection conditions. Digital records are not available for higher resolution.

Medication

- Recently published guidelines for penetrating brain injury recommend antibiotic prophylaxis with cefazolin. Prophylaxis typically is continued until 24 hours following removal of external ventricular device (EVD) or intracranial pressure (ICP) monitor, or a total of 48 hours if no such devices are present. Consideration may be given to extended coverage with gentamicin and penicillin if gross contamination is present. Patients who are allergic to penicillin may be treated with vancomycin and ciprofloxacin.[6]
- Seizure prophylaxis with diphenylhydantoin is initiated preoperatively.

Operative Field Preparation

- Vigorous cleansing of contaminated adjacent soft tissue is completed with irrigation, soap and water, alcohol, and povidone iodine or chlorhexidine. Exposed brain tissue is irrigated with saline only. Contrary to standard practice in the elective setting, the hair is clipped widely both to remove gross contamination and to allow better visualization of additional areas of penetration.
- The incisions are marked and infiltrated with 1% lidocaine with epinephrine 1:100,000.

Operative Procedure

Positioning and Preparation (Fig. 23.2)

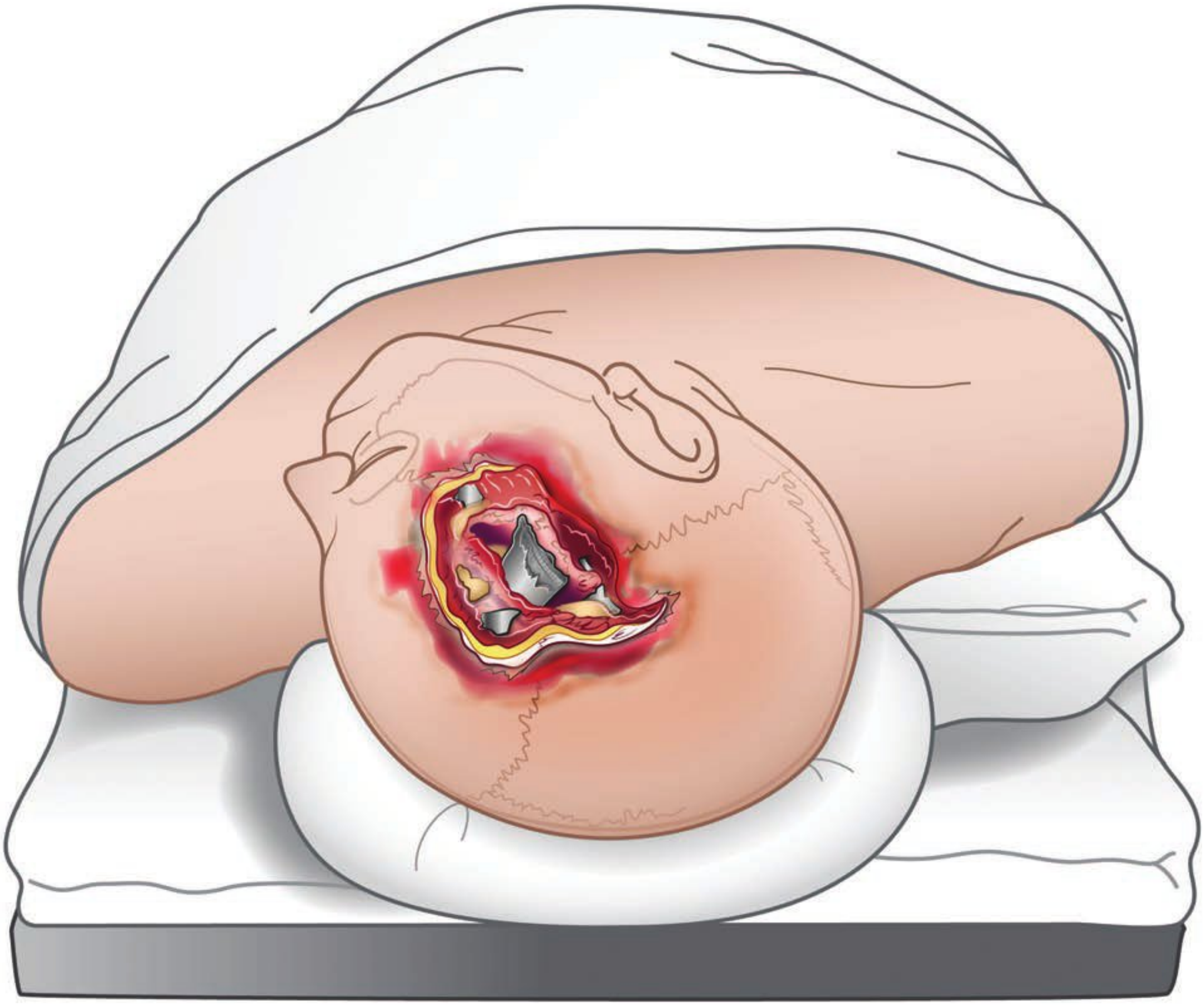


Figure	Procedural Steps	Pearls
Fig. 23.2	**Removal of debris is recommended prior to final prep. If a fragment is firmly embedded or adjacent to vascular structures the fragment is prepped into the field.** **The head is turned in a manner that optimizes visualization of the most severely injured area. Typically, the most devastated portion of the wound is placed at the highest point in the operative field, angled slightly toward the surgeon for best visualization and operative control of any deep injuries along the wound tract.** **Copious normal saline irrigation is used on any exposed brain tissue.** **If there is sufficient uninjured space on the lateral thigh, it is prepped for a potential fascia lata graft.**	• Alcohol, iodine, and other noxious prep agents are not applied to exposed brain.

Urgent Hemostasis (Fig. 23.3)

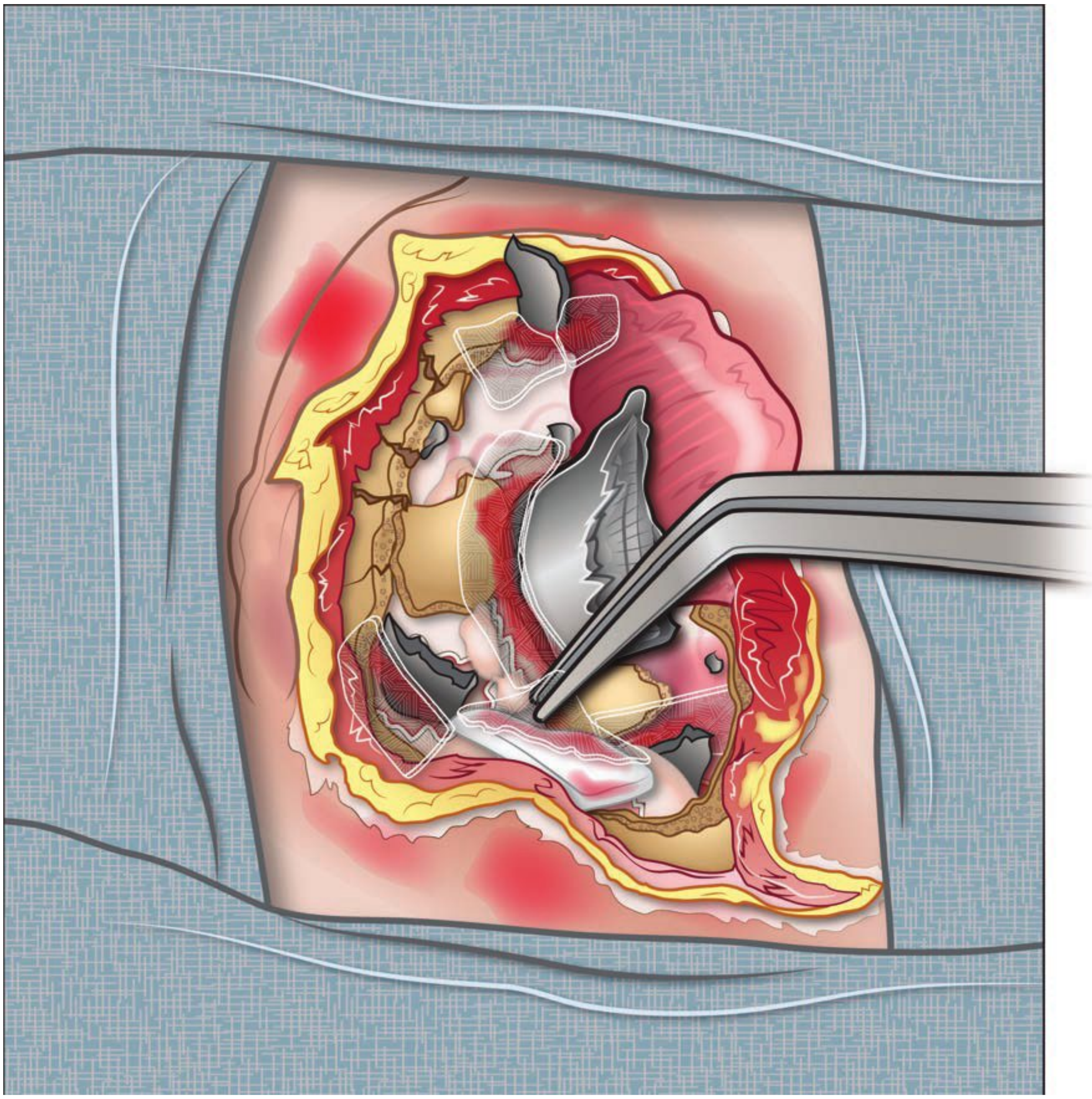


Figure	Procedural Steps	Pearls
Fig. 23.3	**Hemostasis within the brain parenchyma must be achieved rapidly in the case of severe penetrating trauma. Significant intracranial sources of bleeding often preclude working slowly from “superficial to deep.” Continuous arterial bleeding from intracranial sources is commonly encountered upon removal of field dressings and use of saline irrigation. Hemostasis must be achieved before attending to non-lifesaving interventions such as soft tissue debridement.** **All methods of hemostasis must be considered. The best method is often “time.” When encountering multiple areas of significant active hemorrhage, the surgeon must pack off the least worrisome with gelatin sponge, strips of hemostatic oxidized cellulose polymer, cotton patties, etc. and gain control of the most vigorous bleeding points.**	• Often, excellent hemostasis of low-volume bleeding zones within a massive area of injury can be achieved by allowing the topical hemostatic agents to remain in place—if one can resist the temptation to remove them.

Soft Tissue Debridement (Fig. 23.4)

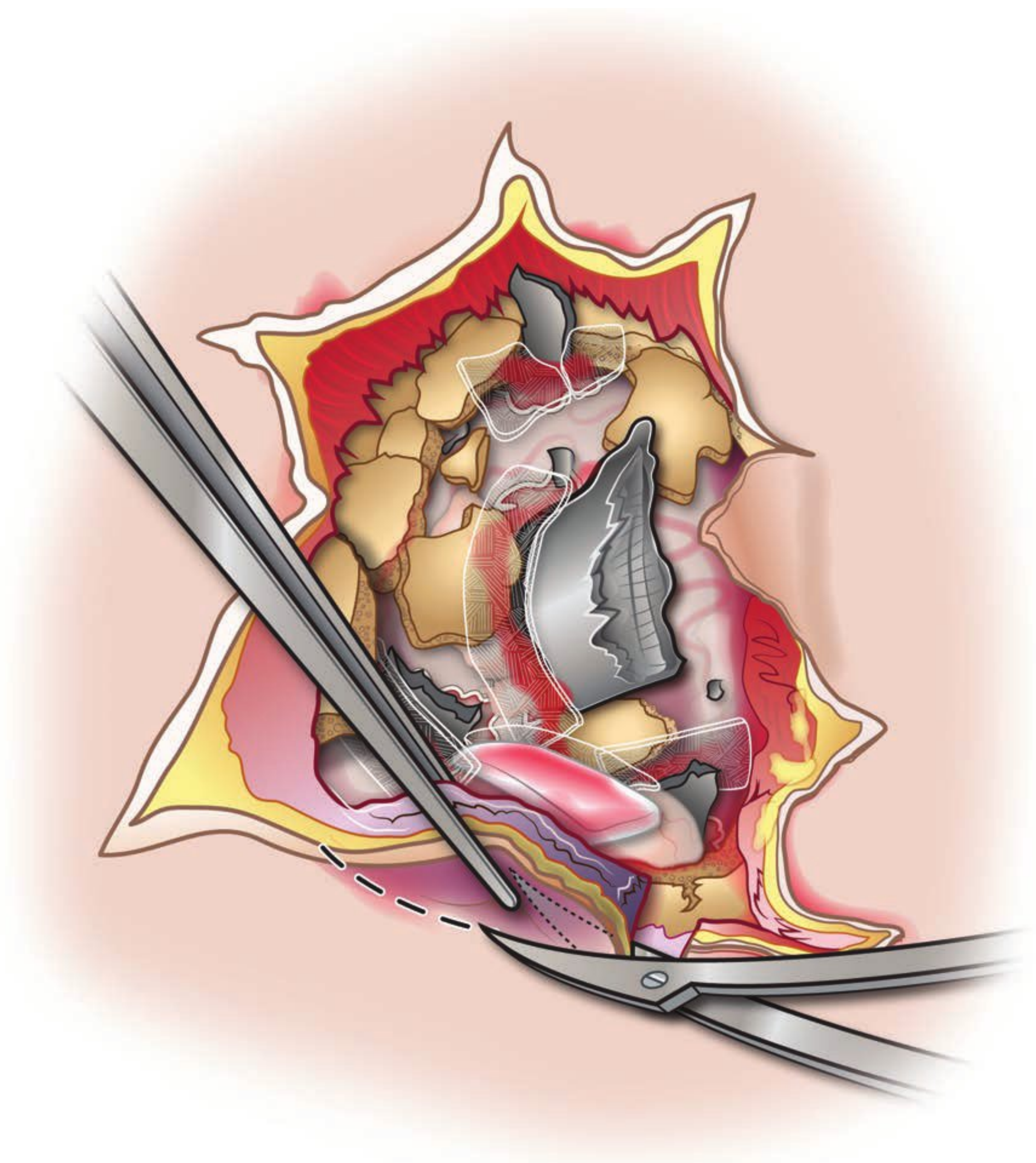


Figure	Procedural Steps	Pearls
Fig. 23.4	**Soft tissue debridement is accomplished with a combination of sharp and blunt dissection. Devitalized and grossly contaminated soft tissue is removed. It is important to keep in mind the requirement for soft tissue coverage of the final construct and to minimize the excision of soft tissue which is not clearly devitalized. A significant portion of the muscle and skin may be severely contused, yet quite viable, and should be salvaged.**	• Even with wounds such as in **Fig. 23.2**, the elasticity of the scalp is such that primary closure is the norm. Aggressive undermining of the scalp (which aids in pericranial graft harvest) also helps to achieve primary coverage if a significant portion of the scalp has been devitalized.

Bony Debridement (Fig. 23.5)

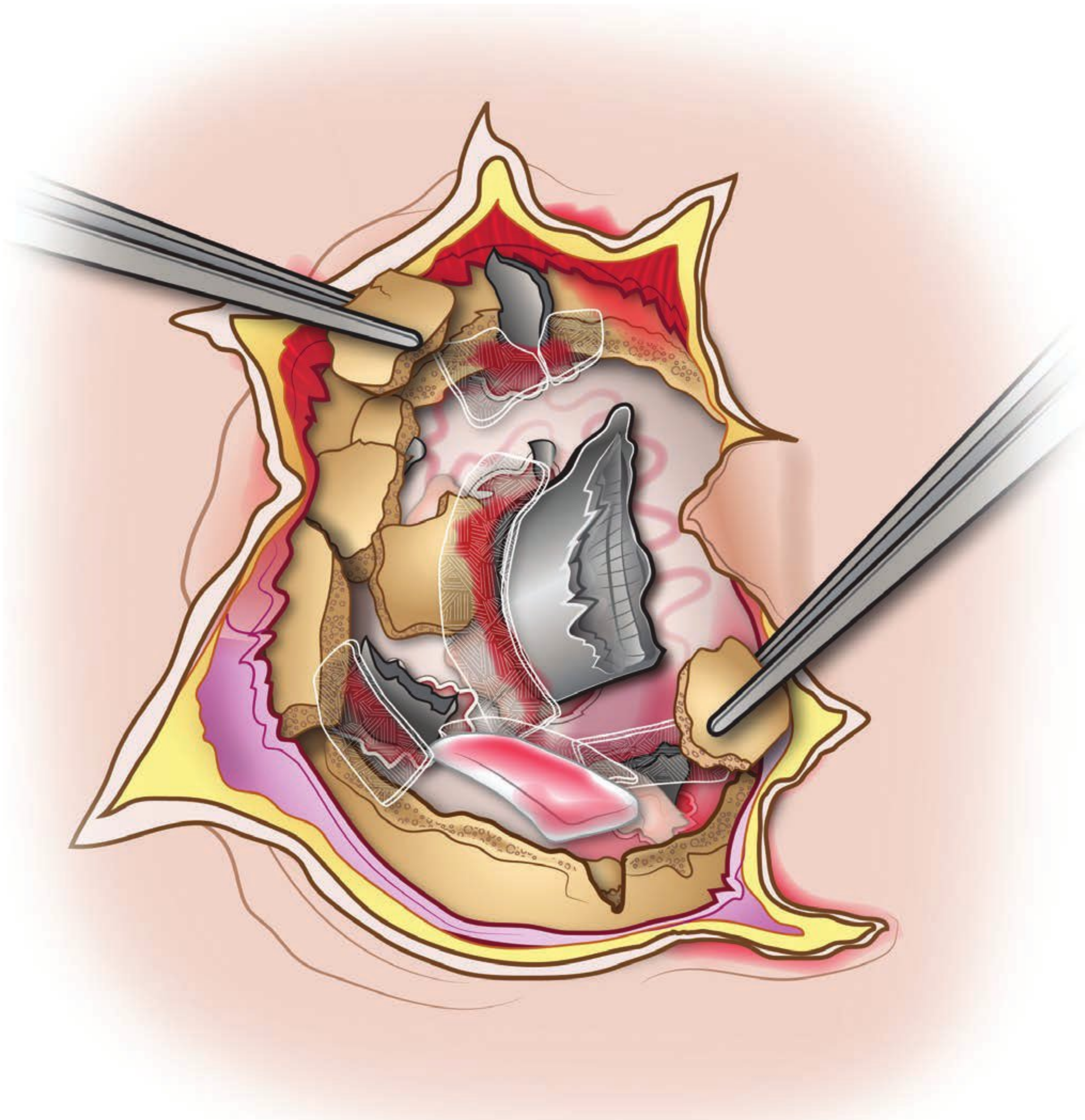


Figure	Procedural Steps	Pearls
Fig. 23.5	**Aggressive debridement of superficial bone fragments is indicated. The availability of excellent modern modeling techniques for calvarial reconstruction precludes the need to preserve complex, three-dimensional bony structures where comminution is present.[7]**	• Particularly in the case of contaminated wounds, the absence of blood supply to bone fragments may increase infection risk.

Scalp Incision (Fig. 23.6a, b)

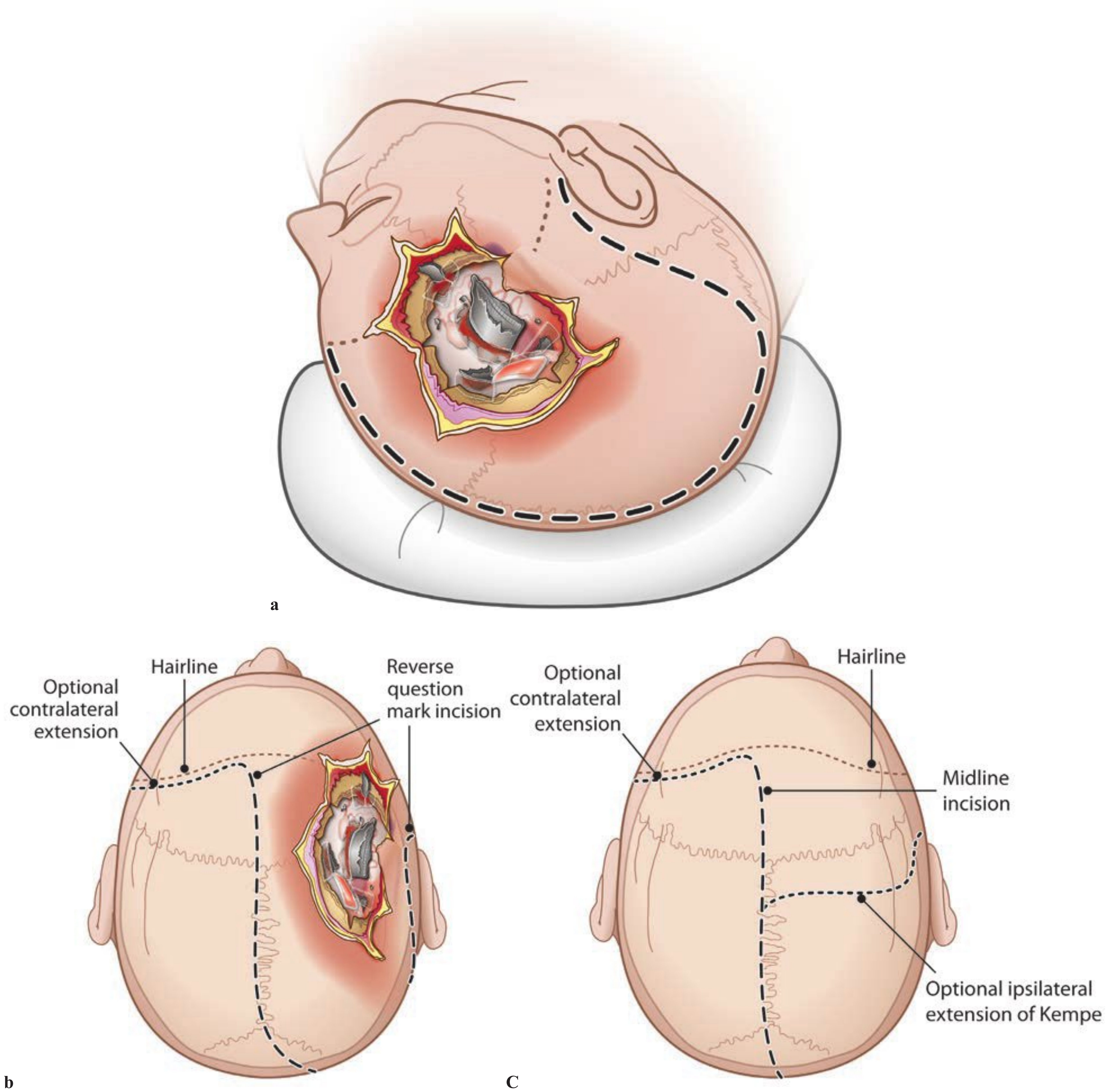


Figure	Procedural Steps	Pearls
Fig. 23.6	**(a) An extended reverse question mark incision allows for a generous hemicraniectomy and provides excellent access to harvest a large, vascularized pericranial graft—essential to the reconstruction of often massive skull base and aerated sinus defects.** **(c) In some cases, the very large scalp flap described above may be vulnerable to posterior scalp breakdown. The surgeon may consider a midline incision and ipsilateral extension of Kempe, as revisited by Martin,[1] taking advantage of the angiosomes of the occipital artery to improve results with cosmetic reconstruction.[8]**	• **(b)** Extension of the lateral incision anterior to the tragus and the midline incision behind the contralateral hairline, if necessary, can provide excellent exposure of the frontal fossa and zygoma. • While this incision forfeits the advantage of a vascularized pericranial pedicle, free grafts may be harvested from the posterior scalp.

Hemicraniectomy (Fig. 23.7)

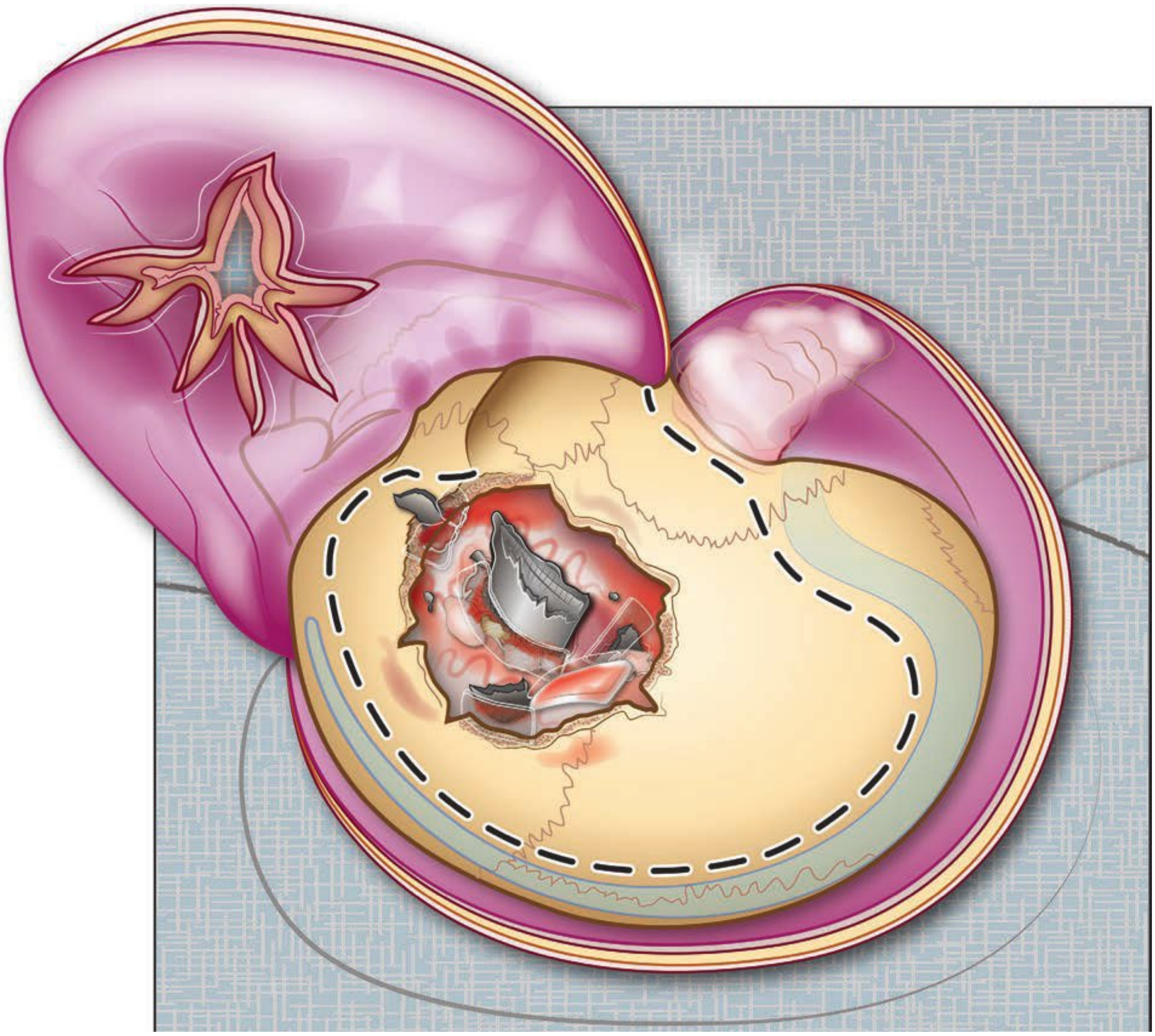


Figure	Procedural Steps	Pearls
Fig. 23.7	**The ideal bony incision is just lateral to the superior sagittal sinus, just above the transverse sinus, and along the temporal and frontal fossa floors.**	• Over the course of the recent conflict, we have become advocates of very large, nearly hemispheric bone flaps—in part, due to an inability to provide emergency neurosurgical intervention during a lengthy transport. On occasion, if minimal damage to the brain is accompanied by significant loss of brain tissue and very little postoperative swelling is anticipated, primary reconstruction of the bony injury can be accomplished acutely. Primary reconstruction should be considered for relatively superficial wounds, even with severe fragmentation of bone and disruption of soft tissue. Frontal injuries, where the potential for brainstem compression is less of a concern, are often good candidates. The ability to monitor ICP becomes more important in this setting.

Brain Debridement (Fig. 23.8)

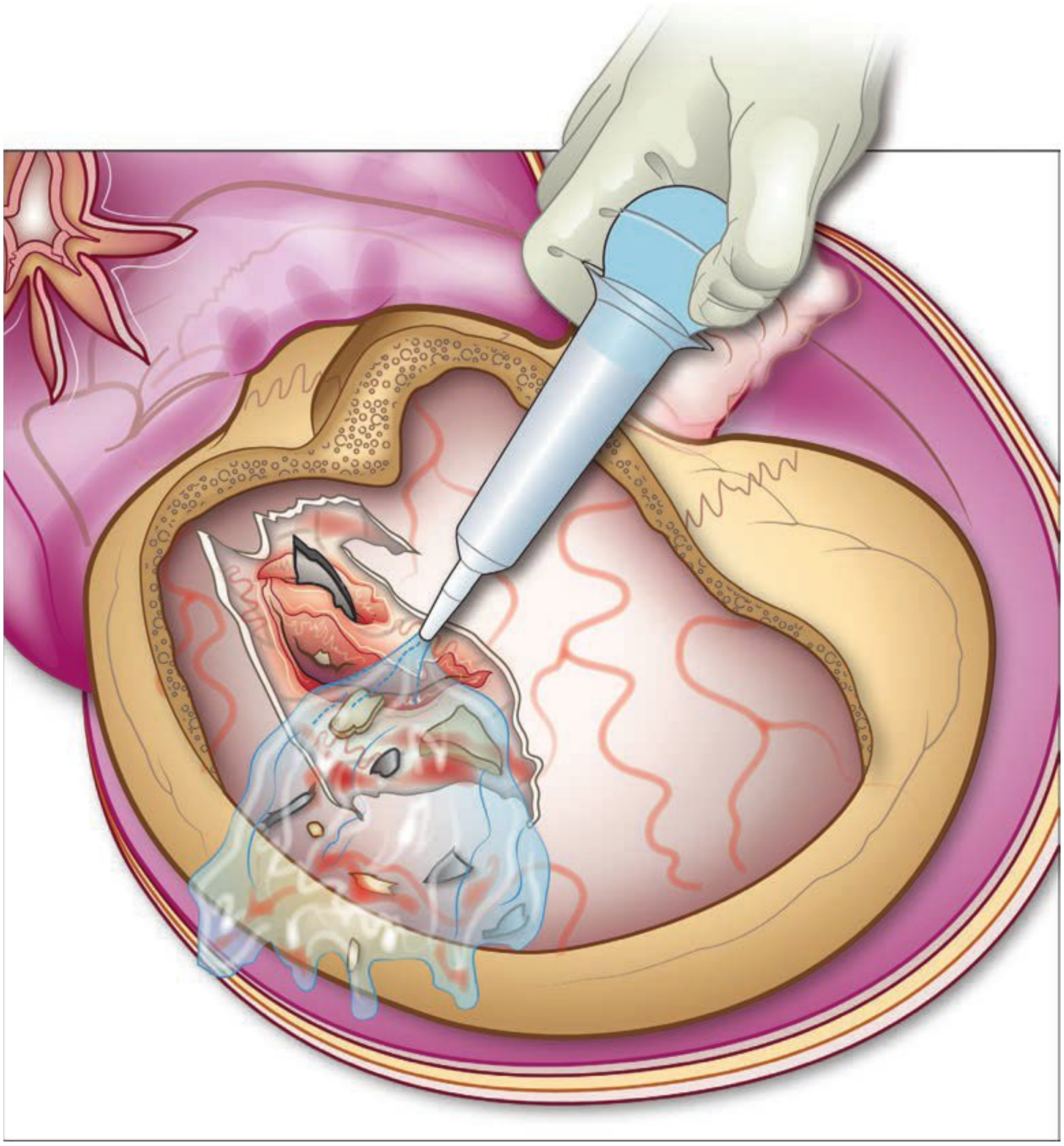


Figure	Procedural Steps
Fig. 23.8	**Brain debridement is performed using normal saline bulb irrigation to wash away large fragments of obviously devitalized brain tissue. Hemostasis is attained, further irrigation is applied, and gross areas of contamination are removed. Gentle exploration of wound tracts is appropriate in order to remove obvious and easily accessible contaminants, but deeply embedded fragments are not removed unless indicated by later angiography or a subsequent infection.**

Skull Base Reconstruction, Pericranial Graft (Fig. 23.9)

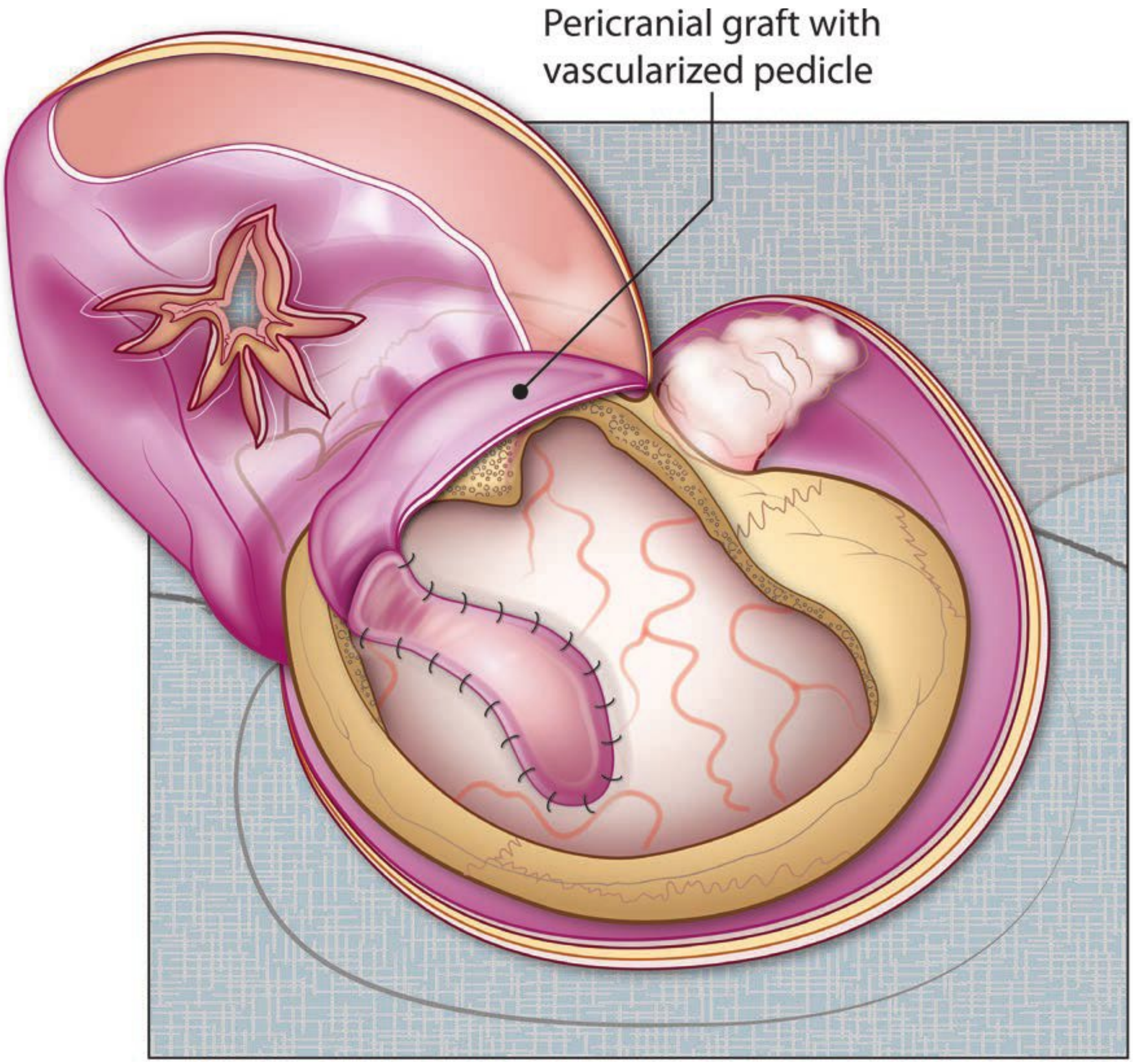


Figure	Procedural Steps
Fig. 23.9	**Dural coverage is obtained using primary dural tissue when available. Fascia lata is harvested if sufficient dura is not available. Dural substitutes are available in theater if neither can be used.** **Reconstruction of the skull base is done with local bone, if available; otherwise, harvested bone is employed for this purpose. In the rare circumstance that neither is available, artificial materials such as titanium can be used over small areas as long as pericranial coverage is used.** **It is important to ensure obliteration of any involved air-filled sinuses. This is done by widely opening the sinus, removing mucosa, and packing the sinus fully with muscle and/or fat.** **Extensive pericranial graft tissue, with a vascularized pedicle, can be harvested due to the expansive scalp exposure (see Fig. 23.6). The graft can be maneuvered into place to cover an exenterated air-filled sinus (or skull base reconstruction) and sewn over the packed sinus cavity to the adjacent dura.** **When possible, anchor the temporalis muscle to scalp or bone in order to preserve its normal anatomic position and allow for later optimal cosmetic reconstruction.**

Closing

Cranial Incision

- The intracranial space and wound cavity are irrigated with copious amounts of saline. The surgical site is reassessed for hemostasis.
- An ICP monitoring device is placed prior to closure. Ventriculostomy is preferred, since it is both diagnostic and therapeutic. Care must be taken to properly allow for pressure relief when the patient is taken high altitudes for intercontinental transport.
- The temporalis and subcutaneous tissue are reapproximated with absorbable 0 or 2-0 suture. The scalp typically is closed with staples.

Lower Extremity Incision

- After copious antibiotic irrigation, the fascia lata harvesting site is closed with a deep layer of 2-0 absorbable suture, followed by skin staples.

Postoperative Management

Monitoring

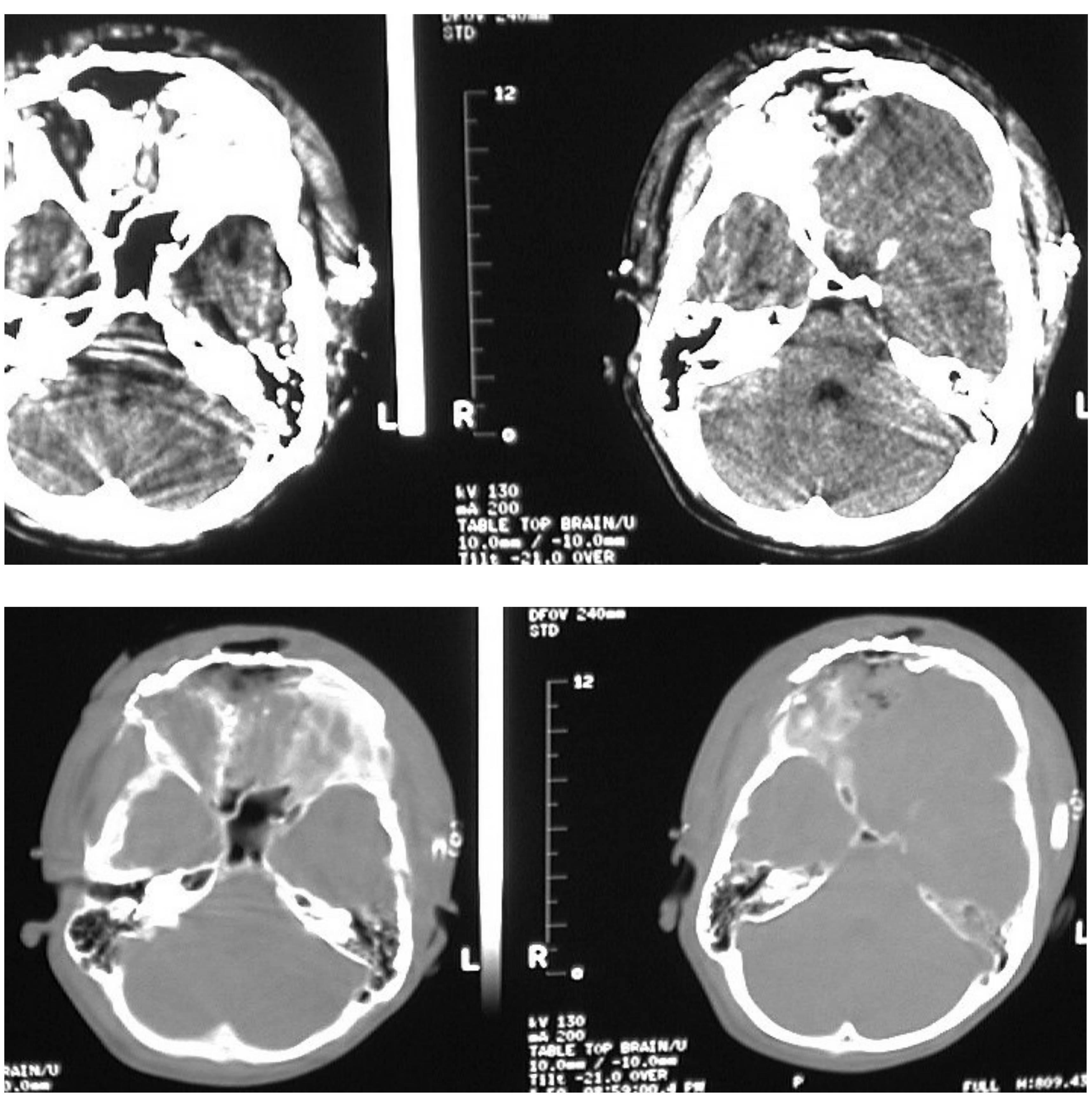
- If placed in theater, invasive ICP monitoring devices are retained throughout transport to Germany and the continental United States.
- Sedation, pain control measures, and ventricular drainage to control ICP are closely monitored and managed by on board intensivists and critical care nursing staff.

Medication

- Antiepileptic prophylaxis is continued for 7 days.
- Prophylactic antibiotics are continued for 48–72 hours.

Radiographic Imaging

- Repeat CT imaging is typically obtained postoperatively, the next morning, and on an as-needed basis thereafter for neurologic changes. Imaging requirements are balanced against hemodynamic stability and other risks of transport to imaging suite.
- We have become much more aggressive with angiography due to increased incidence of vasospasm, pseudoaneurysm, and delayed hemorrhage in patients exposed to blast energy. In addition to incidences of obvious vascular injury, we routinely perform angiograms in the following patients to look for occult injury: penetrating injury near the circle of Willis, Sylvian fissure, or posterior fossa; known vasospasm; and blast-associated blunt trauma.
- Postoperative imaging (**Fig. 23.10a, b**).



a

b

Fig. 23.10a, b CT **(a)** brain and **(b)** bone windows obtained in the postoperative period.

Special Considerations

- We have noted postoperative challenges with vasospasm, pseudoaneurysm formation, very low pressure hydrocephalus, and multidrug resistant organism ventriculitis.
- Additionally, reconstructive procedures for the more massive injuries require a multidisciplinary effort involving neurosurgery, plastic surgery, oral and maxillofacial surgery, otolaryngology–head and neck surgery, ophthalmology, prosthodontics, and imaging/three-dimensional fabrication experts.

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24 Combat-Associated Penetrating Spine Injury

Corey M. Mossop, Christopher J. Neal, Michael K. Rosner, and Paul Klimo Jr.

Introduction

- Combat-related penetrating spine injuries (PSIs) are due to firearms and explosive devices, most notably improvised explosive devices (IEDs).
- PSIs account for up to 25% of all spinal cord injuries, of which approximately half present with complete paraplegia and more than one-quarter are associated with other injuries.[1] An article comparing penetrating and blunt military spine injuries in the recent U.S. military conflicts (Operation Iraqi Freedom and Operation Enduring Freedom) reported that of 598 injured service members, 104 (17%) sustained spinal cord injuries, comprising 10% of blunt injuries and 38% of penetrating injuries (*p* , 0.0001).[2]
- The thoracic spine accounts for the majority of injuries, with the lumbosacral and cervical spine following in second and third, respectively.[1,3]
- Given the relationship of kinetic energy (KE), mass (m), and velocity (v) (KE 5 1/2mv^2), the most critical factor affecting the destructiveness of a projectile is its velocity,[4] making the high-velocity PSIs seen in combat settings particularly devastating.[3,5] Therefore, it is not surprising that patients with military PSI in general have a worse neurologic injury on presentation and have less potential for neurologic recovery than those with closed spinal cord trauma.[3]

Indications

- **Fig. 24.1** depicts a treatment algorithm for combat-related PSI.
- Incomplete spinal cord injury with mass lesion in the spinal canal, with or without progressive neurologic deficit
  - While the literature is mixed regarding the exact benefit of decompressive surgery (usually in the form of multilevel laminectomies), most still favor operative intervention in a medically stable patient with an incomplete spinal cord injury and evidence of persistent cord compression such as bone or metallic fragments within 24–48 hours of the initial injury.[1,3–10] An incomplete spinal cord injury may exist *without* impingement on the spinal canal due to the energy released to the surrounding structures by the passage of the projectile (i.e., "shock wave"). In this scenario, surgery is not recommended.
- CSF—cutaneous/pleural fistula
- Prolonged CSF leakage and its concomitant infectious risks constitute a definitive surgical indication in PSI[1,3] (**Fig. 24.2**).
- Fragment-induced nerve root compression
  - Patients with both clinical and radiographic evidence of either bony or foreign body–induced nerve root compression should have the involved roots decompressed, ideally in the first 24–48 hours after injury.[1]
- Spinal instability
  - Since the majority of civilian PSIs are from low-muzzle velocity handguns and knife wounds, biomechanical instability is not, in general, an issue. As such, these patients require no instrumentation and/or fusion during operative intervention.[1,3,9,10] In combat PSI, however, the projectiles involved (bullets or fragments from an explosive device) have a greater energy that can be dissipated to the surrounding anatomic structures, thus increasing the likelihood of spinal instability. With high-velocity ballistic trauma, the rate of instability can approach 20% and is most common in injuries with a side-to-side trajectory involving the facet joints bilaterally[7]; however, the concept of spinal stability remains nebulous and ultimately rests on a case-by-case consideration of multiple clinical and radiographic findings with clinical intuition playing an equally strong role (**Fig. 24.3**).
  - If the patient has a transgastrointestinal and unstable spinal injury, we recommend that instrumentation be postponed until the patient has completed a full course of intravenous antibiotic therapy and, if necessary, the abdomen has been thoroughly debrided and washed out by a general surgeon.
- Recent literature has established that the following clinical scenarios are *not* indications (in and of themselves) for operative intervention:
  - Complete spinal cord injury (in the absence of spinal instability or CSF leakage) (**Fig. 24.4**)[1,3–10]
  - Wound debridement/closure (in the absence of gross wound contamination)[11]
  - Copper- and/or lead-based fragments
    - Given how rare heavy metal toxicity is with PSI, the composition of a fragment should not dictate operative intervention based on current evidence.[3]

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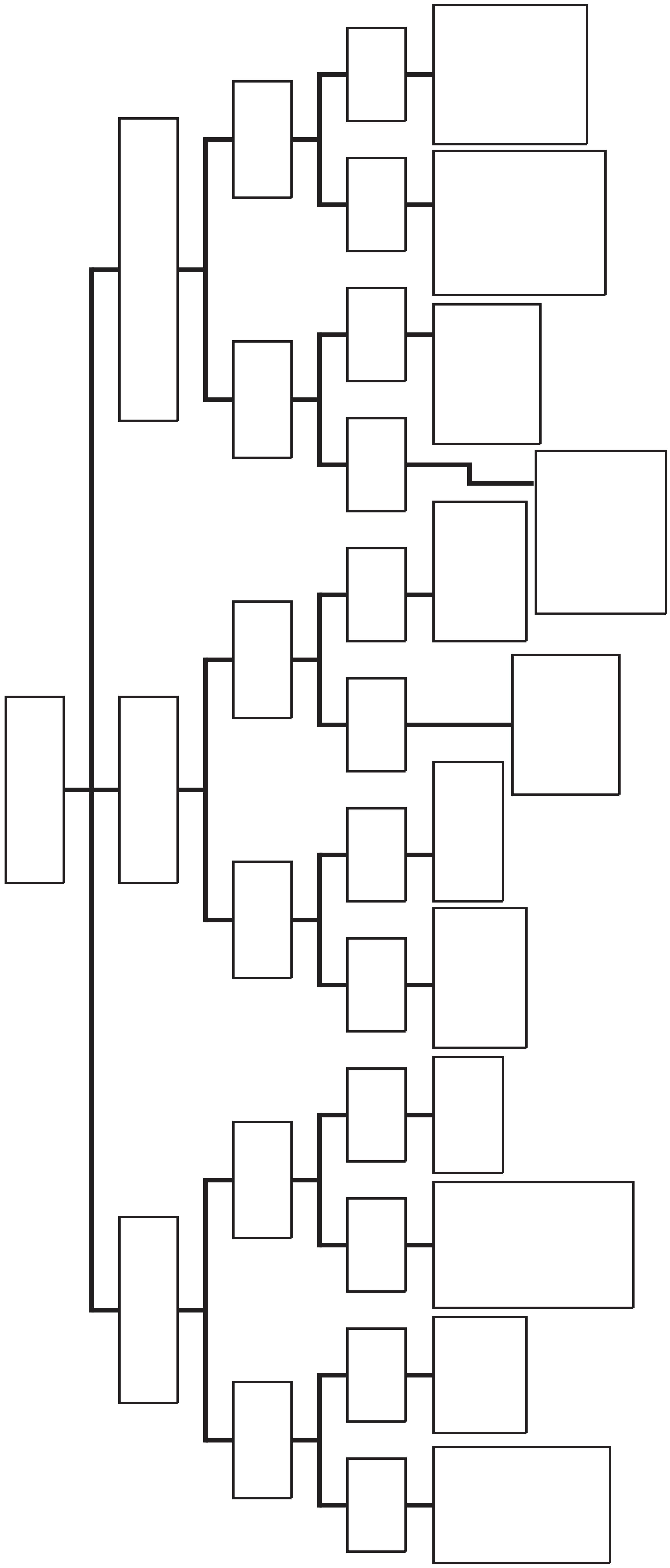
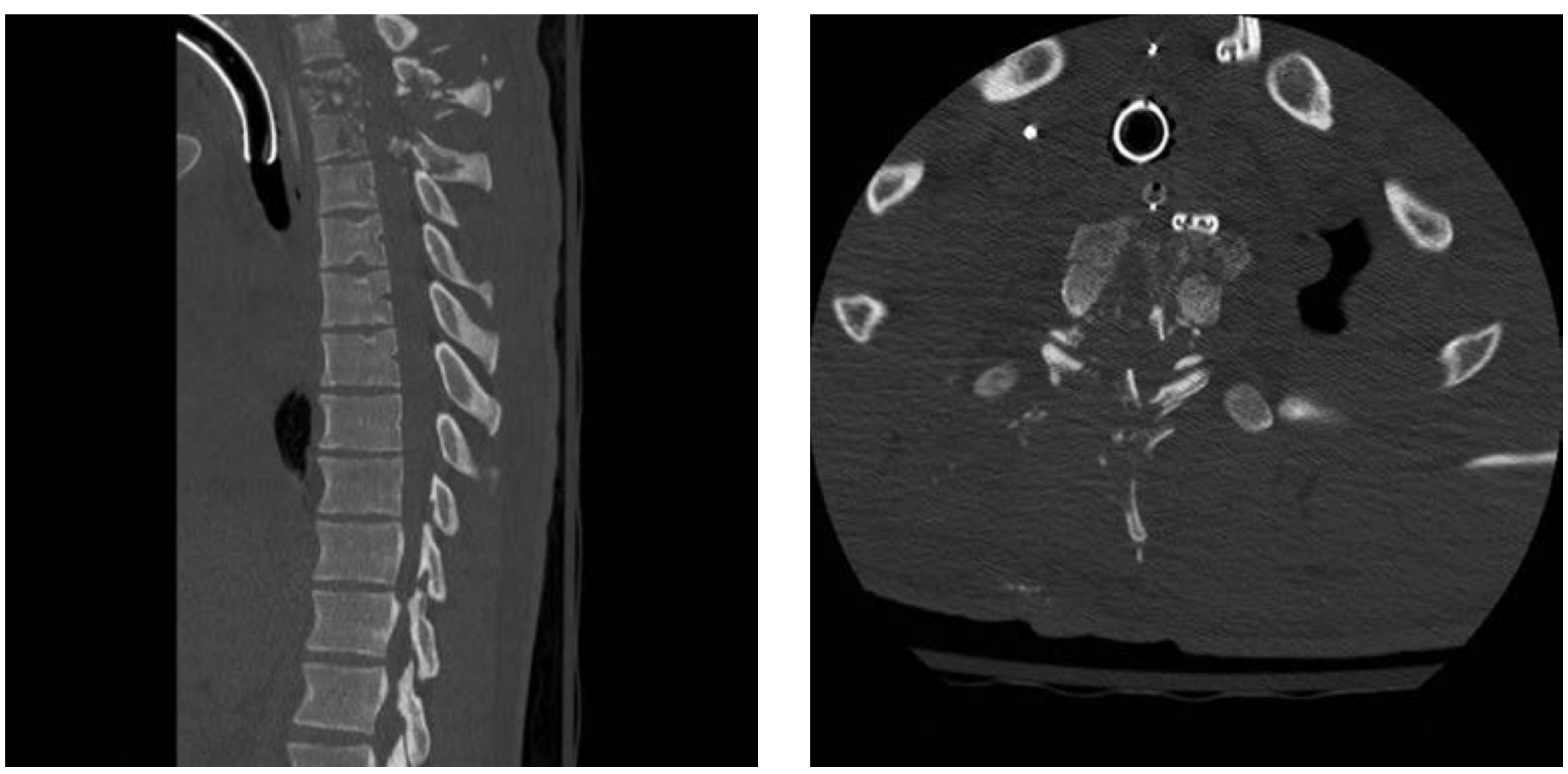


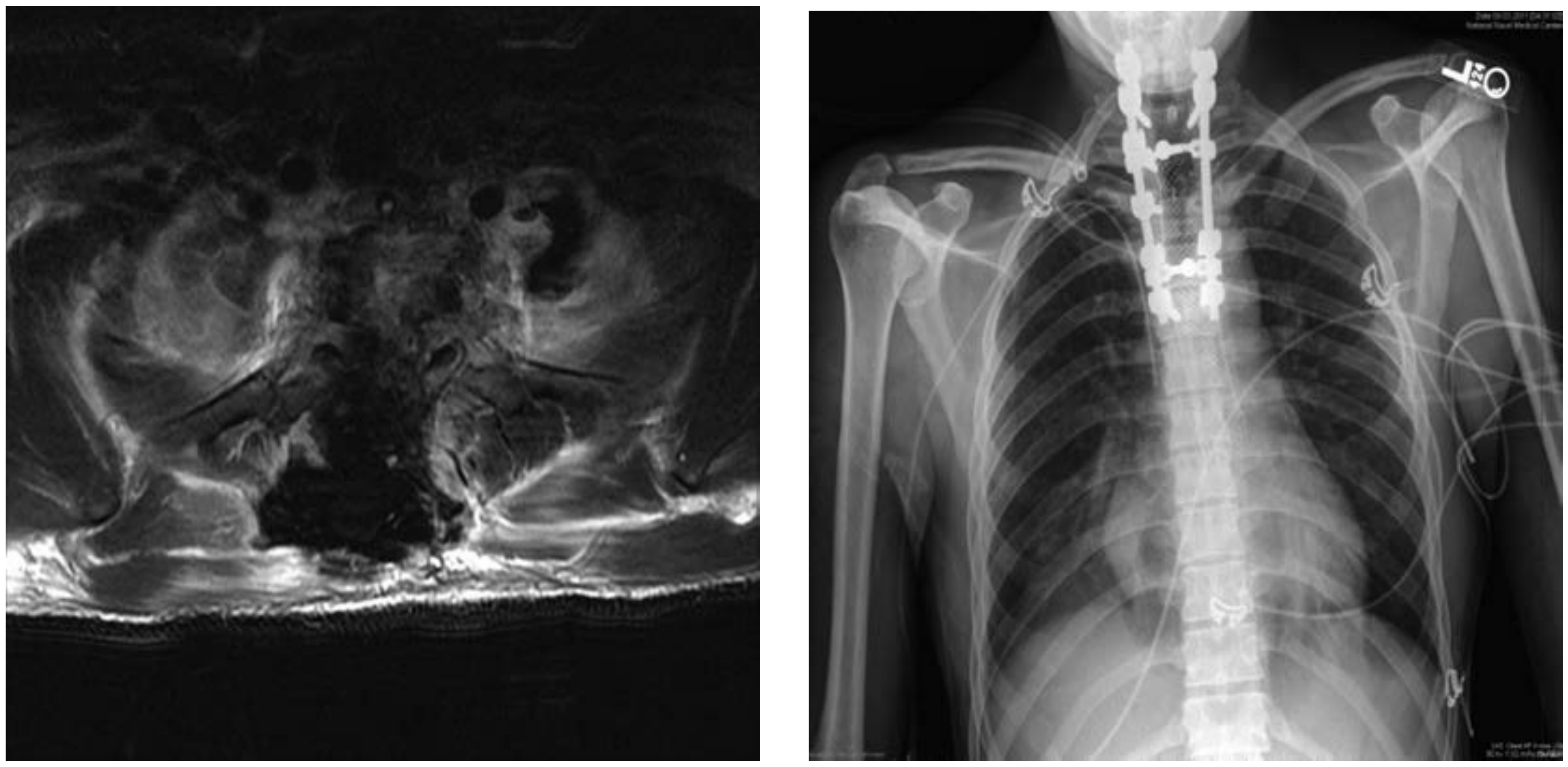
Fig. 24.2 This is an example of a complex exit wound from a penetrating spine injury. Management of dural violation and cerebrospinal fluid fistulas is paramount for wound healing in these patients. Vascularized tissue coverage is critical and may require the assistance of a plastic surgeon.



a b

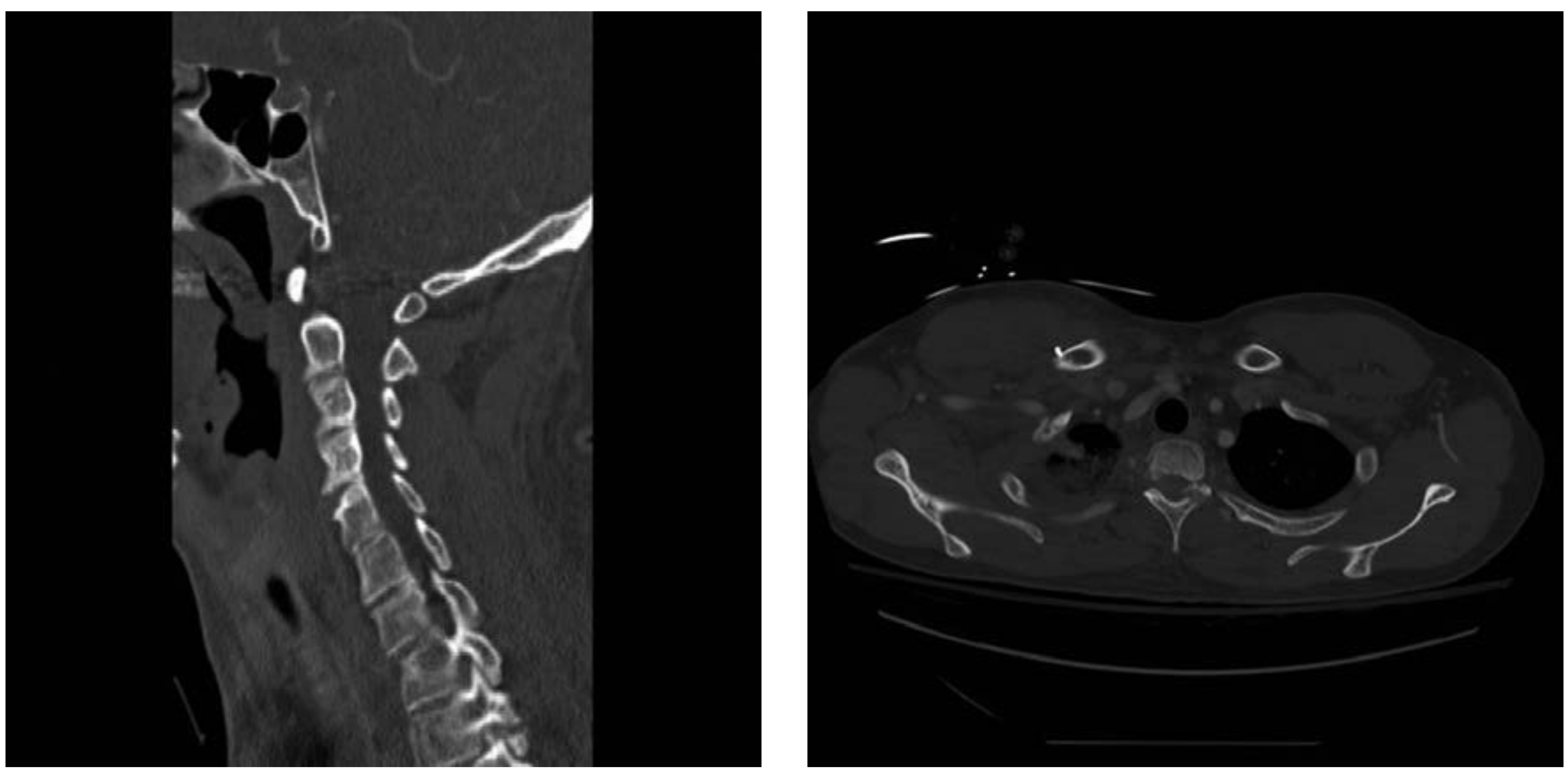
c

Fig. 24.3a–e This 27-year-old man sustained a high-velocity gunshot wound that entered through the left neck (with associated tracheal/esophageal injuries and severe bilateral pulmonary contusions) and resulted in complex (**a, b**) multicolumn fractures of T2-4 with bilateral facet joint involvement, (**c, d**) complete cord transection, and a resultant complete (ASIA A) spinal cord injury. His tracheal and esophageal injuries were repaired and the entry/exit sites were debrided and closed while in theater. Because of the patient's poor pulmonary and infectious status, his spinal injuries could not be addressed until post-injury day 15. (continued)



d e

Fig. 24.3 (continued) (**e**) At that time, he underwent a C7-T5 posterior spinal fusion with ligation of the thecal sac above the level of injury.



a b

c

Fig. 24.4a–c This 39-year-old man sustained a gunshot wound that entered medial to the left scapula and traversed the left T2-3 pedicle, (**a, b**) exiting into the thoracic cage via the right T2-3 neuroforamen. He presented with a complete (ASIA A) spinal cord injury with no sacral sparing and MRI evidence of severe spinal cord injury (**c**). Given that the injury was thought to be stable and that there was no evidence of CSF leakage, it was managed nonoperatively with bracing.

Preprocedure Considerations

Initial Evaluation

- Full evaluation/resuscitation protocol in accordance with the Advanced Trauma Life Support (ATLS) guidelines.
- Detailed neurologic assessment to include motor function in all key muscle groups, sensory status, reflexes, and sphincter tone as detailed by the American Spinal Injury Association (ASIA) examination protocol.[11]
- Examination of entrance/exit wounds for evidence of cerebrospinal fluid (CSF) leakage.
- Thorough evaluation and assessment of any associated soft tissue or visceral injuries.

Radiographic Imaging

Plain X-ray

- Demonstrates anatomic alignment, the presence or absence of overt bony injury, and the location of most retained foreign bodies.

Computed Tomography (CT)

- Provides superior imaging of the bony anatomy and injury pattern(s). In addition, it also provides information regarding the location of retained foreign bodies. Metallic streak artifact from retained foreign bodies may degrade the imaging.
- For cervical spine injury, CT angiography (CTA) should be performed on all patients to evaluate for carotid or vertebral artery injury: disruption, dissection, thrombosis, or pseudoaneurysm formation. For thoracic or lumbar involvement, CTA and CT venography should be done to evaluate for large vessel injury (e.g., thoracic and abdominal aorta, common iliac arteries, inferior vena cava).
- CT myelography is rarely indicated in the acute setting; it may be valuable in a patient in whom magnetic resonance imaging (MRI) is contraindicated but in whom concern exists for a compressive dural lesion not apparent on bone windows such as an epidural or subdural hematoma.

MRI (When Available)

- Excellent for showing soft tissue anatomy: the integrity of the spinal cord, nerve roots, ligaments, muscles, joint capsules, and intervertebral disks. MRI is usually contraindicated in PSI if there are retained metallic fragments.

Initial Medical Management[12]

- Admission to monitored setting.
- Immobilization until spinal stability established.
- Avoid hypotension (systolic blood pressure , 90 mm Hg) and maintain mean arterial pressures at 85–90 mm Hg for the first 7 days if the patient has suffered a spinal cord injury.[13]
  - Use careful intravenous hydration with pressors (dopamine) if needed to maintain mean arterial pressure (MAP) goals.
- Place in-dwelling (Foley) urinary catheter and nasogastric tube (connected to suction) to prevent urinary retention and vomiting/aspiration, respectively.
- High-dose methylprednisolone is not indicated in the management of PSI.[14]
- Stress ulcer and pharmacologic deep vein thrombosis prophylaxis is encouraged.
- High-dose broad-spectrum intravenous antibiotics given for 7–10 days are indicated, especially in the case of a transabdominal trajectory with an associated bowel injury.[15,16]

Operative Considerations/ Techniques

The patient with a PSI is at high risk for a wide range of perioperative complications that the surgeon must anticipate and try to prevent. In a recent article by Possley et al,[17] complications—defined as unplanned medical events (surgical or nonsurgical) that require further intervention—occurred in 35% of service members with PSI who underwent surgical intervention.

Tactical Scenario

- Does the current tactical setting allow for operative intervention in a safe, sterile environment?

Associated Injuries

- For transthoracic injuries: Is the patient able to tolerate being prone from a respiratory and hemodynamic standpoint?
- For transperitoneal injuries: Does the patient require intervention for a possible intestinal/vascular injury? Can the patient tolerate being prone for the duration of the operation?

Operative Field Preparation

Radiographic Imaging

- See Imaging section for details
- Plain X-rays: For posterior thoracic approaches to determine the number of ribs for localization

Equipment/Set-Up

- Headlight, loupes, bipolar/Bovie cautery
- Intraoperative fluoroscopy
- Mayfield head holder: For posterior cervical approaches
- Prone table: Open/closed Jackson table with Wilson frame or bolsters depending on surgeon preference for posterior thoracolumbar approaches
- Basic spine tray with Kerrison rongeurs
- High-speed drill
- Basic spinal instrumentation tray: Should have on stand-by for all cases
- Dural repair materials: Should have appropriate sutures (4-0 braided nylon, etc.) available for primary dural repair,

synthetic dural substitutes, and dural sealants for all cases. Also, materials for thecal sac ligation if indicated (see **Fig. 24.1** and Operative Technique section) should be available.
- Lumbar drain: Should have available if needed for CSF diversion in lumbosacral decompressions

Anesthesia Issues

- Consider awake fiberoptic intubation if spinal instability suspected
- Prophylactic intravenous antibiotics 30 minutes prior to incision if not already on broad-spectrum antibiotics
- Foley catheter
- Arterial line to maintain mean arterial pressure . 85 mm Hg for the entirety of the case

Neuromonitoring

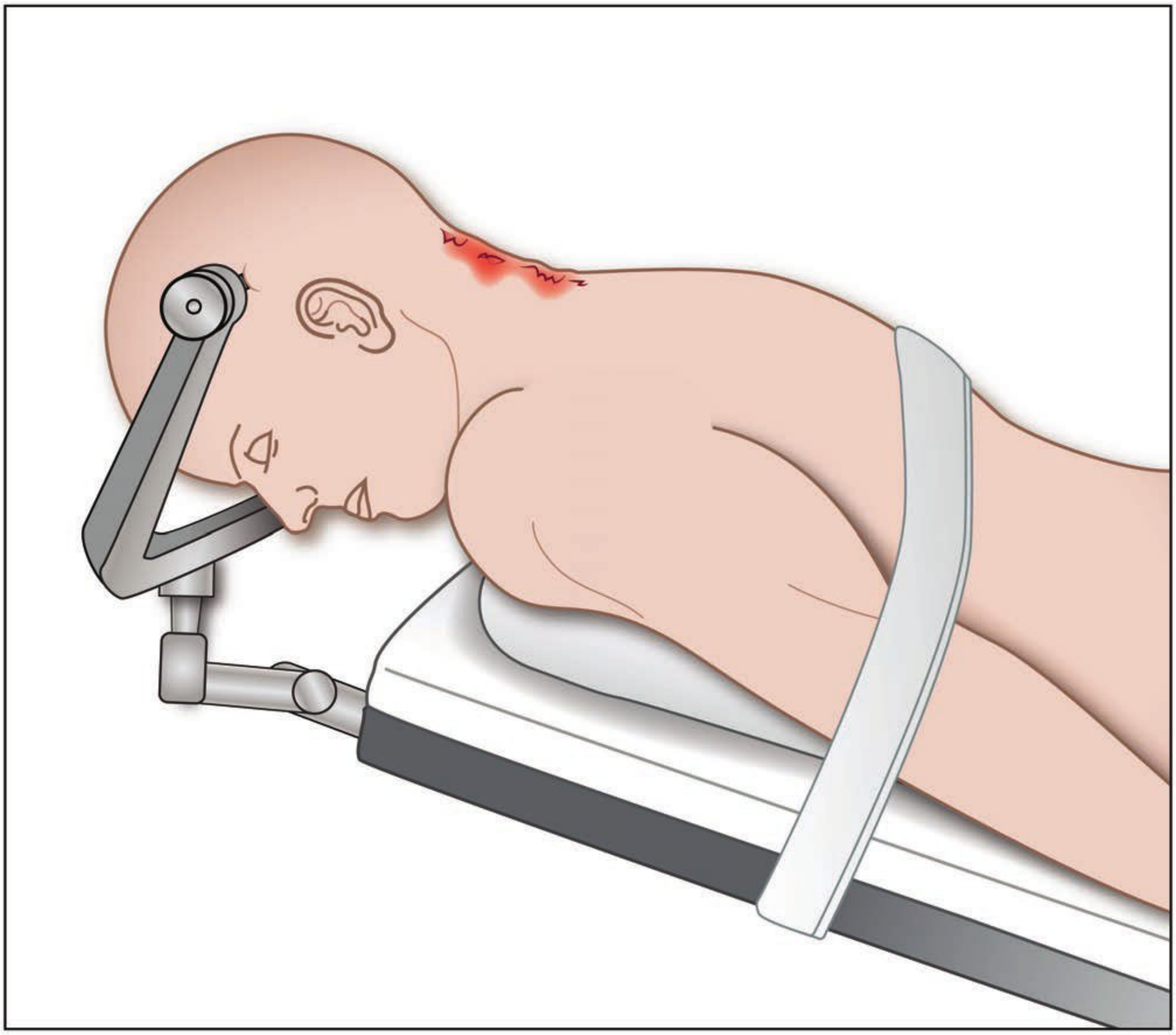
- Recommended if available for monitoring of somatosensory evoked potentials (SSEPs) and electromyography (EMG)

Prepping/Incision

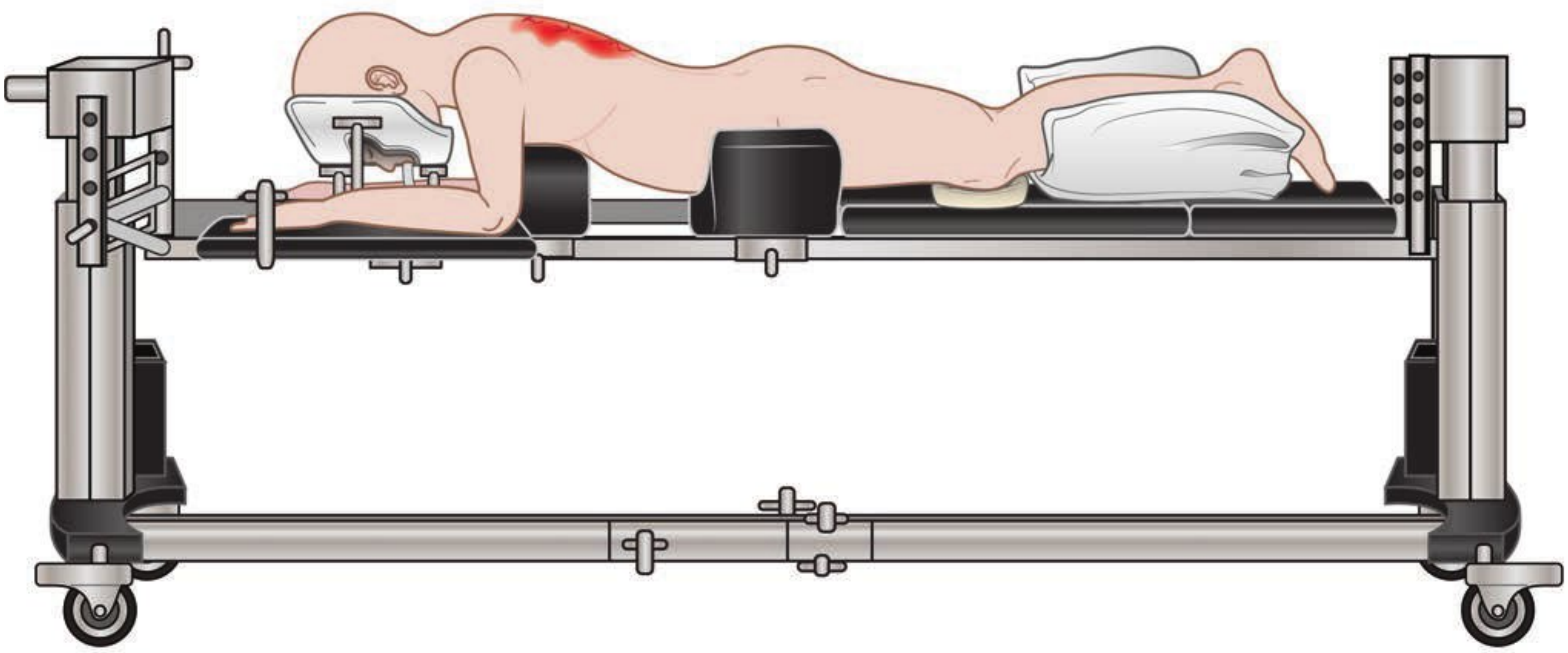
- Shave with electric hair clippers
- Surgical preparation in the standard sterile fashion

Operative Procedure

Positioning (Fig. 24.5a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 24.5	**(a) Posterior cervical approach: Prone in Mayfield head holder on standard operating room table with appropriate padding and arms tucked on the patient's sides in reverse Trendelenburg to promote venous drainage. Use fluoroscopy to confirm normal physiologic cervical alignment.** **(b) Posterior thoracolumbar approaches: Prone on open/closed spinal table with Wilson frame or bolsters depending on surgeon preference. For pathology above T6-7, the arms should be tucked at the patient's side. Below this level, the arms may be abducted and placed on a padded surface.**	• Use fluoroscopy to plan the incision to span at least two levels above and below the levels of planned decompression and/or fusion. • Consider both anteroposterior and lateral fluoroscopy to aid in localization for posterior thoracic approaches (requires preoperative knowledge of rib number). Bony injury or retained metallic fragments will allow rapid localization of the injured level(s).

Dissection (Fig. 24.6)

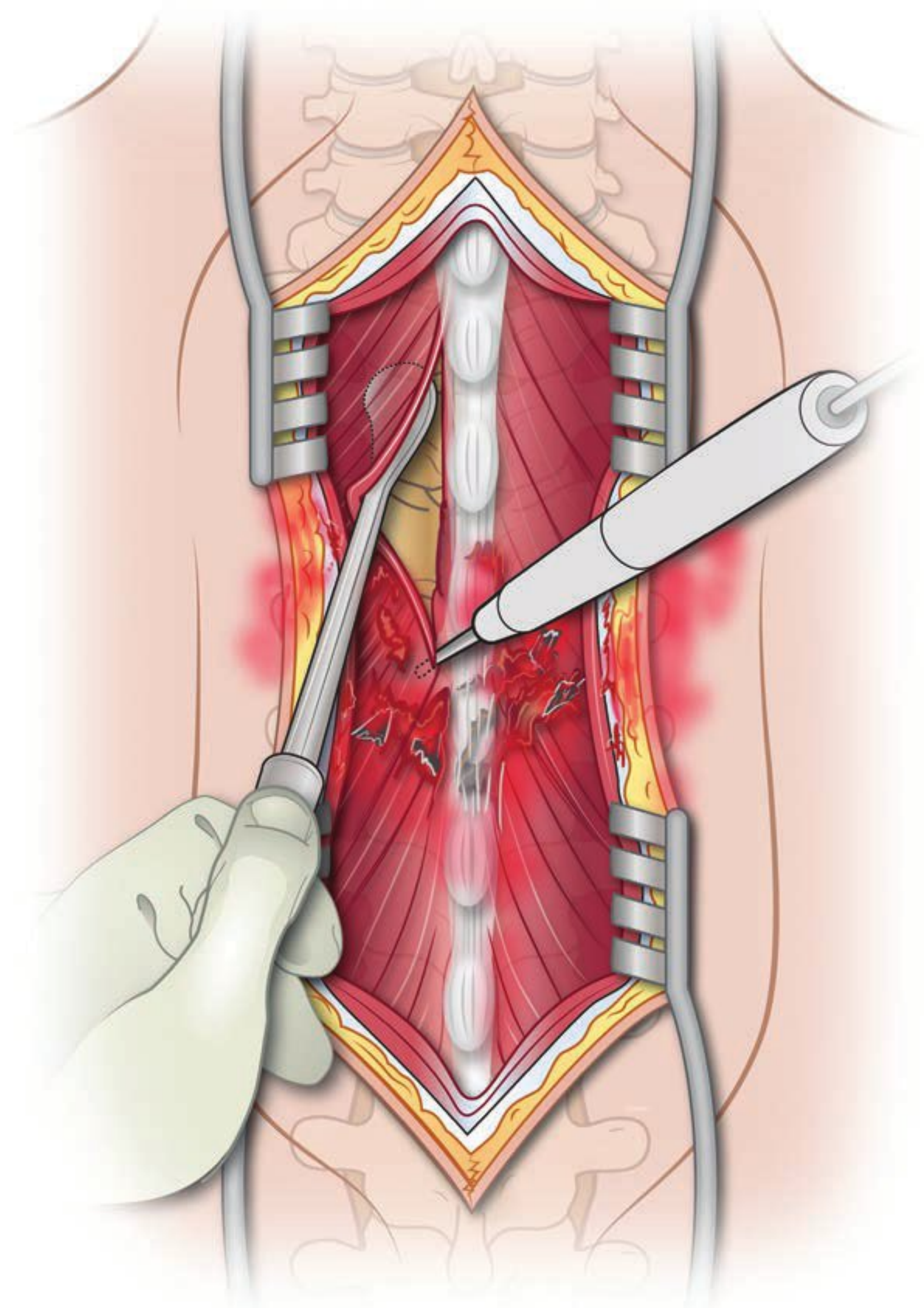


Figure	Procedural Steps
Fig. 24.6	**A midline incision is made with no. 10 scalpel blade (length as dictated by fluoroscopic localization).** **Using monopolar cautery, continue a midline dissection with the assistance of self-retaining retractors to the level of the spinous processes.** **Verify operative level fluoroscopically.** **Complete a bilateral subperiosteal dissection on the planned levels of decompression to the medial edges of the facet joints. If an instrumented fusion is not planned, take special care to leave the facet joint capsules intact.**

Laminectomy (Fig. 24.7)

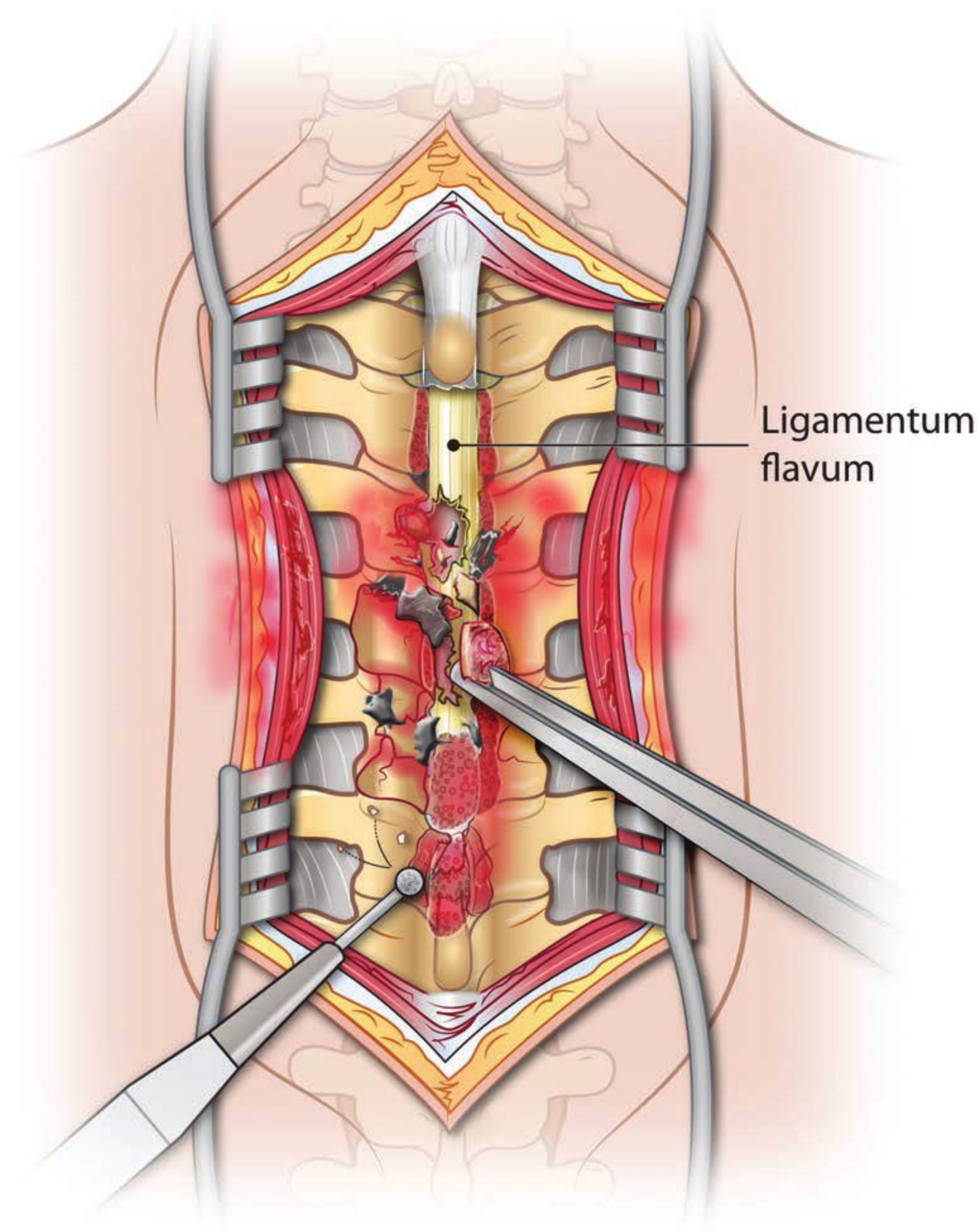


Figure	Procedural Steps
Fig. 24.7	**Using the high-speed drill and Leksell/Kerrison rongeurs, remove the spinous processes and perform laminectomies at least one level above and below the pathologic level.** **Remove the underlying ligamentum flavum with Kerrison rongeurs.**

Decompression (Fig. 24.8)

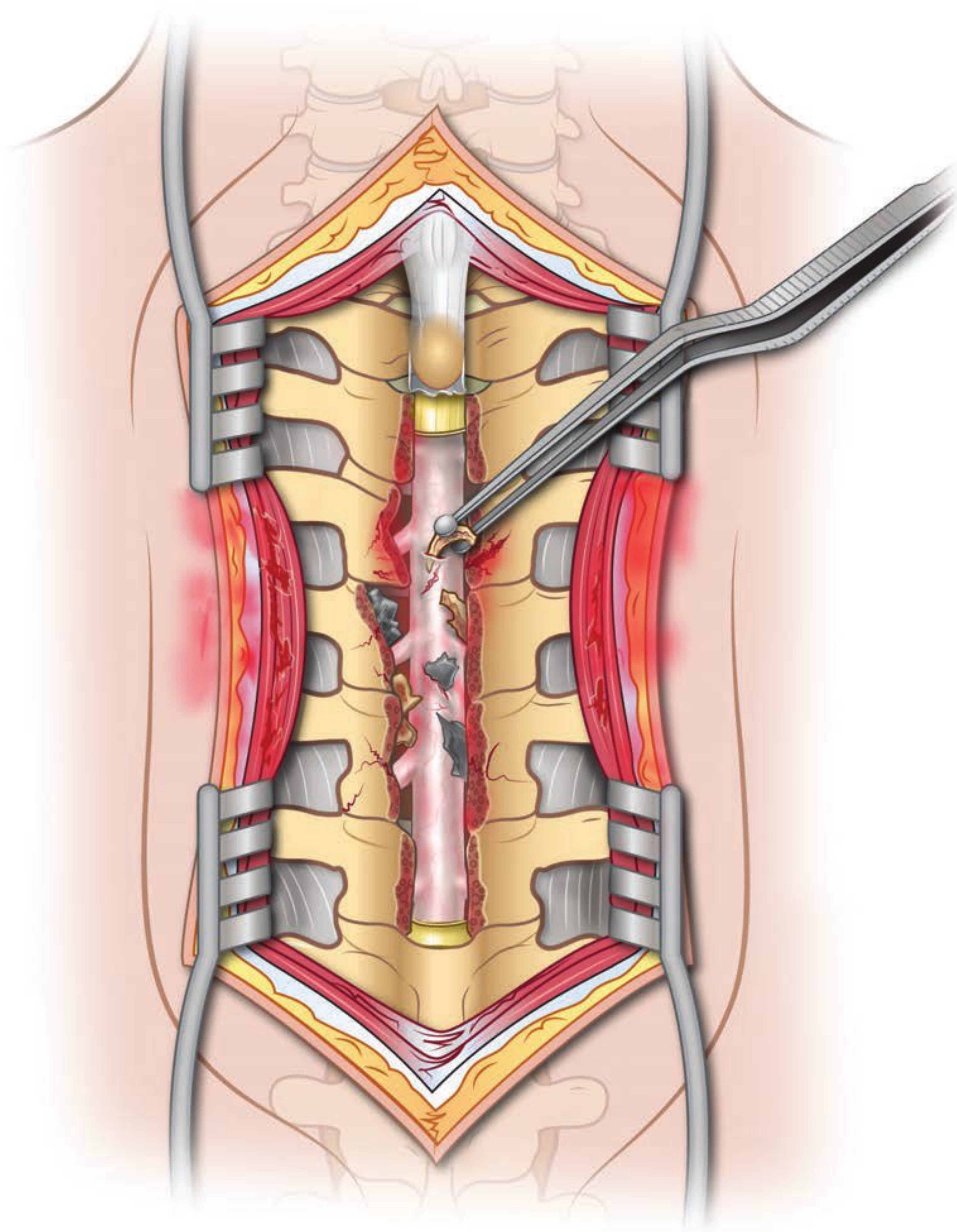


Figure	Procedural Steps
Fig. 24.8	**Carefully remove any foreign bodies or bony fragments causing any compression on the underlying nerve roots, thecal sac, or spinal cord.**

Dural Exploration/Repair (Fig. 24.9)

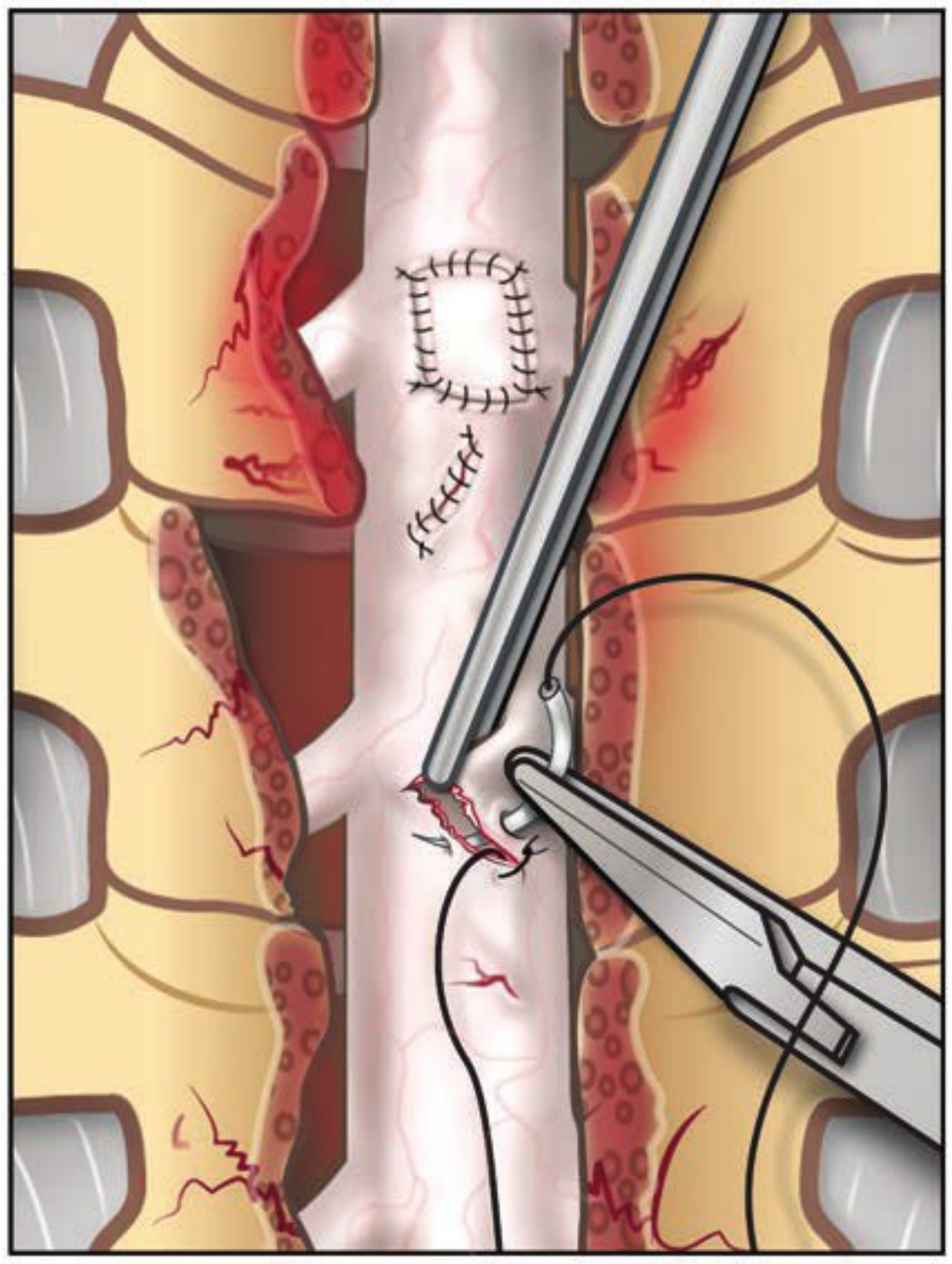


Figure	Procedural Steps	Pearls
Fig. 24.9	**Carefully explore the thecal sac and exiting nerve roots for the presence of any dural tears.** **If present, attempt primary repair with 4-0 braided nylon suture that can be augmented by the use of either dorsal autologous fascia/muscle or a suturable synthetic dural substitute for larger defects.** **Perform Valsalva maneuver to judge the integrity of the dural repair.**	• Further augmentation with synthetic dural substitutes and sealants may then be attempted. • In the instance of CSF leakage in the setting of a complete spinal cord injury, consideration may then be given to ligation of the thecal sac as a primary means of halting CSF egress. • Consider intraoperative placement of a lumbar drain for protection of lumbosacral dural repairs.

Instrumentation/Fusion (See Chapters 14 and 15)

- If indicated, perform instrumentation and fusion after the primary operative goals of decompression and dural repair have been accomplished.

Closing

- Suction canister/Jackson-Pratt drain(s) if needed (avoid when dural repair performed).
- Close dorsal fascia in a watertight manner with interrupted 0-0 braided absorbable sutures.
- Close subcutaneous tissue with inverted, interrupted 2-0 braided absorbable sutures.
- Close skin with either staples or running 2-0/3-0 nylon suture.

Postoperative Management

- Admission to a monitored setting with continued blood pressure goals as specified for up to 7 days after the initial injury.
- Monitor drain output with removal when output is minimal or if any concern exists for CSF leakage.
- Obtain early postoperative imaging if instrumentation performed.
- Maintain appropriate antimicrobial coverage with intravenous antibiotics for 7 days if visceral injury is confirmed.
- In the case of a low thoracic or lumbar dural repair, maintain the patient flat for 48–72 hours postoperatively. For cervical or proximal thoracic dural repairs, maintain the patient with the head of bed at 90 degrees for 48–72 hours in the postoperative setting. In the case of mid-thoracic dural repairs, the positioning of the patient postoperatively is at the discretion of the operating surgeon.
- Mechanical deep vein thrombosis (DVT) prophylaxis should be initiated upon admission and continued throughout surgery and postoperatively. When it is determined to be appropriate, institute pharmacologic DVT prophylaxis.
- Recommend postoperative scoliosis survey in the sitting or standing position (depending on the patient's clinical status) to provide baseline knowledge regarding regional and global spinal balance. This should be repeated at regular intervals (as determined by the operating surgeon) to monitor for any deformity progression in the post-surgical setting, particularly in those patients with complete spinal cord injury and those with incomplete injury but who are nonambulatory.

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V Reconstructive Surgery

25 Replacement of Cranial Bone Flap

Jamie S. Ullman

Introduction

Craniotomy bone flaps are often frozen or stored in the subcutaneous layer of the abdominal wall after decompressive craniectomy for intracranial hypertension from traumatic brain injury, cerebrovascular disease, or other causes. Bone flap restoration will be needed once the acute issues have resolved. There is no consensus regarding the optimal timing of bone flap replacement.[1–4] Replacements can be performed from as little as 2 weeks to more than 1 year after injury.[5,6]

Indications

- Sufficient abatement of swelling has occurred with the brain noted on clinical or radiological examination to be “sunken” or not significantly protruding beyond the defect.
- There is no indication of systemic or local infection, or evidence of significant decubitus ulcers in proximity to the cranial defect or incision.
- Increasing lethargy or new focal deficit is present on examination and not otherwise attributed to metabolic or structural abnormalities. Such deficits are potentially due to the effects of altered cerebrospinal fluid (CSF) dynamics or atmospheric pressure on the brain.
- There may be significant brain depression at the defect and computed tomography (CT) may reveal brain shifting to the contralateral side. Evidence suggests that earlier restoration of cranial integrity can improve neurologic deficits in addition to helping those patients who exhibit early signs of communicating hydrocephalus.[5,7,8]

Preprocedure Considerations

Radiographic Imaging

- CT is essential to evaluate the condition of the brain and its relationship with the defect prior to performing reconstruction (**Fig. 25.1**).

Fig. 25.1 Preoperative computed tomography study indicating a large left cranial defect. The brain is largely flush with the bone edges.

Medication

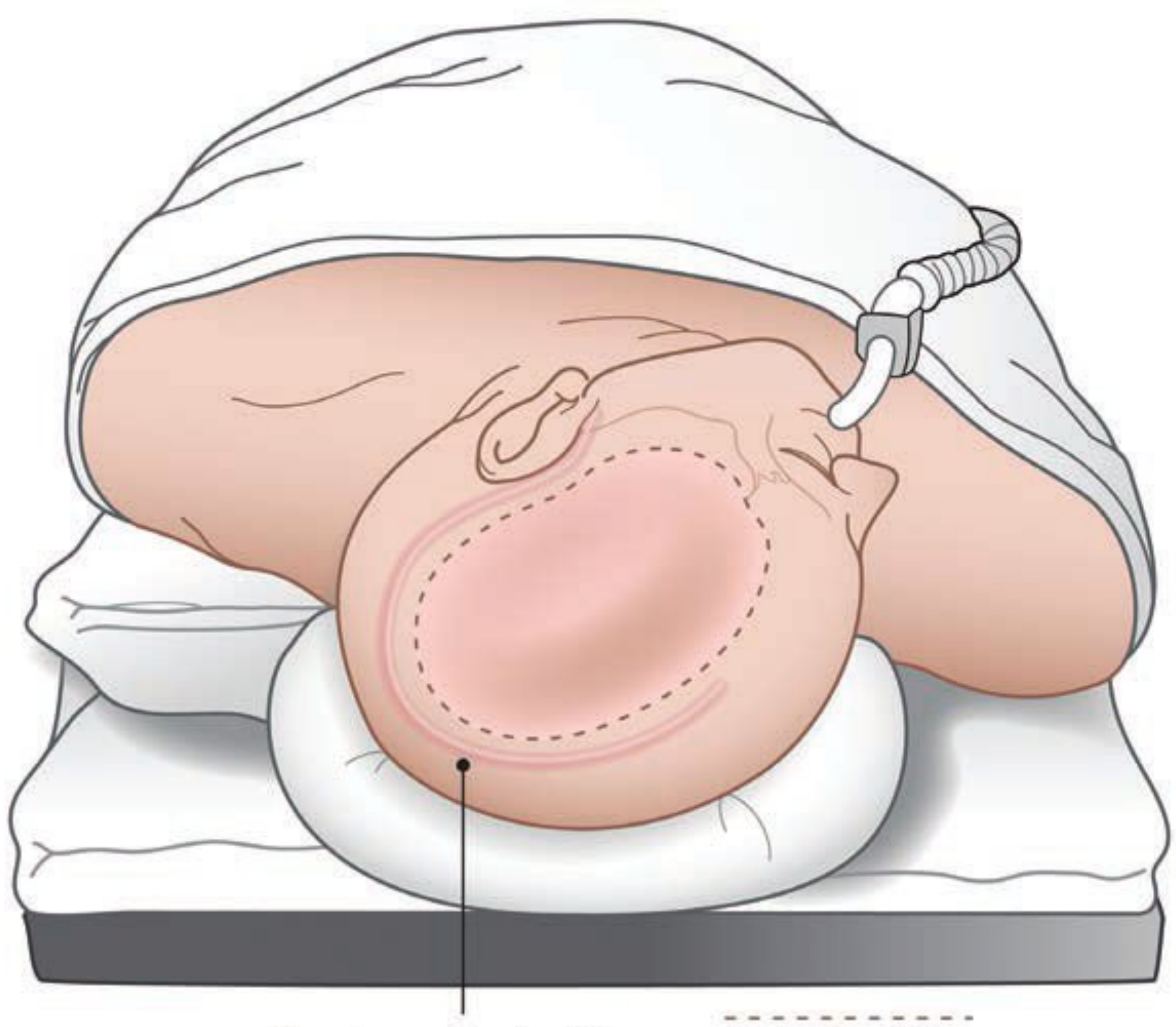
- The author prefers vancomycin and gentamicin for antibiotic prophylaxis, provided the patient does not have renal failure or other contraindications. Often patients have been hospitalized for significant periods of time and there is a possibility for the skin to be colonized with methicillin-resistant *Staphylococcus aureus*.
- Diphenylhydantoin is administered at 15 mg/kg in nonallergic patients who are not on standing antiepileptic medication. Levetiracetam can be used alternatively at a 1000-mg loading dose.

Operative Field Preparation

- Alcohol prep is performed before povidone iodine or chlorhexidine application.
- The incisions are marked and infiltrated with 1% lidocaine with epinephrine 1:100,000.

Operative Procedure

Positioning and Preparation (Fig. 25.2a, b)



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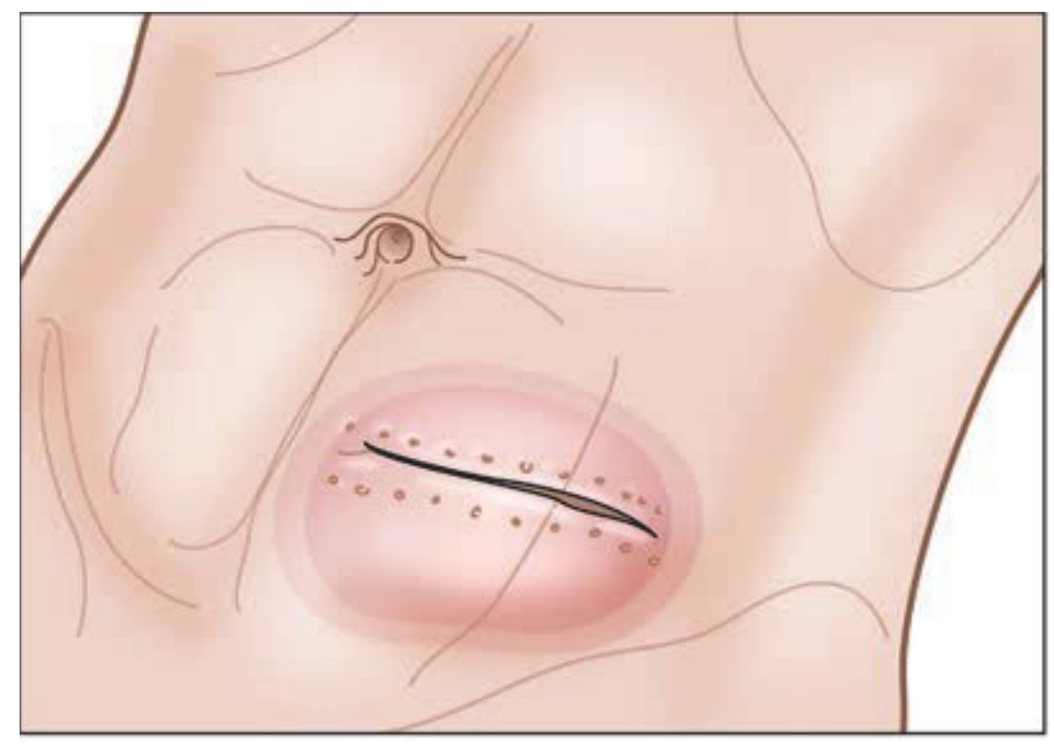
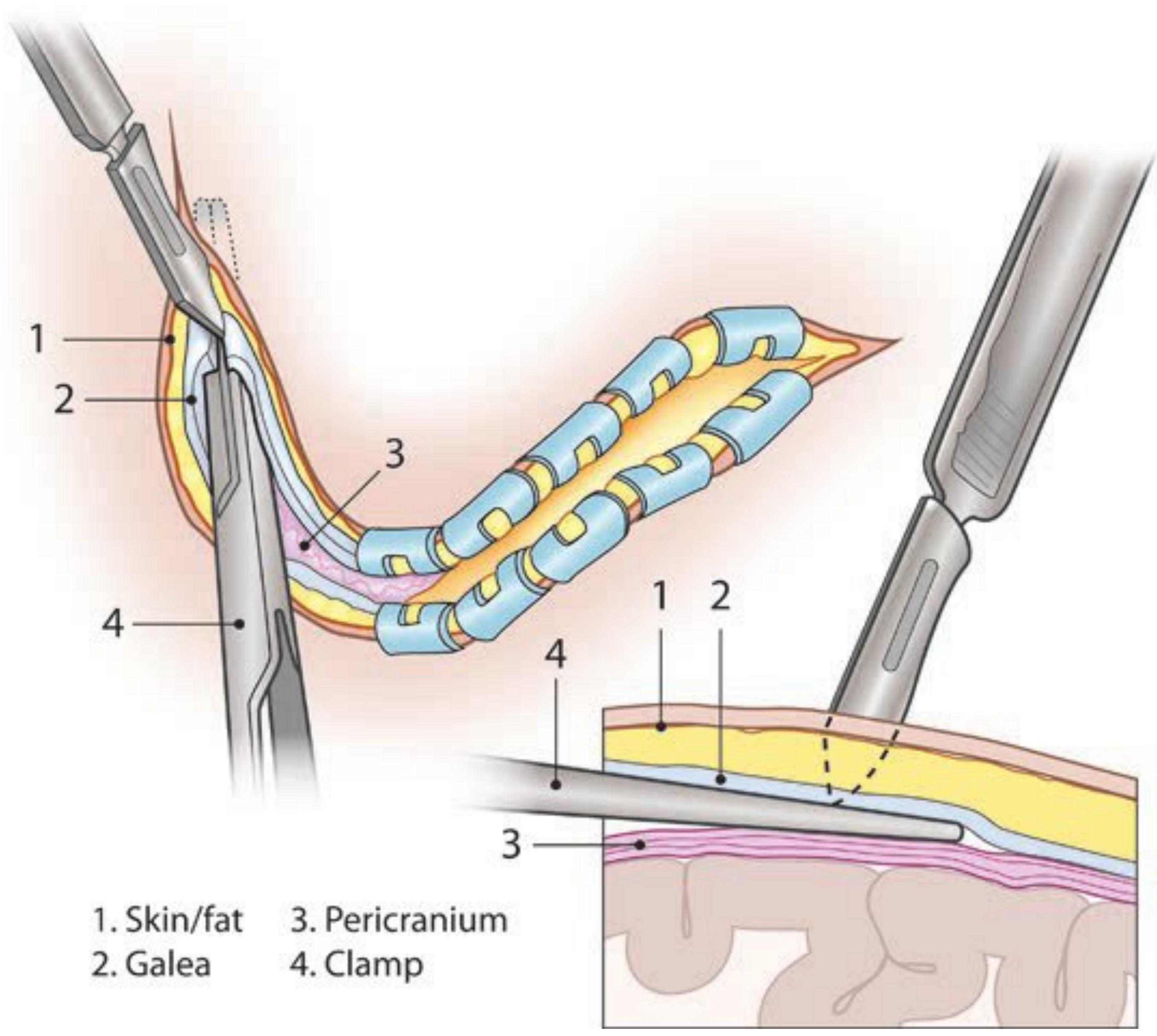


b

Figure	Procedural Steps	Pearls
Fig. 25.2	**(a) Patient positioning. The head is turned approximately 60 degrees in the contralateral direction and the prior frontotemporoparietal scalp incision is exposed and prepared.** **(b) The abdominal incision housing the subcutaneously placed bone flap is exposed and prepared.**	• While this chapter discusses subcutaneously placed autogenous bone grafts as opposed to those stored in a freezer, the techniques of reopening the craniotomy incision and bone flap replacement remain the same. For the commonly performed hemicraniectomy or frontotemporoparietal (occipital) defect, the patient is positioned in the supine position with the head turned approximately 60 degrees in the contralateral direction. The head is placed on a donut and a roll is placed under the ipsilateral shoulder. For bifrontal craniectomies, the patient is placed supine, head straight position; the subcutaneous dissection described forthwith is essentially the same (see Chapter 26).

Skin Incision (Fig. 25.3a, b)



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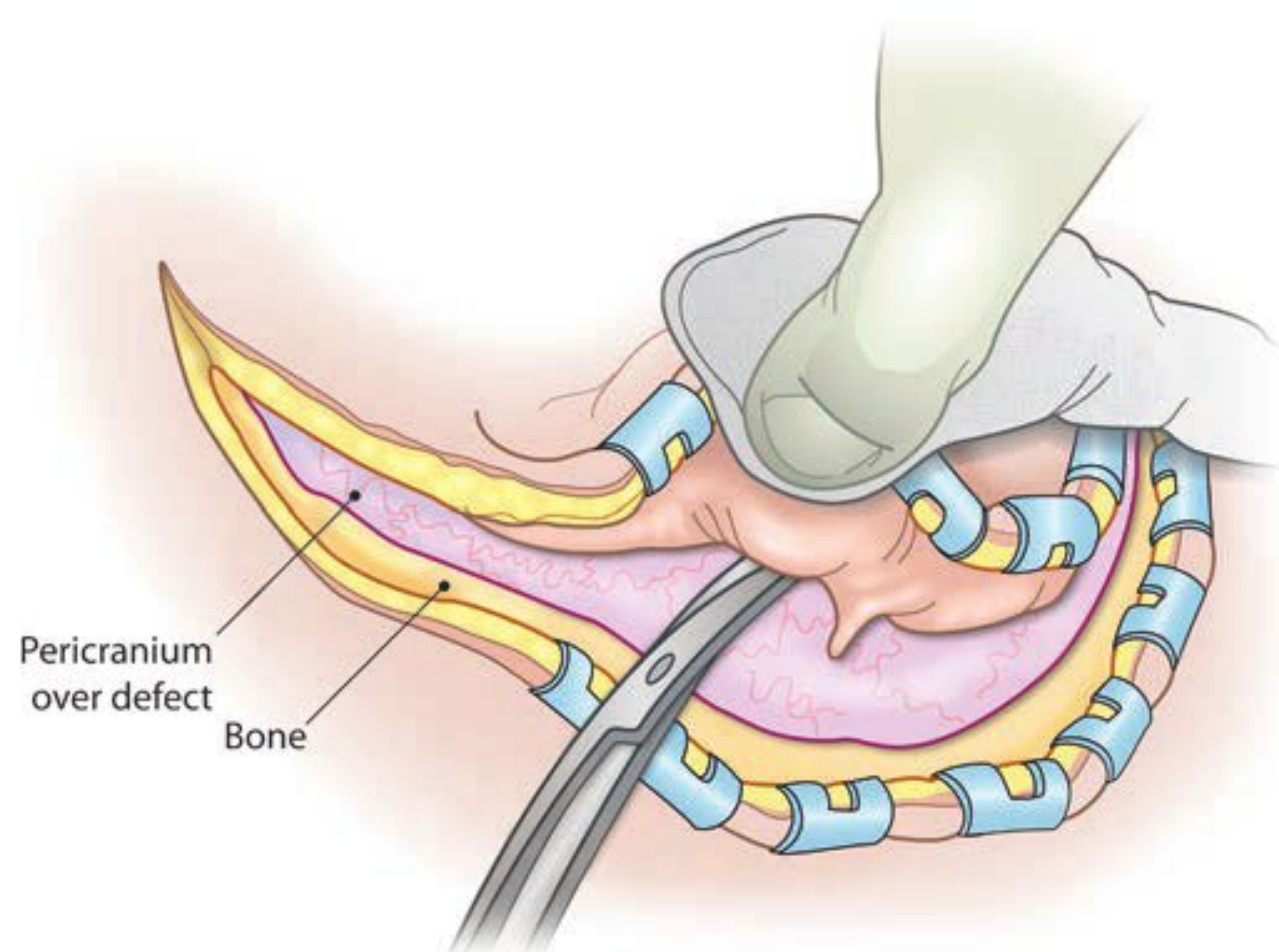


b

Figure	Procedural Steps	Pearls
Fig. 25.3	**(a) The incision is made with a no. 10 blade from the superoanterior frontal region first and opened in progressive fashion. The bone edge is palpated under the incision. If there is no bone edge, a straight clamp is used to separate the pericranium from the galea to provide protection from the knife blade when bone cannot be palpated underneath the incision.** **(b) The incision is opened in stages starting with the frontal, superior portion, placing galeal clamps when this layer has been properly separated. The plane between the pericranium and galea is developed with sharp dissection. The scalp layer can be properly reflected forward by developing the plane between the vascularized pericranium and the galea.**	• In cases where the pericranium was elevated with the scalp during the initial procedure, this layer is virtually unscarred. The galea–pericranial plane is developed with a Metzenbaum scissors. Unscarred planes can also be developed with blunt dissection using a gauze sponge. The pericranium will cover the defect as the new "pseudodural" plane. If the pericranium is intact, the defect area will be well-vascularized and the underlying duraplasty or brain tissue will not be seen.

Subcutaneous Dissection (Fig 25.4)

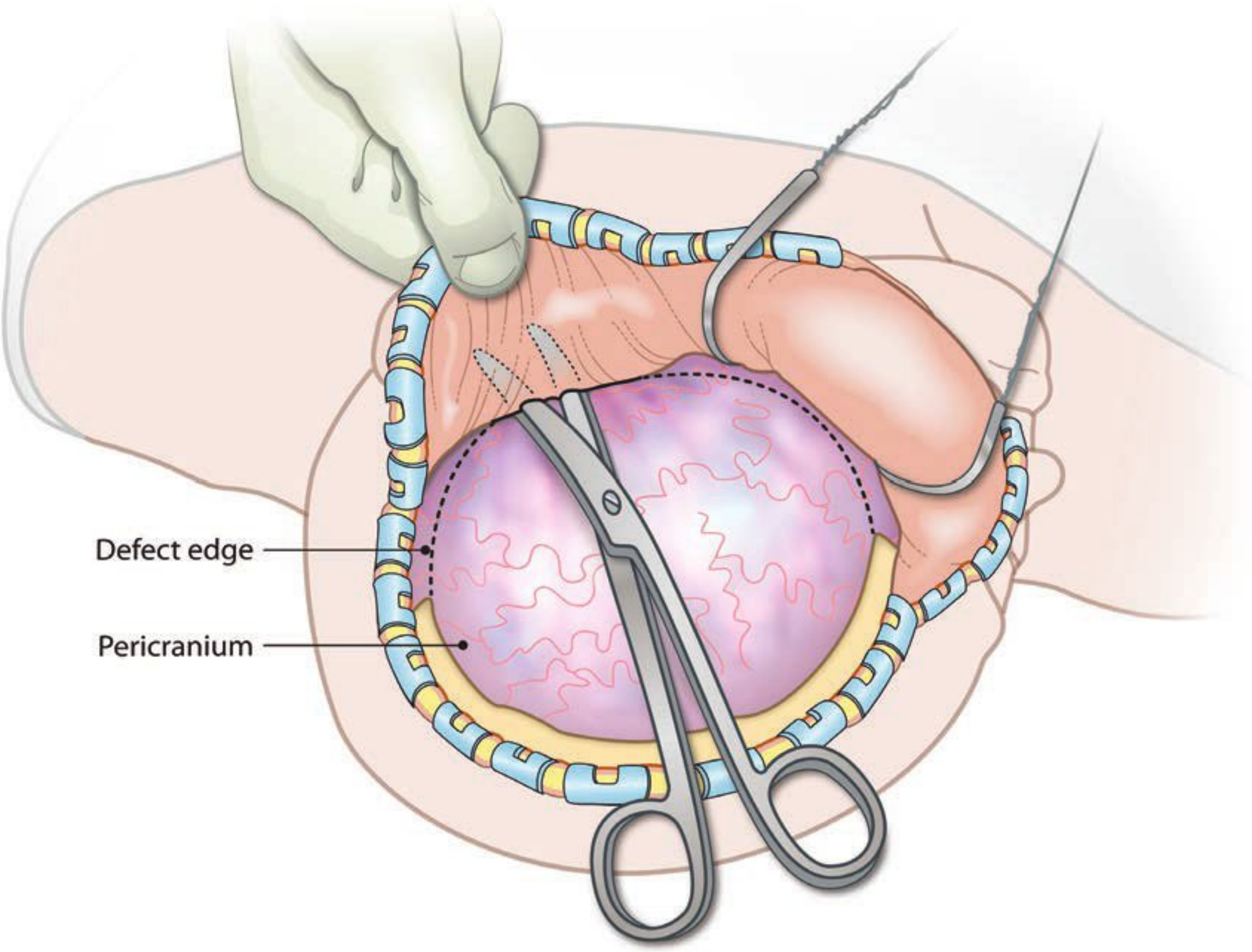
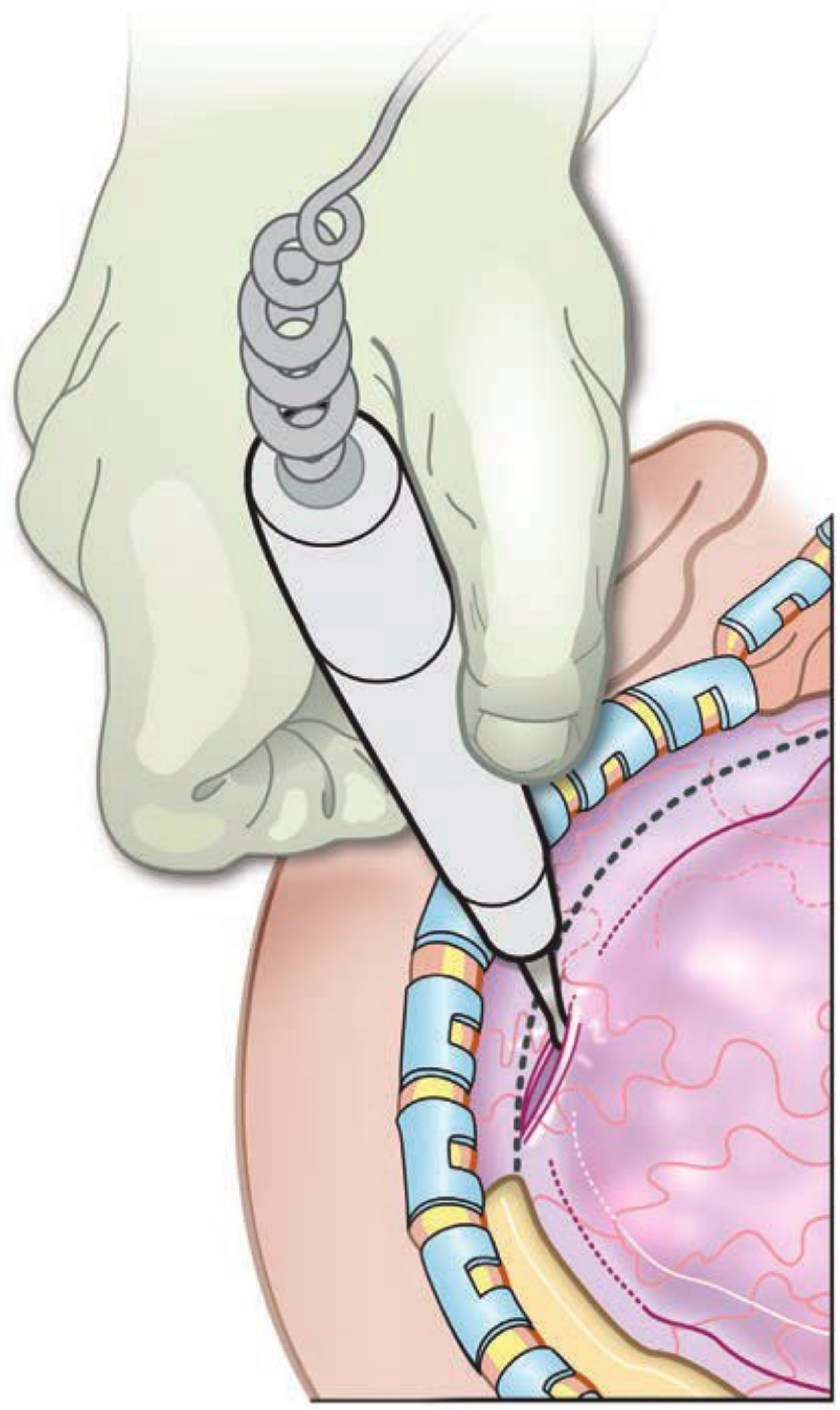


Figure	Procedural Steps	Pearls
Fig. 25.4	**After dissection becomes limited, the skin is opened further. Progressive alternation of skin opening and galeal–pericranial plane dissection is completed until the wound is completely reopened and the entire scalp flap has been reflected. Galeal clamps are placed for hemostasis. The scalp flap is then retracted anteriorly with scalp hooks or 2-0 braided nylon sutures attached to rubber bands and clamps. Hemostasis is achieved with mono- and bipolar cautery.**	• Maintaining vascularized tissue in the epidural plane can help combat potential infections and promote osteoinduction.[9] Surgeons who have previously performed a duraplasty with collagen or allo/xenographic dural substitutes may choose to dissect the pericranial–dural plane. However, if the cranioplasty is performed prior to sufficient incorporation of the dural graft material, the resulting dural layer may not yet have sufficient vascularity.

Identifying the Temporalis Muscle and Separation (Fig. 25.5a–c)



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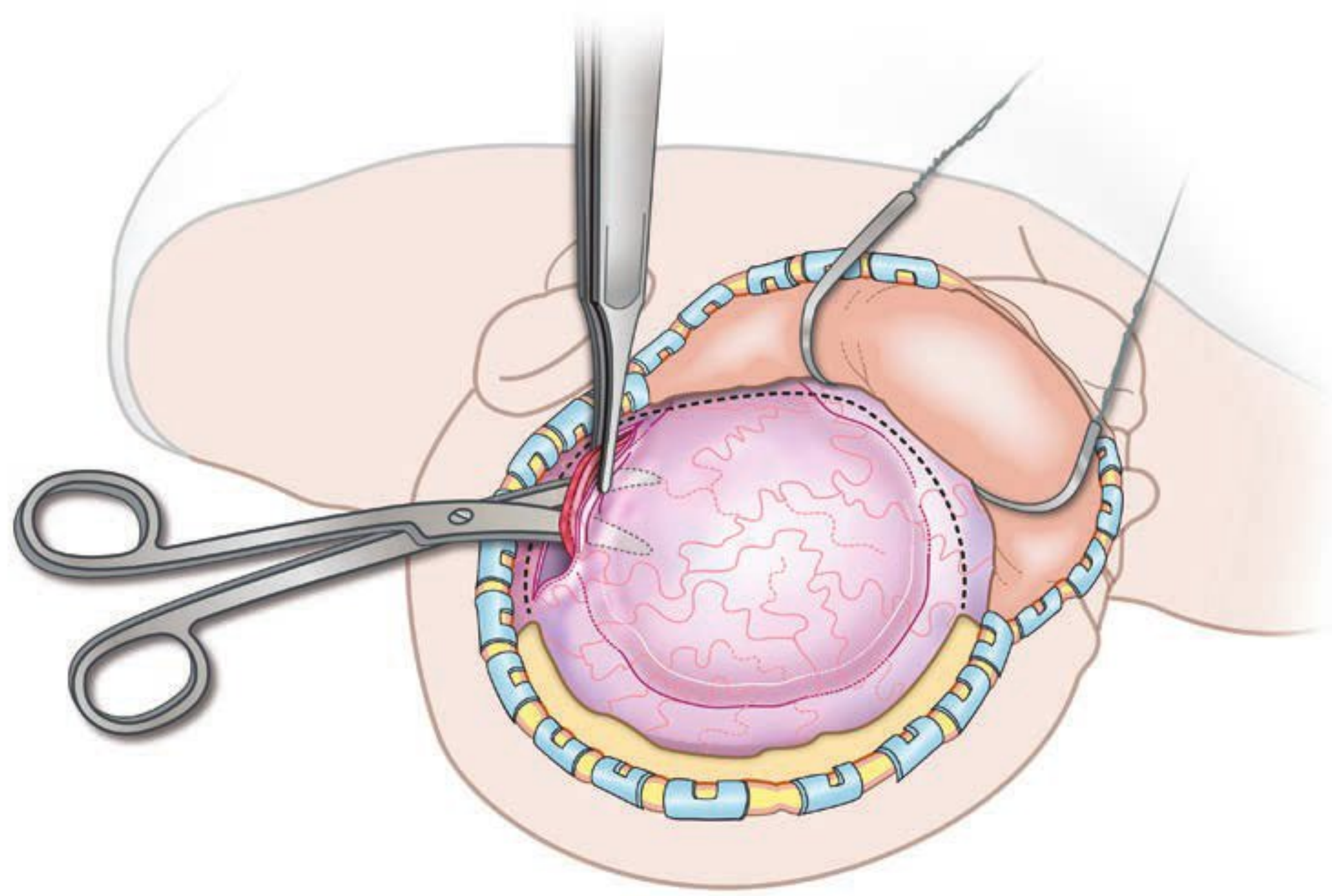

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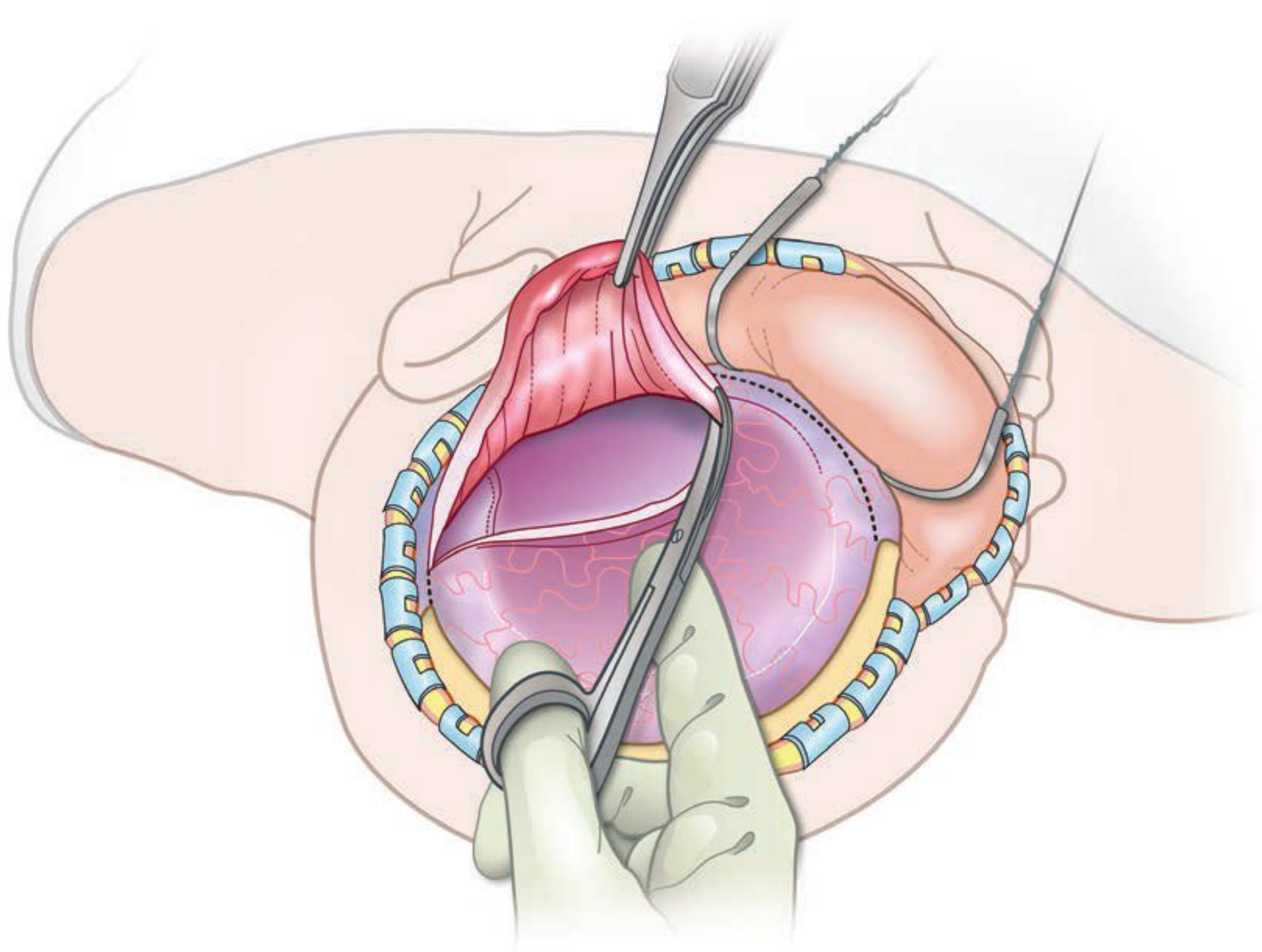
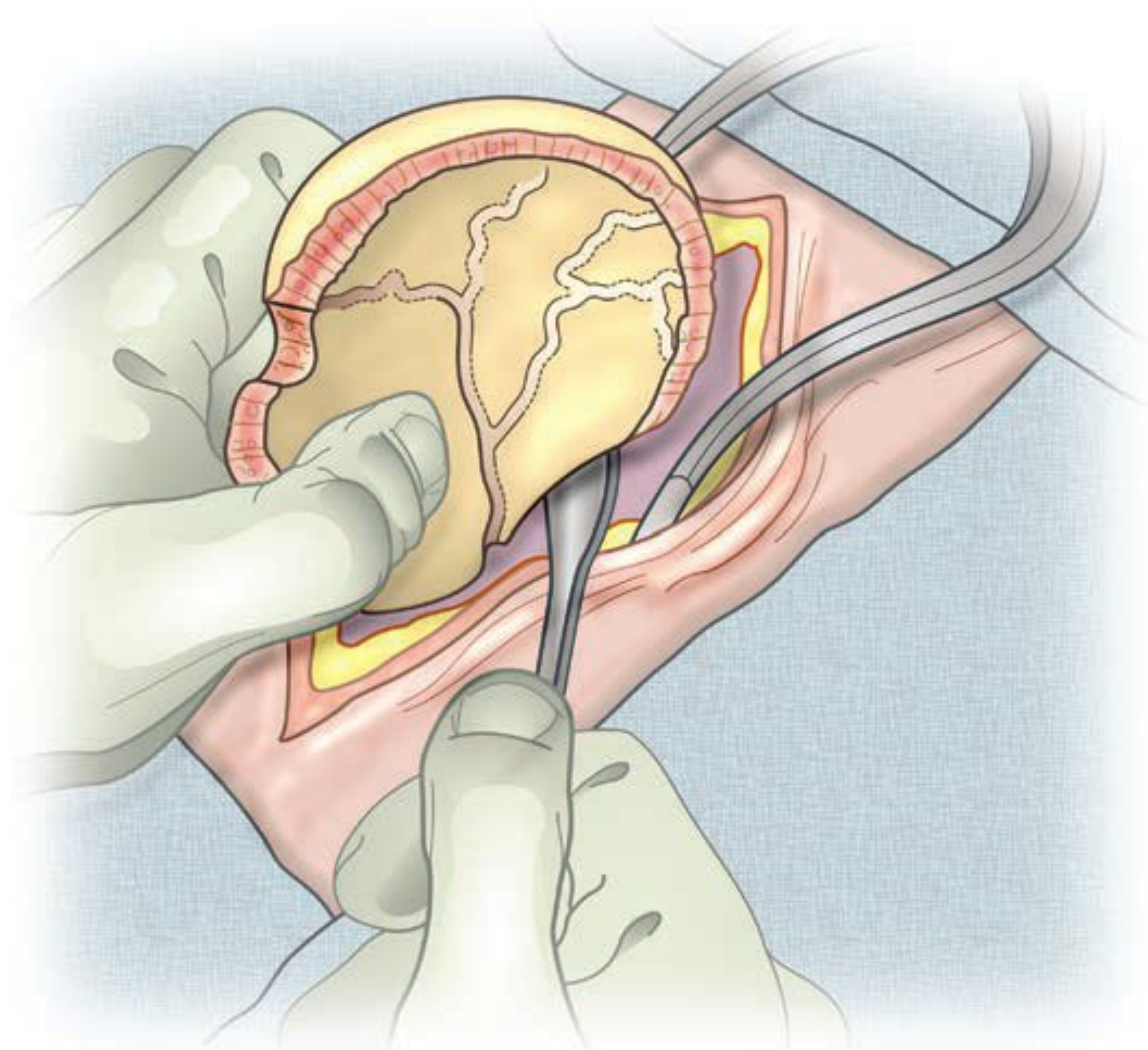


c

Figure	Procedural Steps	Pearls
Fig. 25.5	**(a) Monopolar cautery or a scalpel is used along the posterior bone edge to expose and incise the temporalis muscle for dissection and transposition.** **(b) The plane between the muscle layer and the underlying duraplasty is developed with dissecting scissors. If a dural plane is not well established underneath the muscle during the initial procedure, disruption of the cerebral cortex may occur. Well-preserved muscles can be separated from the underlying tissues safely using sharp dissection and leaving behind a thin layer of muscle fibers.** **(c) The fascia is incised with the temporalis muscle and reflected inferiorly with a 2-0 suture although it is not always easy to distinguish the temporalis fascia from the surrounding tissues.**	• There is scant discussion in the literature about the temporalis muscle disposition during cranioplasty.[10] • The author attempts to transpose the temporalis if there is sufficient muscle volume to warrant such attempts. • If the bone flap is replaced over functional muscle tissue, the patient may experience movement restriction and discomfort during mastication. If significant muscle atrophy is present along with the risk of disrupting cerebral cortex, it is advisable to abandon muscle transposition. Methods to preserve the temporalis during the initial craniectomy procedure have been reported.[11]

Subcutaneous Abdominal Bone Flap Retrieval (Fig. 25.6a, b)



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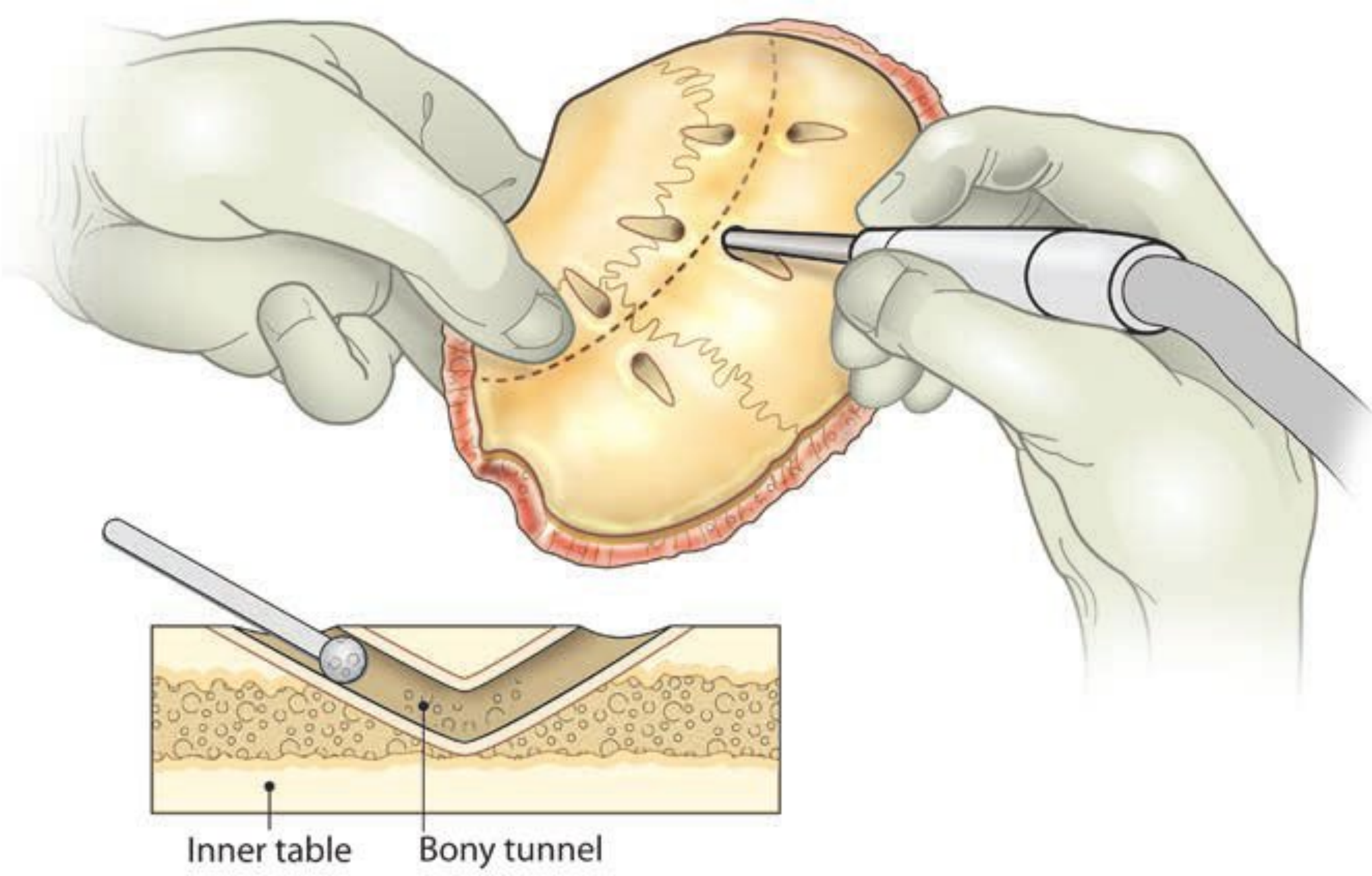
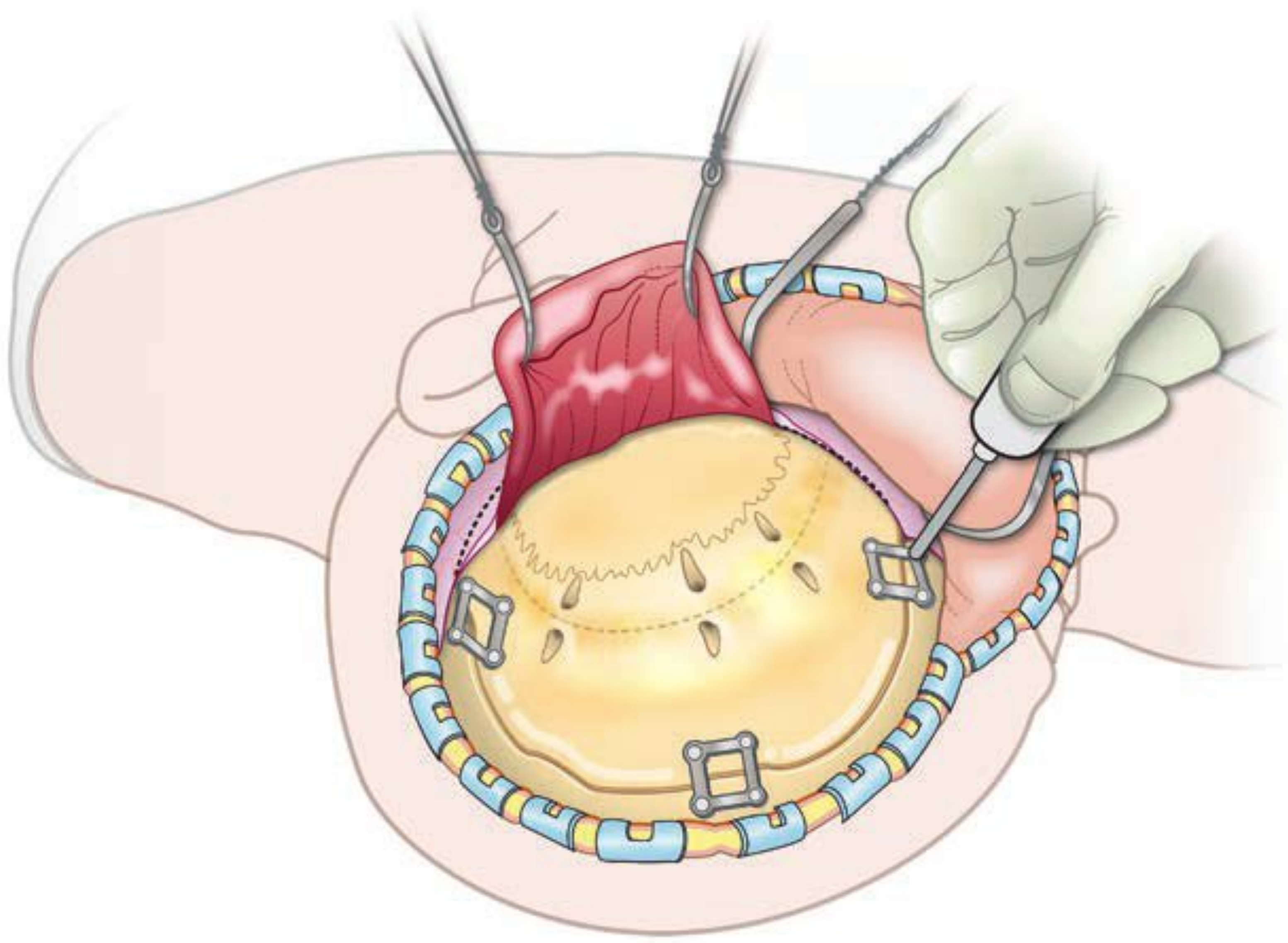


b

Figure	Procedural Steps	Pearls
Fig. 25.6	**(a) The prior abdominal wall incision is opened with a no. 10 blade down to the bone. The bone is dissected from its "pseudocapsule" and surrounding tissues with a periosteal elevator along the superficial surface, then the lateral edges, then the undersurface, then, lastly, the superior, inferior, and medial edges. A laparotomy pad is placed in the abdominal wall pocket to assist with hemostasis. The bone is briefly soaked in a half peroxide/saline solution then irrigated clean with saline. Debris is scraped from the bone surface with a periosteal elevator.** **(b) Before bone flap replacement, tangential holes are created with the drill along the superior temporal line for temporalis fixation to re-create the temporalis insertion, if the temporalis is to be transposed.**	

Bone Flap Replacement (Fig. 25.7a, b)



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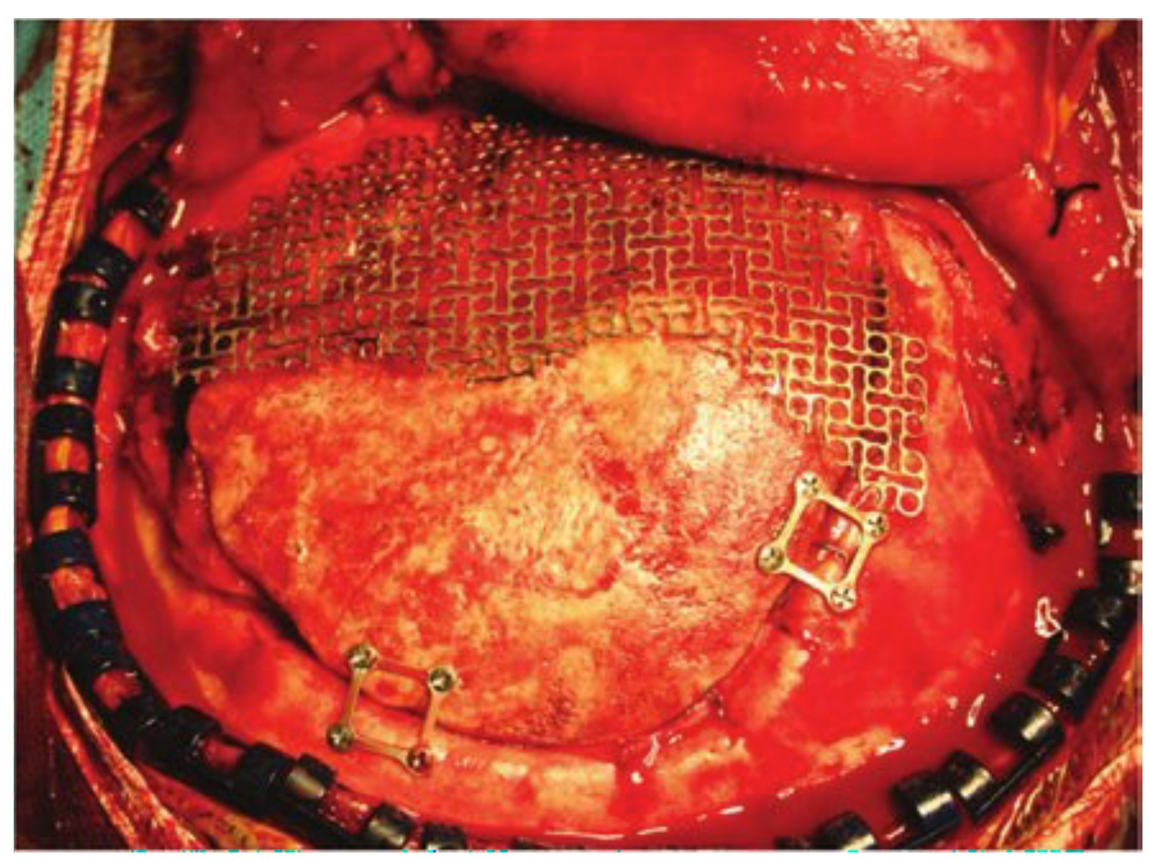
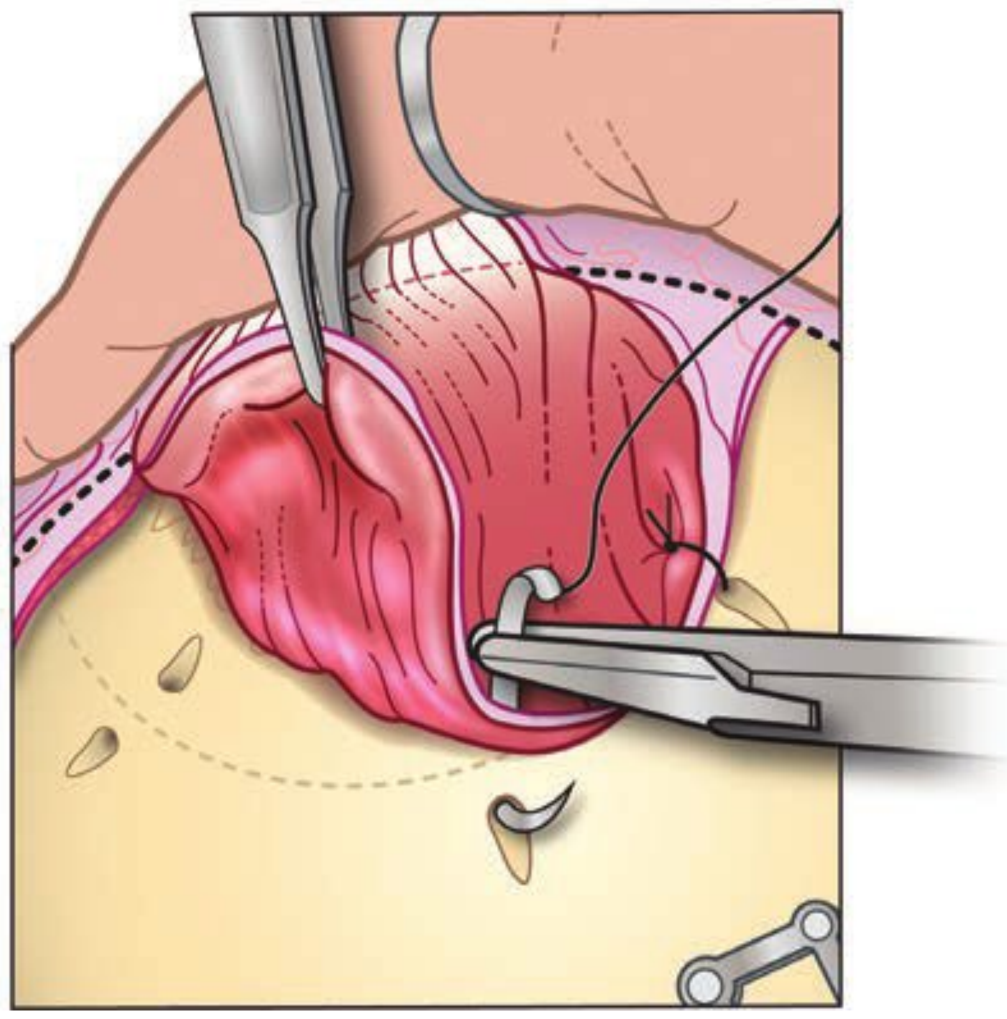


b

Figure	Procedural Steps	Pearls
Fig. 25.7	**The craniectomy defect is prepared to receive the graft. Hemostasis, especially epidural, is obtained with bipolar coagulation and irrigation. The bone edges are palpated. The posterior and anteroinferior portion of the pericranial graft is left attached to its vascular pedicle.** **(a) The bone flap is then placed into the defect for alignment and to mark the areas for titanium plate placement. Titanium plates are screwed onto the graft bone edge. The graft is then replaced onto the defect and the plates are secured to the bone edge. Where pericranium has been left on the bone surface to maintain its vascularity, the screw is placed through the pericranium.**	• If extant, protrusion of the brain through the defect during surgery can be controlled with head of bed elevation, mannitol, and/or mild hyperventilation. If an intradural cyst is causing protrusion, it can be drained with ultrasonic guidance prior to replacing the bone flap. On occasion the author has elected to hinge the bone flap at the superior edge to allow brain swelling to decrease slowly over time. If hinged, placement of plates around the circumference of the flap can help to prevent sinking of the flap once the swelling resolves. It is often not necessary to secure these other plates in the future, but the option remains open. • In cases where the bone has remodeled and the graft fit is not precise, a bur may be used to make the bone edges more even. (b) In such cases where there may be significant gaps or a good deal of temporal and sphenoid bone resection was performed at the initial procedure, titanium mesh may be placed atop the graft and the inferior bone edges and secured with titanium screws.

Temporalis Transposition (Fig. 25.8a, b)



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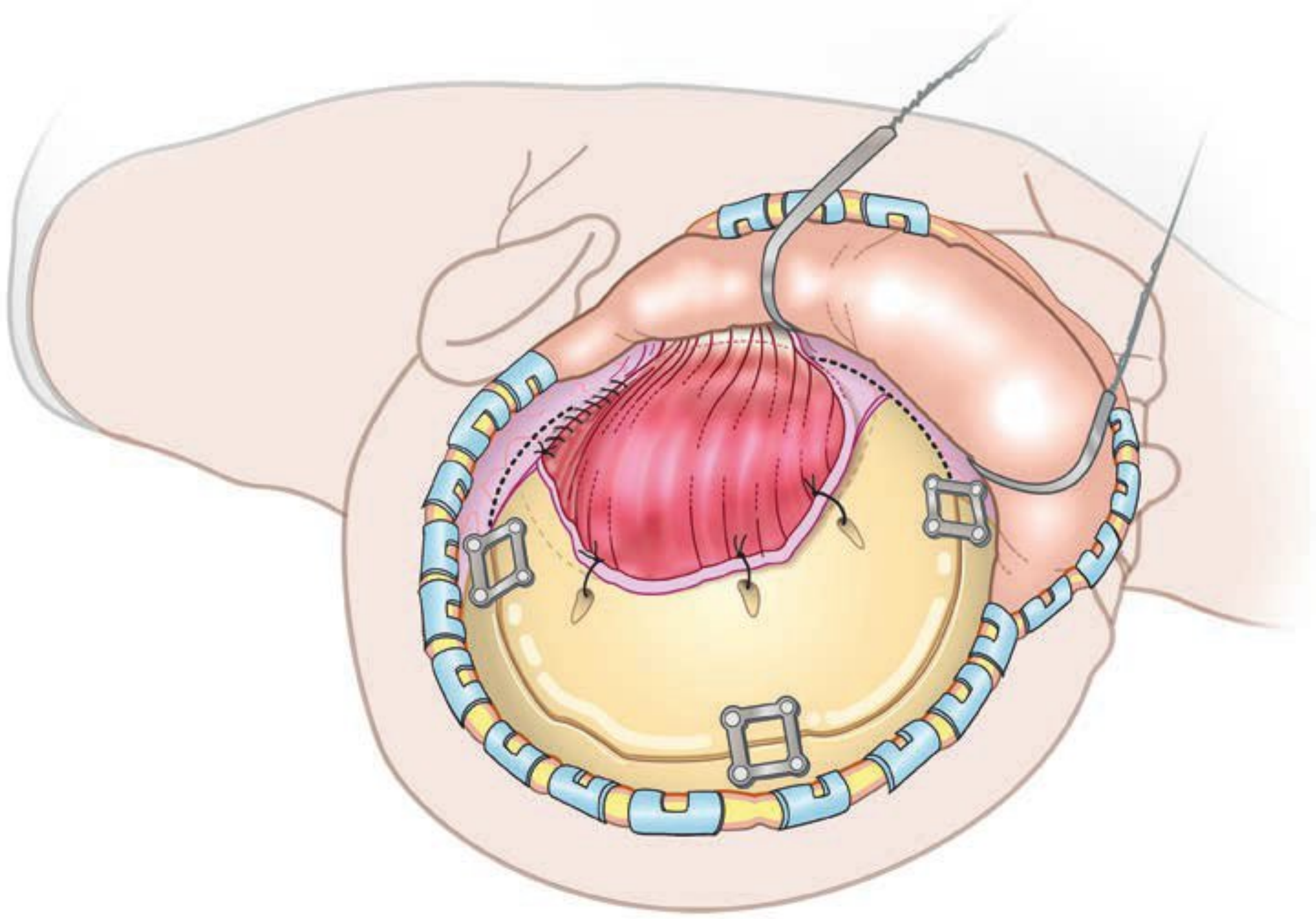

b

Figure	Procedural Steps	Pearls
Fig. 25.8	**(a) If preserved, the temporalis muscle is secured to the holes created as its "insertion" at the superior temporal line with 2-0 braided nylon sutures to complete its transposition.** **(b) The posterior portion of the temporalis is reapproximated with 2-0 braided nylon suture or absorbable suture.**	• It is optional to place polymethylmethacrylate or hydroxyapatite atop the mesh or any other existing defect after the bone flap has been replaced. Precontoured materials for these defects are available (see Chapter 26).

Completed Construct (Fig. 25.9)

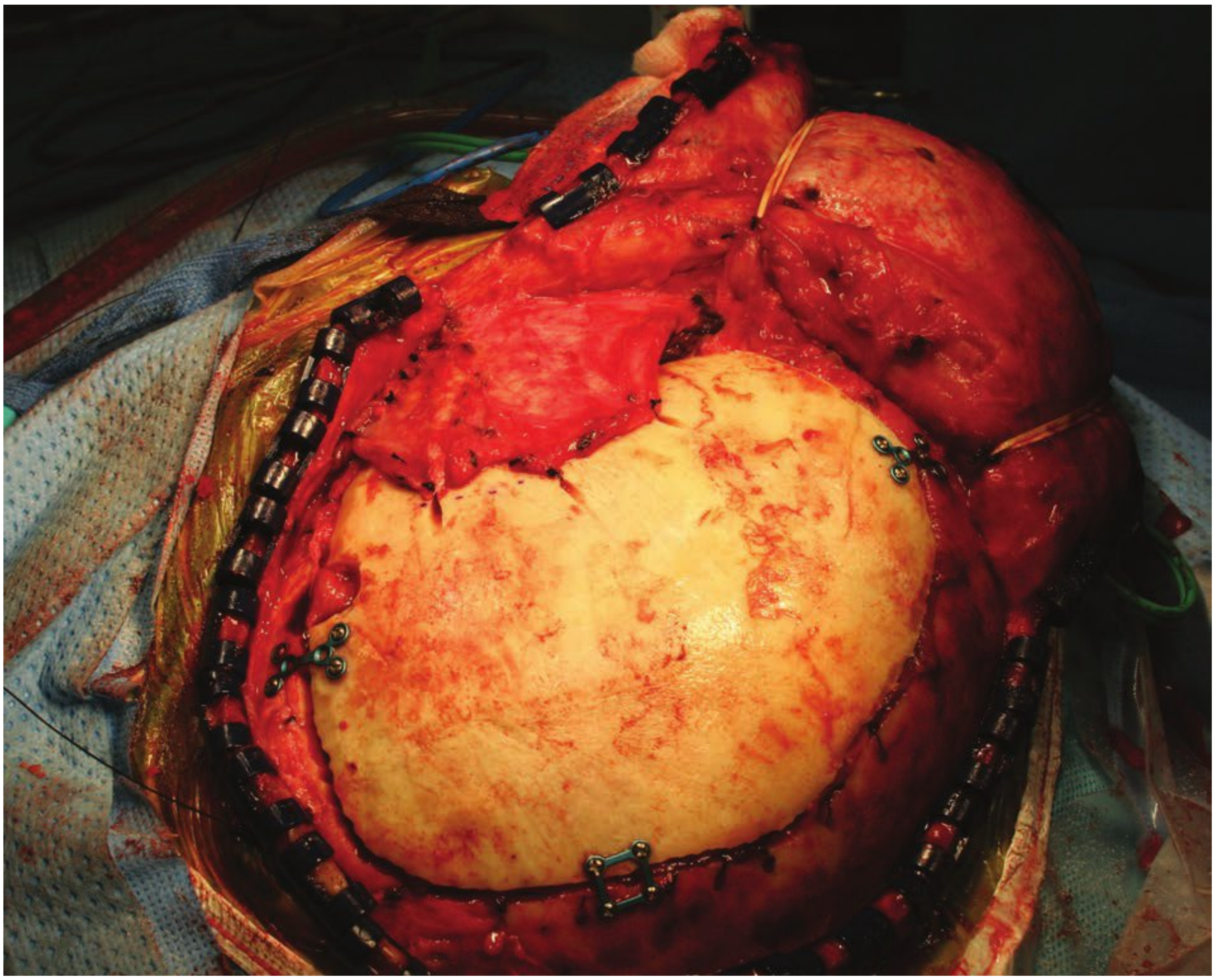

Figure	Procedural Steps
Fig. 25.9	**Photograph of completed construct prior to closing.**

Closing

Cranial Incision

- The wound is heavily irrigated.
- A medium suction drainage device is placed in the subgaleal plane.
- The scalp is approximated with 3-0 braided absorbable suture in an inverted, interrupted fashion.
- The skin is closed with 3-0 nylon or with staples.

Abdominal Incision

- After hemostasis is obtained at the abdominal site with monopolar cautery, an optional suction drainage device is placed in the abdominal wall cavity.
- The pseudocapsule and fat layers are closed with 3-0 absorbable suture.
- The skin is closed with staples or 3-0 nylon sutures.

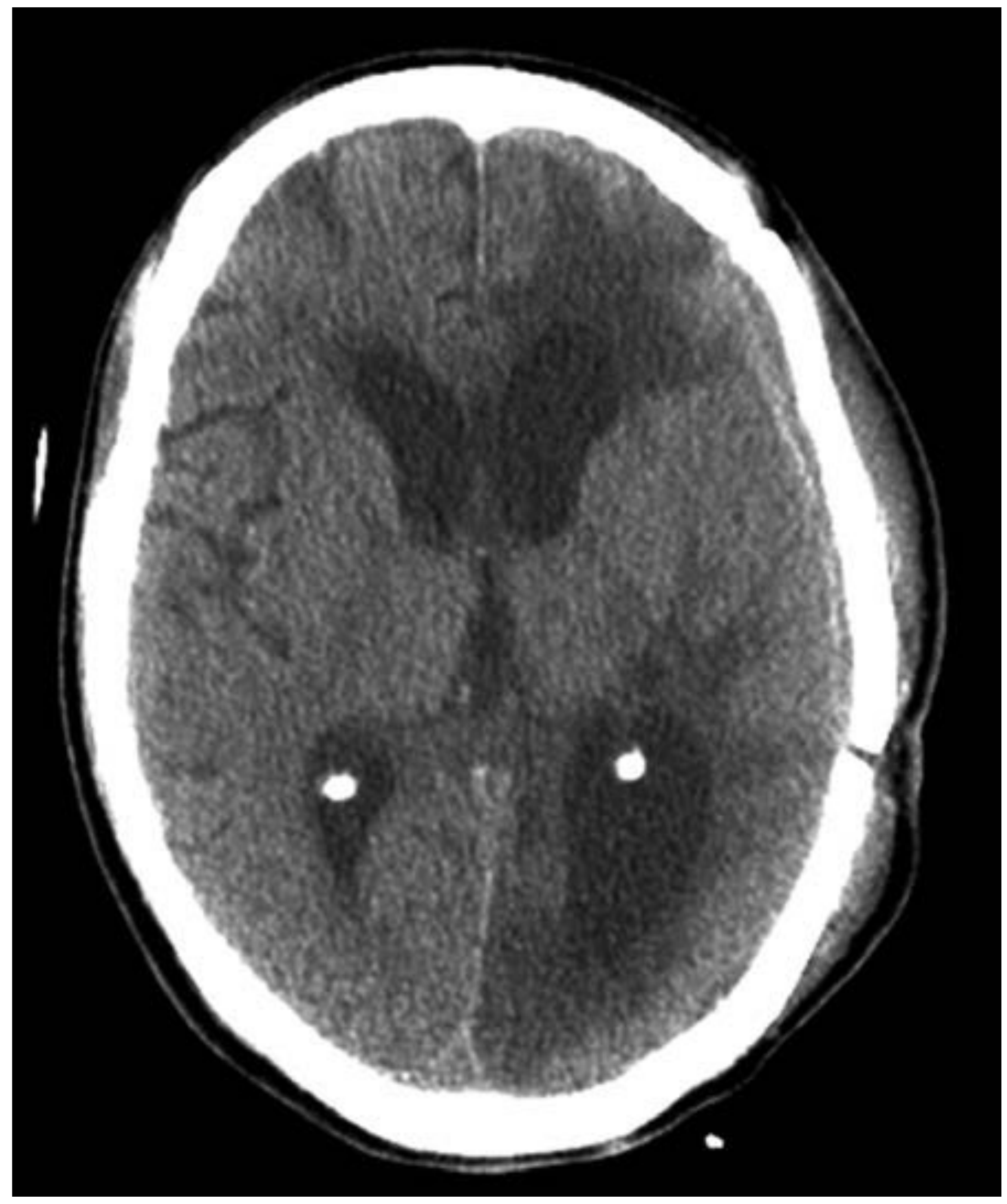

Fig. 25.10 Computed tomography head scan after bone flap replacement.

Postoperative Management

Monitoring

- It is the author's practice to place the patient in a monitored setting overnight in the postoperative period to observe for seizure activity or evidence of intracranial bleeding.

Medication

- The prophylactic antiepileptic agent is continued for a total of 7 days provided there are no interim seizures.
- It is optional to give two to three doses of prophylactic antibiotics in the immediate postoperative period.

Radiographic Imaging

- A postoperative CT scan may be obtained to evaluate for extra-axial collections or other hemorrhage (**Fig. 25.10**).

Further Management

- Drains are removed in 1 or 2 days.
- Skin sutures or staples are removed after 2 weeks.

Special Considerations

Explanted craniotomy flaps can also be stored in sub-zero freezers under aseptic conditions.[12,13] The available literature suggests that the rate of infection or complications do not differ between grafts stored by either method.[9,12,13] The disadvantage of subcutaneously stored bone grafts is that bone remodeling occurs over time. Though this time period is not certain, it is likely to occur sometime after 3 months of storage.[14] Subcutaneously stored bone grafts have been noted to have histological evidence of both bone destruction and osteogenesis.[14,15] Therefore, earlier placement of this type of stored graft may be preferable. Frozen grafts may have a higher incidence of bone resorption once implanted, especially in children.[9,12,16,17] This resorption may also be mitigated by earlier bone flap replacement.[6]

While the focus of this chapter does not include indications for shunting, questions arise as whether to perform a shunt or how to manage an existing shunt prior to bone flap replacement.[1,8,18–20] It is the author's practice that, when patients develop posttraumatic normal pressure hydrocephalus with no protrusion of brain through the defect and patients are ready for bone flap restoration, the latter is performed first with careful postoperative monitoring of the neurologic examination and radiographs. The shunt is then placed in a delayed fashion (1 to 2 weeks postoperatively) to allow for extra-axial air or fluid to resolve prior to shunt placement so as to avoid potentiating a collection in this space. In patients who have shunts prior to cranioplasty, the clinical condition may allow for temporary shunt occlusion in the pre- and perioperative period with close monitoring to effect brain expansion and thereby minimizing subdural collection development. However, this decision is based upon taking into consideration the patient's clinical condition, history of shunt dependence, and radiographic studies. Programmable shunt valves may permit the practitioner to adjust drainage pressure to a higher setting prior to cranioplasty. Afterward, progressive reductions in the pressure settings can help prevent subdural collections.[1] These programmable valves may also be useful in shortening the time frame between cranioplasty and delayed de novo shunting.

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26 Techniques of Alloplastic Cranioplasty

Erin N. Kiehna and John A. Jane Jr.

Introduction

When an autologous cranioplasty is not an option—whether from contamination, infection, fragmentation, bony reabsorption, or growth in the cranial vault (in children)—neurosurgeons often have to turn to implantable synthetic cranioplasties. The goals of a cranioplasty remain the same: lasting repair of the cranial defect with good anatomic contour. This can be performed at any time point following a reduction in brain swelling.[1] Since the 1600s, neurosurgeons have experimented with several different constructs in the quest for the perfect cranioplasty.[2] Recent developments in computer-aided design and manufacturing, tissue engineering, and osteoinductive capabilities allow for the fabrication of an alloplastic implant with excellent aesthetics that withstands biomechanical stresses and allows for tissue integration.[3]

Indications

- Sufficient abatement of swelling has occurred when neuroimaging demonstrates that brain is not protruding beyond the defect and lacks any evidence of systemic or local infection.
  - Unsuitability of autologous cranioplasty
  - Bone was fragmented (primary injury was a depressed skull fracture)
  - Bone was contaminated at the time of injury (foreign body contamination or open fractures)
  - Bone flap infection/osteomyelitis
  - Significant disproportion between the skull and the bone flap resulting in aesthetically unpleasing outcome
    - Bony reabsorption following initial autologous cranioplasty (**Fig. 26.1**).
    - Bony remodeling
    - Significant growth of the cranial vault (in children)
  - Growing skull fractures and traumatic defects in the skull (**Fig. 26.2**)

Preprocedure Considerations

Radiographic Imaging

- Neuroimaging is required prior to any cranioplasty to evaluate the condition of the brain, its relationship with the cranial defect, any degree of hydrocephalus, external hydrocephalus, and/or leptomeningeal cysts.
- Magnetic resonance imaging (MRI), while not necessary, allows for more detail of the brain; it also may be more suitable for children when there is a goal to limit radiation exposure.

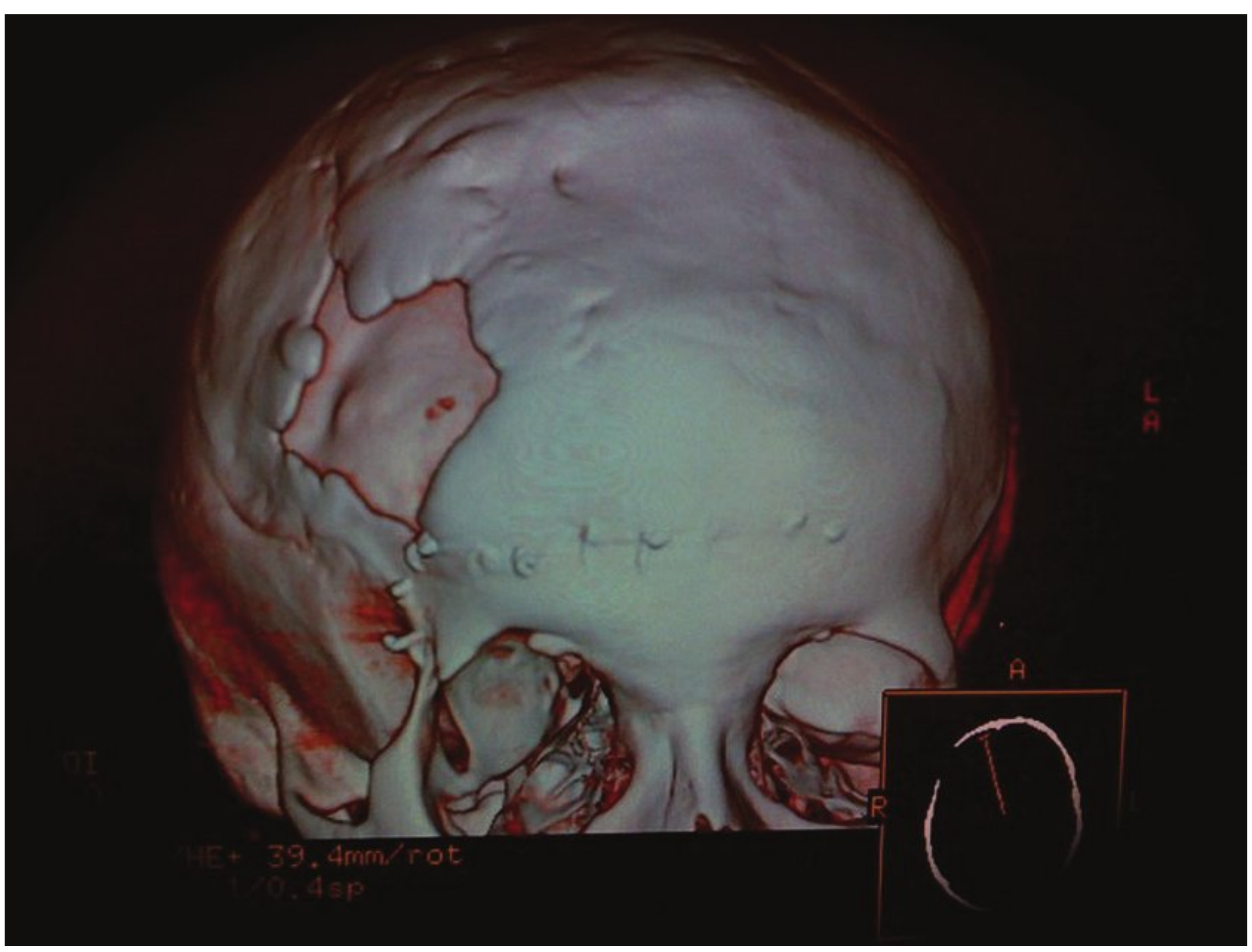


Fig. 26.1 Three-dimensional CT scan of bony reabsorption following cranioplasty in an infant.

Fig. 26.2 Growing skull fracture in an infant.

- Computed tomography (CT) allows for visualization of the thickness of the bone to determine the "splitability" in children.
- A three-dimensional anatomic CT is necessary for construction of custom, implantable cranioplasties.

Medication

- Antibiotic prophylaxis includes the standard preoperative dose 30–60 minutes prior to skin incision. Some neurosurgeons also provide 24 hour antibiotic prophylaxis postoperatively.
- Antiepileptic prophylaxis may be considered in patients who are not on standing antiepileptic medication. Our institution utilizes phenytoin or levetiracetam.

Operative Site Preparation

- The skin incision used for the decompressive craniectomy or craniotomy site is typically sufficient.
- Incisions should be made as cosmetic as possible, staying behind the hairline and preserving blood flow to the scalp flap.
- Approximately 1–2 cm of hair clipping may be performed.
- The skin is prepped as per physician preference, with the recommendation that alcohol is used during a stage of the skin cleansing process.
- The incisions are marked and infiltrated with 0.2% ropivacaine with epinephrine 1:100,000.
- Algorithm for cranioplasty selection (**Fig. 26.3**).

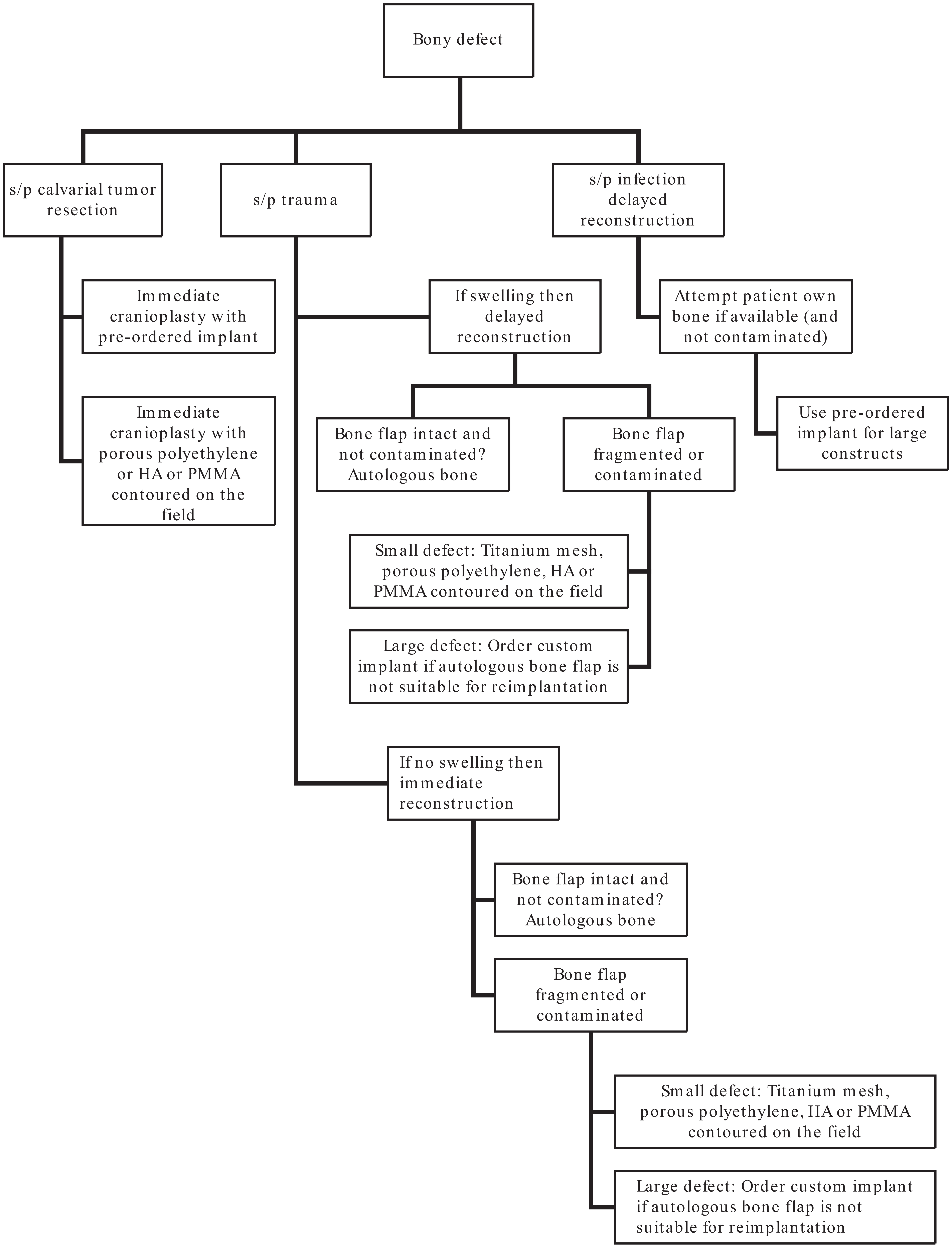


Fig. 26.3 Algorithm for cranioplasty selection. HA, hydroxyapatite; PMMA, polymethylmethacrylate.

Operative Procedure

Positioning Unilateral Craniectomy (Fig. 26.4)

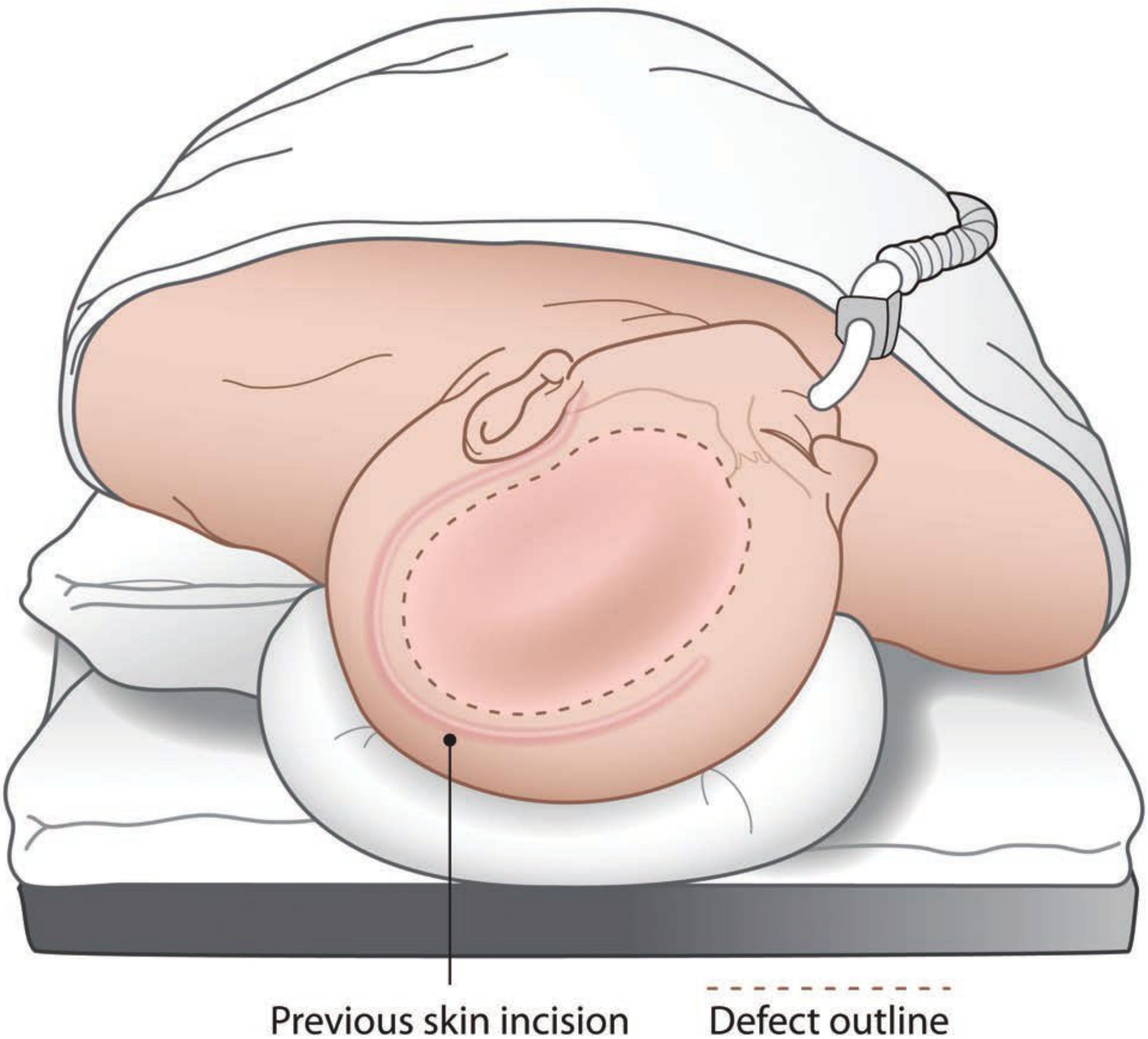


Figure	Procedural Steps	Pearls
Fig. 26.4	**For most cranioplasties, it is sufficient to place the head on a donut or horseshoe with a roll placed under the ipsilateral shoulder for relief of strain. The head is turned approximately 60 degrees in the contralateral direction and the prior frontotemporoparietal scalp incision is exposed and prepared.**	• For cranioplasties that extend to the occipital region, it may be necessary to "pin" the patient to optimize the surgical field.

Positioning for Bifrontal Craniectomy (Fig. 26.5)

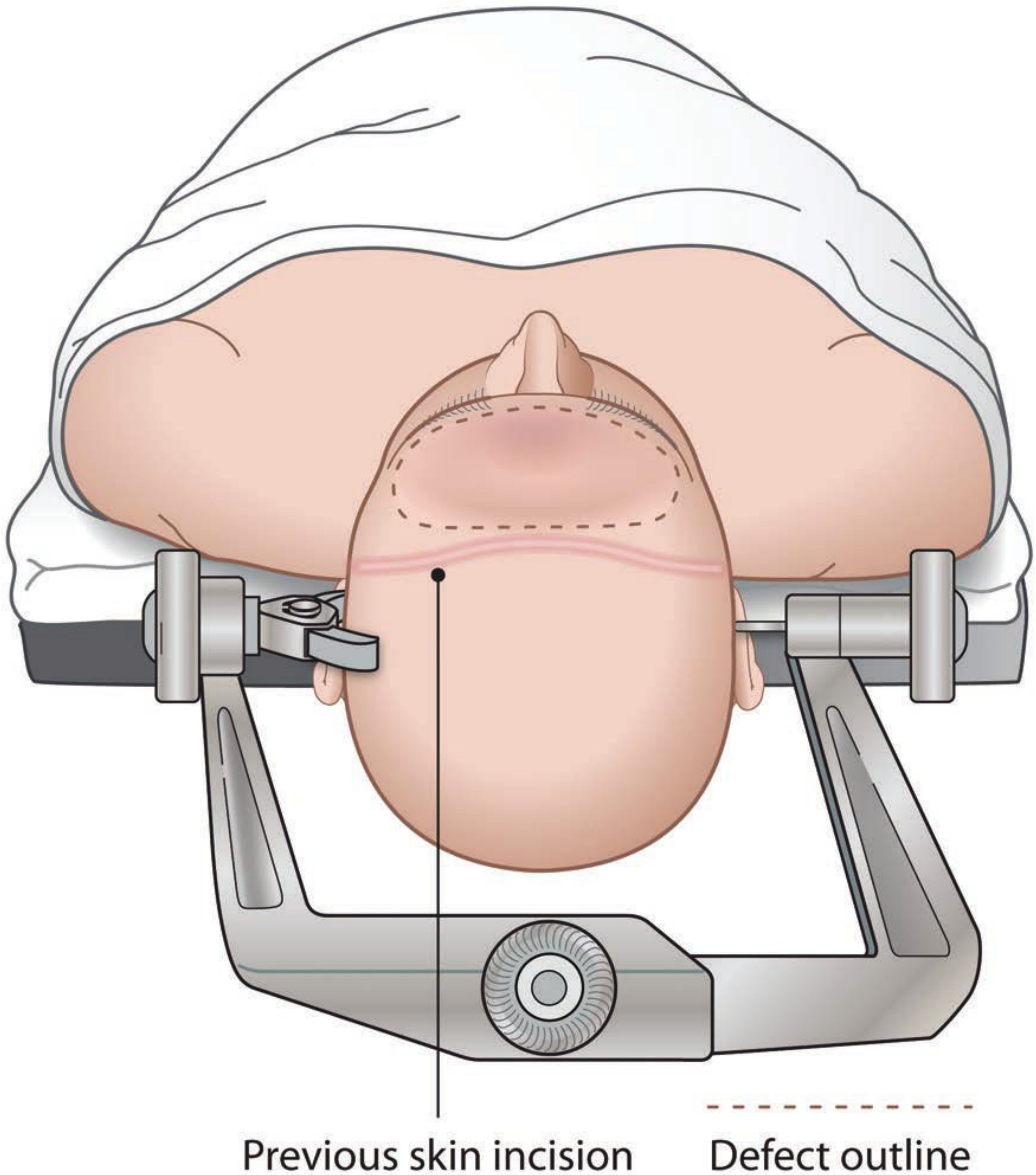


Figure	Procedural Steps	Pearls
Fig. 26.5	**For bifrontal cranioplasties, the patient is positioned supine with the head in a neutral position on either a gel donut or three-point fixation.**	• For bilateral hemicraniectomies it may be necessary to do one side at a time, reprepping and redraping in between.

Skin Incision Unilateral (Fig. 26.6)

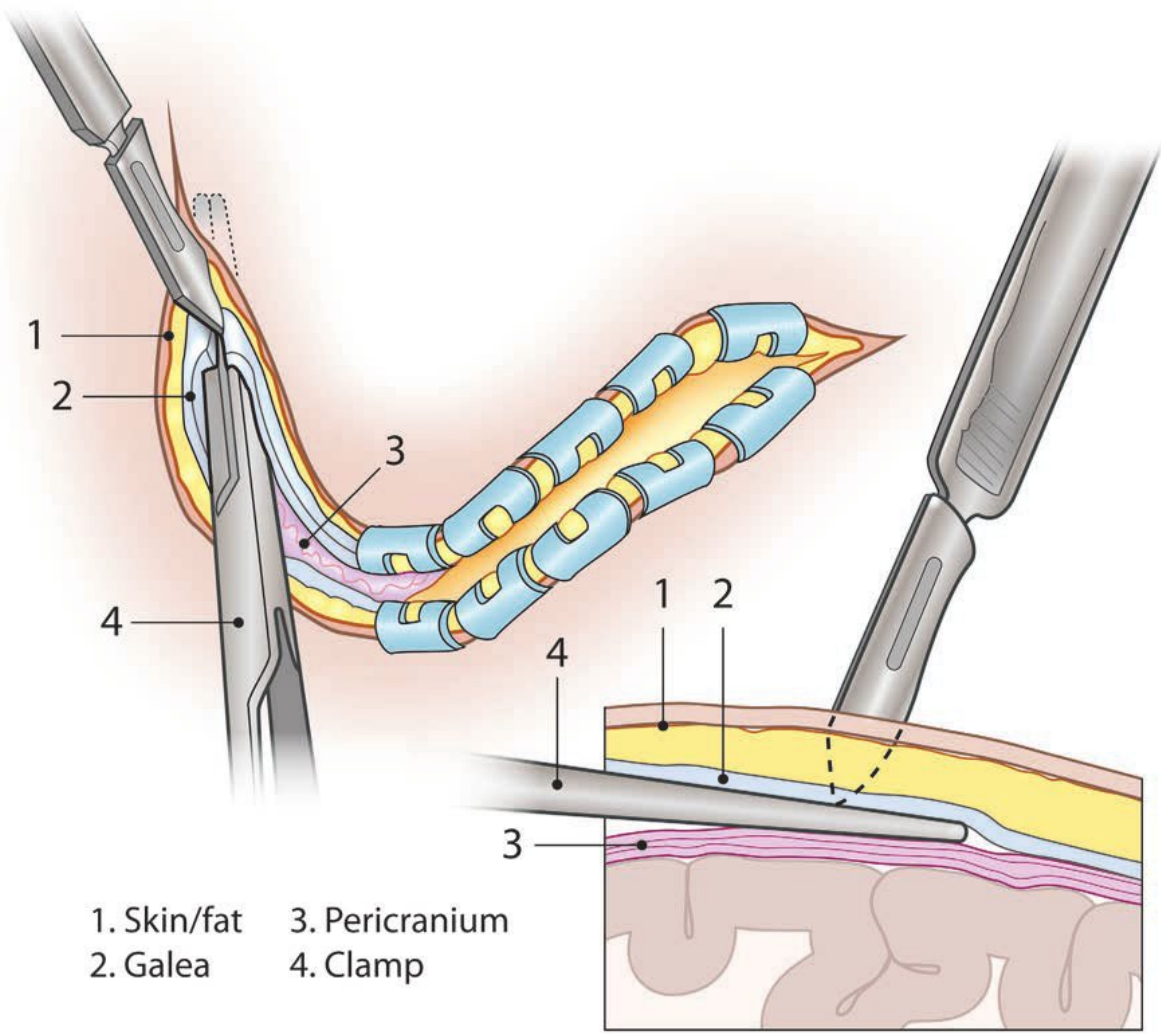


Figure	Procedural Steps	Pearls
Fig. 26.6	**The incision is made with a no. 10 blade from the superoanterior frontal region first and opened in progressive fashion until the temporalis muscle is reached. The bone edge is palpated under the incision. If there is no bone edge, a straight clamp is used to separate the pericranium from the galea to provide protection from the knife blade when bone cannot be palpated underneath the incision. Care should be taken to open the scalp flap separately from temporalis muscle.** **The incision is made with a no. 10 blade from the sagittal suture down to the zygoma bilaterally.**	• Alternatively, one can open with a monopolar electrocautery with a needle tip cautery.

Subcutaneous Dissection (1) (Fig. 26.7)

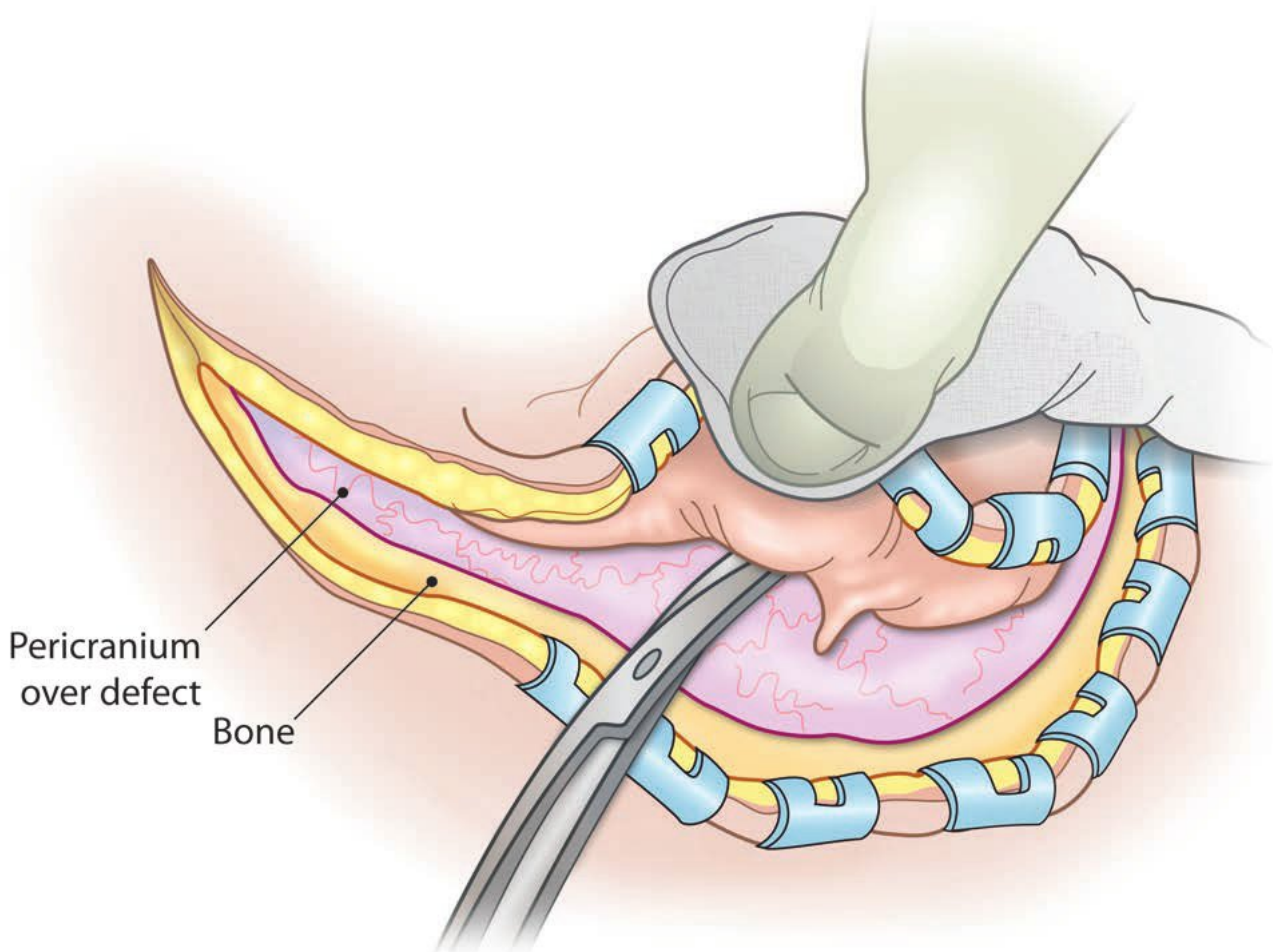
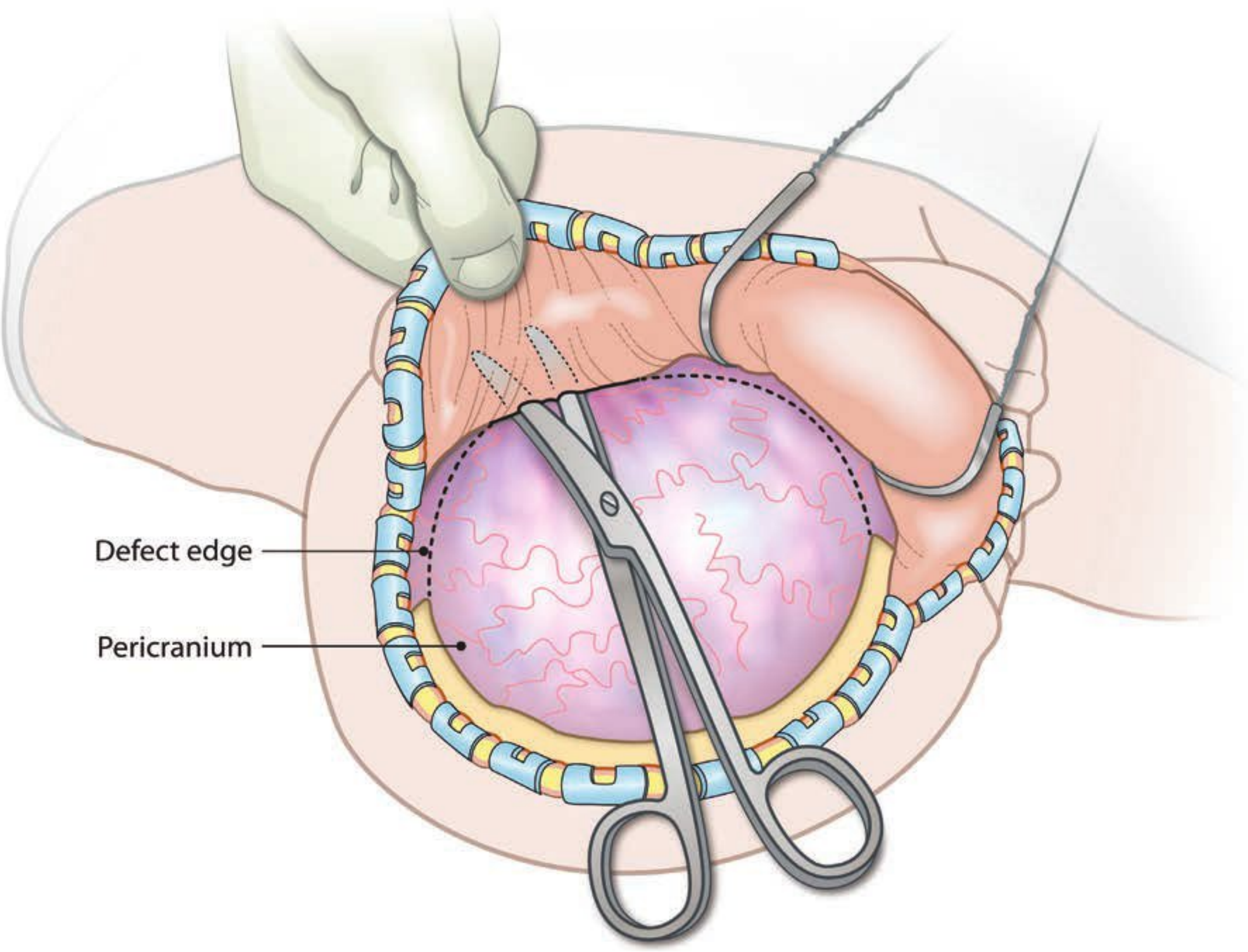


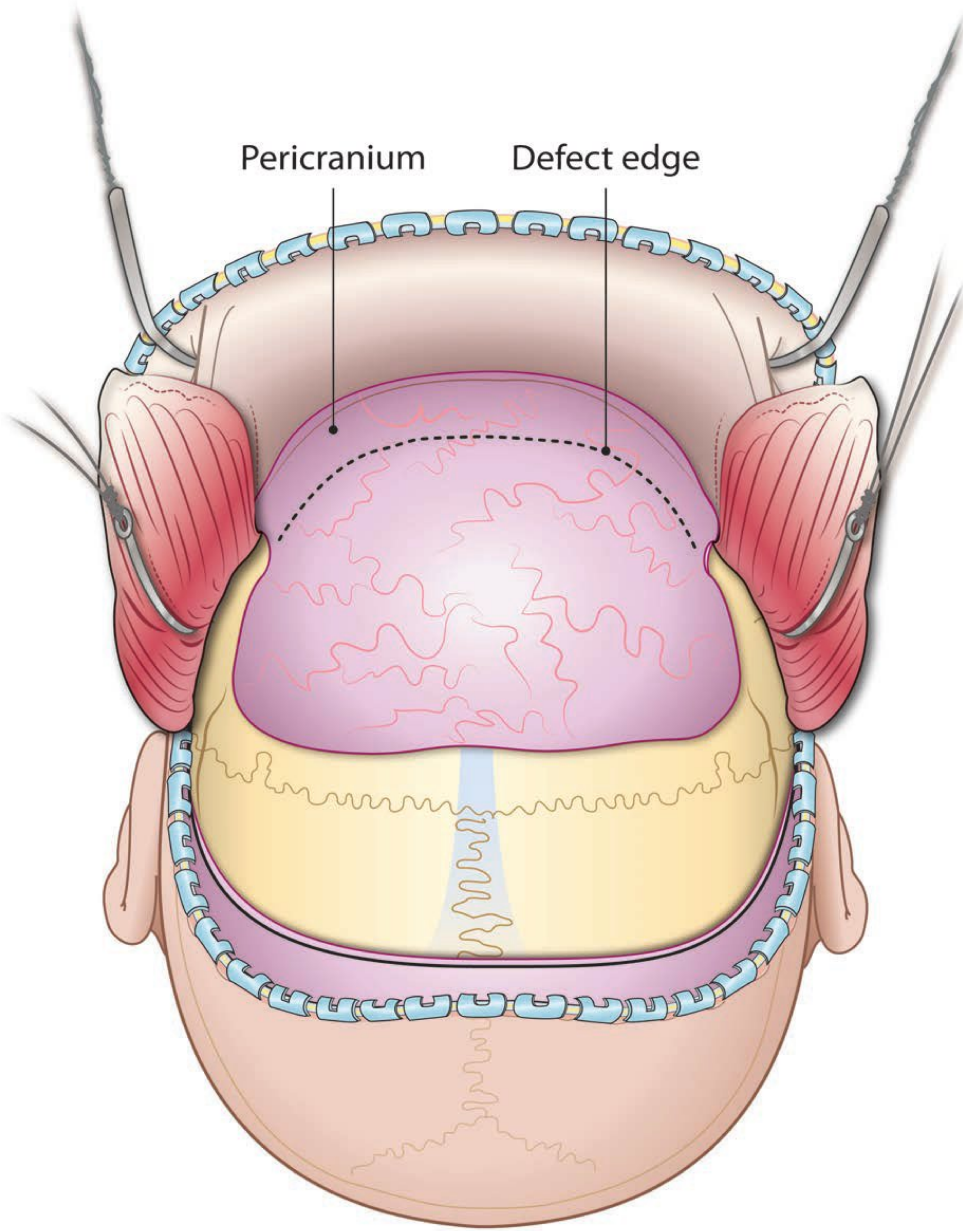
Figure	Procedural Steps	Pearls
Fig. 26.7	**The incision is opened in stages starting with the frontal, superior portion, and wrapping around to the temporalis, placing galeal clamps when this layer has been properly separated. The plane between the pericranium and galea is developed with sharp dissection (Metzenbaum scissors or no. 15 blade scalpel). The scalp layer can be properly reflected forward by developing the plane between the vascularized pericranium and the galea.**	• The galea–pericranial plane may also be developed with a no. 10 or no. 15 blade scalpel, or with monopolar electrocautery. • In cases where the pericranium was elevated with the scalp during the initial procedure, this layer is virtually unscarred and may be dissected bluntly, leaving the pericranium against the dura.

Subcutaneous Dissection (2) (Fig 26.8a, b)



a

Figure	Procedural Steps
Fig. 26.8	**Once the entire scalp flap has been reflected it is retracted anteriorly with scalp hooks, 2-0 braided sutures, or skin clamps attached to rubber bands and clamps. This is demonstrated for (a) unilateral and (b) bifrontal openings. Hemostasis is meticulously achieved with mono- and bipolar cautery.**



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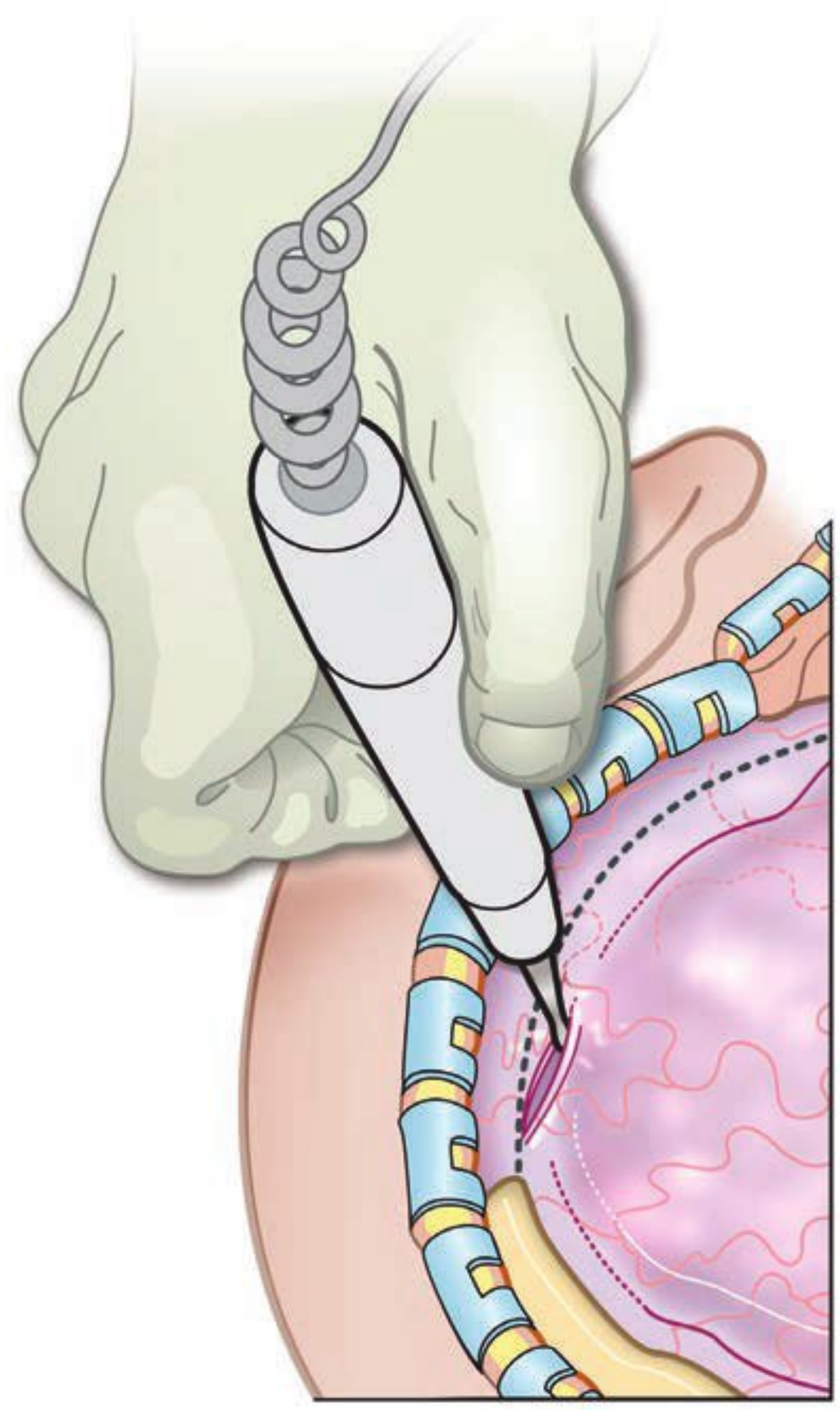
Dissecting the Temporalis Muscle (Fig. 26.9a–d)



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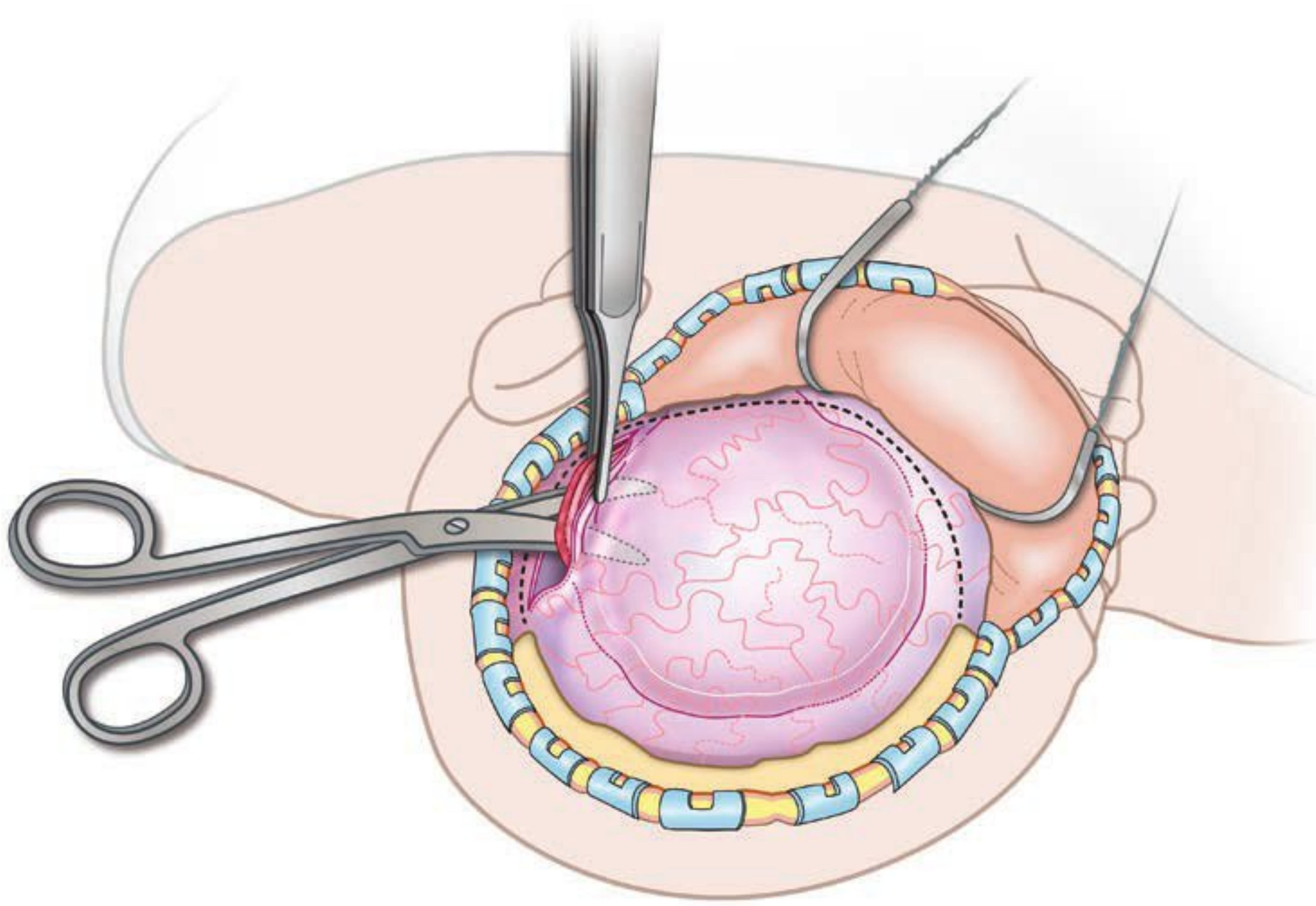

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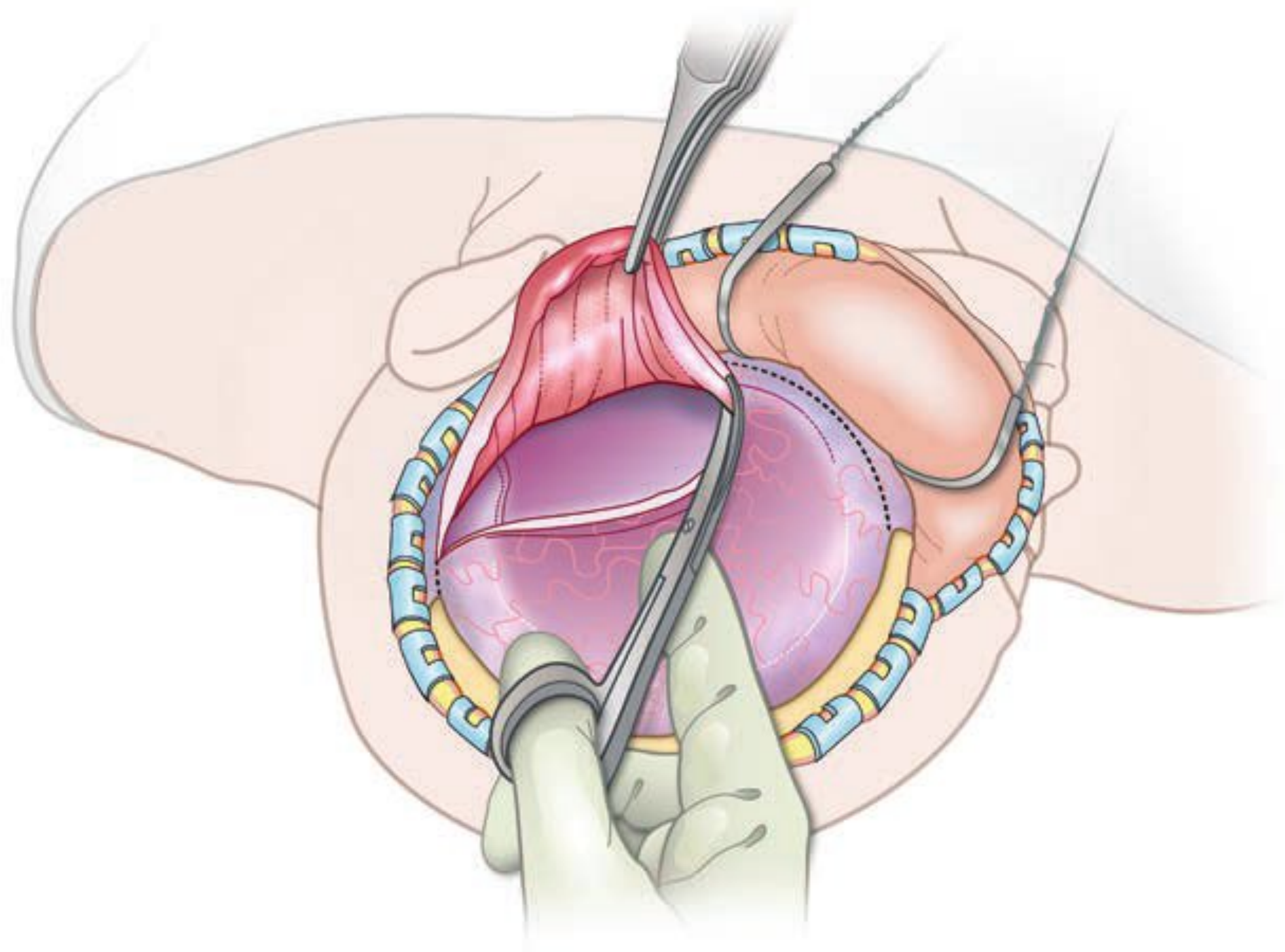

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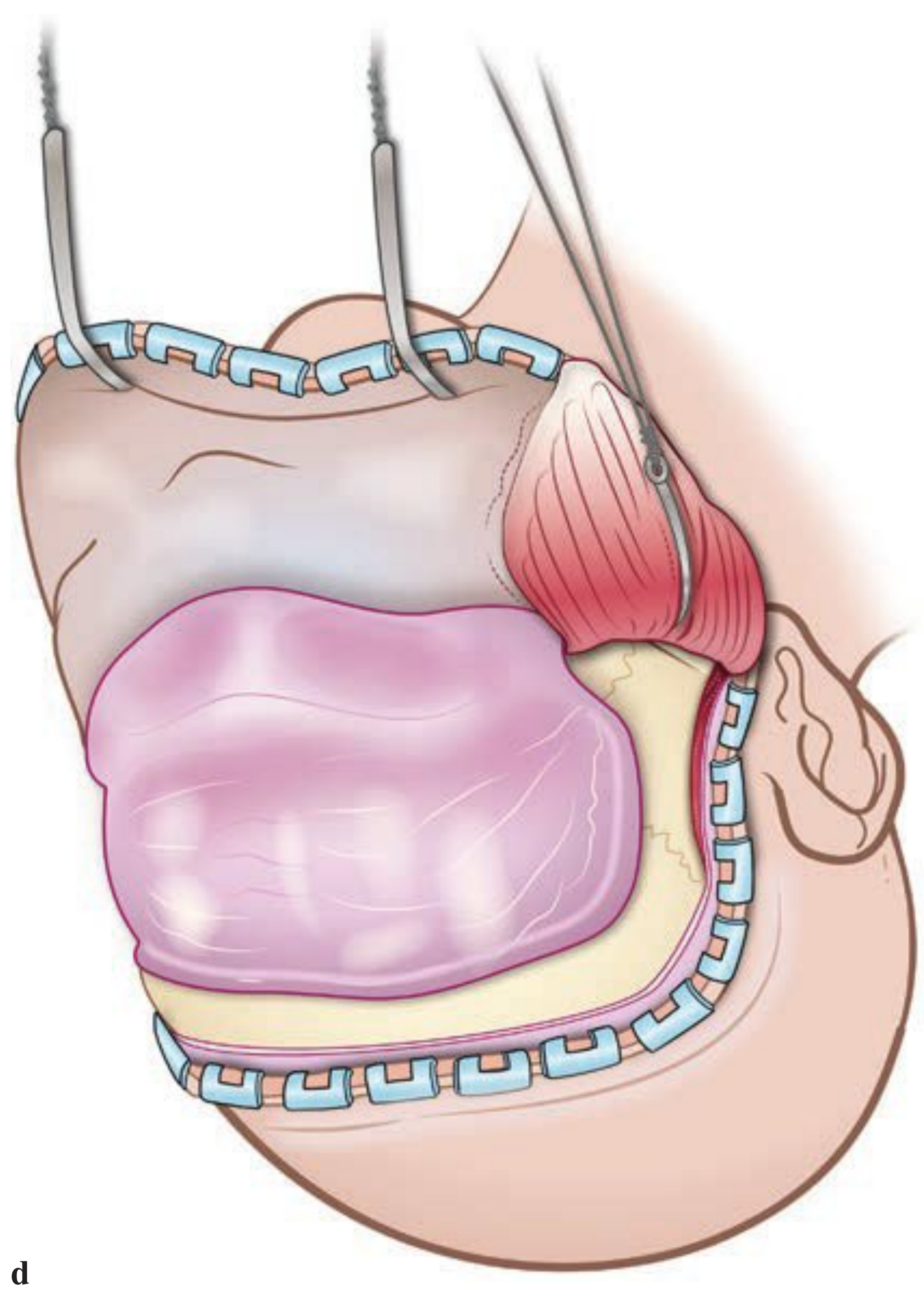


d

Figure	Procedural Steps	Pearls
Fig. 26.9	**(a) The temporalis should be dissected from posterior bone edge with monopolar cautery and then reflected from the dural surface with the use of sharp dissection (b, c). (d) The temporalis is then retracted anteriorly with scalp hooks, 2-0 braided nylon sutures, or skin clamps attached to rubber bands and clamps depicted here with the bifrontal approach.**	• If the bone flap is replaced over functional muscle tissue, the patient may experience movement restriction and discomfort during mastication. • If significant muscle atrophy is present along with the risk of disrupting cerebral cortex, it is advisable to abandon muscle transposition.

Preparation of the Craniectomy Site (Fig. 26.10)

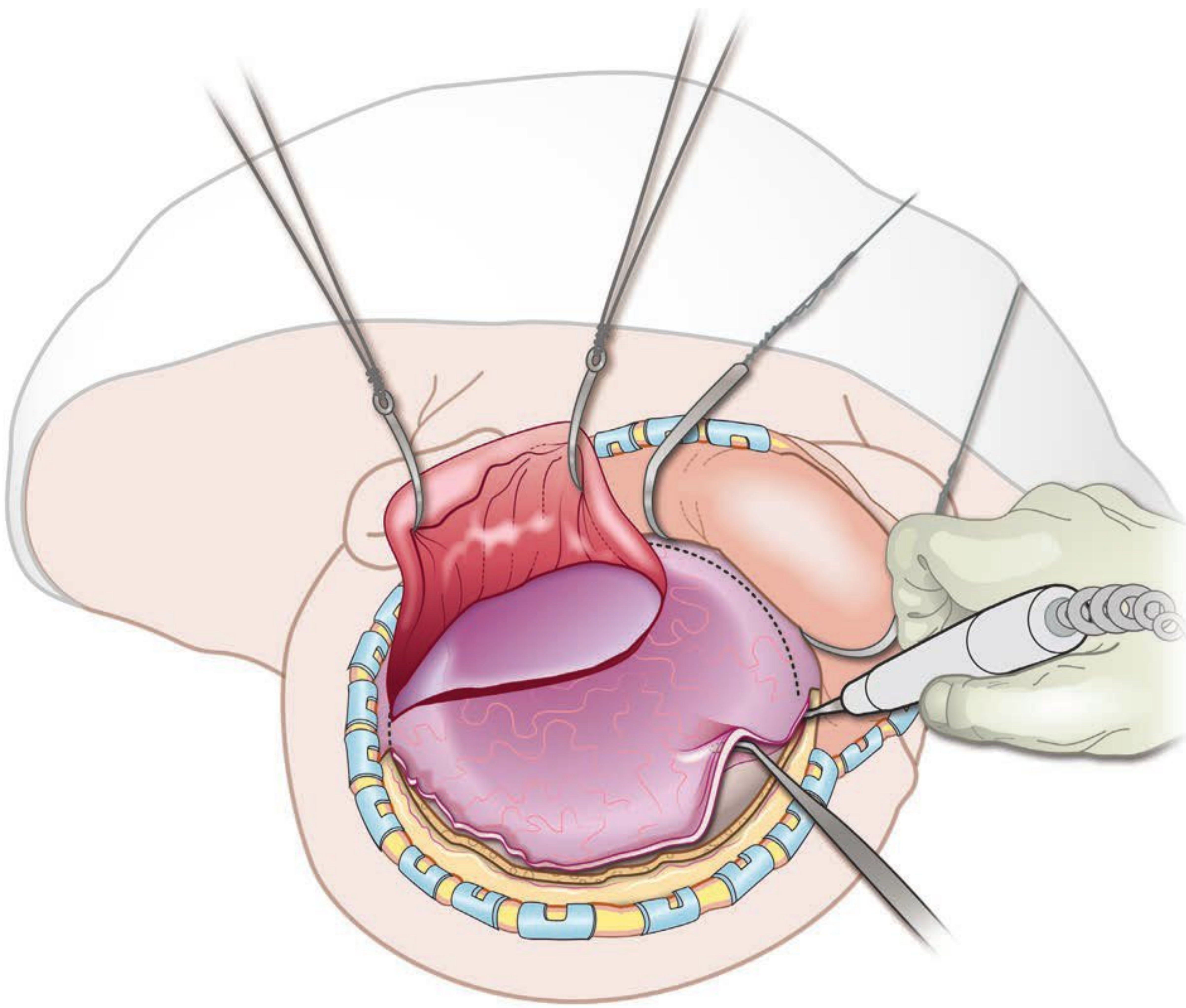
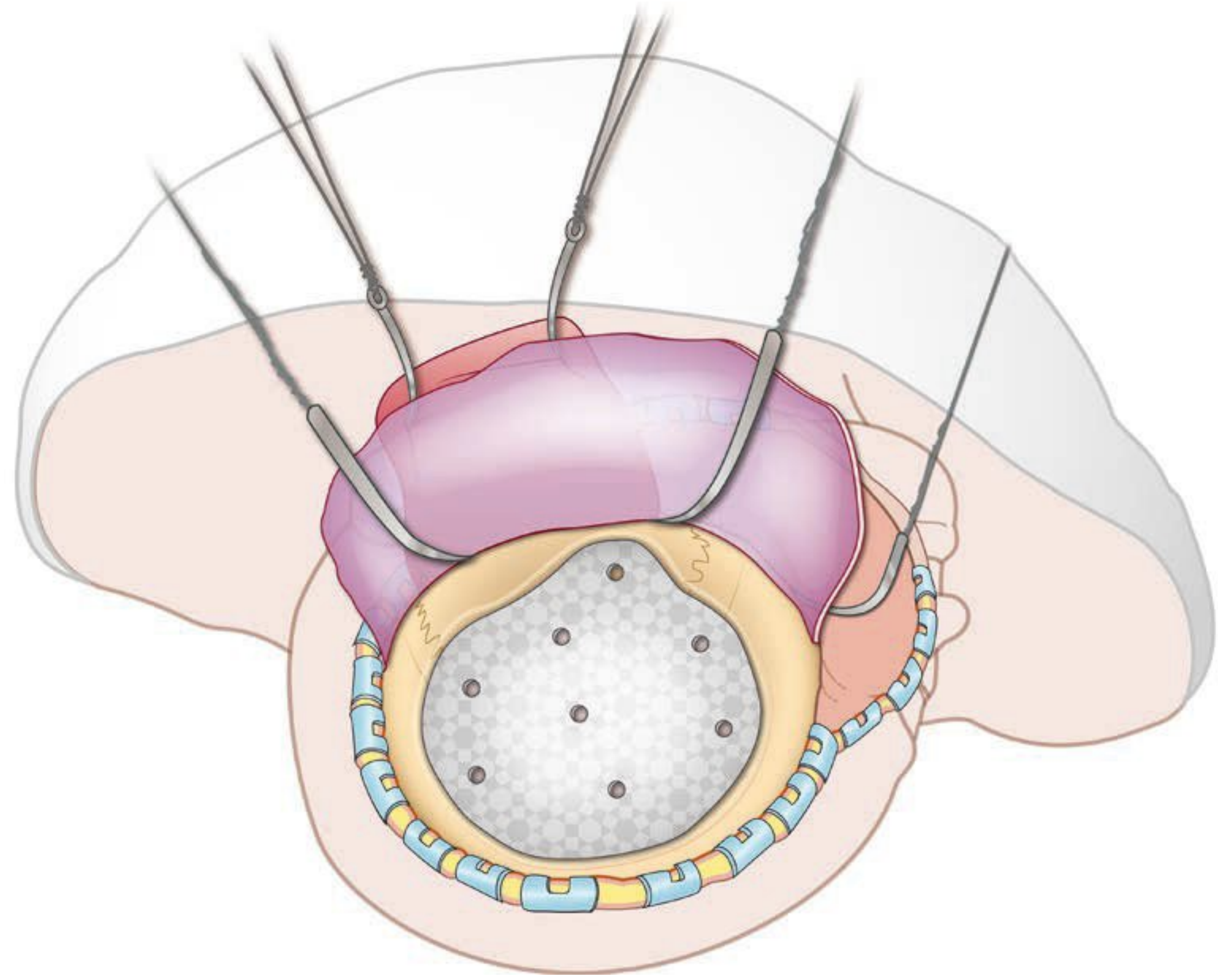


Figure	Procedural Steps	Pearls
Fig. 26.10	**A combination of monopolar cautery and curettes may be used to reflect all of the soft tissue off of the bony edges to allow for a tight fit.** **Any lacerations of the dura should be closed primarily. If there is a large dural defect, one may use pericranium or a dural substitute to close it (depicted in the unilateral approach).**	• If there is protrusion of the brain through the defect during surgery it can be controlled with head of bed elevation, mannitol, and/or mild hyperventilation. • If it persists, one may pass a brain needle into the ventricles using anatomic landmarks or ultrasound guidance to allow for enough decompression to perform the cranioplasty.

Implant Types (Fig. 26.11a–f)



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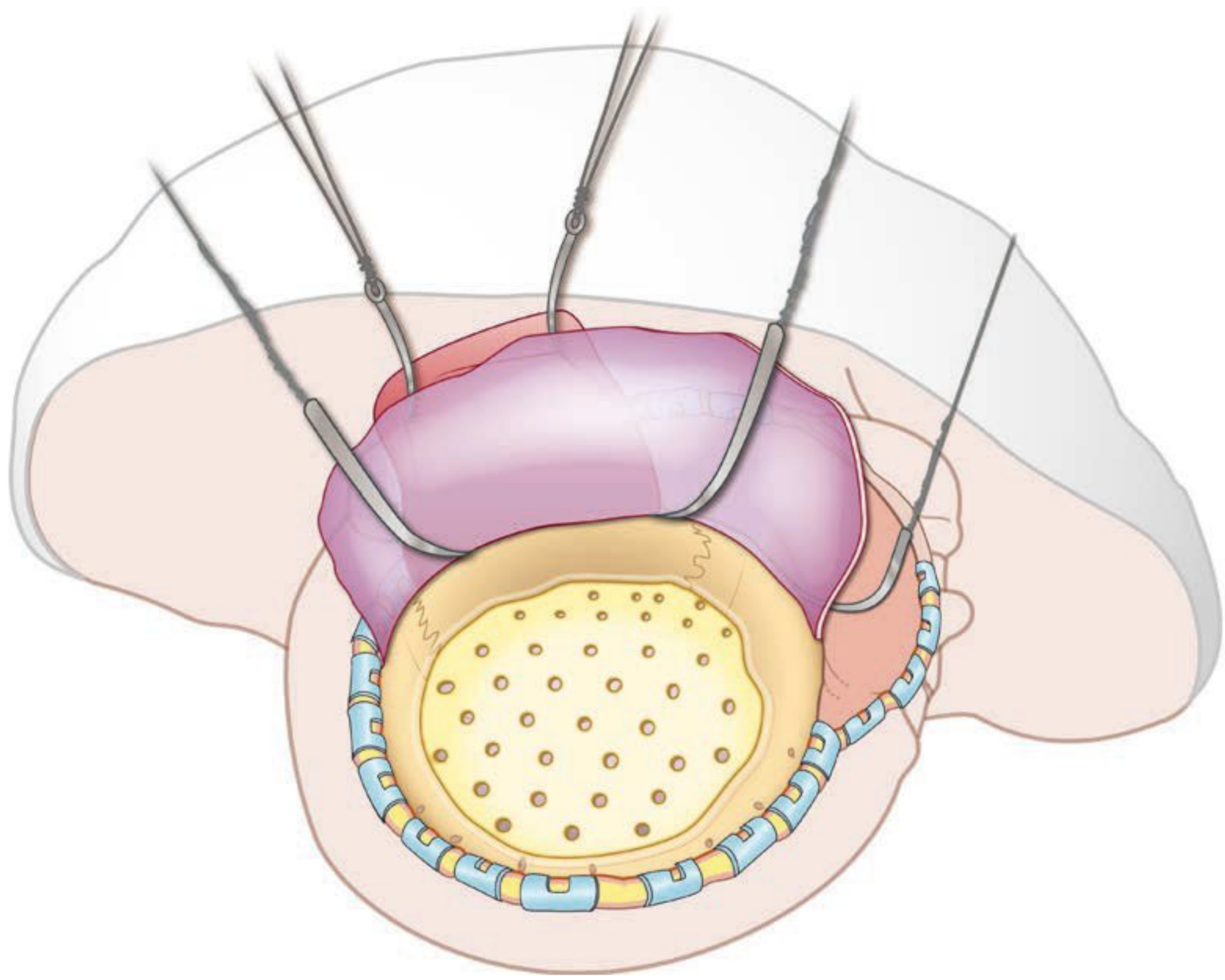

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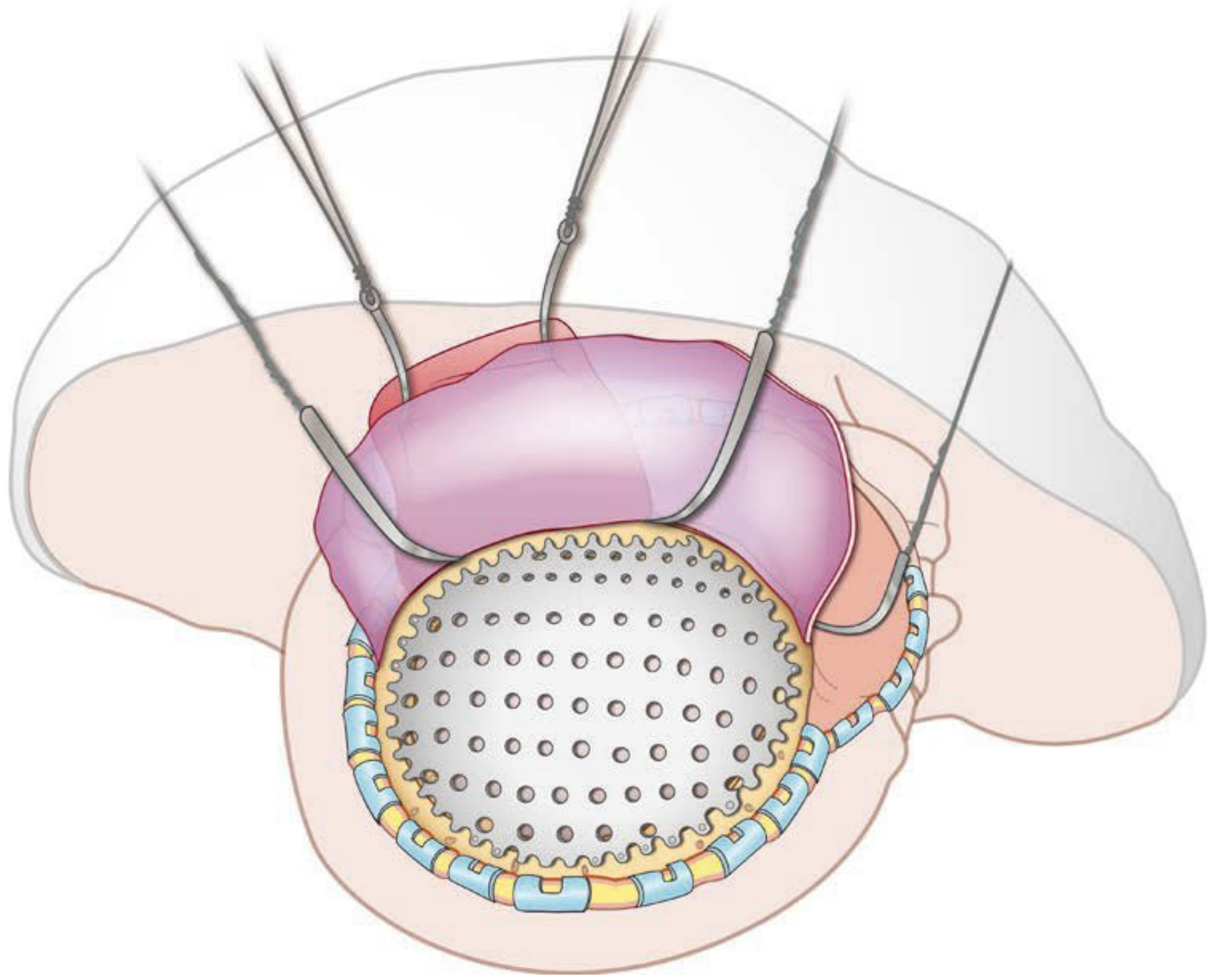

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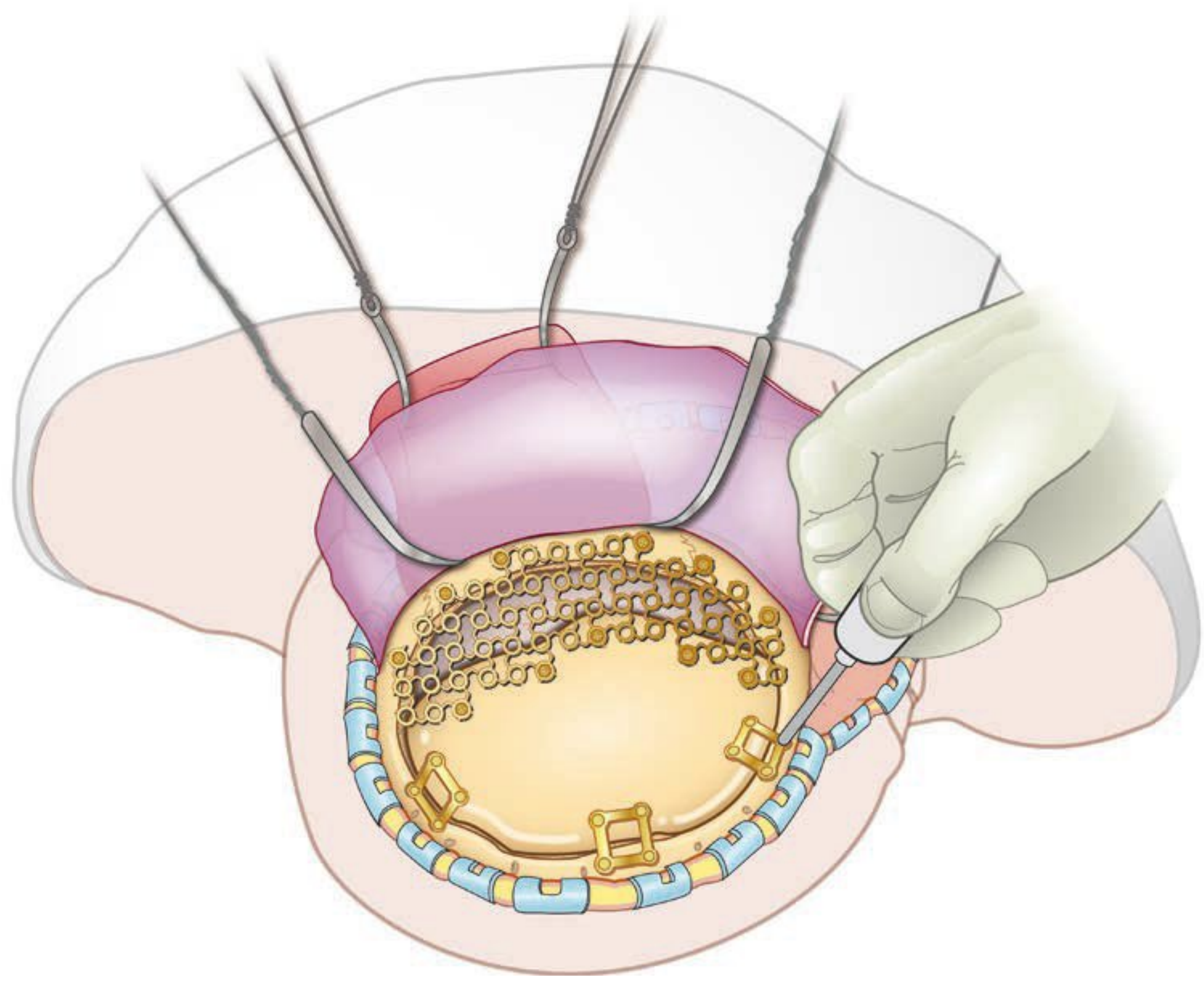

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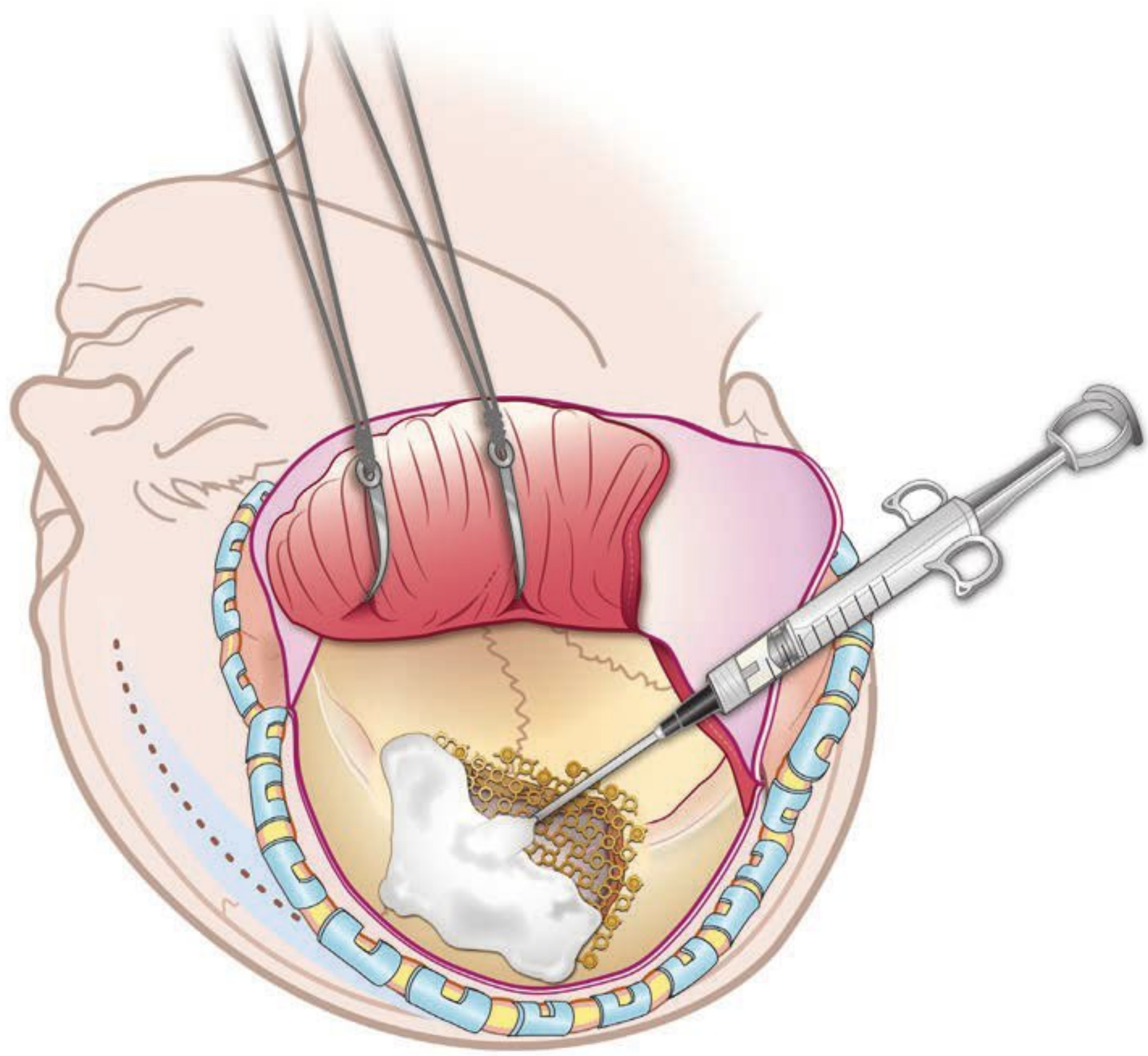

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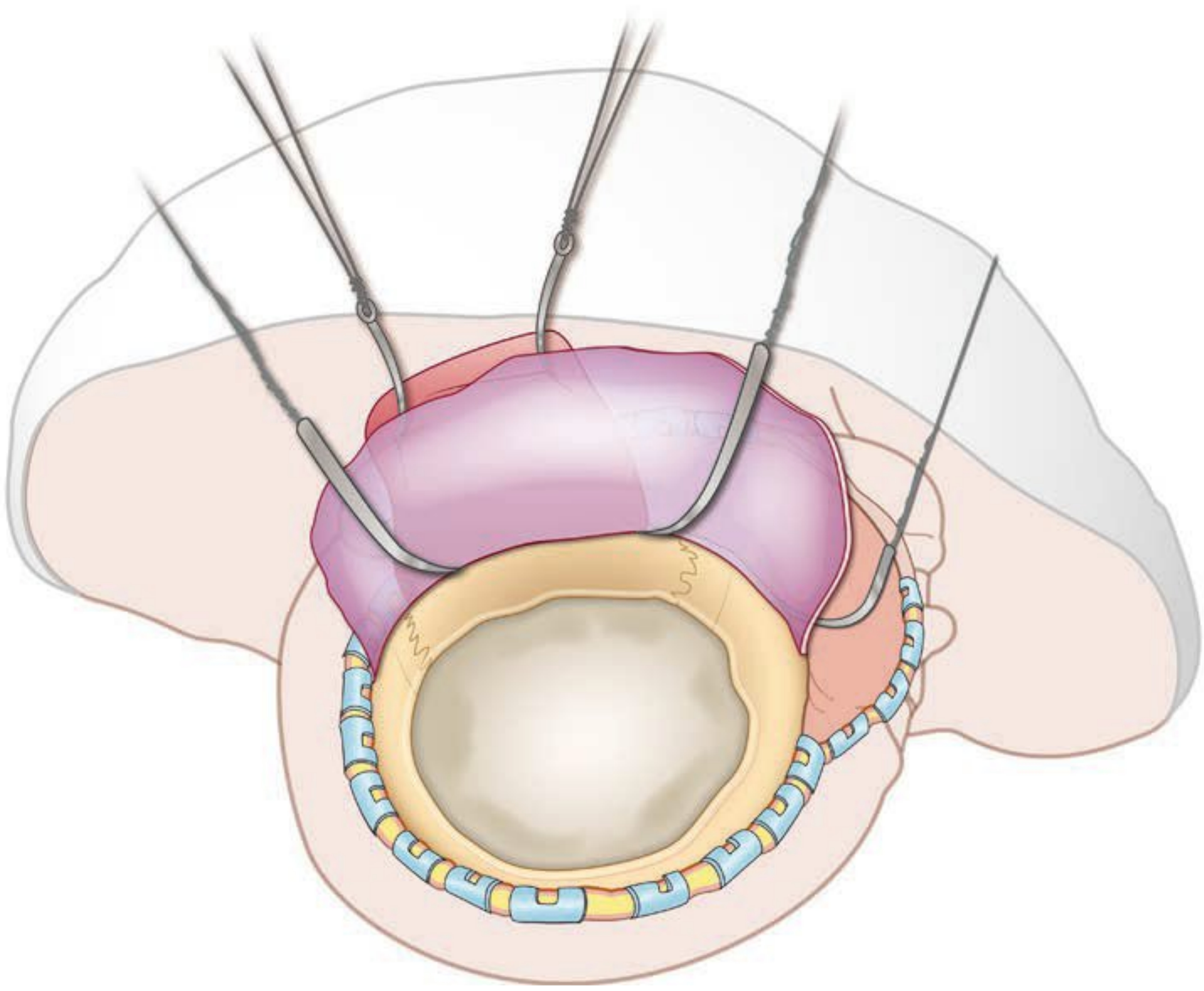

f

	Implant Type	Pros	Cons
Fig. 26.11a	Porous polyethylene	High strength and stability Radiolucent Excellent cosmesis Easily contoured May be molded in the field Easily fixated Custom and anatomic options Minimal surgical time for implantation	Price Custom implants require advance planning, usually 3D CT imaging (but noncustom anatomic implants available)
Fig. 26.11b	PEEK (polyetheretherketone)	High strength and stability Radiolucent Excellent cosmesis Easily contoured Easily fixated Minimal surgical time for implantation	Price Custom implants require advance planning, usually 3D imaging Can be contoured with a drill but not molded in the field
Fig. 26.11c	Titanium plate	High strength and stability Excellent cosmesis Minimal surgical time for implantation	Price Custom implants require advance planning Radiopaque with artifact on imaging Cannot be contoured or molded in the field May require special fixation set
Fig. 26.11d	Titanium mesh	High strength and stability Easily contoured Easily fixated	Radiopaque with artifact on imaging More time spent contouring and plating in the surgical field.
Fig. 26.11e	Hydroxyapatite cement compound	Osteoinductive Radiolucent Excellent cosmesis Easily contoured Easily fixated Less surgical time for implantation than PMMA No advance planning needed	Price May require mesh for strength, stability, and contouring in larger areas
Fig. 26.11f	PMMA (polymethylmethacrylate)	Radiolucent May be contoured in the field No advance planning needed	Long surgical time for set up and contouring, hyperthermic reaction while solidifying requiring irrigation May require mesh for strength, stability, and contouring in larger areas

Repairing the Temporal Defect (Fig. 26.12)

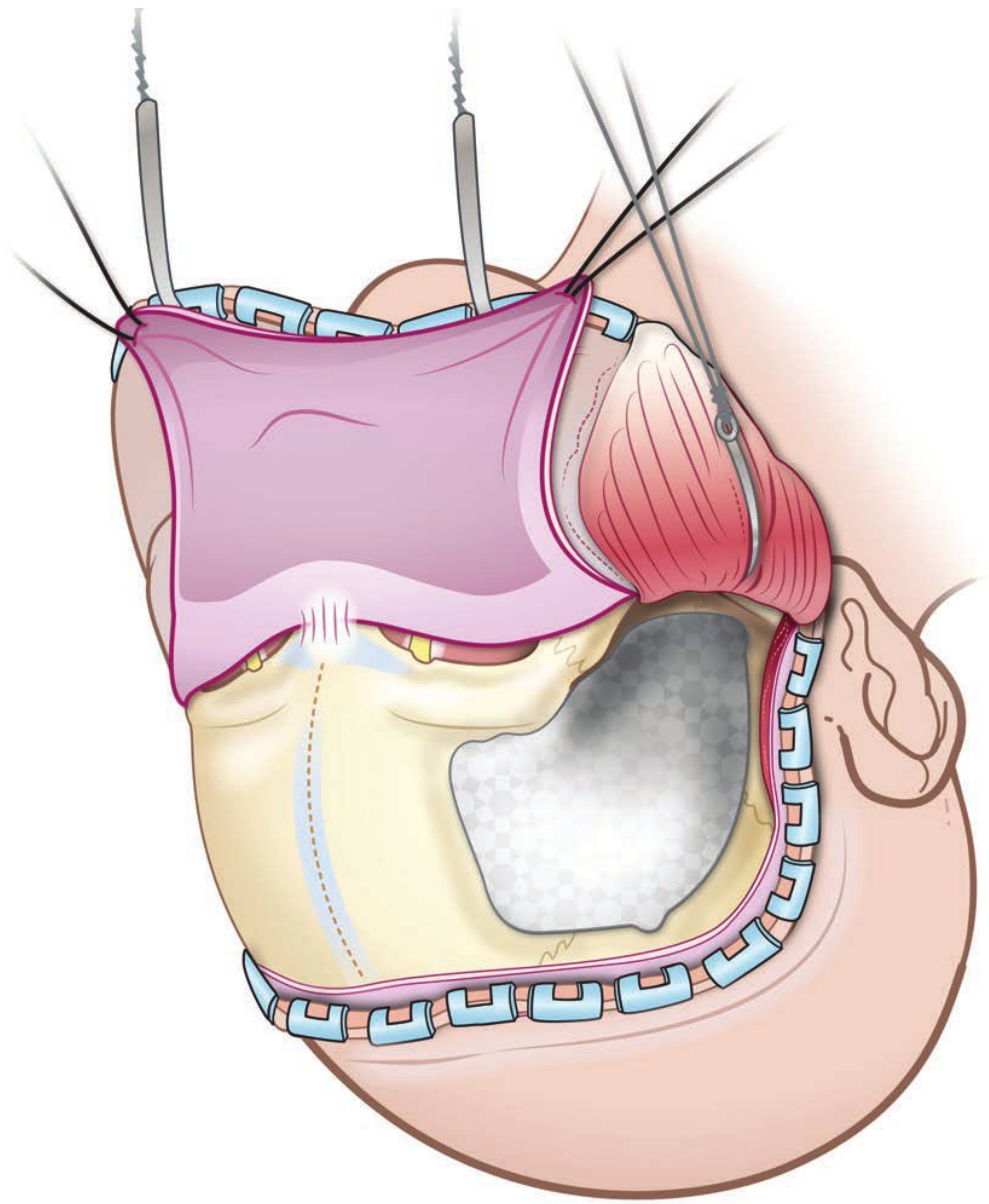

Figure	Procedural Steps
Fig. 26.12	**Anatomic constructs may be placed atop a temporosphenoid defect to improve contour and minimize furrowing of the temporal region.**

Temporalis Transposition (Fig. 26.13)

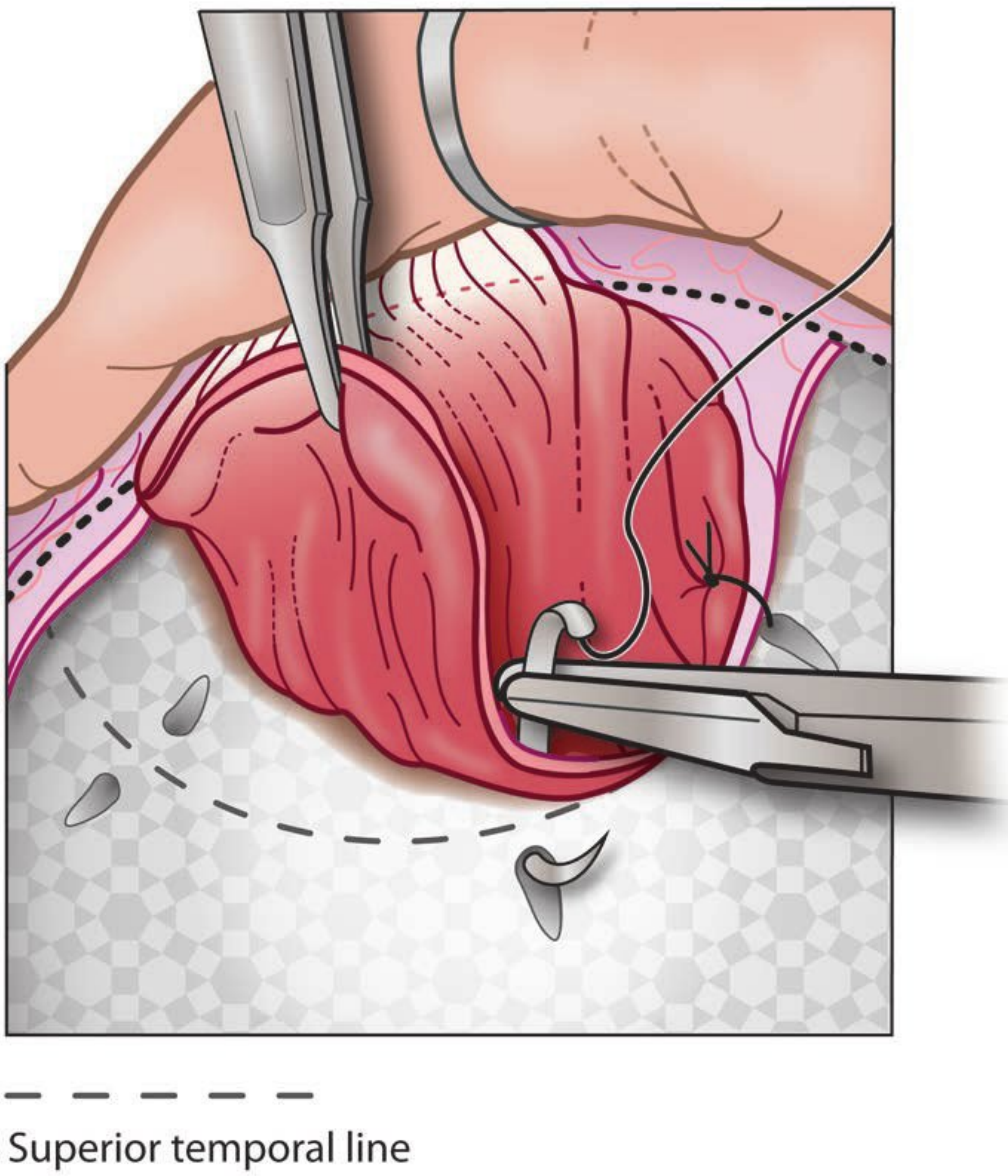

Figure	Procedural Steps
Fig. 26.13	**If preserved, the temporalis muscle is secured to the holes placed to re-create its "insertion" at the superior temporal line with 2-0 braided nylon sutures to complete its transposition.**

Closing

- Hydrogen peroxide may be used at the surgeon's discretion for wound cleansing and hemostasis.
- The wound is heavily irrigated with saline with or without antibiotics.
- A suction drainage device may be placed in the subgaleal plane.
- The posterior portion of the temporalis muscle is reapproximated with 2-0 braided sutures.
- The scalp is approximated with 3-0 braided absorbable suture in an inverted, interrupted fashion.
- The skin is closed with 3-0 nylon in a vertical mattress fashion or with staples.

Postoperative Management

Monitoring

- It is the authors' practice to place the patient in a monitored setting overnight in the postoperative period to observe for seizure activity or evidence of intracranial bleeding.

Medication

- Phenytoin or levetiracetam is maintained at previously mentioned levels for a total of 7 days.
- It is optional to give two to three doses of prophylactic antibiotics in the immediate postoperative period.

Radiographic Imaging

- A postoperative CT scan may be obtained to evaluate for subdural collections or other hemorrhage.

Further Management

- Drains are removed the next postoperative day or sooner if they appear to be draining cerebrospinal fluid.
- Skin sutures or staples are removed after 2 weeks.

Special Considerations

The patient's own bone flap is the ideal material for a cranioplasty; however, if the bone flap is lost to osteolysis or infection, autologous bone (split thickness or harvest from other parts of the body) is less ideal because of donor site morbidity and shaping problems. As such, in these situations, an alloplastic cranioplasty is an appropriate solution. The type of cranioplasty most often depends on the surgeon's preference and experience as well as costs and availability. The most frequently used cranioplasty materials are polymethylmethacrylate (PMMA), hydroxyapatite, titanium, polyethyleneetherketone (PEEK), and porous polyethylene.

PMMA is the most frequently used alloplastic material because of its good biocompatibility and low cost and proven efficacy in the long term.[4] Although it can be used at the time of craniotomy for immediate single stage cranioplasty, the intraoperative time and energy spent contouring the material exceeds that of other implants. In addition, it is difficult to obtain a cosmetic result that approximates that of the custom implants. Utilizing a custom designed mesh with the PMMA implant with larger cranial defects may allow for the optimal cosmetic implant at a lesser expense than other custom implants.[5]

Hydroxyapatite (HA) is probably the most frequently used ceramic in cranioplasty secondary to its high biocompatibility arising from osteointegration.[6] It sets up faster, is easier to contour, and is isothermic—all benefits over PMMA.[7] However, inflammatory reactions have been described in the postoperative period. Furthermore, the costs of HA, especially if combined with a custom mesh for larger implants, may be exceed that of custom implants and thus be cost prohibitive.

PEEK[8] and porous polyethylene[9] are both biocompatible materials that provide high strength and radiolucency for postoperative imaging. The use of custom designed implants for cranioplasty is increasing in calvarial reconstruction, due to the ease of use, strength, and excellent cosmetic results. They can both be contoured in the surgical field and easily fixated. Furthermore, should a postoperative infection occur, they may be removed and re-sterilized for later reimplantation. Porous polyethylene has the additional advantage of being able to be

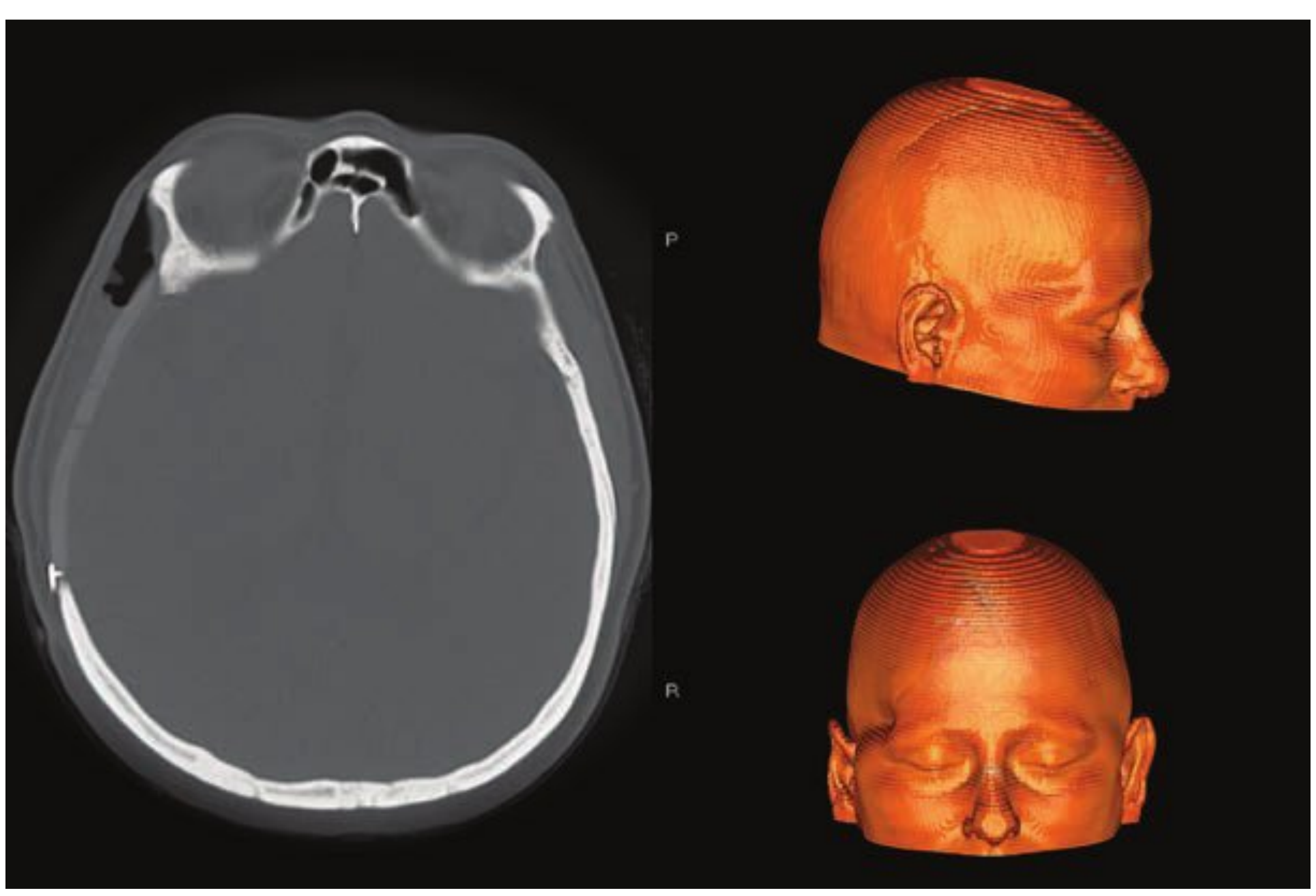

Fig. 26.14 Three-dimensional CT rendering of preoperative soft tissue defect and axial CT image of porous polyethylene pterional implant (arrow).

reshaped with hot saline at the time of surgery,[10] and premade anatomic contours, sheets, and blocks are available at a decreased cost compared to custom implants.[11]

Custom titanium implants offer a good choice for cranioplasty based on their strength, biocompatibility, handling characteristics, and suitability for postoperative imaging techniques.[12] However, they are more difficult to shape in the field and may require special fixation systems. In addition, the titanium artifact may be suboptimal for the follow-up of meningioma and other tumors.

Another consideration after reconstructing the calvarial defect is soft tissue reconstruction over the calvarium/alloplastic cranioplasty. Often when a decompressive craniectomy has been performed, and the temporalis muscle undergoes wasting and is never restored to its previous bulk, causing temporal hallowing. Both porous polyethylene pterional implants (**Fig. 26.14**) and/or hydroxyapatite cement may be used to augment the temporalis and restore aesthetics.[7]

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27 Surgery for Frontal Sinus Injuries

Abilash Haridas and Peter J. Taub

Introduction

External force directed to the anterior portion of the forehead can result in injury to the frontal sinus. The frontal bone is the strongest component of the craniofacial skeleton and can withstand between 800 and 2200 lb of force before fracturing.[1,2] The sinus is roughly pyramidal in shape and often divided by a midline or paramidline septum of bone. The sinus is absent at birth, but begins to actively pneumatize between 7 and 8 years of age to reach an adult volume after puberty. By their mechanism, most injuries produce posterior displacement of the bone into the frontal sinus, although bone at the periphery of the injury can protrude outward. Depending on the force and direction of the injury, fractures can involve either the anterior table of the sinus, both the anterior and posterior tables, or solely the posterior table.

Indications

- Surgical treatment, if indicated, should be instituted within the first 12 to 48 hours after the injury, depending on the overall health of the patient. Early treatment reduces the incidence of long-term complications.[3,4]
- With respect to the anterior table, depressed fractures that will produce noticeable deformity after the resolution of edema or that could potentially result in mucocele formation require repair. If there is no computed tomography (CT) evidence of nasofrontal outflow tract obstruction (opacified sinus, associated anterior ethmoid complex fracture, or frontal sinus floor fracture), observation may be recommended with less likelihood of future complications developing.[4]
- With respect to the posterior table, the presence of pneumocephalus has been an indication for repair by some authors.[5] The pneumocephalus represents communication between the sterile meningeal space and the external environment, which could lead to potentially life-threatening intracranial complications, such as meningitis, encephalitis, and brain abscess. Some authors elect to closely observe patients with a posterior table fracture and associated leakage of cerebrospinal fluid (CSF) for a defined period of time, such as 7 days.[1]
- For nondisplaced posterior table fractures, the management is more controversial. Some authors suggest that all posterior table fractures should undergo exploration and be examined directly via sinuscopy. Others treat these injuries with close observation and explore if complications develop.
- Persistent rhinorrhea indicates leakage of cerebrospinal fluid due to injury to the dura that has not healed with observation alone and requires intervention.
- Secondary correction is indicated for wounds that were observed in lieu of operative intervention and have healed with noticeable deformity.

Preprocedure Considerations

Since the etiology is trauma, and is often of significant force, a full trauma workup should be performed. Initial confirmation that the airway is patent, the patient is breathing, and there is adequate circulation is paramount. The mechanism of frontal sinus fracture places the cervical spine at risk for injury. Careful physical examination of the cervical spine as well as appropriate imaging studies is indicated. Adequate plain films should be obtained and CT added if the initial films are either inadequate or inconclusive.

Radiographic Imaging

- CT is the gold standard imaging modality for the craniomaxillofacial skeleton. Historically, plain films were obtained, which were able to identify the presence of fluid in the frontal sinus, but presented difficulty when trying to determine the presence of anterior, posterior, or through-and-through injuries. CT scans are able to provide axial, coronal, and sagittal images that can separately evaluate the anterior and posterior aspects of the sinus (**Figs. 27.1, 27.2,** and **27.3**).

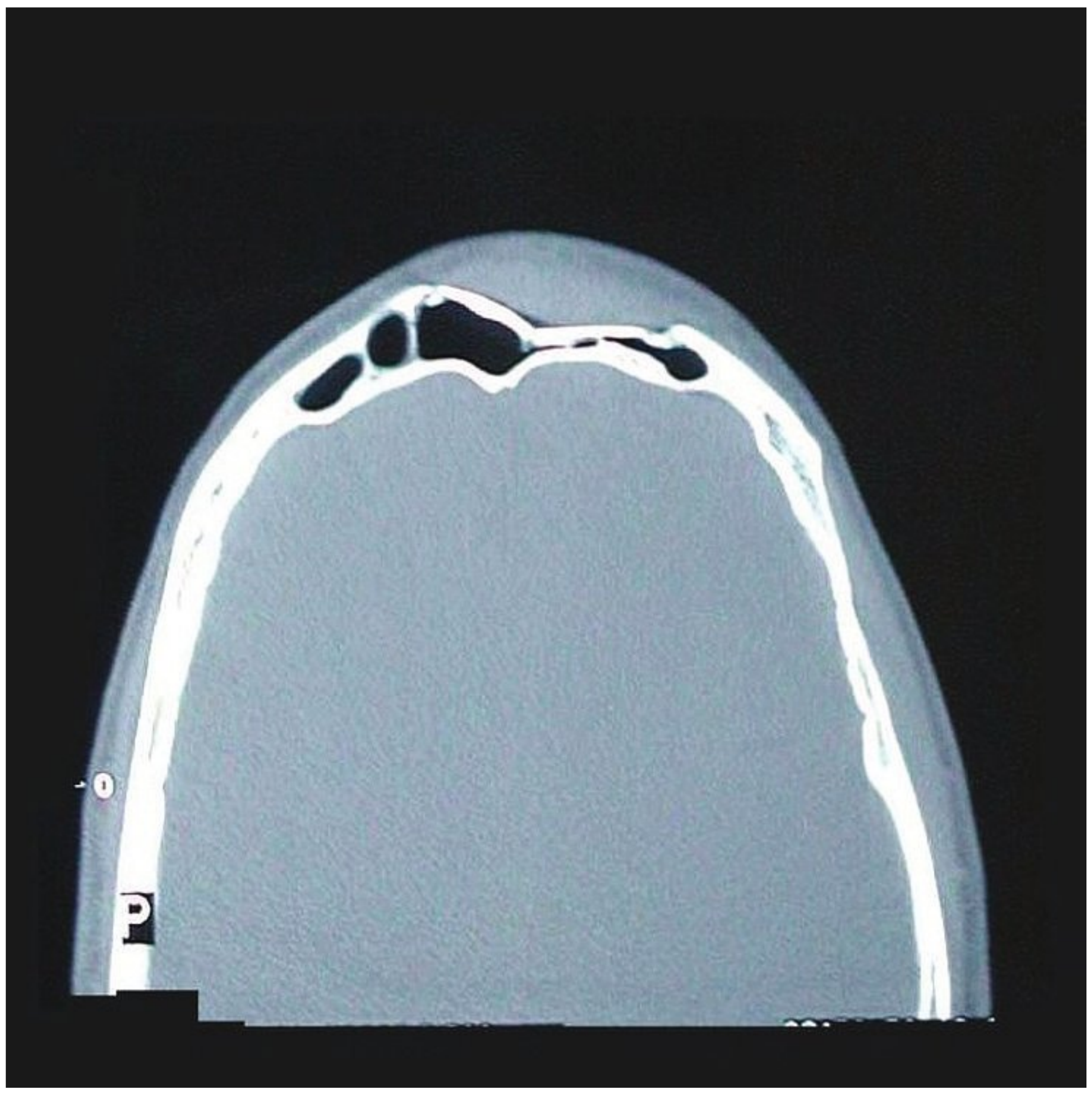


Fig. 27.1 CT demonstrating an isolated fracture of the anterior table of the frontal sinus.

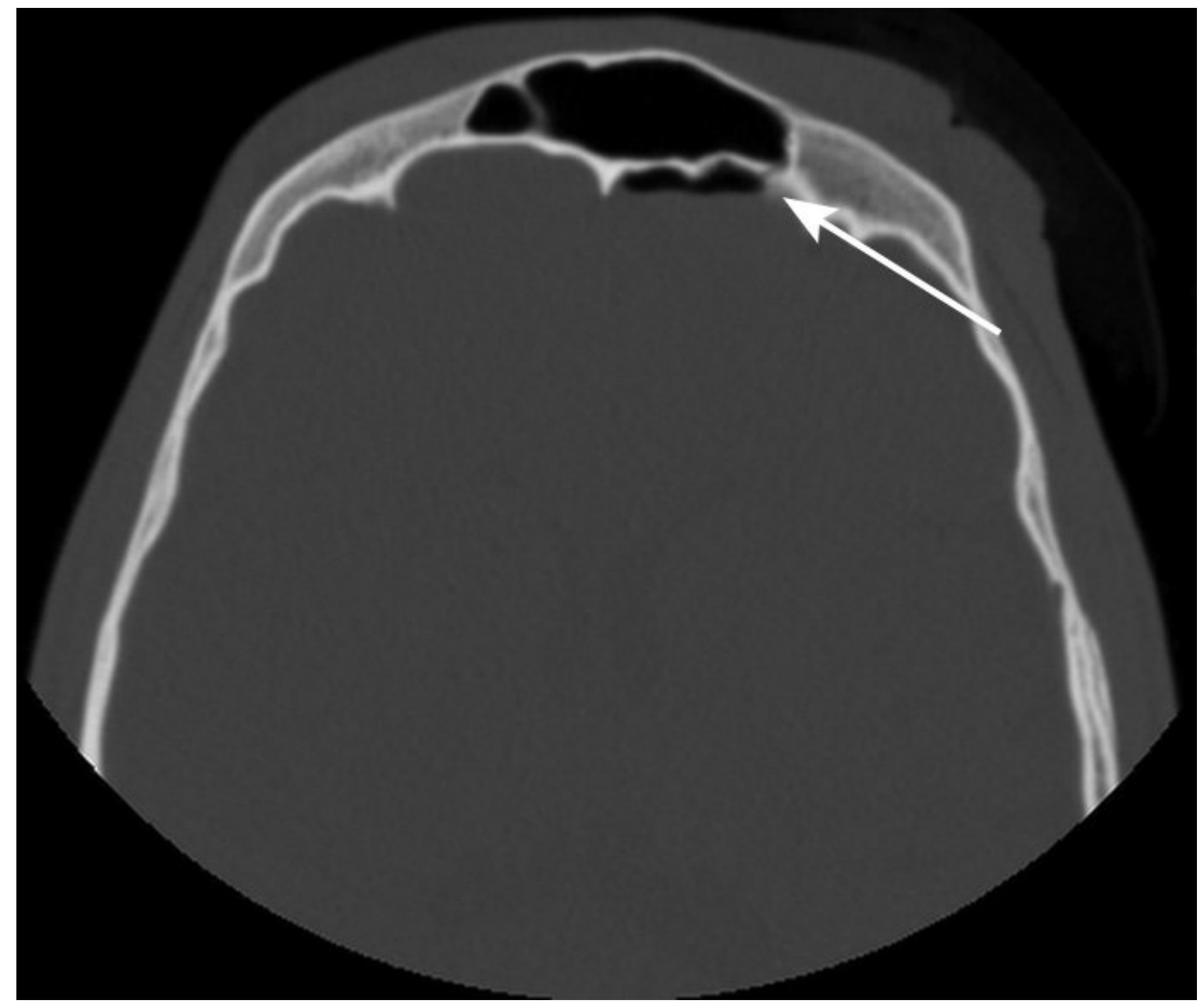


Fig. 27.2 CT demonstrating an isolated fracture (arrow) of the posterior table of the frontal sinus. Note the presence of pneumocephalus.

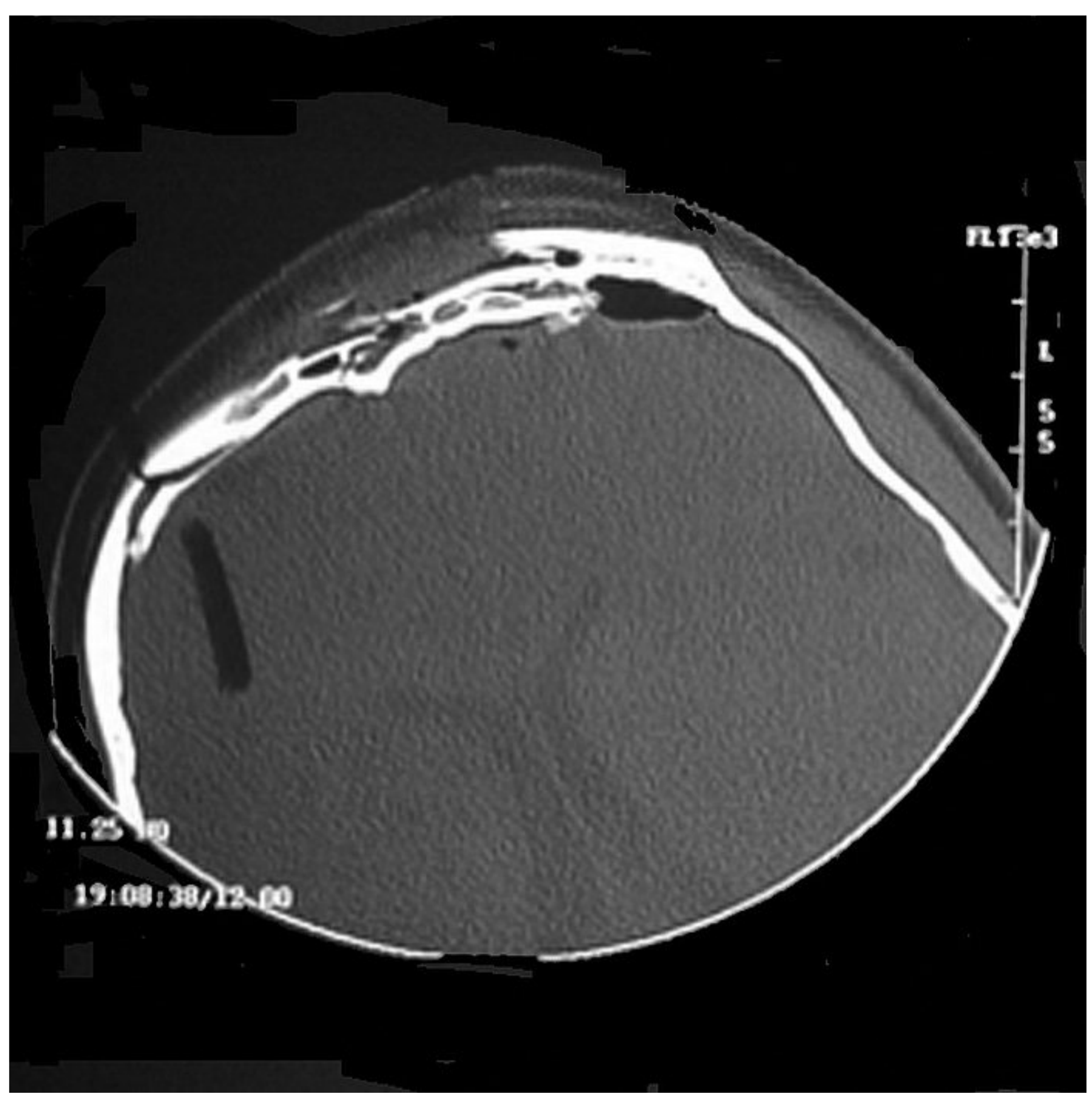


Fig. 27.3 CT demonstrating a fracture involving both the anterior and posterior tables of the frontal sinus.

Operative Procedure

Bicoronal Incision (Fig. 27.4)

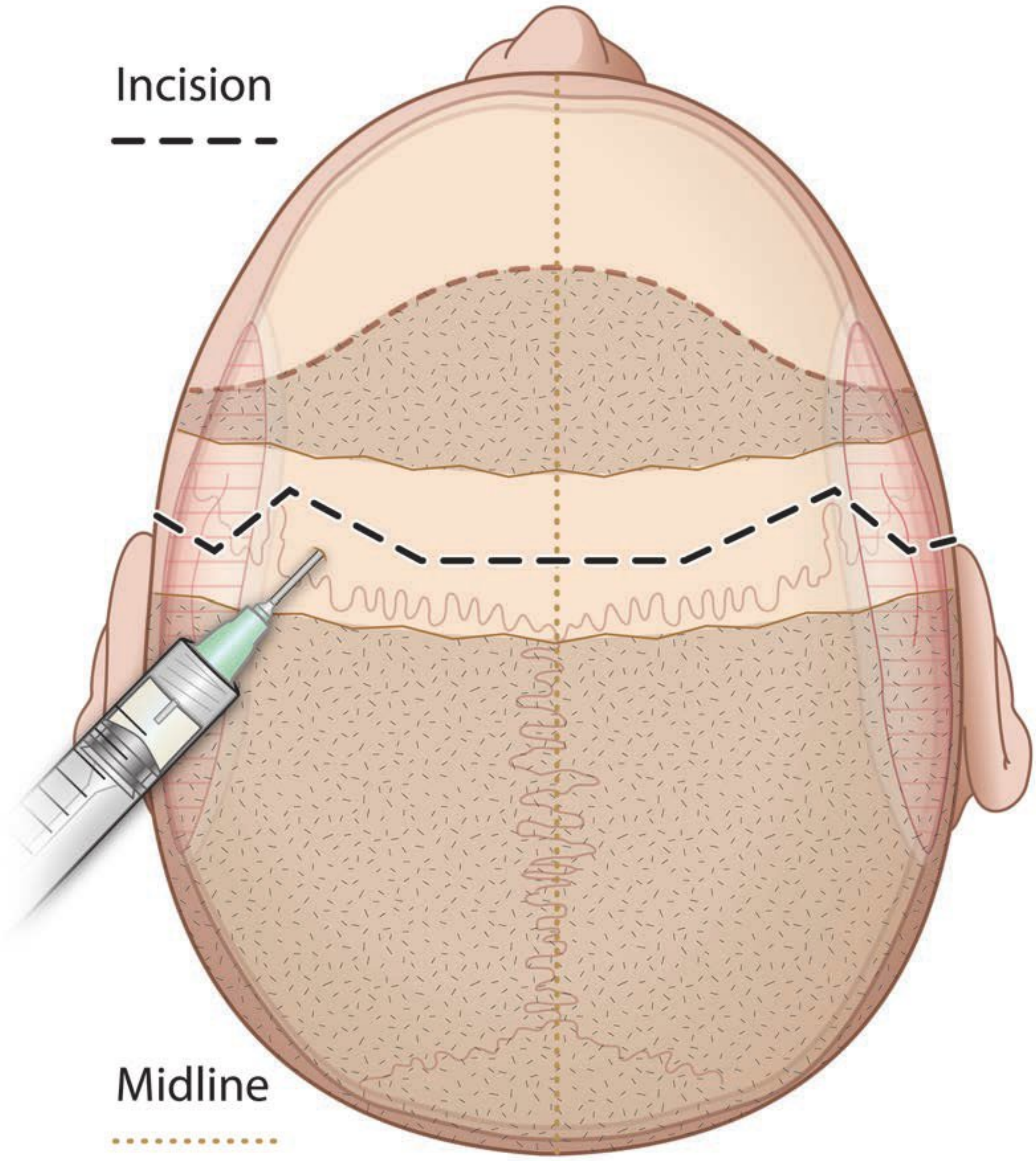
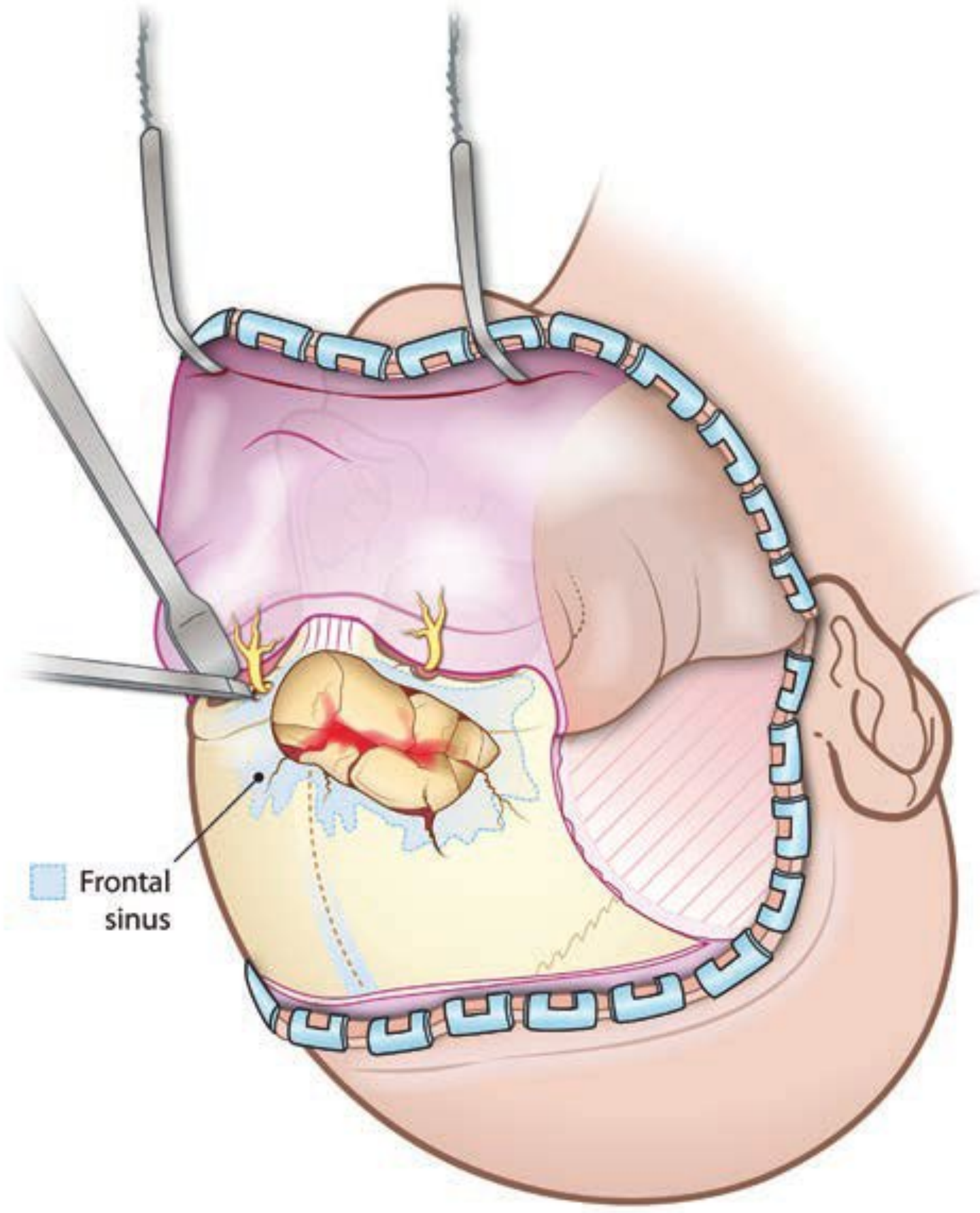


Figure	Procedural Steps
Fig. 27.4	**A bicoronal incision several centimeters behind the hairline provides the best access for exposure of the anterior forehead and frontal sinus. The residual scar is inconspicuous if attempts to minimize alopecia are taken. Superficial electrocautery should be avoided. A stair-step incision is designed along the wound to break up the wound and prevent the hair, especially when wet, from falling all in one direction. A strip of hair over the area of the incision is shaved for exposure and to facilitate ultimate closure. The incision is infiltrated with 1% or 0.5% lidocaine with 1:100,000 or 1:200,000 epinephrine, respectively. After prep and drape, the incision is made with a scalpel blade in the direction of the hair follicles. The deeper subcutaneous tissues may be divided with electrocautery down to the level of the periosteum.**

Subperiosteal Dissection (Fig. 27.5a, b)



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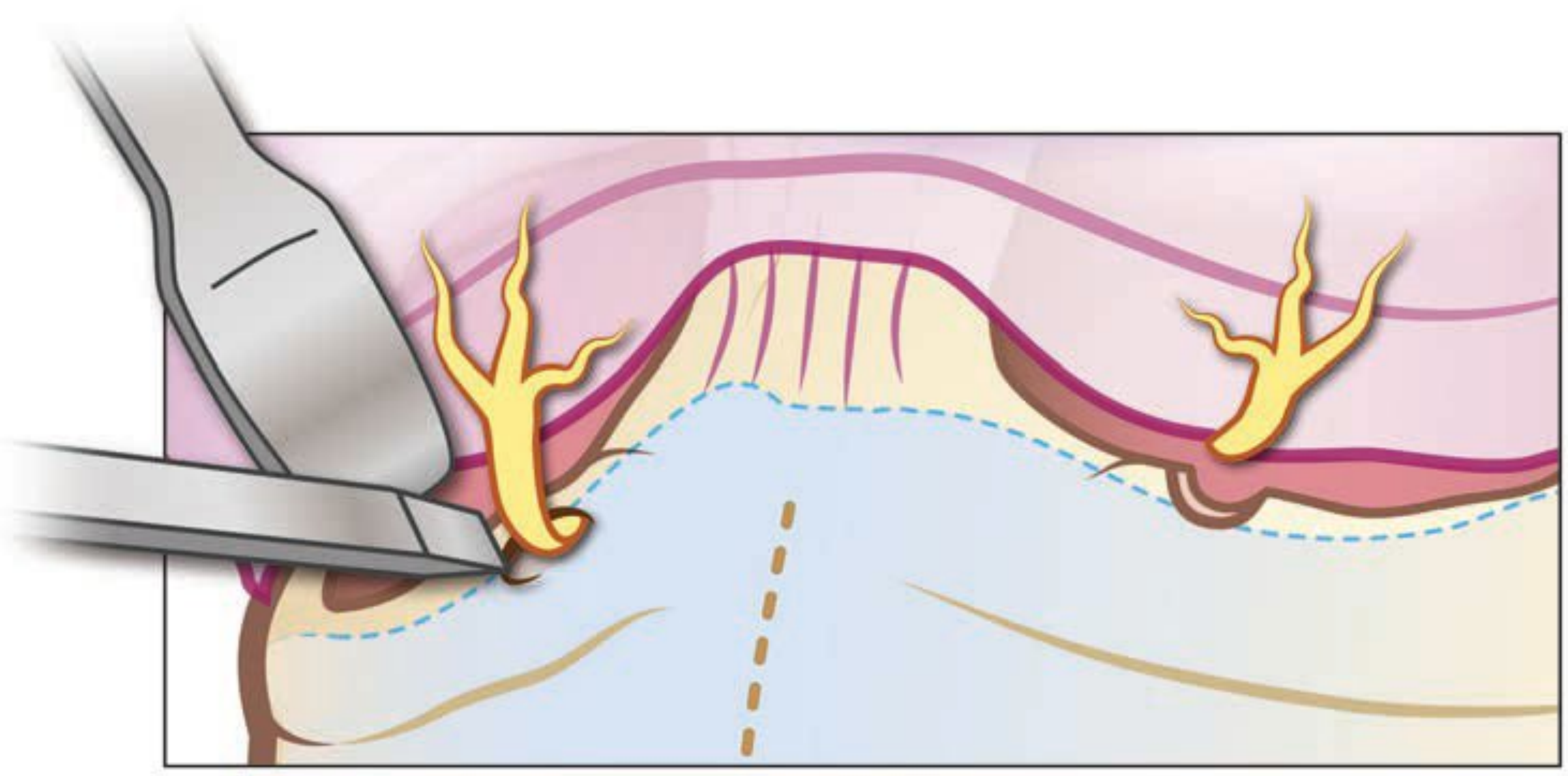

b

Figure	Procedural Steps
Fig. 27.5	**(a) Dissection superior to the fractured area may proceed in either a subgaleal or subperiosteal plane. However, once the fracture fragments are encountered, dissection in a subperiosteal plane is required to mobilize and reduce the fracture fragments. If the entire supraorbital rim needs to be visualized, the supraorbital nerves may need to be taken out of their foramina. This does not need to be done if the nerves merely rest within a notch.** **(b) To easily convert each foramen into a notch, a 2-mm osteotome is placed inside the medial and lateral aspects of the foramen and directed inferiorly. Once the nerves are free, the soft tissues on the orbital rim and roof can be dissected in a subperiosteal plane for exposure.**

Fragment Removal and Cataloguing (Fig. 27.6)

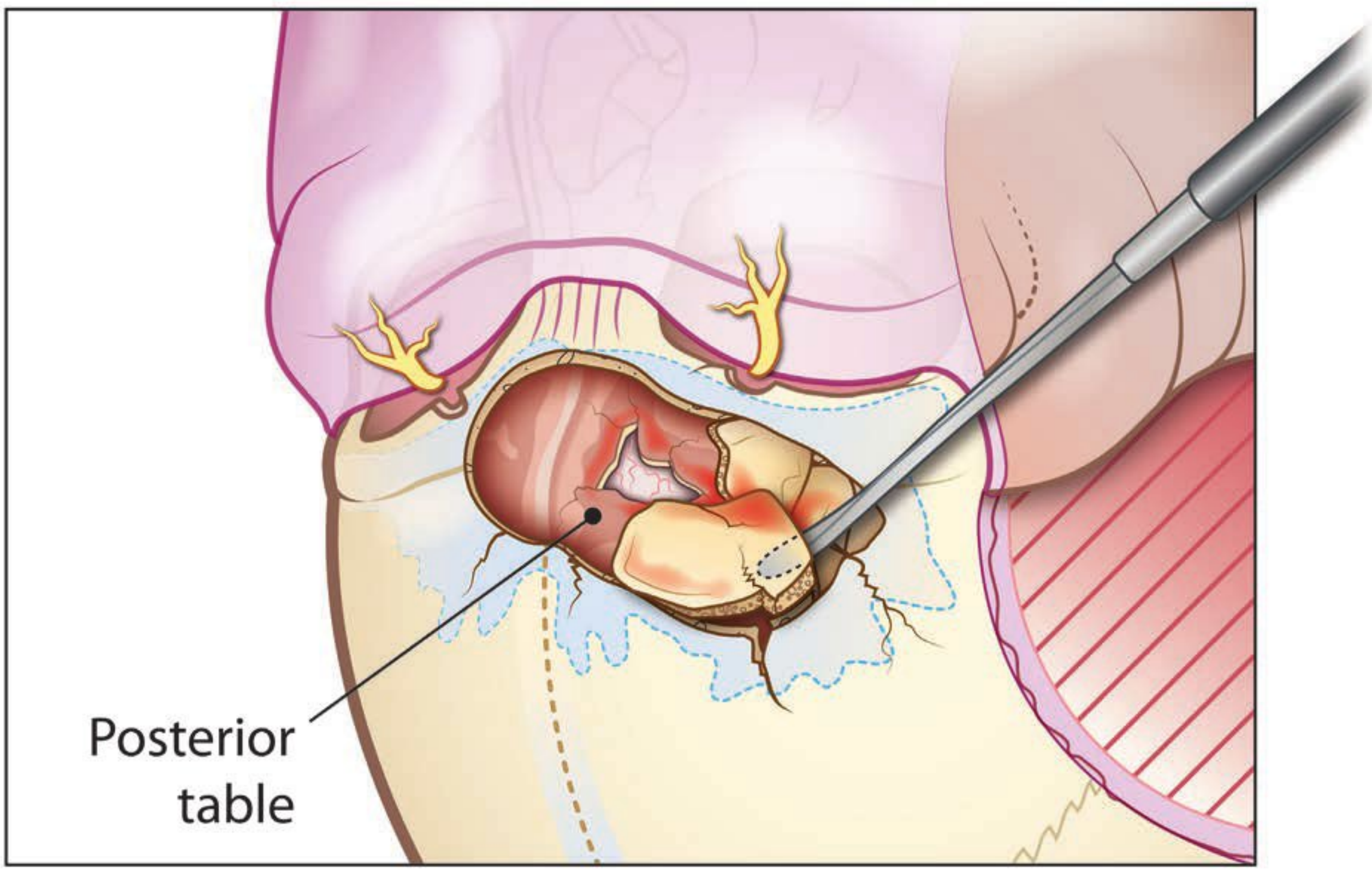

Figure	Procedural Steps	Pearls
Fig. 27.6	**An elevating tool (Freer, bone hook, etc.) can be inserted between the fragments to reduce them into a more anatomic position or remove them for access to the sinus and posterior table.**	• If the fragments are loose and exposure of deeper structures is required, the fragments should be labeled and catalogued so that they may be replaced in the correct position and alignment.

Confirming Frontonasal Duct Patency (Fig. 27.7)

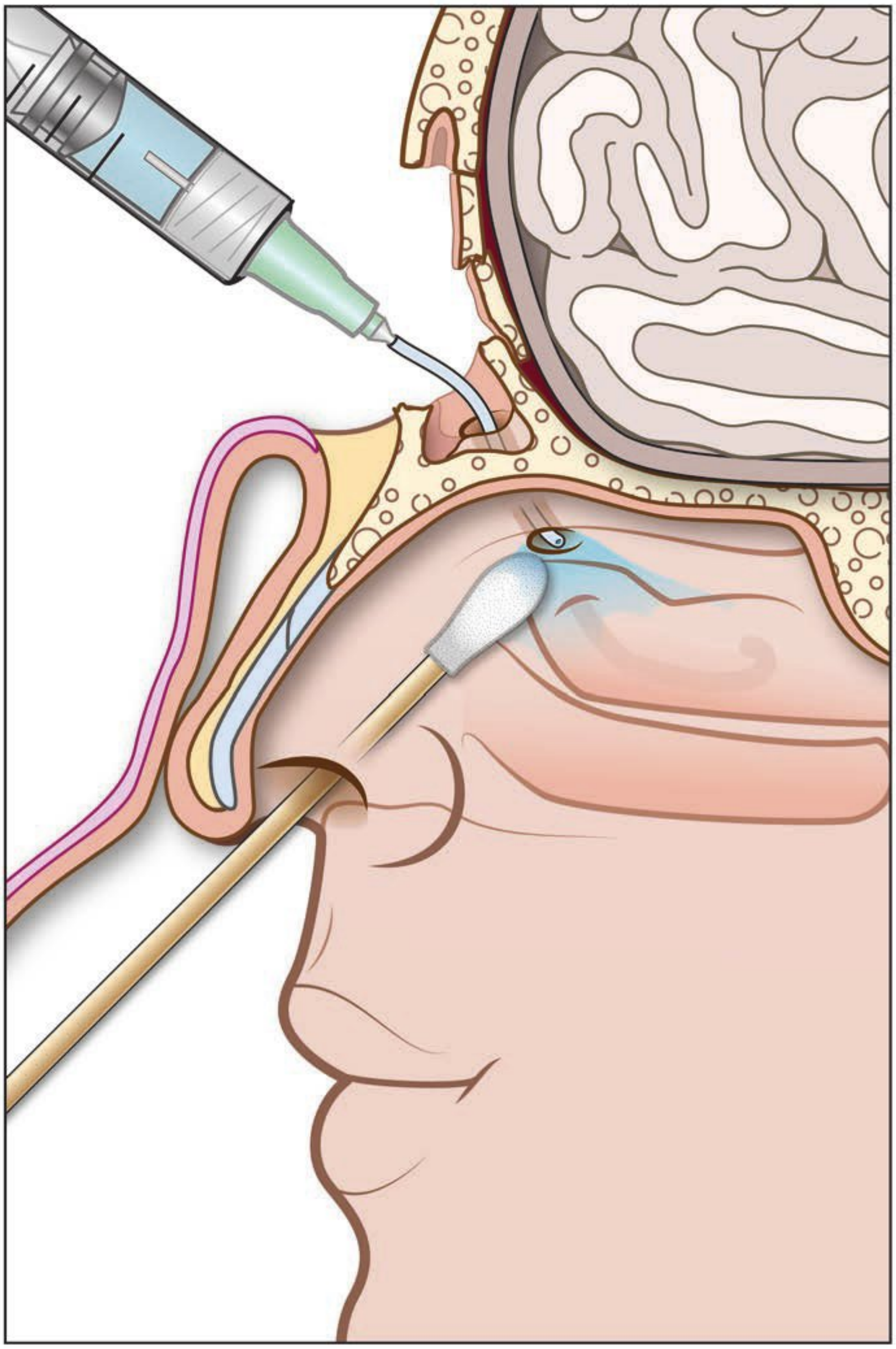

Figure	Procedural Steps	Pearls
Fig. 27.7	**Placing a clean cotton swab in each of the nostrils and instilling a dilute solution of methylene blue in saline via a syringe and catheter into each of the ducts can rapidly confirm frontonasal duct patency. Transmission of dye down the ducts, into the nose at the anterosuperior aspect of the middle meatus, and onto the cotton swab indicates patency.**	

Removal of the Posterior Table, if necessary (Fig. 27.8)

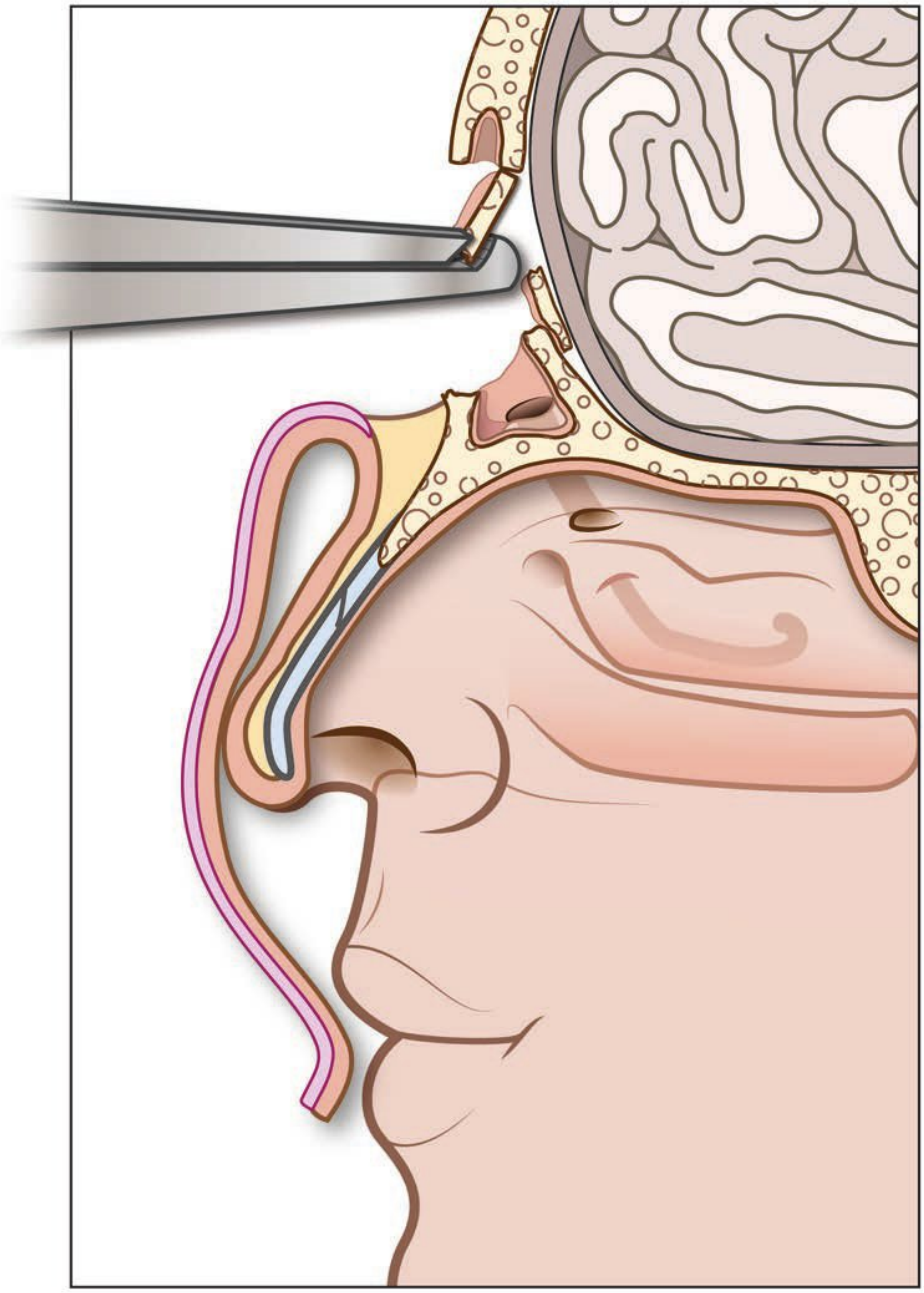

Figure	Procedural Steps	Pearls
Fig. 27.8	**In the presence of pneumocephalus or displacement of the posterior table fracture fragments, the entire posterior table can be removed, allowing the sinus to be "cranialized" (see Fig 27.10).**	• The bone fragments removed from the posterior table can then be used for autogenous graft material to plug the frontonasal ducts. Alloplastic material should be avoided. When possible, dural breaches should be repaired either primarily or with a dural patch.

Burring the Sinus Mucosa (Fig. 27.9)

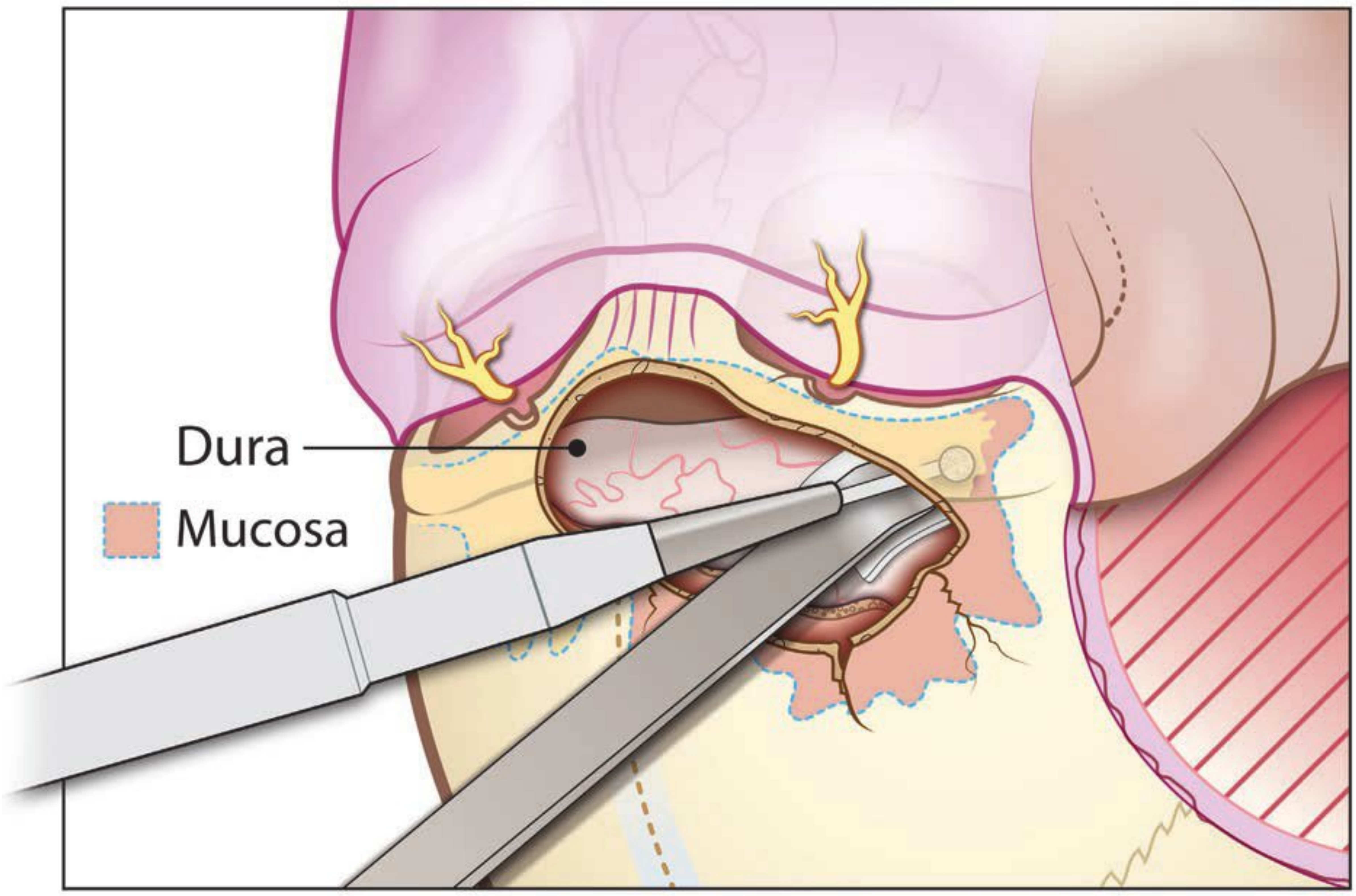

Figure	Procedural Steps
Fig. 27.9	**The sinus mucosa does not stretch flat against the wall of the sinus but rather follows small invaginations across the surface. Therefore, adequate removal of the mucosa requires obliteration of the superficial depressions in the bone with a power bur. Every surface and facet of the sinus should be debrided to remove the mucosa.**

Packing the Frontonasal Ducts (Fig. 27.10)

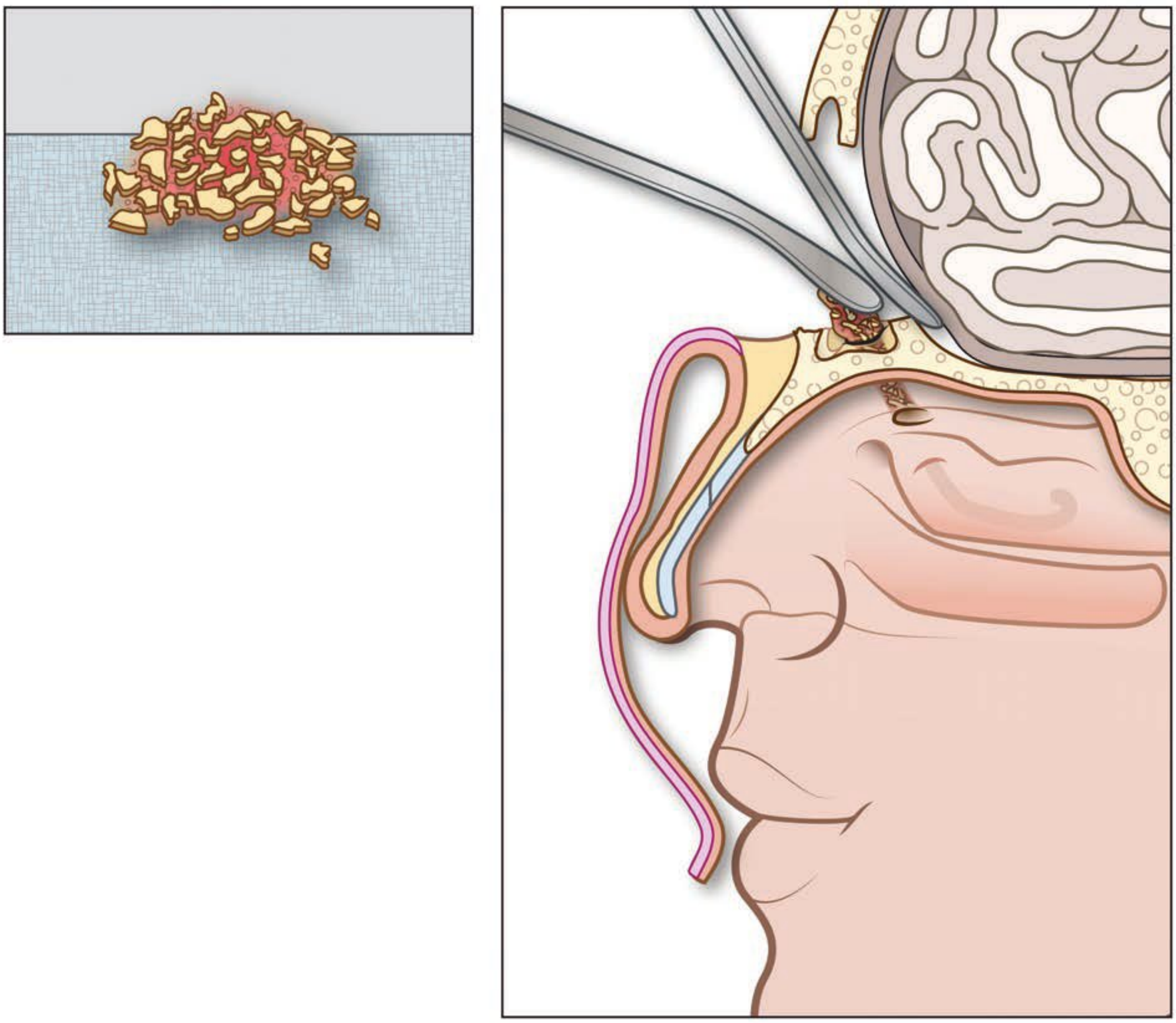

Figure	Procedural Steps
Fig. 27.10	**If the posterior table is removed and the sinus allowed to cranialize, the frontonasal ducts must be obliterated to avoid an ascending infection from the nonsterile respiratory tract. Plugging of the ducts has been described using muscle, fat, or alloplastic material. However, morselized bone graft from the remnants of the posterior table provides excellent graft material. The bone is crushed with a rongeur on a back table and packed into the ducts.**

Elevation and Rotation of Pericranial Flap (Fig. 27.11a, b)

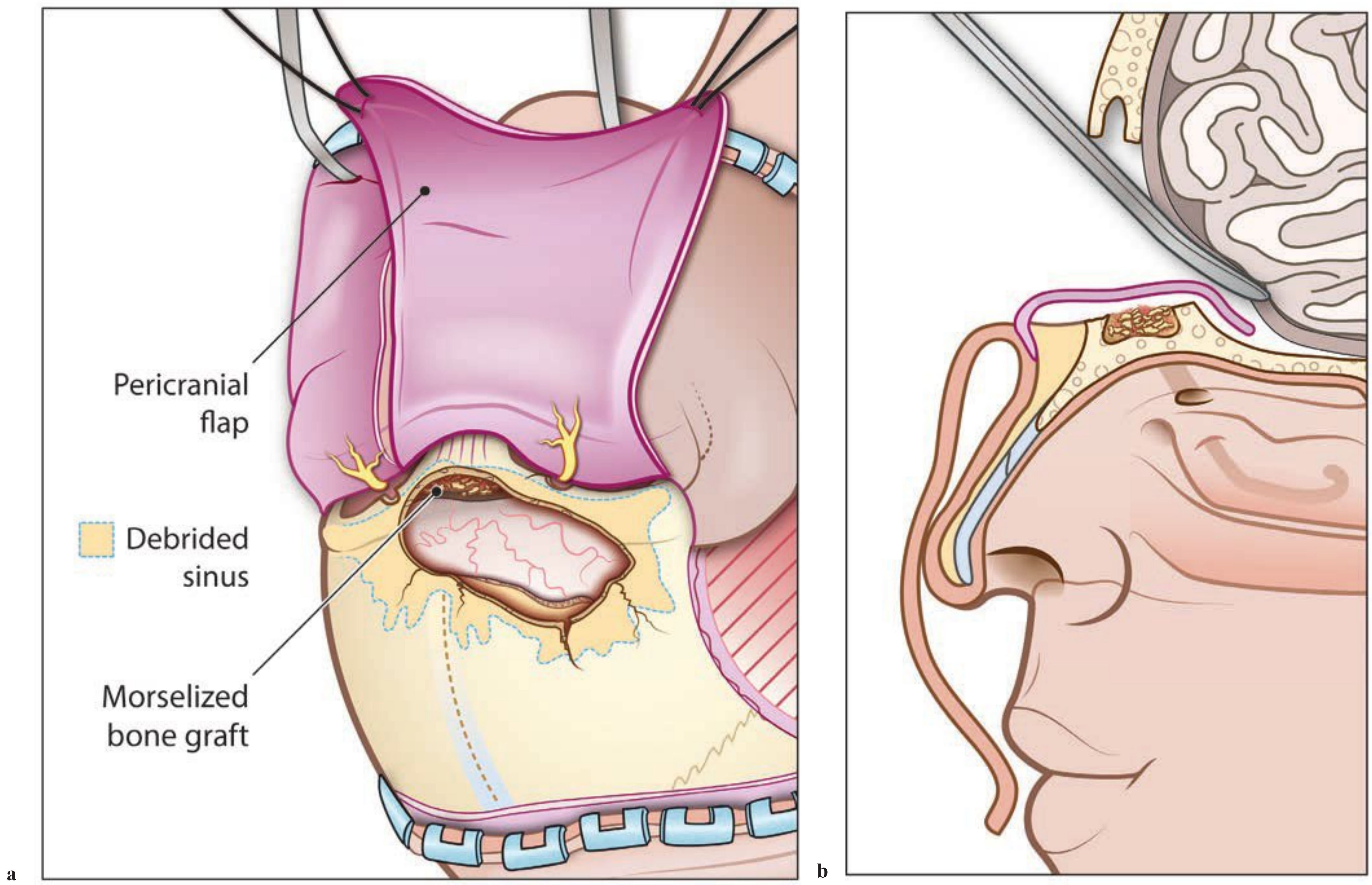

Figure	Procedural Steps
Fig. 27.11	**(a) A flap of pericranial tissue provides further separation of the nasal mucosa and meningeal space. The flap is harvested from the deep surface of the bicoronal flap and based inferiorly along the supraorbital rim.** **(b) The pericranium should be elevated as large as possible to wrap over the inferior aspect of bone and down into the anterior fossa. It can be incised with the electrocautery and dissected free with a scissors.**

Application of Fibrin Sealant (Fig. 27.12)

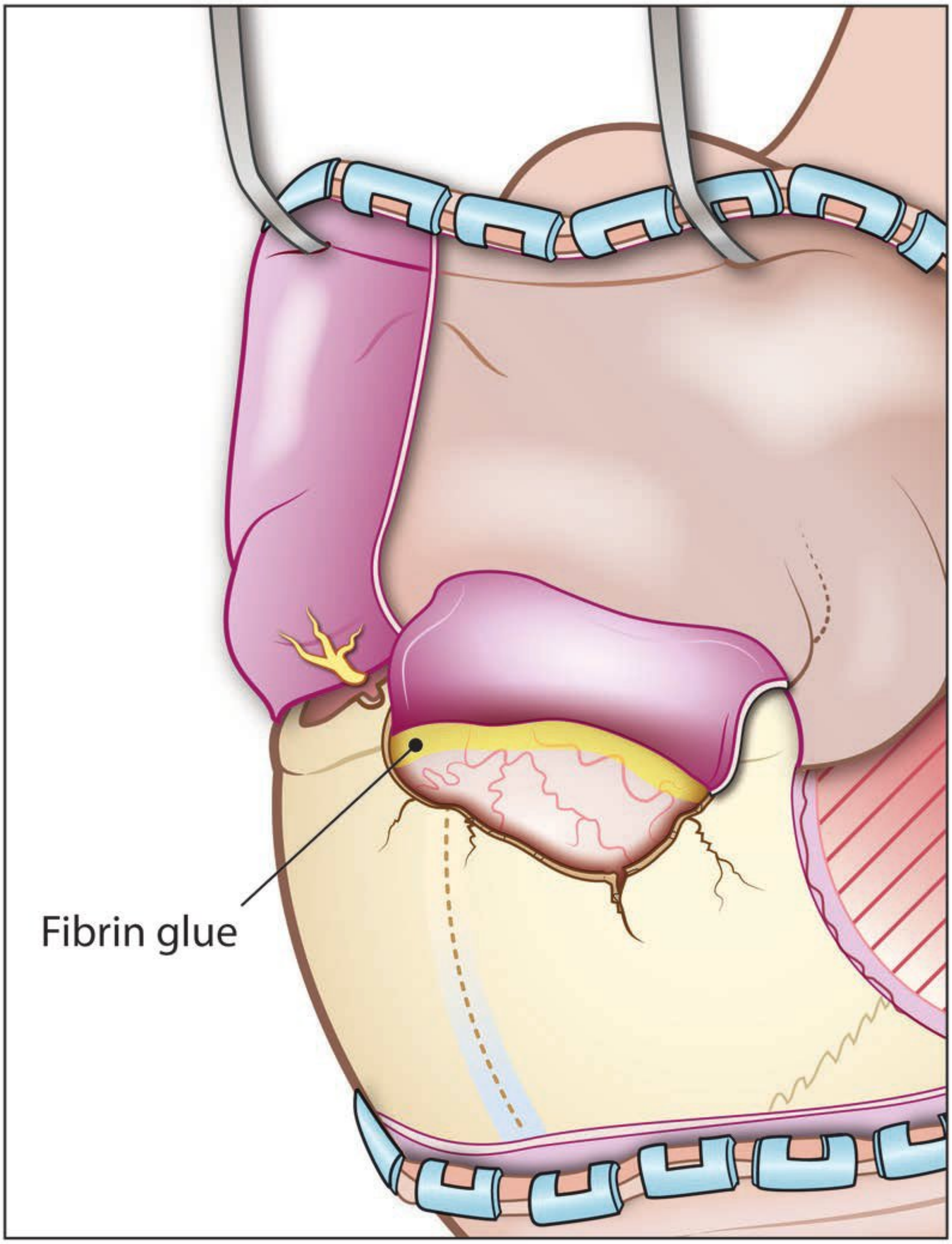

Figure	Procedural Steps
Fig. 27.12	**Final separation is achieved with fibrin sealant placed over the pericranial flap.**

Replacement of Cranial Bone Flap Components (Fig. 27.13)

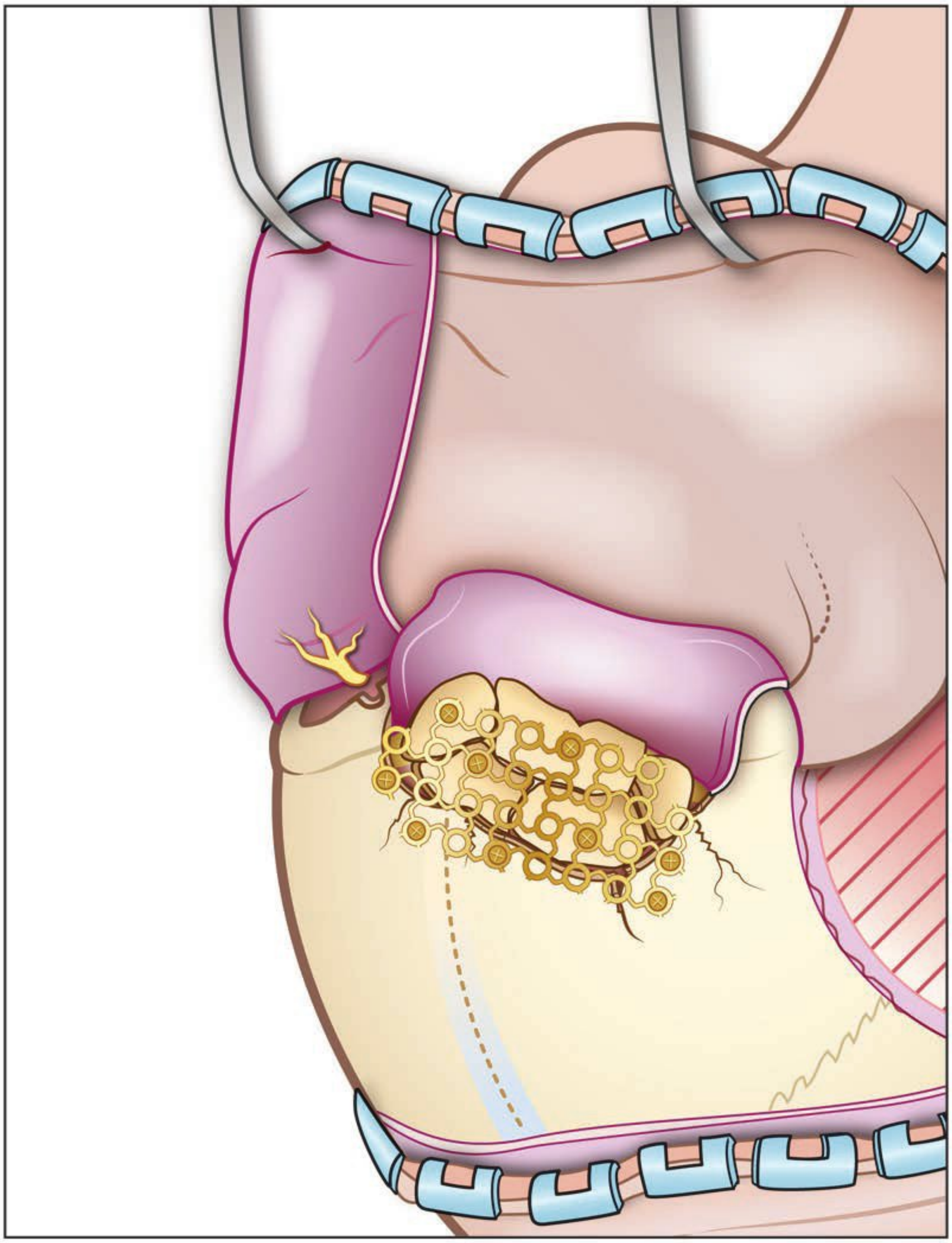

Figure	Procedural Steps	Pearls
Fig. 27.13	**The anterior table fracture fragments can be reconstituted on a back table with plates and screws made of either titanium or resorbable material. The entire construct is then replaced over the forehead and fixated in the same manner.**	• Low profile plates are preferable since the bone is not weight bearing and any superficial irregularity may be noticeable.

Closing

Cranial Incision

- The wound is irrigated with copious warm normal saline with or without antibiotics.
- A flat suction drain is placed across the vertex of the skull.
- The scalp is closed in layers. Depending on the age of the patient, the galea is reapproximated with interrupted 3-0 absorbable sutures.
- The skin is closed with running locked 4-0 plain gut sutures or alternative techniques, such as staples.
- A dressing consisting of petroleum gauze, individual dry gauze, and a head wrap is applied.

Postoperative Management

The patient is kept in the hospital until awake and alert. The drain is kept to self-suction and the output followed for quantity and color. If it is noted to be too sanguineous, the scalp should be carefully inspected for evidence of hematoma and a serum hematocrit checked. Evidence of ongoing bleeding warrants return to the operating room for evacuation and hemostasis. When drainage is minimal, it may be removed.

Radiographic Imaging

- Postoperative imaging with CT can be obtained at the discretion of the surgeon.
- Patients should be followed closely in the early postoperative period for the development of meningitis, encephalitis, brain abscess, osteomyelitis of the frontal bone, nonunion, cavernous sinus thrombosis, CSF leak, mucopyocele, and meningoencephalocele.
- Mucoceles have an insidious course over many years, warranting long-term follow-up with imaging.[1,4]

Special Considerations

Persistent leakage of fluid from the nose must be evaluated for CSF. Antibiotic prophylaxis is controversial in frontal sinus trauma. One recent retrospective study by Devaiah et al showed no benefit with respect to the rate of postoperative infections with additional antibiotics, but suggested that antibiotic usage may be warranted in the presence of severe facial trauma and multiple open fractures.[3,6] Although significant brain injury may accompany frontal sinus injuries, the use of steroids is not recommended to reduce intracranial pressure, and, in fact, is contraindicated.[7] Although an emerging technique, the role of endoscopic repair has been limited to contouring of minimally displaced anterior table fractures.[1,8]

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VI Special Considerations in Pediatric Emergency Neurosurgery

28 Special Considerations in the Surgical Management of Pediatric Traumatic Brain Injury

Anthony Figaji and P. David Adelson

Introduction

Children and adults are physiologically different. Even within the pediatric population, there is a wide range of physiological normative values across the age spectrum. This is perhaps most relevant in the neurosurgical setting for the management of intracranial pressure (ICP) and blood pressure. Pathophysiology after traumatic brain injury (TBI) is also different in children. Diffuse brain injury is more common. Focal injury and extra-axial hematomas are less common. There also are differences in the pressure–volume relationships within the skull, metabolic responses to injury, and cerebral hemodynamics—all of which have clinical implications for treatment. Furthermore, the technical aspects of operative management in the pediatric population—with regard to anesthetic control, operative planning, and tissue handling—require special consideration. Although it is beyond the scope of this chapter to cover all the details of every specific emergency operation performed in children, key principles common to the most important of these procedures are addressed.

Indications

- **Insertion of parenchymal monitors** (ICP, brain oxygen, microdialysis, etc.). It is the authors' practice to place (at minimum) an ICP monitor for all patients who require ventilation after TBI and who have an abnormal head computed tomography (CT) scan. Invasive monitoring may also be considered for patients with diffuse injuries, as a normal CT does not preclude a patient from potentially having intracranial hypertension. Intracranial monitoring also may be considered for patients with other acute neurologic pathologies that result in coma and that may be associated with brain swelling and brain ischemia. Open sutures and fontanels in young children should not discourage monitoring, as these patients remain at risk for increased ICP.
- **Insertion of ventricular drainage catheters.** External ventricular drain (EVD) placement enables accurate monitoring of ICP and allows for therapeutic drainage of cerebrospinal fluid (CSF) in the setting of increased ICP. Appropriate indications for EVD placement include a need for ICP monitoring in patients with severe TBI (Glasgow Coma Scale [GCS] ≤ 8) and the presence of hydrocephalus. While there is Class III evidence for use of lumbar drains with a concurrent EVD and open cisterns on CT, it has not been the practice of the authors to use such devices because of concern of herniation.
- **Operative treatment of depressed skull fractures**. Not all closed, depressed fractures require surgery. Minor depressions often will remold over time, especially in the young child. Indications for operative repair include depressed fractures associated with significant mass effect—with or without subadjacent hematoma; compound, depressed fractures; and fractures in cosmetically important areas.
- **Craniotomy/craniectomy for extra- or intra-axial hematomas.** The indications for evacuation of intracranial hematomas conform largely to the corresponding principles in adult trauma. Hematomas associated with significant mass effect are removed. Contusions are most suitable for removal if—in addition to demonstrating mass effect—they are discrete and close to the cortical surface. Hematomas of the temporal lobe and posterior fossa present the greatest risk for significant mass effect.
- **Decompressive craniectomy.** The indications for decompressive craniectomy are similar to those in adults. The expectation of clinical benefit from the procedure, however, may be greater in children than in adults. Craniectomy, if contemplated, should be performed early rather than late—as a second tier therapy in the management of increased ICP refractory to medical treatment.
- **Cranioplasty.** Delayed cranioplasty may be necessary to replace the bone flap after decompressive craniectomy or to address other trauma-related cranial defects.
- **Repair of growing skull fractures**. A growing skull fracture, or leptomeningeal cyst, is a potential complication of skull fractures in young children. Leptomeningeal cysts usually start to develop within a few months of the injury. Pulsation of the brain against an unrecognized dural tear—with interposition of tissue between the edges of the fracture—leads to progressive widening of the fracture and increasing size of the dural defect. The diagnosis becomes clinically evident as a progressively enlarging, pulsatile mass in the region of the previous fracture. Surveillance is warranted for all young children with skull fractures. Clinical follow-up at 2–4 weeks post-injury, with or without further radiographic imaging, is indicated to assess for persistent or increasing swelling in the region of the fracture. If a growing fracture is diagnosed, it requires operative repair.

Preprocedure Considerations

Radiographic Imaging

CT

- CT scans of the head (6 cervical spine) should be acquired as soon as the child is hemodynamically stable. Abdominal or thoracic CT can be performed at the same time for polytrauma patients *if* there is a clinical indication. Routine use of body scans is not advocated for several reasons, including the increased dose of radiation.
- Open subarachnoid cisterns on a head CT do not indicate normal ICP.
- Particular attention should be paid to the posterior fossa on head CT. It is easy to miss hematomas here, and the consequences may be severe, given the relatively compact size and important anatomical content of the compartment. Brainstem compression and hydrocephalus are common complications. Such hematomas are often associated with a fracture in the occipital or suboccipital region and may occur in conjunction with a venous sinus injury.
- The lowest axial cuts should be reviewed for evidence of an extra-axial hematoma ventral to the lower brainstem. Hematoma in this location may be a marker for clival fracture and/or a ligamentous injury at the craniocervical junction.

MRI

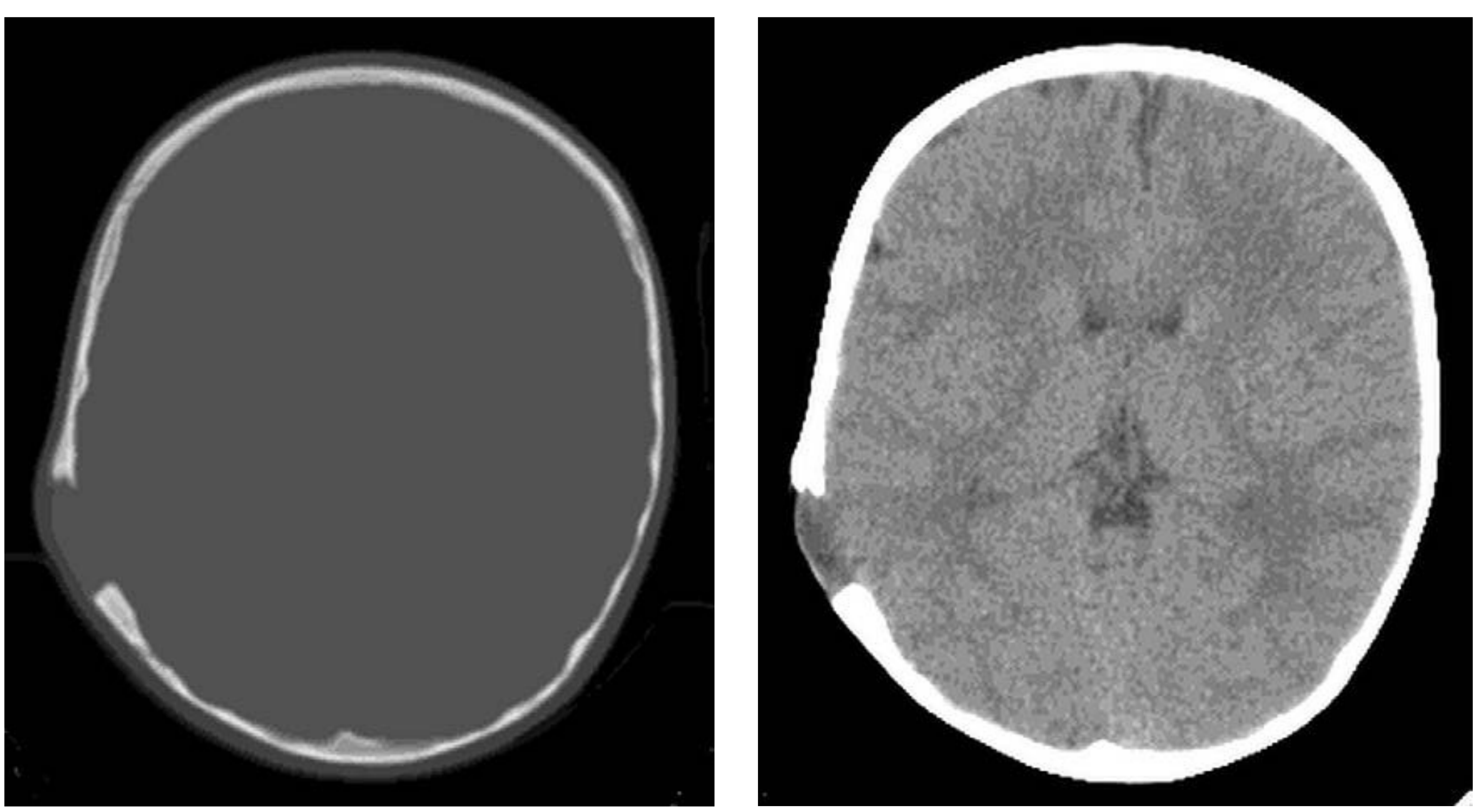
- Magnetic resonance imaging (MRI) of the brain is rarely indicated in the setting of acute trauma, with the exception of studies performed to exclude associated spinal or craniocervical injuries.
- Suspicion of SCIWORA (**s**pinal **c**ord **i**njury **w**ith**o**ut **r**adiographic **a**bnormality) requires an MRI of the spine.

X-ray

- Plain skull radiographs are obtained only on rare occasion. A normal skull radiograph does not exclude an intracranial injury, and a skull fracture detected on radiographs does not necessarily indicate an associated intracranial hematoma; therefore, skull radiographs do not change the indication for head CT. Plain radiographs may have a role in the follow-up of fractures in young children and as part of the bone survey in the setting suspected nonaccidental injury.
- Plain radiographs of the cervical spine are still used routinely for severe TBI patients, with the addition of MRI if ligamentous injury or SCIWORA is suspected. Even in absence of suspected SCIWORA though, it is recommended to practice basic spinal cautionary measures and keep the head in the midline position for children who have a depressed level of consciousness.
- Preoperative imaging (**Fig. 28.1a, b**).

Anesthetic Considerations in Children

- It is essential that the anesthesiology team have both pediatric and polytrauma experience. Secondary insults contribute substantially to worse outcome and so should be aggressively avoided.
- Inadequate management of the respiratory and circulatory systems may lead to secondary insults such as hypoxia and hypotension. Brain swelling may be exacerbated by hypo- or hypertension, hypercarbia, and inadequate pain control.
- The endotracheal tube must be fastened securely, particularly if the child's head is to be turned. Loss of the airway is of greater consequence in children because they deteriorate rapidly. The TBI patient, in particular, has a reduced capacity to tolerate hypoxic insults. Hypocarbia may exacerbate the



a b

Fig. 28.1a, b Axial CT (**a**) bone and (**b**) soft tissue windows demonstrating a bony defect with protrusion of meninges. This patient fell from a bed, striking his head on the concrete floor, and presented approximately 8 months later with a tender, pulsatile postauricular mass.

decreased cerebral blood flow often seen early after TBI, and hypercarbia may increase cerebral blood volume and, consequently, ICP.
- Induction of anesthesia must be smooth; coughing or bucking may have fatal consequences in patients who already have life-threatening increased ICP.
- Often, anesthesiologists are accustomed to maintaining patients at blood pressures in the lower range of normal during elective surgery. This practice may be hazardous when managing the TBI child at risk of early brain ischemia. Also, impairment of pressure autoregulation may result in reduced capacity to accommodate a blood pressure in the lower range of normal. Large bore intravenous access allows adequate response to hemodynamic instability, especially when there may be occult abdominal or thoracic injury.
- To estimate what blood pressure is adequate, the anesthesiologist must have access to charts for normal mean arterial pressure ranges for age (and, preferably, height and gender as well).
- If a craniotomy or craniectomy is planned, ensure that blood is cross-matched for possible transfusion, especially in the very young. The circulating blood volume of a child is only 70–85 mL/kg depending on age, so relatively small volumes of blood loss in these patients may rapidly lead to hemodynamic instability.
- Placement of central venous and arterial lines is recommended for severe TBI patients, not only for adequate intraoperative hemodynamic control, but also to facilitate intensive care unit management thereafter.
- If mannitol is required intraoperatively to assist the reduction of brain swelling, the anesthesiologist must ensure that the patient remains euvolemic throughout and that there is an adequate response to the mannitol infusion by monitoring urine output.
- Do not use hypotonic or glucose-containing fluids.

Operative Field Preparation

- The child is positioned according to the type of procedure planned. If the spine has not been cleared, pay careful attention to protecting the cervical spine while positioning for surgery.
- Antistaphylococcal antibiotics are given routinely at the time of skin incision.
- The head of the operative table is slightly elevated to promote venous return.
- Blood pressure should be well maintained throughout surgery. At no time should the blood pressure be allowed to drop.
- If brain swelling and increased ICP are suspected, a dose of mannitol can be given just after induction.
- Ensure that the planned skin flap allows adequate access for the pathology concerned. As a general principle of trauma surgery, a wider exposure is preferred.
- Prepare the skin widely to allow for an increase in the exposure should this become necessary during the operation.
- The planned skin incision is infiltrated with 0.25%local anesthetic and epinephrine 1:400,000.
- Drape and position the patient so that the anesthesiologist has adequate access to the airway.
- The surgeon should have a clear view of the anesthesiology monitors during the operation.

Operative Management

An exhaustive description of the full range of emergency procedures performed in pediatric patients presenting with TBI would exceed the scope of this publication. Therefore, we review some basic principles that distinguish the surgical approach to pediatric patients and offer operative pearls relevant to specific procedures. Finally, we provide more detailed guidance regarding the repair of growing skull fractures—an entity that is unique to the pediatric population.

General Surgical Principles

- Take care when incising skin overlying open fontanels and sutures.
- Control bleeding from the scalp flap early with the application of scalp clips. Continued ooze during the operation can lead to significant blood loss in young children. Once the scalp flap has been turned, remember to check intermittently that the flap remains dry throughout the operation.
- The skin and scalp of young children is thinner than in adults. Treat the tissues gently and do not crush them between pick-ups. Avoid acute bends in the reflected scalp flap as this may cut off its blood supply. This poses a greater risk than in adults because the scalp flap is thinner and the blood pressure is lower.
- The dura is often adherent where cranial sutures are still open. Use a dissector to separate the dura from the bone carefully and thoroughly beneath suture lines.

ICP and Other Parenchymal Brain Monitors

- ICP and other invasive probes (e.g., brain tissue oxygen) may be introduced via single or double lumen bolts or inserted via a small bur hole and tunnelled to exit the skin. Bolt systems can be used even in very young children; measure the thickness of the skull from the head CT and plan insertion accordingly.
- Unless there is a compelling reason to do otherwise, monitors are placed in the frontal region on the nondominant side.
- For probes that require accurate placement in white matter (e.g., brain oxygen monitors), measurements can be made from the head CT. In practice, placement of the probe tip 2.5 cm beneath the cortical surface is usually adequate.
- Consideration should be given to the location of any invasive probes (and the scalp incision used) relative to the possibility that the child may need further surgery.

External Ventricular Drains

- Typically, an EVD is placed in a standard frontal location on the nondominant side, through a precoronal bur hole in the midpupillary line.
- The catheter is passed with a trajectory that is angled toward the ipsilateral inner canthus in the coronal plane and just anterior to the ipsilateral external auditory meatus in the sagittal plane.

- The catheter should be passed slowly, anticipating the tactile feedback when the ependyma of the ventricle is penetrated.
- If the ventricle is not entered with the first pass, a slightly more medial trajectory may be attempted.
- No more than three passes should be attempted.
- TBI-related brain swelling in children may result in compression of the lateral ventricle; however, with experience, the ventricle still can be cannulated in most cases. If neuronavigation is available, introduction of the navigation probe through the lumen of the ventricular catheter may assist accurate placement in difficult cases.
- Antibiotic-impregnated catheters and periprocedural antibiotics are options that may reduce the incidence of ventriculostomy-related infections.

Craniotomy

- The skin incision should be planned based on the location of the lesion.
- Typically, for a unilateral lesion, an ipsilateral question mark or T-shaped incision is performed to enable wide access to the hemisphere.
- In general, aim for as large a flap as possible. The base of the skin flap should be broad enough to ensure adequate perfusion to the skin.
- When the flap is turned, wrap and tuck an antibiotic-soaked swab or cotton sponge beneath the flap to prevent the creation of an acute angle that might compromise perfusion to the flap. This may be a particular problem in very young children. Intermittently moisten the sponge during the procedure.
- Dissect the flap in a subgaleal plane to prepare a free bone flap. Preserve the pericranium as this can be used later for a dural graft if needed.
- The extent of the bony opening is planned according to the underlying lesion. If there is generalized swelling, the bone should be removed down to the temporal base to maximize the space achieved at the level of the tentorial hiatus.
- If dural opening is necessary to evacuate a hematoma, a cruciate incision is performed over the hemisphere. Any subdural hematoma then may be evacuated.
- If evacuation of a contusion is planned, careful preoperative planning or neuronavigation is required to optimize the location of the corticectomy. Often a subdural hematoma is associated with a “burst” lobe in which the contusion can be identified at the surface. A discrete hematoma can be evacuated aggressively. A contusion mixed with brain tissue should be handled with greater caution, depending on several factors, including the eloquence of the involved brain and the degree of brain swelling. The conservative approach of allowing the contusion/hematoma to decompress itself may be all that is required.
- If the brain is swollen, the dura should be expanded with a dural graft harvested from local pericranium. Use nonabsorbable sutures and close the dura in a watertight fashion.
- The decision of whether to replace the bone flap depends on the preoperative imaging, intraoperative findings, and anticipated postoperative risk for ongoing increased ICP. If the bone flap is left out, it should be managed as below for decompressive craniectomy.
- Epidural hematomas overlying a venous sinus present a particular hazard in children due to the potential for rapid blood loss in the setting of an already small total blood volume. If the hematoma must be evacuated, prepare for blood loss from the sinus and monitor for possible air emboli. Plan a skin and bone flap that allows for adequate exposure and control of the sinus both proximally and distally. If a sinus tear is identified, this must be controlled with immediate pressure over the sinus to stem bleeding, surveillance for air emboli, and repair of the sinus using a pericranial patch graft. If bleeding is too vigorous to allow adequate visualization, maintain pressure over the tear and temporarily control the sinus proximally and distally to enable suturing of the patch. Maintain a patent sinus to prevent additional venous engorgement of the brain.

Surgery for Depressed Fractures

- The principles of depressed fracture management in children are similar to those of adults, with a few exceptions.
- If the depressed fracture is closed, the skin incision is planned based on the location of the depressed fragment, blood supply to the flap, and cosmesis. If the fracture is compound, the wound must be debrided and extended in a curvilinear, S-shape to expose the extent of the fracture.
- Bone is much thinner and softer in children. Often a ping-pong type fracture can be elevated by drilling a bur hole to the side of the fracture and by positioning a slightly angled instrument (e.g., a no. 3 Penfield or small periosteal elevator) through the bur hole, elevating the fracture from inside.
- If the dura is torn, a bur hole should be placed at the margin of the depressed fracture—over intact dura. Then the craniectomy, or craniotomy, can be performed to uncover the area of dural violation. The dural tear is sutured, and bone fragments, if clean, may be laid over the defect.
- Bony defects in children usually heal very well with new bone growth, as long as the dura is intact. Larger lesions may require later cranioplasty if adequate remodeling does not occur and the result is a significant cosmetic and/or functional defect. The use of autologous bone is optimal. The best bone is split calvarial bone, preferably taken from the corresponding location on the opposite side. The harvested bone can be split through the diploic space, creating two pieces: one for the defect and the other to be replaced at the donor site. In young children, this may not be possible. Rib graft or cranioplastic material—resorbable or nonresorbable, prefabricated or not (i.e., methylmethacrylate)—may also be considered.
- Dural defects must always be repaired to avoid the potential complications of a CSF leak and/or a growing skull fracture.
- Devitalized skin must be debrided and the wound thoroughly irrigated. If the skin cannot be closed primarily, the help of a plastic surgeon may be valuable to plan a rotated skin flap.

Decompressive Craniectomy

- Several different approaches have been described for decompressive craniectomy (DC). The following reflects a combination of general principles and personal practice.

- The most important surgical principles of DC are: select a unilateral or bilateral approach as appropriate, make the craniectomy as large as possible, and control the brain swelling before opening the dura.
- The choice of a bifrontal or hemicraniectomy depends both on personal preference and the nature of the injury. Predominantly unilateral hemispheric injury may be better suited to hemicraniectomy, whereas diffuse injury or frontal contusions may be better suited to bifrontal craniectomy. Though the specifics of each technique differ, the principles of decompression are the same.
- Duraplasty increases the complications associated with craniectomy; however, opening and expanding the dura leads to substantially lower ICP, and complications are generally avoidable if done correctly.
- The hemicraniectomy is performed similar to the hemispheric craniotomy. Maximizing the bony opening helps minimize the degree to which the swollen brain pushes against the bony limits. Pressure at the bony edges may further injure the swollen brain and constrict venous outflow of that segment. The temporal bone is removed as low as possible down to the base to maximize the decompression at the level of the tentorial incisura. The dura is opened and expanded with a large pericranial graft, the edges of which can be sutured so that they lie within the dural edge, to minimize the risk of the sharp dural edge cutting into the swollen brain.
- The bifrontal craniectomy is performed through a bicoronal skin incision, positioned behind the hairline. The scalp is reflected anteriorly, preserving the pericranium for a dural graft. Keyhole and paramedian bur holes lateral to the sagittal sinus are used to create a large bifrontal, single-piece bone flap extending posteriorly to the coronal suture. Pay particular attention when separating the dura from the bone, especially over the midline, to avoid injury to the sagittal sinus and its bridging veins. The dura is incised in a U-shape from lateral to medial. The midline sagittal sinus is tied off at the frontal base and the falx is sectioned from anterior to posterior along the skull base to allow for maximal expansion of the brain. When doing this, take care to preserve cortical veins, especially bridging veins leading to the sagittal sinus. The harvested pericranial graft is used to expand the dura.
- Regardless of approach, it is of utmost importance that the dura not be opened abruptly if tense to the touch. Otherwise, massive brain swelling may produce rapid, uncontrolled herniation of the brain through the dural opening with resultant compression of superficial draining veins and progressive engorgement of the entrapped brain. Although, by definition, the patient is in surgery for refractory intracranial hypertension, it is nearly always possible to control the swelling for the short period of time it takes to open the dura and secure the graft in place. The surgeon must work with the anesthesiologist to maximize brain relaxation by the time of dural opening. Potential interventions include controlling blood pressure, administering mannitol and/or hypertonic saline at the time of skin incision, elevating the head of the bed, and lowering the arterial CO_2 (while increasing the FiO_2). The pericranial graft must be prepared prior to the dural opening. When pressure management has been optimized, the dura should be opened quickly and the graft incorporated with suture.

Repair of Growing Skull Fractures (Leptomeningeal Cyst)

- Though not requiring emergent intervention, growing skull fractures do represent a late consequence of trauma and, as such, deserve mention here.
- Optimal treatment of a growing skull fracture requires understanding of the pathology (see Indications).
- The dura is always torn; this tear widens with time as the bone edges separate. Usually the dural edges retract well beyond the bone edge so that the dural defect is larger than the bony defect.
- The affected patients are young, so there must be adequate preparation for blood loss. Do not underestimate the potential for blood loss in these operations.

Operative Procedure

Repair of Growing Skull Fractures

Positioning (Fig. 28.2)

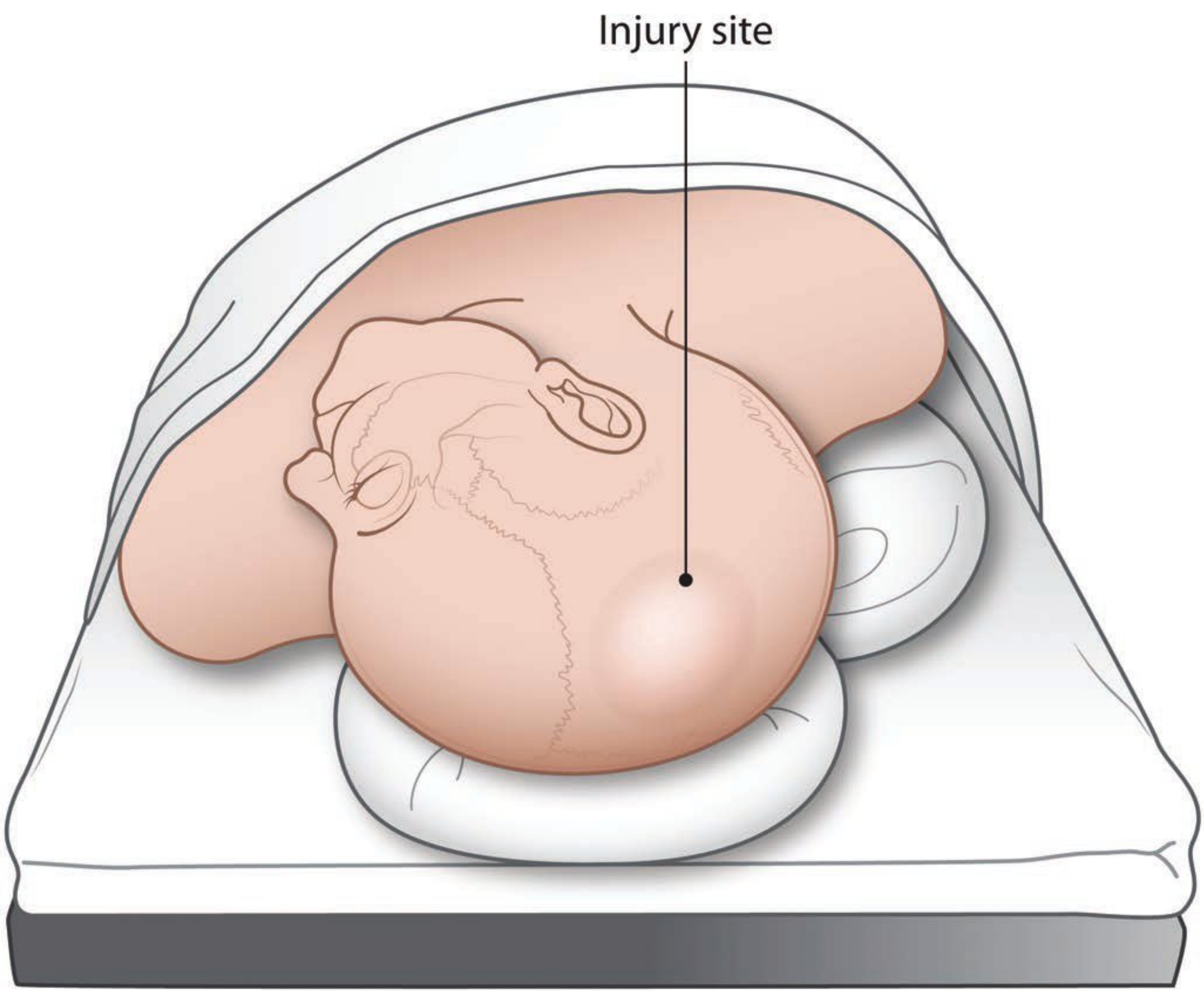


Figure	Procedural Steps
Fig. 28.2	**Positioning will be dictated by the anticipated need for anatomic access.**

Incision (Fig. 28.3)

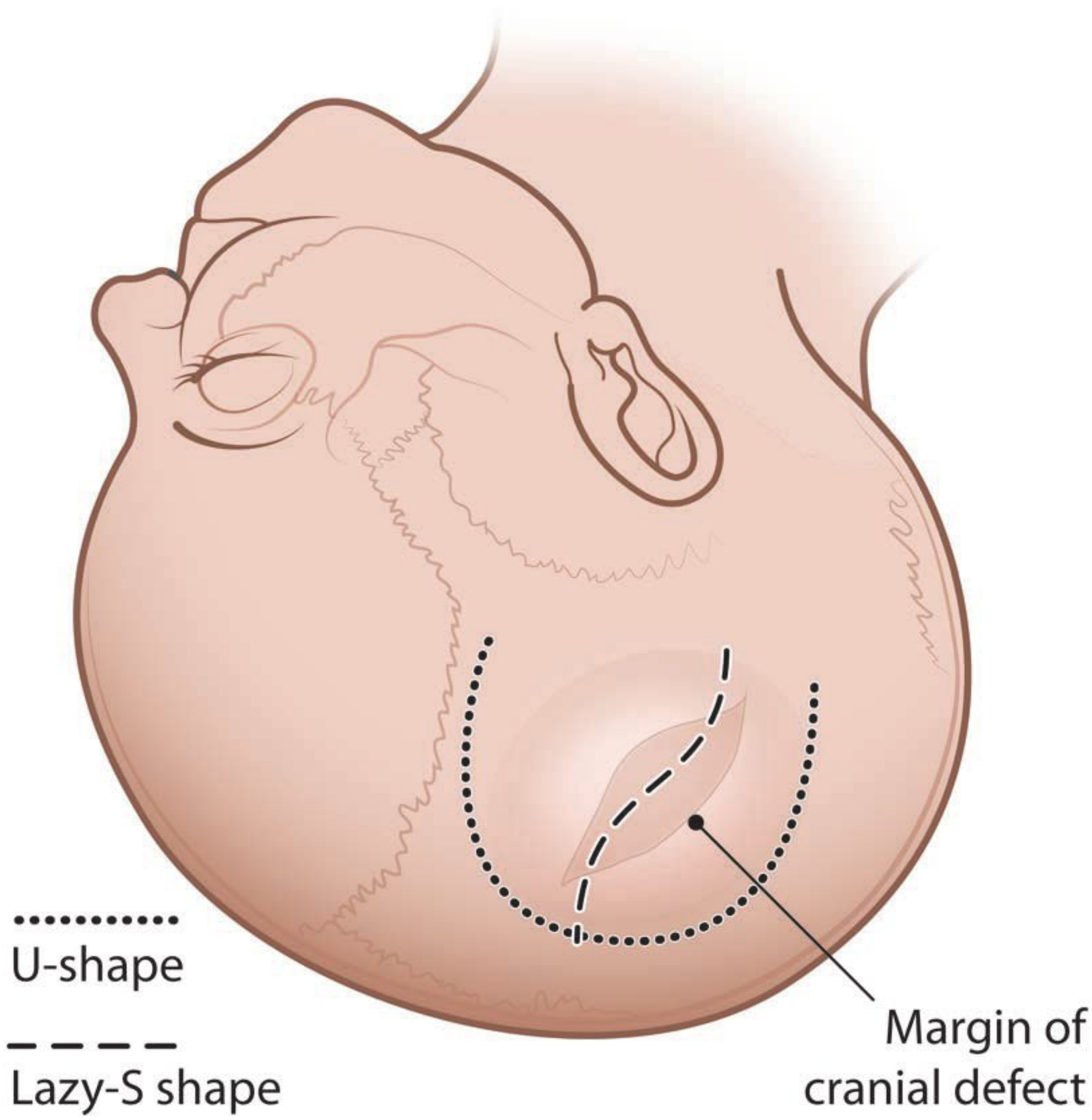
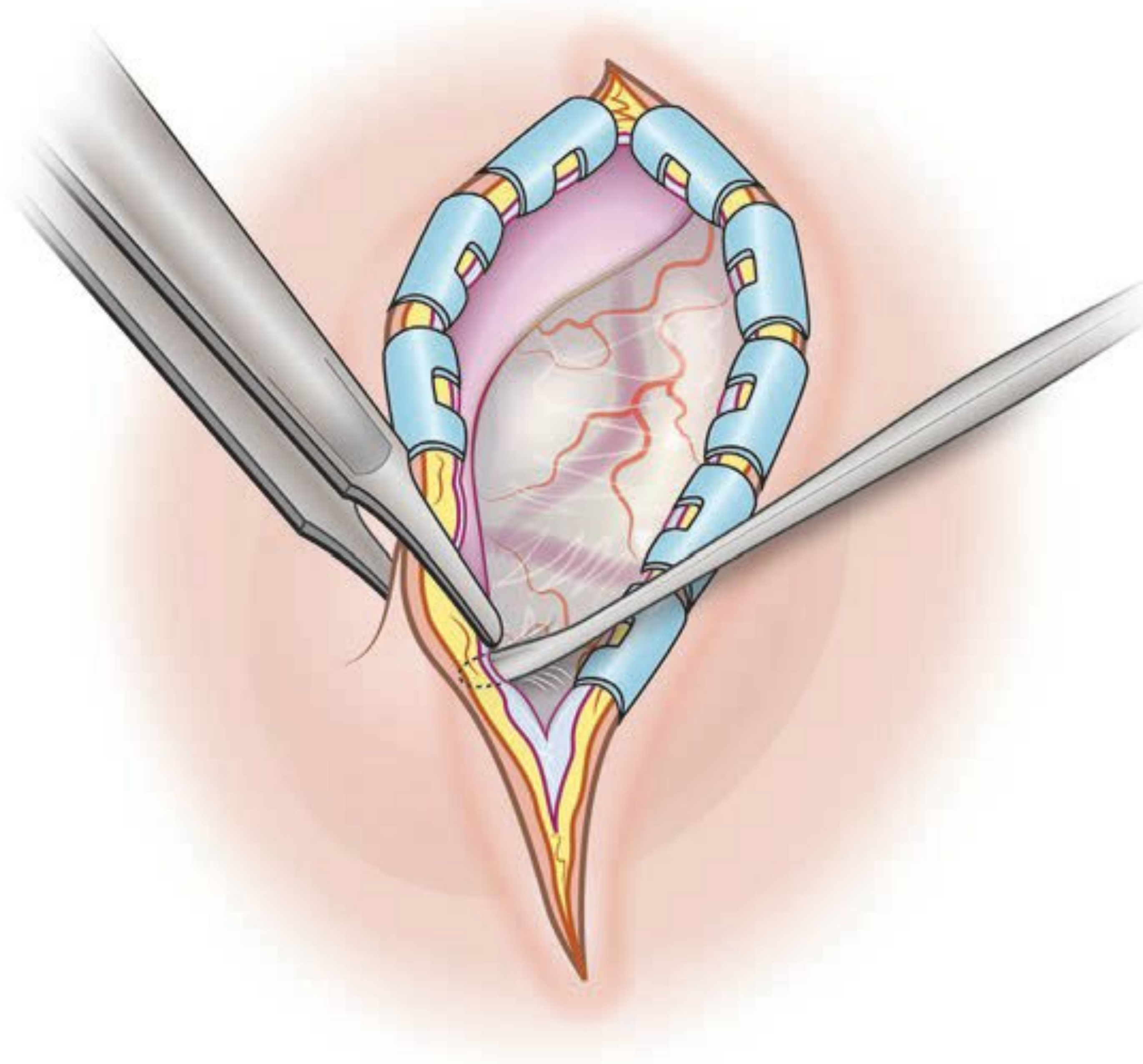


Figure	Procedural Steps	Pearls
Fig. 28.3	**A curvilinear, S-shaped, or U-shaped incision is made to access the cranial defect.**	• The extent of necessary exposure is planned from the CT head findings and palpation of the edges of the defect.

Subcutaneous Dissection (Fig. 28.4a, b)



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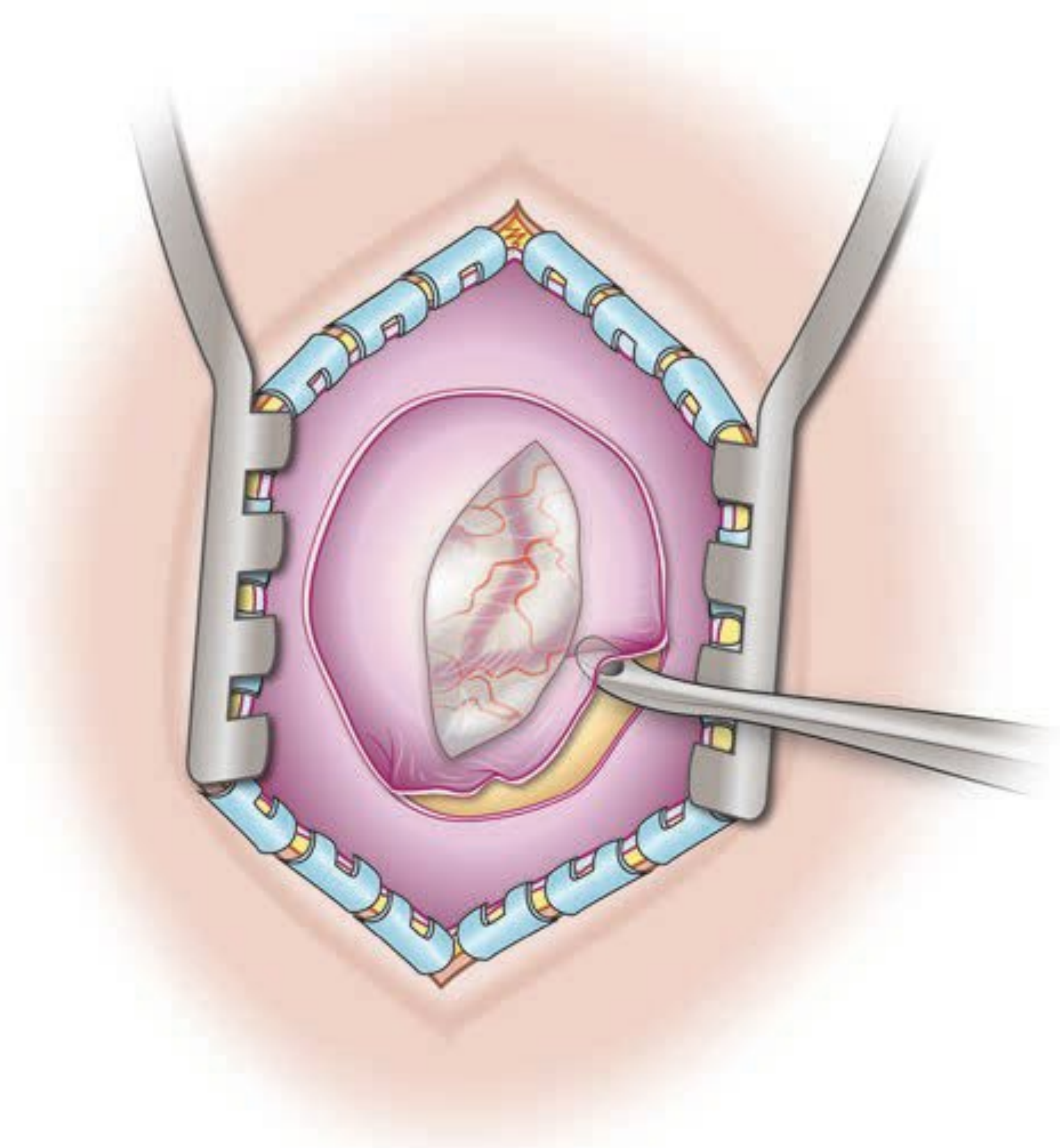
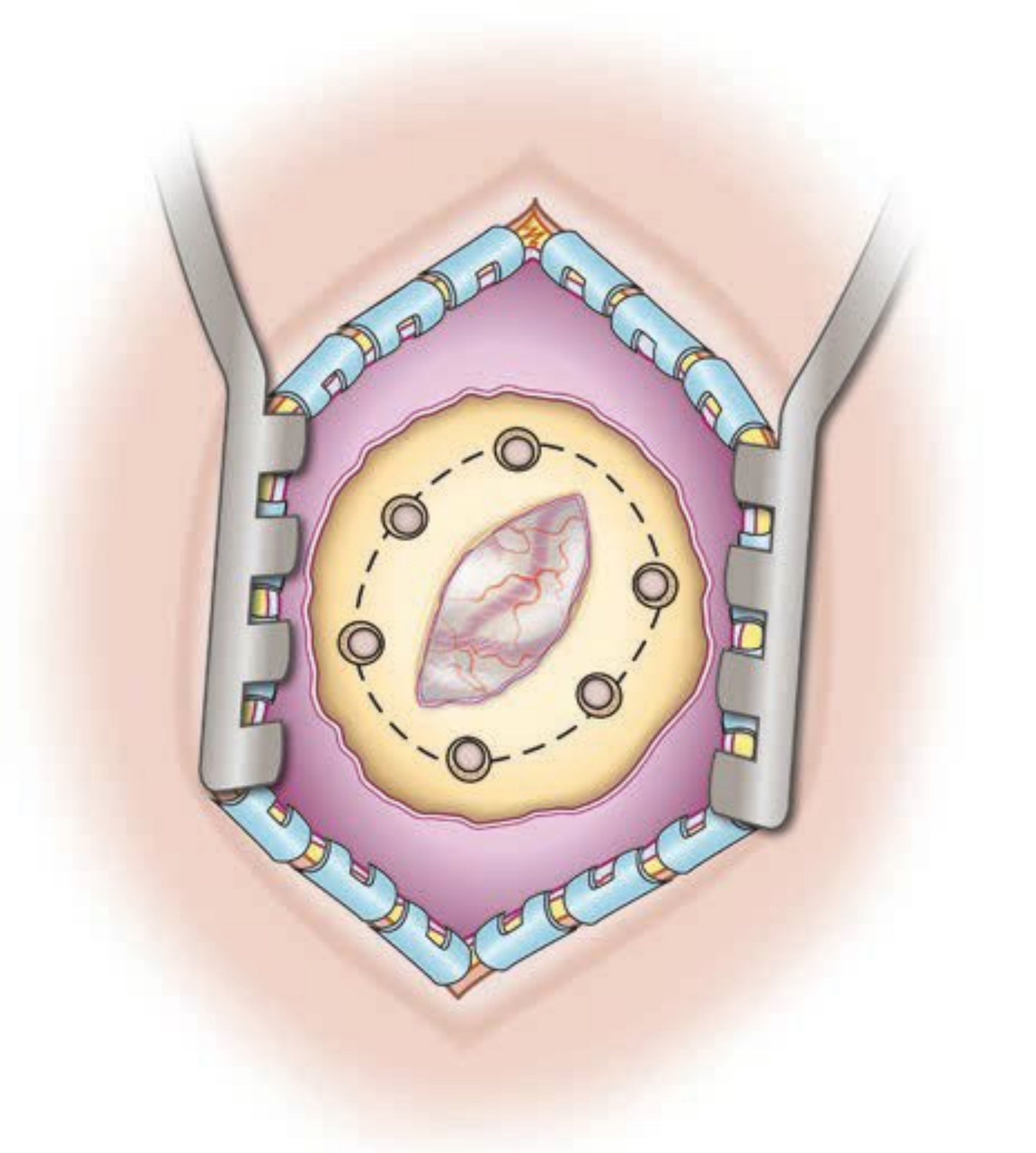


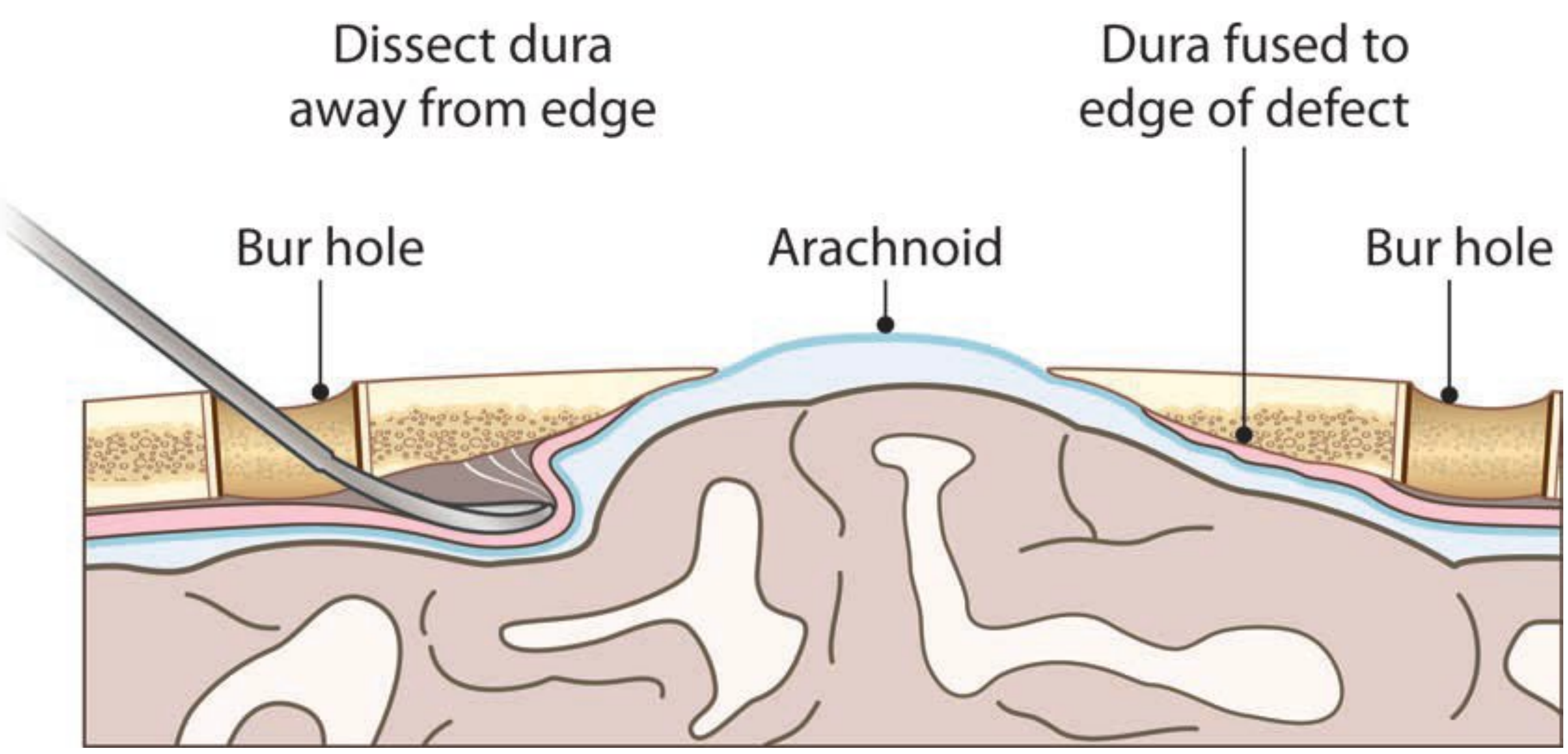
b

Figure	Procedural Steps
Fig. 28.4	**(a) Subgaleal dissection of the scalp flap is used to expose the full extent of the defect. (b) The periosteum is incised, following the edges of the cranial defect. The periosteum is reflected inward, toward the defect. Using a sharp periosteal dissector, the periosteum–dura junction is freed circumferentially from the edges of the bone margin.**

Craniotomy (Fig. 28.5a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 28.5	**(a) Several bur holes are placed at the periphery of the bony defect, overlying normal dura. The exact position of the bur holes in relation to the defect depends on the anticipated dural retraction beneath the bone edges. Typically, larger lesions are associated with greater retraction of the dura beneath the bone edges. Preserve the periosteum overlying the bone to use as a dural graft.** **(b) A dissector is introduced through each bur hole and used to separate the dura from the overlying bone. A craniotome then is used to connect the bur holes, creating a "ring" bone flap (including the defect) that, in turn, is elevated away from the underlying dura.**	• The margin should be several centimeters from the edge of the bony defect or approximately 50% of the width of the defect, to create a bone flap that can be used to cover the defect. • Prior MRI may give the surgeon an approximation of this distance; however, often it is the surgeon's judgment based on the size of the defect. • The dural edges are adherent to the underlying gliotic brain and must be separated from it circumferentially.

Closure of the Dural Defect (Fig. 28.6)

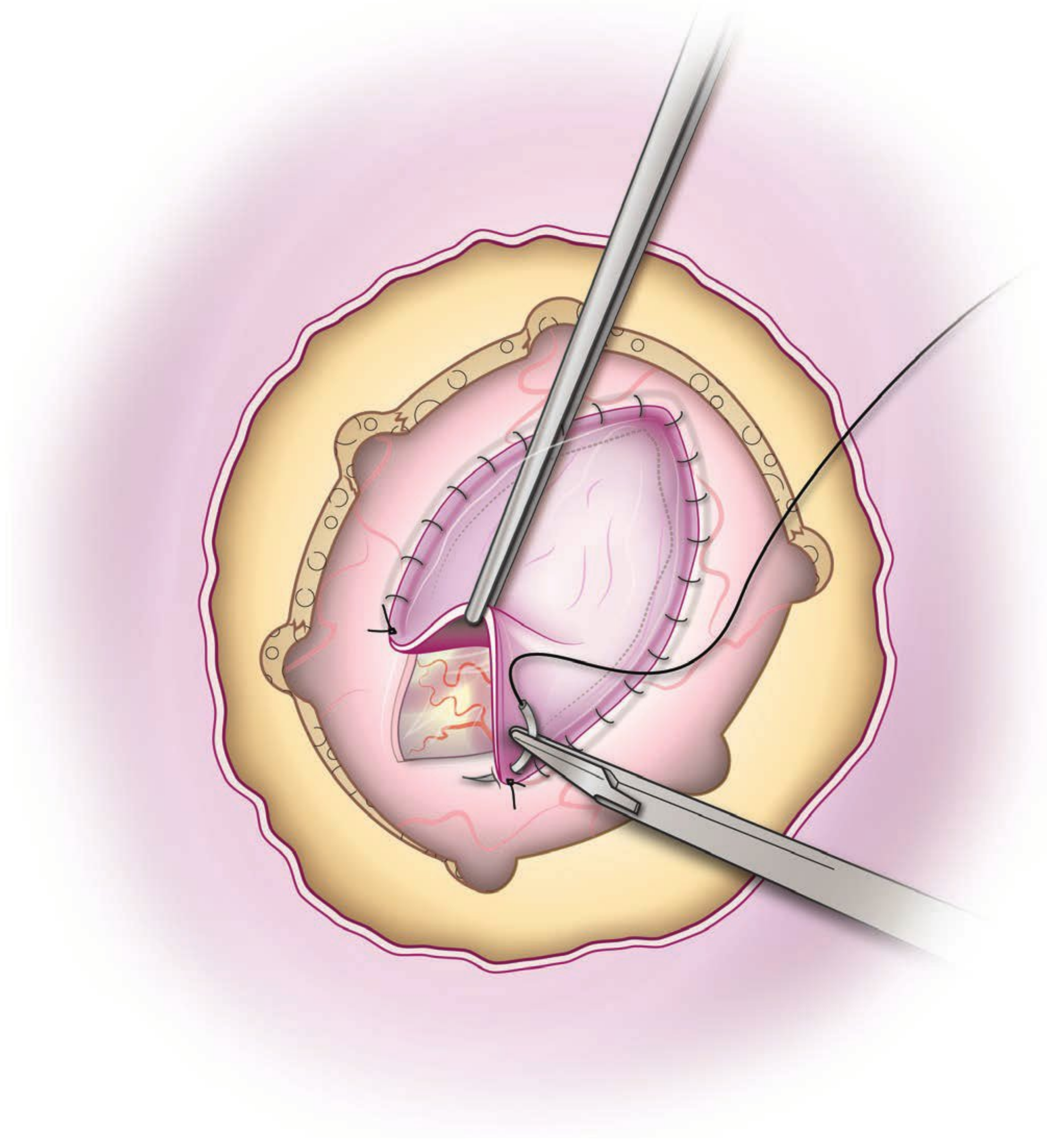
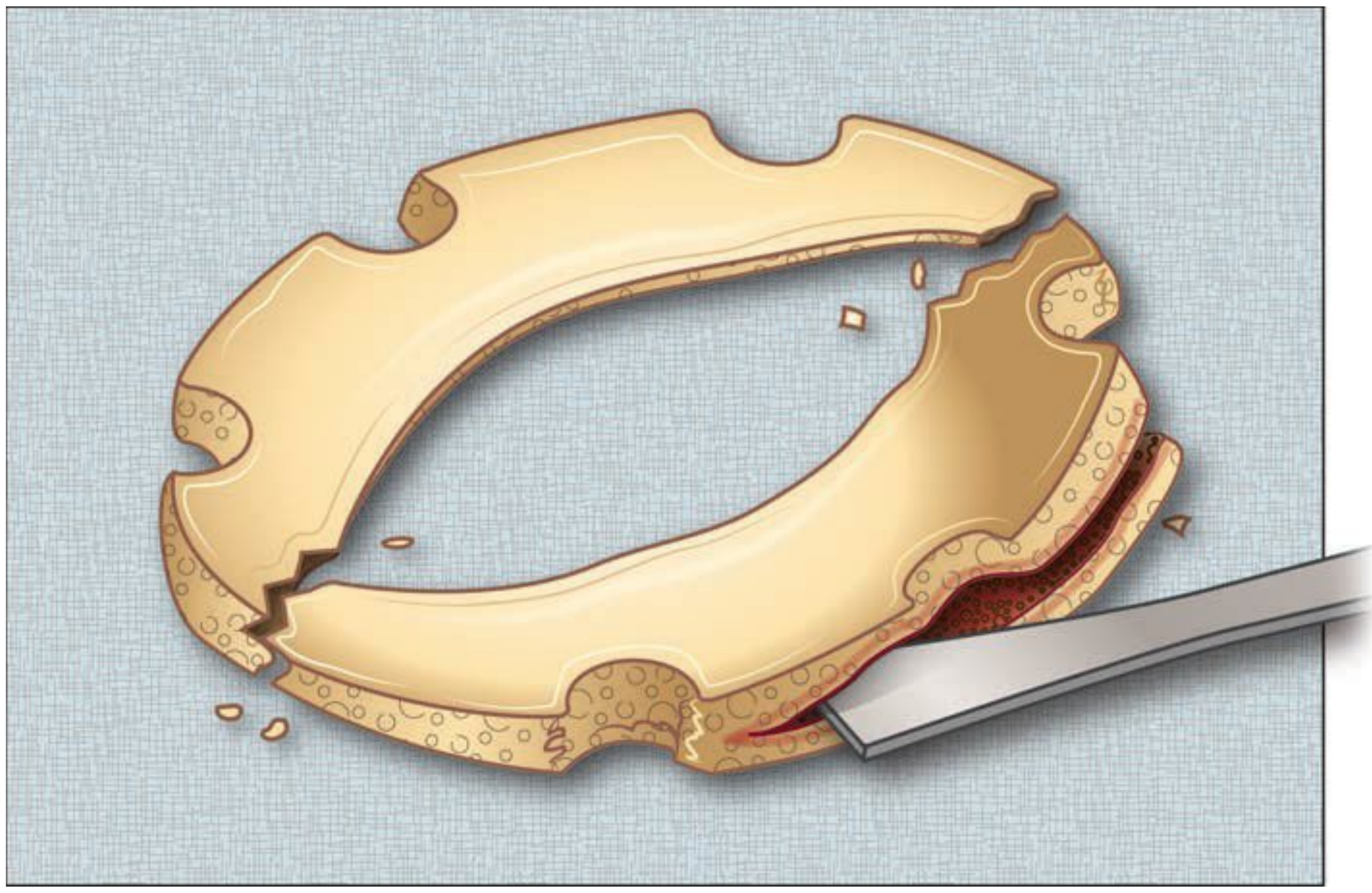
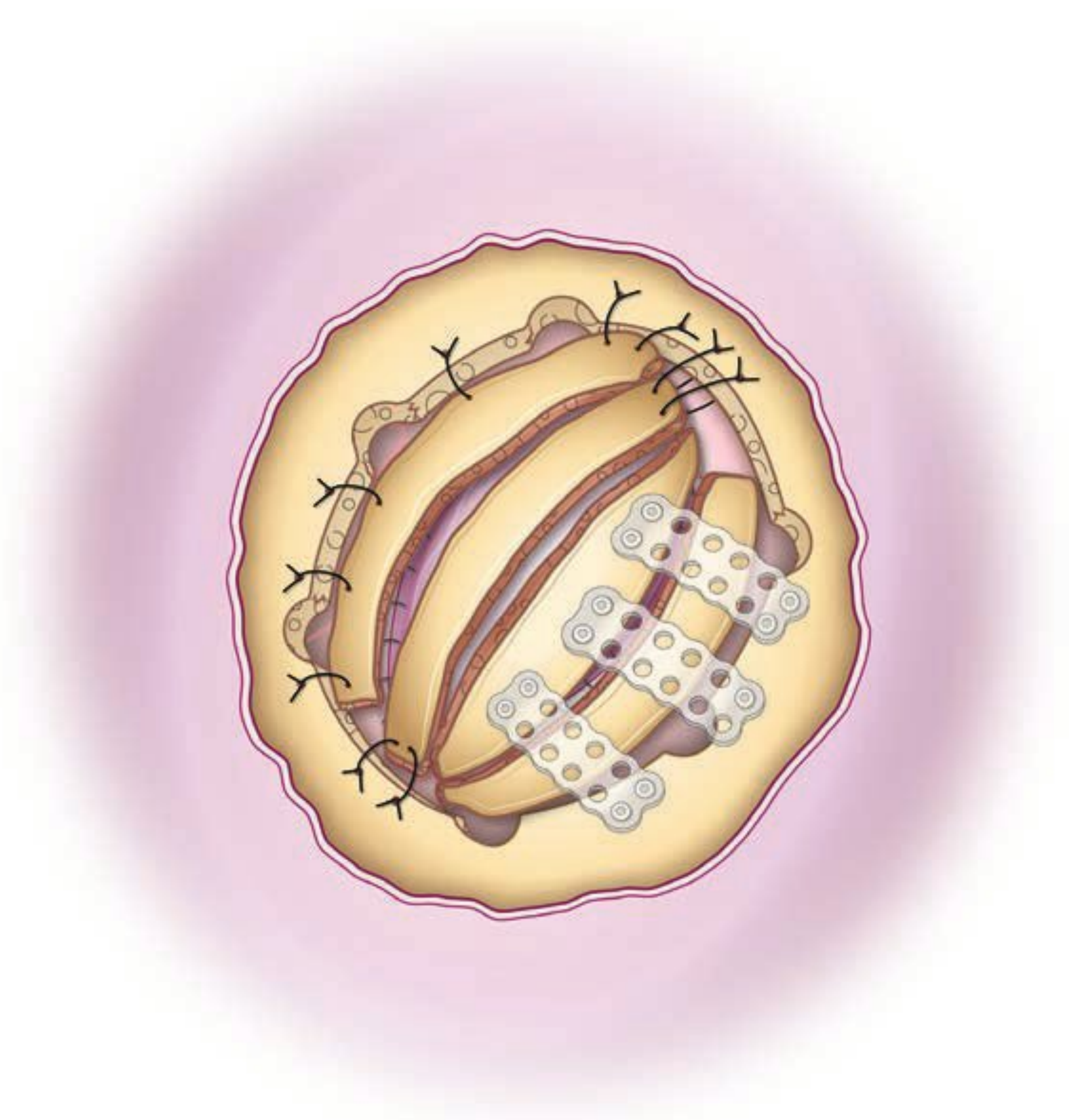


Figure	Procedural Steps	Pearls
Fig. 28.6	**A periosteal graft from normal bone is harvested to close the dural defect. The graft is incorporated circumferentially with 4-0 braided nylon stitches.**	

Repair of the Bony Defect (Fig. 28.7a, b)



a



b

Figure	Procedural Steps	Pearls
Fig. 28.7	**(a) The harvested bone flap can be divided into two halves. If possible, each half then can be split with an osteotome (though the diploic space) into inner and outer tables, yielding a total of four pieces that may be used to cover the defect. (b) The bone graft is secured to the surrounding bone using resorbable or permanent mini plates. If the bone can be secured with sutures, this is preferable. Alternatively, mini plates are used.**	• If the dural defect has been closed adequately, any residual bony defect will usually close over time.

Closing

- If the bone is replaced, it is secured with absorbable or nonabsorbable plates and screws. The size of the screws should be matched to the thickness of the bone. Long screws risk perforation of the dura. On the other hand, screws must be of a sufficient length to achieve adequate bony purchase.
- If the bone is left out, it should be handled and processed for freezing in accordance with the institution's bone bank protocol. Alternatively, the bone can be placed in a subcutaneous abdominal pocket. The following caveats apply: comorbid abdominal trauma may preclude access to this site; it may be difficult to create an adequate pocket in a young child; and, if a bifrontal flap has been elevated, it may be necessary to split the bone down the midline and superimpose the halves to create the optimal contour that will fit in the pocket.
- The skin is closed with a 4-0 monofilament suture or staples.

Postoperative Management

Monitoring

- Invasive ICP monitoring is usually routine in children with severe TBI. Benign head CT features do not exclude increased ICP or the risk that ICP will increase in the subsequent days. ICP monitoring is standard at the authors' institution for any child requiring ongoing ventilation, without immediate plans for extubation, after TBI.
- The monitoring of brain tissue oxygen and other measures of cerebral hemodynamics or metabolism is less well established in children than in adults, but is increasingly common in clinical practice and research.
- Typically, ICP is more fragile, or brittle, in children than in adults. Because these observed dynamic changes are largely hemodynamic in nature, invasive monitoring of blood pressure and volume status may allow for better characterization of the pathophysiology in individual patients, and, in so doing, permit more targeted treatment of elevations in ICP.

Wound Management

- Subgaleal drains may be used in the immediate postoperative period but should be removed within 12 hours, if possible, or when the drainage is below 25 mL per 12–24 hours.
- Compression, cotton wrap–type dressings used for wound hemostasis postoperatively may require loosening or cutting.

Radiographic Imaging

- As a general principle, the frequency of CT imaging of children should be limited because of the long-term risk of radiation. Unnecessary follow-up imaging also exposes the child with severe injury to potential secondary insults associated with transport out of the intensive care unit environment.
- However, if indicated, appropriate imaging may be lifesaving. There should always be a clear indication for repeat imaging, such as clinical deterioration. When the initial scan was performed very early after trauma (e.g., within the first 2 hours), repeat imaging may be indicated to detect hematomas that were not demonstrated initially. When there is a hematoma on the initial scan that is treated nonoperatively, repeat imaging may be necessary to ensure that the hematoma has not enlarged. For lesions with mass effect in the posterior fossa, repeat imaging may be required to exclude the development of hydrocephalus. Also, if the patient is managed without intracranial monitoring, there is a lower threshold for repeating imaging.
- A planned follow-up head CT may be considered to look for optimal position of intracranial monitors, evolution of hematomas/contusions, and brain swelling. At our institution, this is done 24–48 hours after admission, depending on stability of the intracranial variables and nature of the initial scan. Decisions are individualized; however, in general, earlier scans are indicated when there is greater concern about the initial imaging findings and when there are significant perturbations in ICP or brain oxygen.
- Postoperative imaging (**Fig. 28.8**).

Further Management

- Concerns about ongoing injury to the unprotected brain have driven the trend toward early replacement of bone flaps after craniectomy. Reimplantation may be appropriate within 4 weeks of the initial surgery, provided the brain swelling has subsided, the wound is healed, and the patient is free of infection. However, the timing of reimplantation should not be accelerated if conditions are suboptimal, as bone flap sepsis can create substantial problems.
- The bone must not be autoclaved. It is removed from sealed bags and allowed to soak in a diluted solution of betadine at the start of surgery.
- The patient's bone is always preferred to artificial substitutes, not only because of the better fit but also because additional growth of the skull is expected in younger children.
- Very young children may be at increased risk for bone flap resorption problems.

Fig. 28.8 Axial CT image demonstrating repair of the dural tear and bony defect.

29 Special Considerations in Pediatric Cervical Spine Injury

Paul Klimo Jr., Nelson Astur Neto, William C. Warner Jr., and Michael S. Muhlbauer

Introduction

Spine trauma in the pediatric population is a relatively uncommon occurrence (1–2% of all pediatric fractures[1]), but has been observed more frequently with improvements in emergency care, transport services, and trauma life support.[2] Children differ from their adult counterparts with regard to spine anatomy, physiology, and body proportions:

- Ligaments and joints can stretch and expand considerably without tearing
- Facet joints are shallow and horizontally oriented
- Vertebral bodies are wedged anteriorly
- Uncinate processes, which limit rotation, do not form until age 10
- Disproportionately larger head in conjunction with weaker and incompletely developed muscular and ligamentous supporting structures

These unique differences result in a spine that is more malleable than that of an adult. Pediatric cervical spinal injuries follow a predictable pattern related to the child's age. Spinal injuries in children younger than 8–10 years of age are more likely to involve the upper cervical spine, from the occiput to the third cervical vertebra. Most injuries in this age group are ligamentous axis-atlanto-occipital dislocations or spinal cord injuries without radiographic abnormality (SCIWORA). Children older than 8–10 years of age are more vulnerable to cervical spine injuries involving the lower segments (C3–C7); the pattern of injury in this group is similar to the adult population.[3,4]

Spinal cord injury (SCI) is a rare occurrence in the pediatric population and accounts for less than 4% of the total annual incidence of SCI (National Spinal Cord Injury Statistical Center, 2004). Neurologic recovery in children with SCI tends to be better than in adults.[5] SCI occurring before the adolescent growth spurt is a great risk factor for the development of posttraumatic scoliosis.[5]

Indications

Pediatric cervical spine injuries can be divided into injuries that affect the upper cervical spine (occiput–C2) and those that affect the subaxial spine (C3–C7). Below is a list of the injuries that are more commonly encountered in children. As stated previously, older children will have a physiologically developed adult spine, and thus, the spine injuries are similar to those seen in adults. There is a myriad of congenital cervical anomalies that may cause or place a child at risk for spinal cord injury. A detailed review of these entities is beyond the scope of this chapter.

- Upper cervical spine injuries
  - Atlanto-occipital dislocation (AOD)
  - Atlantoaxial dislocation (AAD)
  - Atlantoaxial rotatory subluxation (AARS)
  - Translational atlantoaxial subluxation (TAAS)
  - Odontoid fractures, including synchondrosis fractures
  - Traumatic spondylolisthesis of the axis (i.e., hangman's fracture)
  - Pure ligamentous/soft tissue injury (previously known as SCIWORA)
  - Combination of the above pathologies
- Lower cervical spine injuries
  - Pure ligamentous/soft tissue injury (previously known as SCIWORA)
  - Osseous anterior and/or posterior column injuries (e.g., compression and burst fractures, laminar/pedicle/facet fractures)
  - Spinal cord disruption

Biomechanical instability resulting from any of the above injuries may provide an indication for operative intervention.

The appropriate surgical approach is dictated by the specific injury:

- Occipitocervical arthrodesis
  - Atlanto-occipital dislocations, atlas fractures, congenital occipitocervical anomalies
- Atlantoaxial arthrodesis
  - Atlas fractures, odontoid fractures, traumatic C1–C2 ligamentous disruptions, and congenital atlantoaxial instability
- Subaxial cervical posterior arthrodesis
  - Posterior ligamentous disruption, unilateral and bilateral facet dislocations, burst fractures, and spondylolisthesis
- Anterior cervical approach
  - An anterior approach is rarely indicated (except possibly for decompression of a burst fracture) before the age of 12. Thereafter, children assume a more "adult" spine and become more susceptible to adult-type injuries.

Preoperative Considerations

Field and Emergency Room Management

Field management follows the basic principles of the Advanced Trauma Life Support (ATLS). Airway, breathing, and circulation (ABCs) must be addressed. Because of a relatively larger

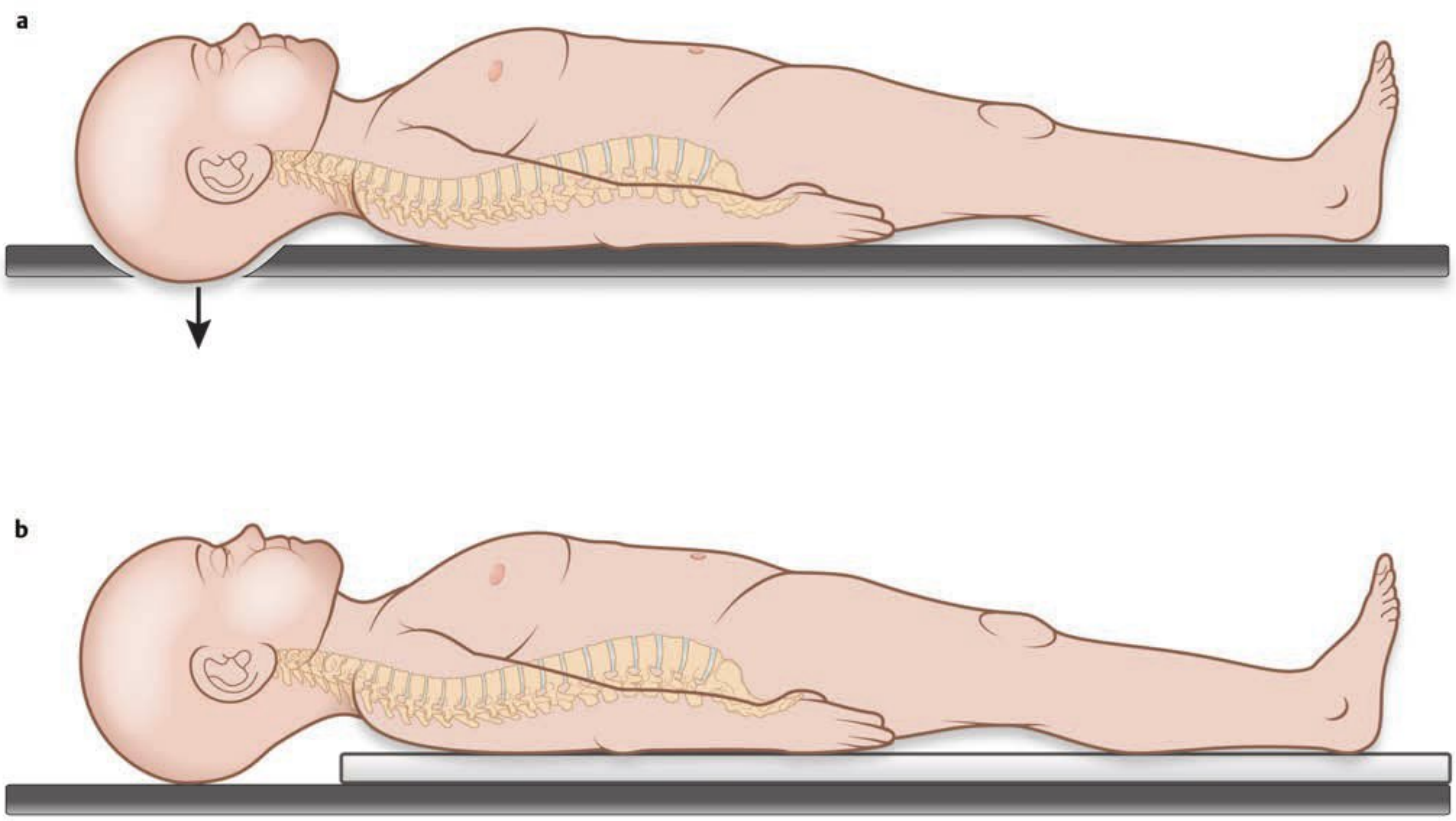


Fig. 29.1a, b Pediatric backboard. Given a relatively larger head size, (**a**) use of a recessed head backboard or (**b**) elevation of the trunk by approximately 25 mm should be considered to maintain neutral alignment.

head size, the cervical spine will be flexed when the child is placed supine on a standard horizontal backboard.[6] A recessed head backboard, or elevation of the trunk by approximately 25 mm, must be considered primarily in children aged less than 8 years of age with suspected neck injury (**Fig. 29.1a, b**).[6,7] Once the child arrives in the emergency room, the ABCs must be repeated, and disability and exposure should be added. In patients presenting with hypotension in the presence of bradycardia, neurogenic shock must be differentiated from hypovolemic shock. If a spinal cord injury is present, management should proceed with vasopressors and modest fluid resuscitation. Neurologic impairment should focus the emergency team on a possible head or spine injury or both.

Radiographic Imaging

After a careful neurologic evaluation, cervical spinal imaging should be obtained. Plain radiographs, computed tomography (CT), and magnetic resonance imaging (MRI) may be considered. Once a spine injury is detected, clearance and imaging of all spine segments should be undertaken, considering a significant prevalence of noncontiguous fractures.[4,8]

Some variants of the normal anatomy or congenital anomalies may be misinterpreted as traumatic injury.[9,10] An anterolisthesis of C2–C3 is a very common finding and could be misdiagnosed as a ligamentous injury when, most of the time, it is a physiologic pseudosubluxation caused by the hyperflexibility of the immature cervical spine. A synchondrosis between the odontoid and the body of C2—which may persist until a child is 12 years of age—may be misinterpreted as an odontoid fracture. Furthermore, a persistent neurocentral synchondrosis of C2 can be misdiagnosed as a hangman's fracture. The atlantodental interval (ADI) in the child spine is greater than in the adult, but should not exceed 5 mm; this limit is because of the thicker child cartilage that does not appear in radiographs. Any persisting doubt with standard radiographs should be further evaluated with CT and MR.

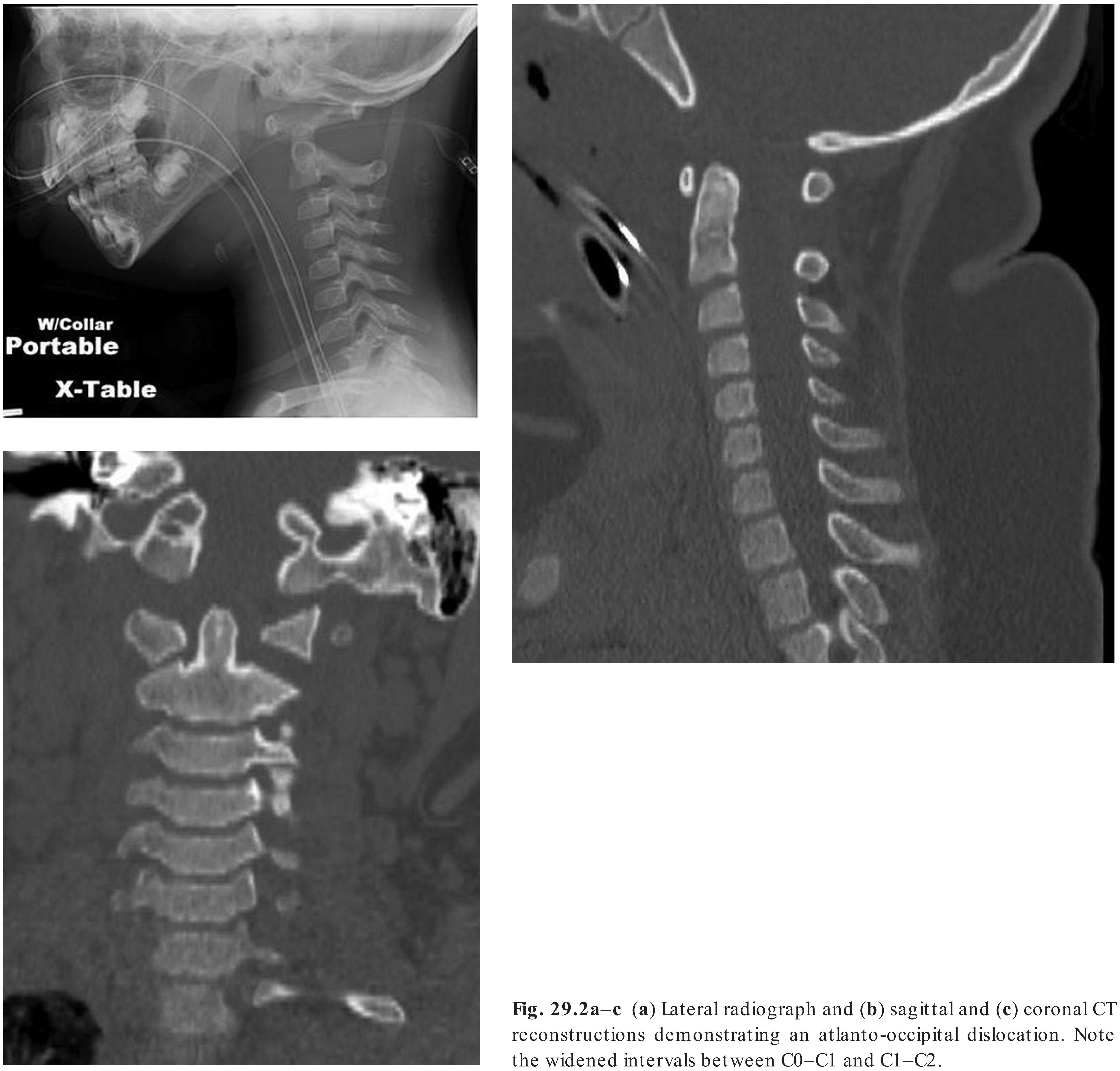
- Preoperative imaging (**Fig. 29.2a–c**).

Medication

Steroid administration in the setting of a spinal cord injury is still controversial and should be based on the institutional protocol. A recent systematic review of the literature found no evidence supporting the use of neuroprotective interventions for the treatment of spinal cord injury in children, including hypothermia and steroids.[7] Furthermore, all studies that have evaluated steroids in spinal cord injury have specifically targeted the adult population.

Surgical Timing

The optimal timing for surgical decompression and fixation is also controversial. A recent systematic review states that early surgical decompression (i.e., in less than 72 hours) may improve neurologic outcomes—especially in the setting of incomplete SCI and when performed in less than 24 hours.[11] While this review suggests early decompression may benefit the general SCI population, neurologic recovery seems to be better in the pediatric population than in adults.



a b c

Fig. 29.2a–c (**a**) Lateral radiograph and (**b**) sagittal and (**c**) coronal CT reconstructions demonstrating an atlanto-occipital dislocation. Note the widened intervals between C0–C1 and C1–C2.

Operative Management

Successful intraoperative management of the child with a cervical spine injury depends on a team approach with the spinal surgeon, pediatric trauma surgeon, anesthesiologist, and surgical and radiology technicians.

Anesthesia

In cervical spine injuries with gross instability, the neck must be maintained in a neutral position throughout the procedure; intubation may be challenging. In-line fiberoptic intubation should be considered, followed by induction of general anesthesia. Care to prevent both subluxation and distraction is imperative when intubating, turning, or transferring. Preoperatively, antibiotics are administered at least 30 minutes before the procedure; the authors prefer vancomycin and cefazolin. If neuromonitoring (e.g., motor-evoked potentials [MEPs] and somatosensory-evoked potentials [SSEPs]) is used, the anesthesia team should be alert that alterations in anesthetic depth can affect the ability to obtain useful signals; the use of bispectral index (BIS) monitoring can minimize this effect. *It is imperative that the anesthesiologist avoid hypotension and hypovolemia during surgery.*

Positioning

Anterior Cervical Approach

- Supine position
- Pad or towel roll between scapulas for slight neck extension
- Stabilize head with a chin or forehead strap
- Neck in neutral position or rotated to contralateral surgical approach site
- Pull both arms together caudally and tape them on the shoulders for better fluoroscopic view of the cervical spine
- Use intraoperative fluoroscopy to mark the correct level on the skin
  - Some surgeons advocate a left-sided approach because of the lower rates of recurrent laryngeal nerve injuries[12]

- Longitudinal incision provides a greater exposure (usually when three or more levels are exposed) whereas a transverse incision heals with better cosmesis
- *Care must be taken not to distract the injured spine with either manipulation or inadvertent elevation of the head of bed when the patient is in Mayfield fixation.*

Posterior Cervical Approach

- Prone position
- Use chest rolls (or a spine table for older children) and a three-pinion skull clamp or Gardner-Wells tongs in neutral position
- Strap arms down at the patient's side
- Slight reverse Trendelenburg positioning allows for better exposure, if the patient does not distract
- Pad all bony prominences and apply tight straps over the patient
- The critical period during which the spine is at greatest risk is the transfer to prone position; a tightly applied rigid collar or halo may be used to reduce this risk.

Occipitocervical Arthrodesis

Indications

Atlanto-occipital dislocations, atlas fractures, congenital occipitocervical anomalies.

Atlantoaxial Arthrodesis

Indications

Atlas fractures, odontoid fracture, traumatic C1-C2 ligamentous disruptions, and congenital atlantoaxial instability.

Subaxial Cervical Posterior Arthrodesis

Indications

Posterior ligamentous disruption, unilateral and bilateral facet dislocations, burst fractures, and spondylolisthesis.

Operative Procedure

Occipitocervical Arthrodesis with Contoured Rod and Segmental Wire

Positioning and Preparation (Fig. 29.3)

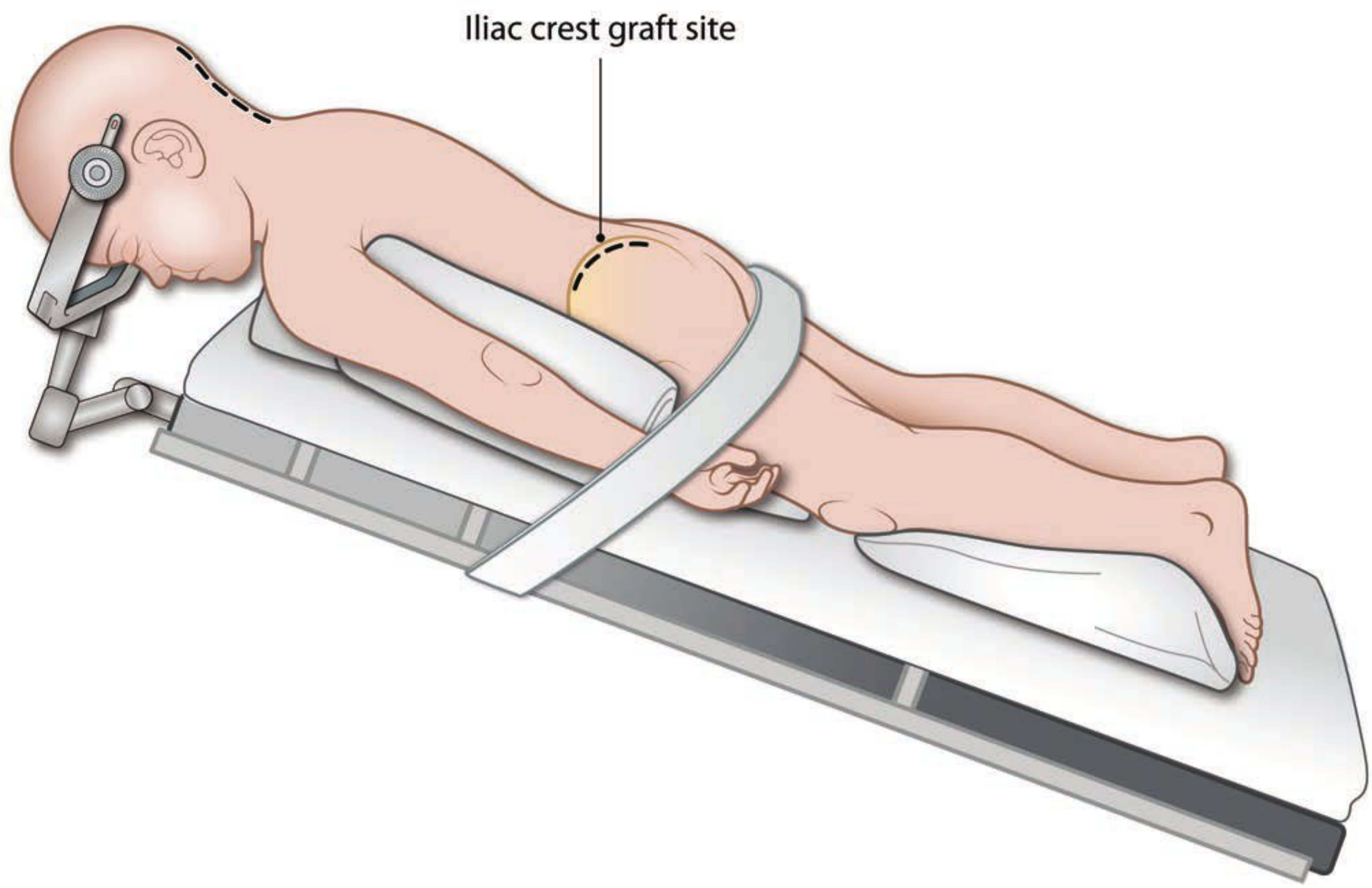


Figure	Procedural Steps	Pearls
Fig. 29.3	**Position the patient prone on a spine table, with the head fixed to the table in a neutral position using either three-pinion head holder fixation or Gardner-Wells tongs. Alternately, a standard operating table—with chest rolls oriented transversely across the chest and hips—may be used.**	• Do not use traction in AOD cases, especially when flipping the patient and in this final position. When in slight reverse Trendelenburg, use a bolster at the feet to prevent the body from sliding down. As the head is elevated, use fluoroscopy to check alignment. • Confirm proper neutral positioning of the occiput over the atlas with fluoroscopy. If fused in hyperflexion, the child may have difficulty swallowing; if fused in excessive lordosis, the child may have difficulty ambulating because he cannot see his feet, and lower levels may have to be in continual kyphosis to compensate. Fusion in neutral or slight flexion may offset the possibility of continued anterior growth causing hyperlordosis if a posterior fusion is performed in a young child. • The surgical fields are prepared and draped to include the posterior inferior one-third of the skull and all the posterior part of the neck. Include preparation of the bone graft harvest site at the region of the posterior iliac crest.

Skin Incision (Fig. 29.4)

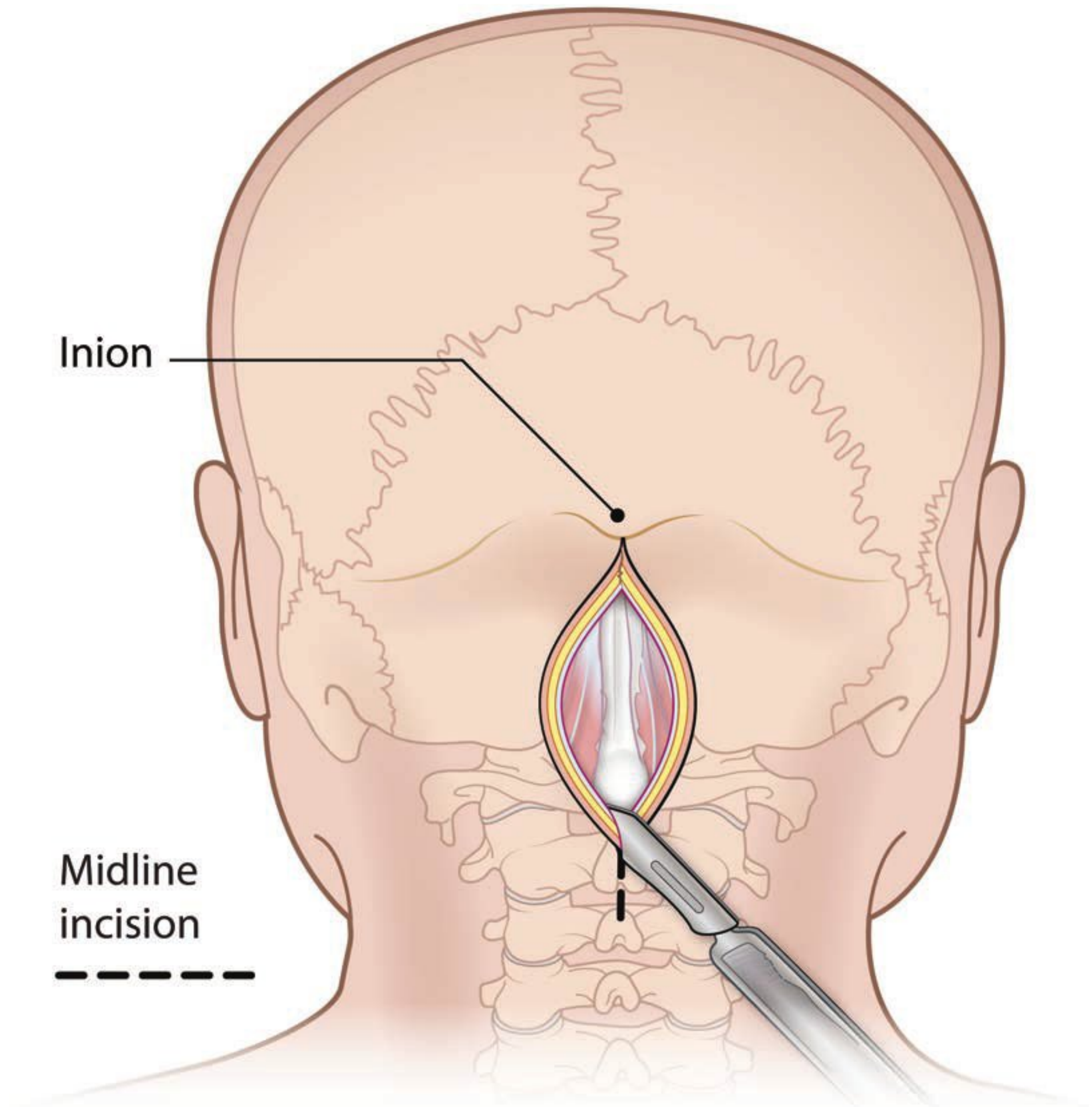


Figure	Procedural Steps	Pearls
Fig. 29.4	**Make a posterior midline, longitudinal skin incision from the base of the occiput to the most caudal spinous process desired for the cervical fusion.**	• Use lateral fluoroscopy for cervical spine level confirmation. • For a short occipitocervical fusion (occiput–C1 or C2) stop the incision at C3 level. • Do not expose more than needed because there is a high rate of fusion in the child spine just by exposing the posterior elements.

Subcutaneous Dissection (Fig. 29.5)

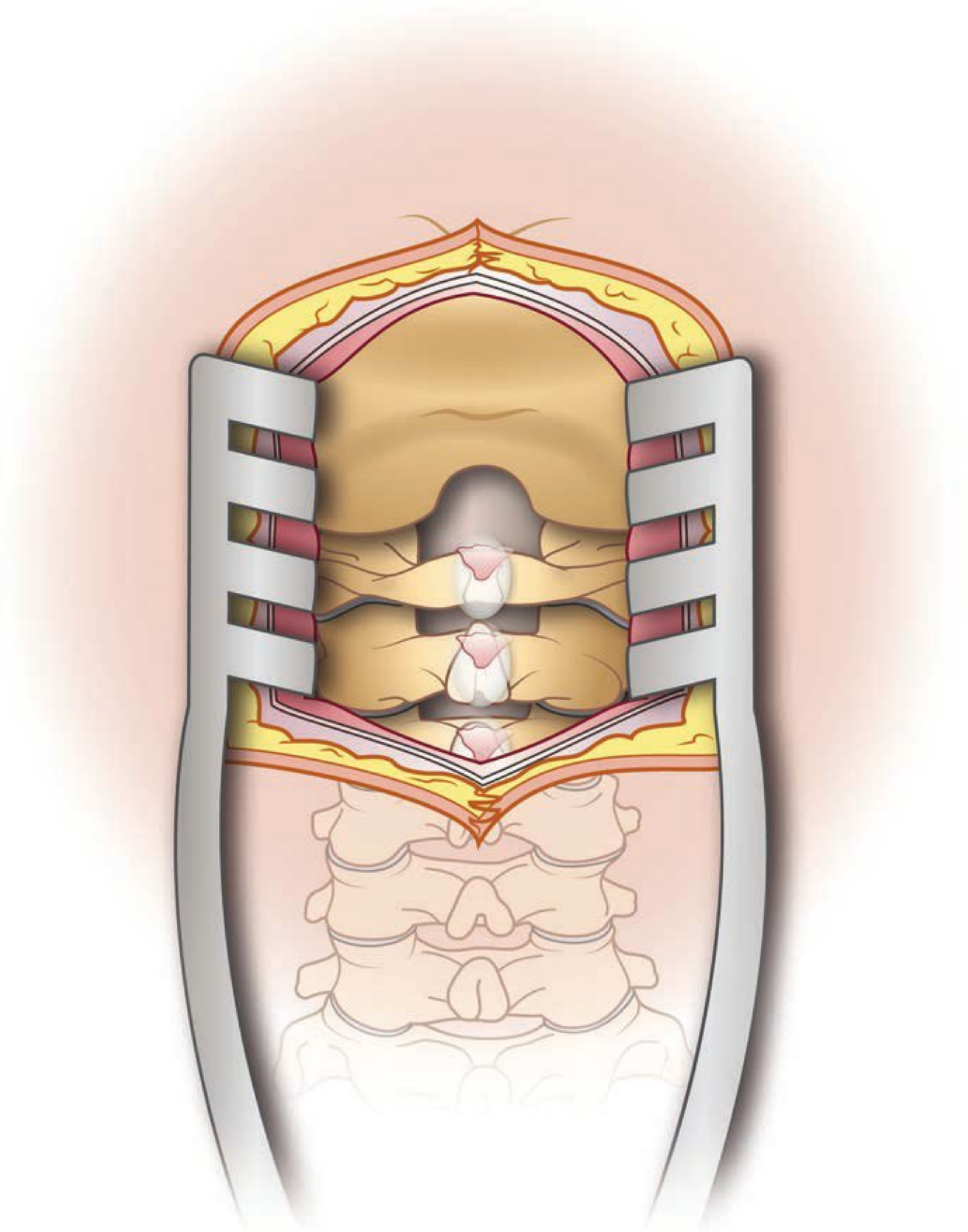
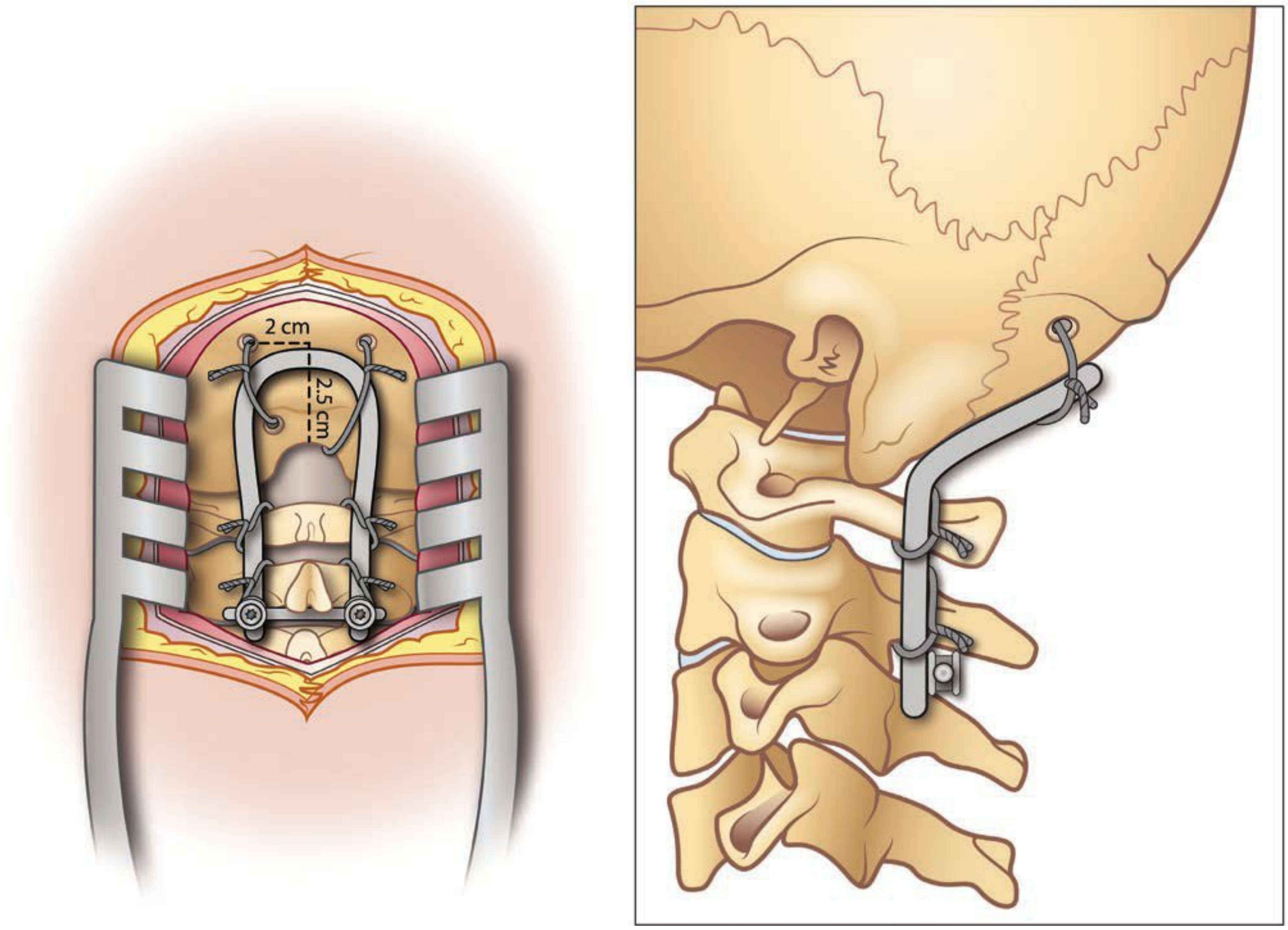


Figure	Procedural Steps	Pearls
Fig. 29.5	**Extend the dissection deep within the relatively avascular intermuscular septum (aka ligamentum nuchae). The suboccipital region—as well as the entire posterior arch of C1, C2, and other desired levels—is exposed subperiosteally.**	• Cerebrospinal fluid leak is not an unusual finding while dissecting. It is very difficult to repair the dural tear primarily. Use gelatin sponge or onlay dural graft substitutes. Laminectomy is not recommended for repair. • While dissecting between C1 and C2 laterally, there is often a robust perivertebral artery venous plexus. Bleeding from this plexus may be brisk but easily controlled with gelatin sponge. • Exercise caution while exposing the C1 posterior arch: do not to expose more than 12 mm to 20 mm laterally, depending on age and anatomy, to reduce the risk of vertebral artery injury. (Always stay on bone!) In young children, there may be a fibrous union in the midline of the arch, which can be easily breached with monopolar electrocautery.

Fixation Points and Rod and Wire Preparation (Fig. 29.6a, b)



a b

Figure	Procedural Steps	Pearls
Fig. 29.6	**(a, b) A template of the intended shape and size of the rod is made with a Luque wire. Two bur holes are made on each side of the occiput: 2 cm lateral to the midline and 2.5 cm above the foramen magnum. An additional pair of bur holes also may be placed above and lateral to the foramen magnum. Titanium cables are passed in an extradural plane from each bur hole to the adjacent bur hole or to the foramen magnum. Sublaminar cables are passed around C1 and C2. Thus, for an occiput to C2 fusion, there are a total of six cables (three on each side). The rod is contoured to match the template, creating a U-shape that will fit the occipitocervical region.** **These six cables will secure and tighten the rod with ongoing fluoroscopy. A cross-link may be added at the caudal extent of the fixation, below the spinous process.**	• Some children may have a low-lying tentorium, which would put their sinovenous structures lower than normal. The suboccipital dura is often quite thin and can be easily torn when making the bur holes. • A minimum of 1 cm of cortical bone should be left intact between the holes for good fixation. • A bending instrument may be helpful in bending the rod.[13] • Usually a 135-degree head–neck angle and a slight cervical lordotic bend will fit the rod to the surgical site.

Bone Graft (Fig. 29.7)

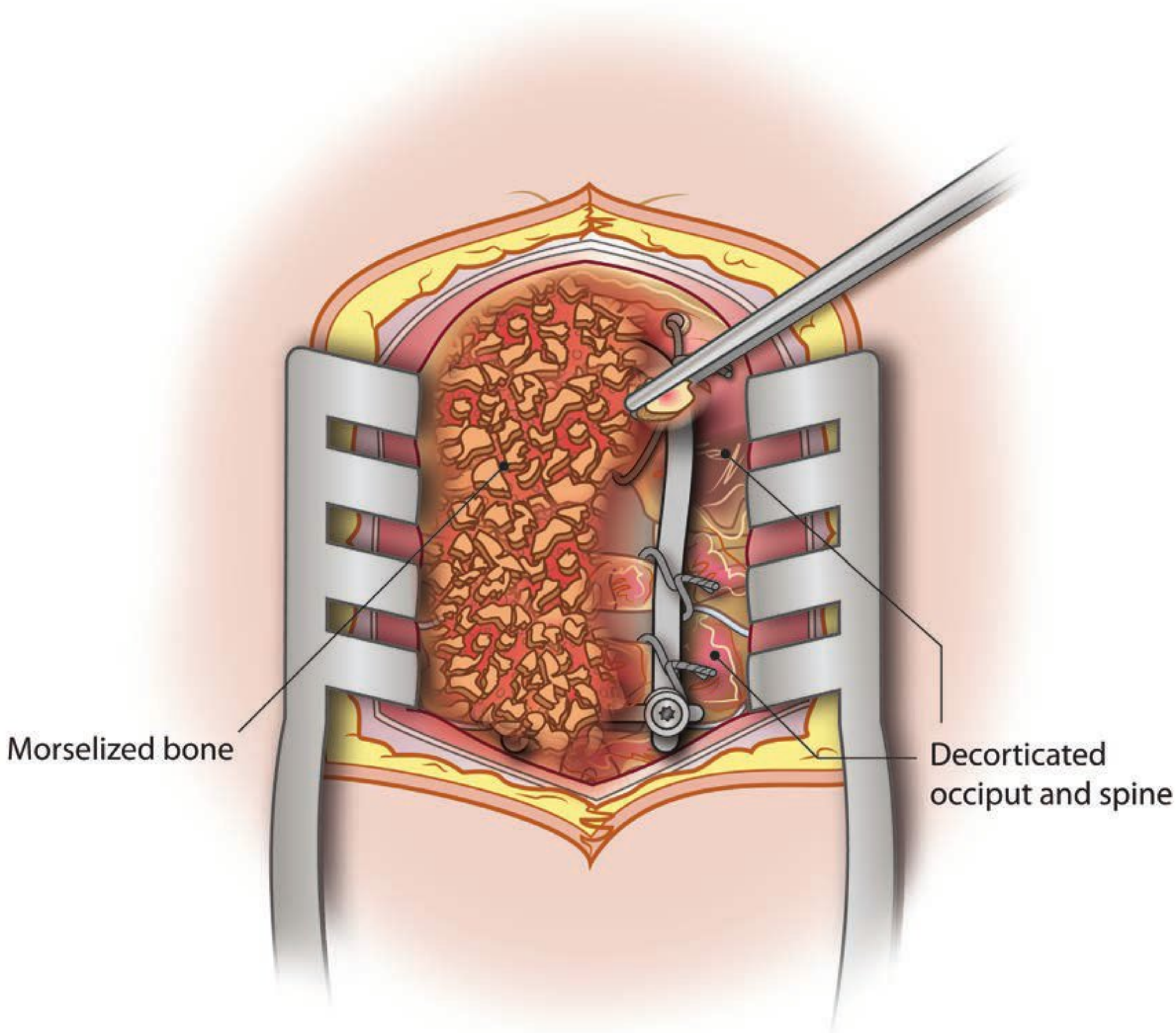


Figure	Procedural Steps	Pearls
Fig. 29.7	**The wound is irrigated with copious amounts of antibiotic solution.** **The spine and occiput are then decorticated and prepared for autogenous, onlay, and corticocancellous bone graft harvested from the posterior iliac crest.**	• Demineralized bone matrix may be mixed in with the autograft, as well as some allograft bone chips, to make a slurry that is then applied to all decorticated surfaces. Bone morphogenetic protein (BMP), if used, should be applied sparingly and only out laterally, away from the dural portion of the spinal canal. Occasionally, if anatomy permits, decortication and fusion mass may include the facet joints at C1–C2 and occipital condyle–C1.

Other Options for Occipitocervical Fixation

Technique: Occipital Plate

This technique is best in skeletally mature patients. After subperiosteal dissection and exposure of the suboccipital bone with Bovie electrocautery, place the plate in position and mark midline using one of the plate apertures. The plate should be placed closer to the inion than to the foramen magnum so there can be enough surface area for appropriate fusion. The suboccipital bone may need contouring to allow the plate to lay flush. Care must be taken not to disrupt the outer cortex fully (thereby, destabilizing the construct). Carefully, make the first previously marked bicortical hole with a power drill and tap it. Replace the plate and secure it with an appropriate screw. Place the other screws with the plate in place in order to guide them. Connect the plate with rods to the cervical fixation. The occipital plate should be fully covered by muscle when closing.

Technique: C1 Lateral Mass Screws[13] (Fig. 29.8a, b)

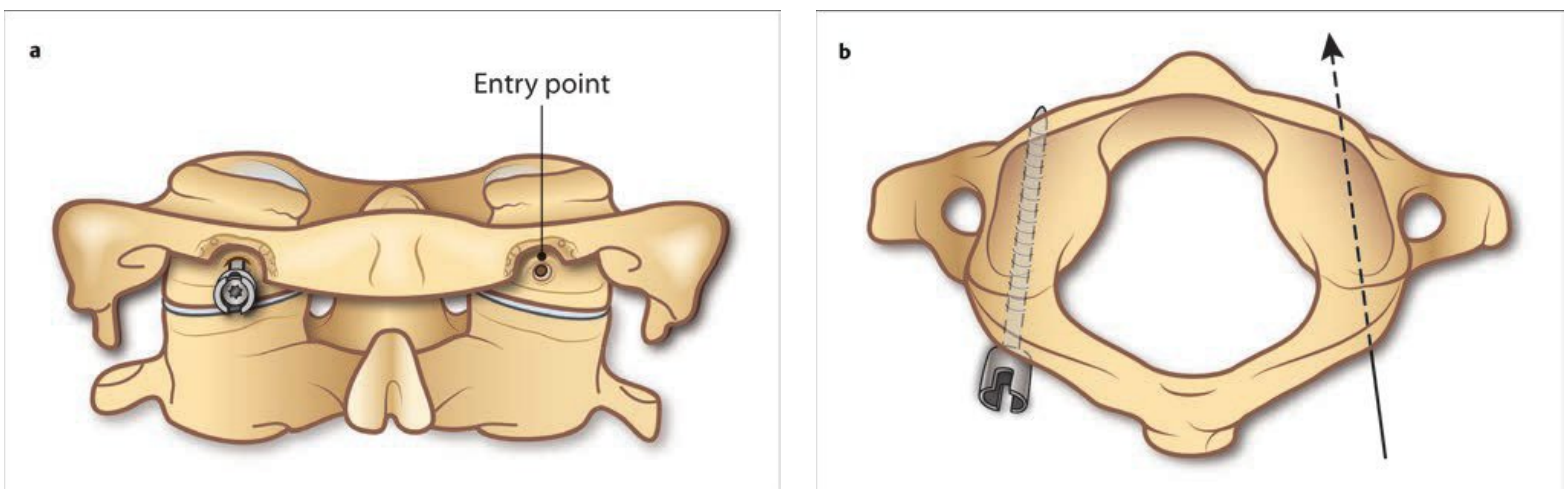


Figure	Procedural Steps
Fig. 29.8	**After posterior approach to the arch of C1, use blunt dissection to expose the posterior arch of C1 and C2. Use the bipolar and hemostatic agents to control bleeding from the atlantoaxial perivertebral venous plexus. Using a Penfield no. 4, retract the C2 nerve root caudally in order to expose the C1 lateral mass and the C1–C2 joint space just inferior to its arch. Find the medial and lateral borders of the C1 lateral mass by palpation. The inferior aspect of the posterior arch of C1 often needs to be drilled down to gain further access to this region and to allow the screw to sit flush with the proper angulation. (a) For the screw entry point, make a small hole with a drill at the center of C1 lateral mass. (b) With the aid of a fluoroscopic lateral view of the high cervical spine, aim the drill toward the anterior tubercle of C1 and medialize the trajectory by 5 to 10 degrees, depending on the anatomy of the lateral mass of C1. Stop drilling when the drill tip is just short of posterior margin of the anterior tubercle or you feel that you have gone through the anterior cortical margin of the lateral mass of C1. Tap the hole and insert a partially threaded screw so that the shaft of the screw in contact with the C2 nerve root does not have any threads. The screw length is typically 34 to 36 mm. For particularly unstable or immature spines, bicortical screw fixation is paramount and requires controlled tapping to penetrate the anterior cortical surface without risking vascular injury. A probe is helpful in determining depth and length of screw.**

Technique: C2 Pedicle Screw (Fig. 29.9)

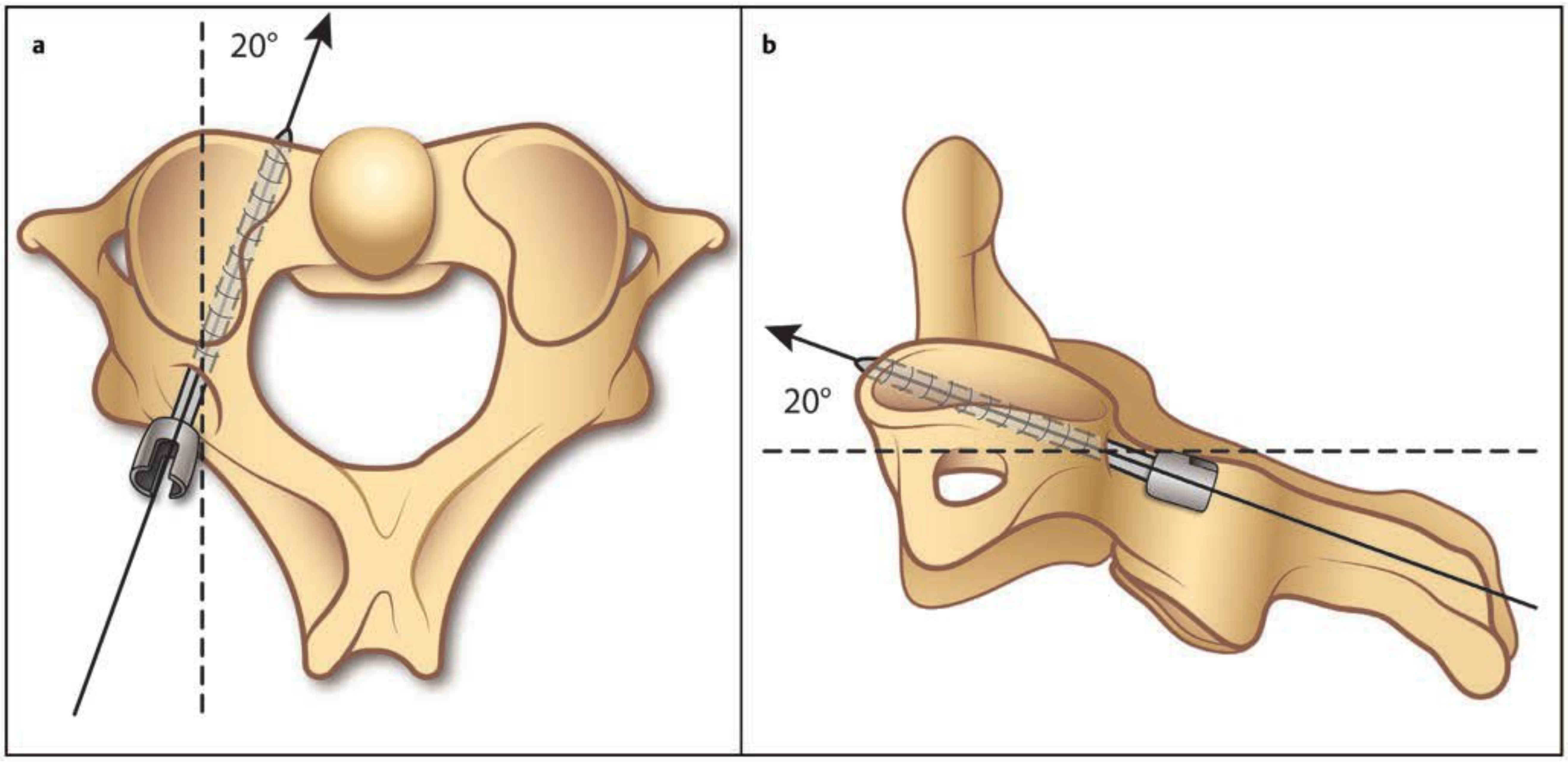


Figure	Procedural Steps
Fig. 29.9	**After exposure of the posterior arch of C2, palpate the medial portion of the C2 pedicle with a nerve hook or a small Penfield and make reference of its trajectory. The entry point will be in the pars interarticularis of C2, lateral to the superior margin of the C2 lamina. (a) Medial and (b) cranial angulation of the screw trajectory is dependent on careful evaluation of the preoperative imaging—usually 15 to 20 degrees and 20 degrees, respectively. Again, the course of the vertebral artery on the preoperative CT will dictate whether placement is advisable; the risks of vascular injury are low.**

Technique: C2 Pars Screw[14]

The technique for placement of a C2 pars screw is similar to that for a C1–C2 transarticular screw (see below), except the target and trajectory do not extend to the C1–C2 articulation. The entry point is just above the inferior articular facet of C2 (3 mm cranial and 3 mm lateral to the inferior medial third of the inferior articular surface of C2). Drilling and screw trajectory should be parallel to the angle of the pars interarticularis, with 45 to 60 degrees of cranial and either "straight up" or 15 degrees of medial angulation. The optimal drilling trajectory is either the anterior tubercle or a few millimeters superior. Preoperative review of the CT is essential, with focus on the sagittal reconstruction to identify the vertebral artery foramen. The length of the screw must be determined on the preoperative CT scan. The screw must stop before reaching the transverse foramen (usually 14–20 mm). See also Chapter 12, Fig. 12.15..

Technique: C2 Translaminar Screw (Fig. 29.10)

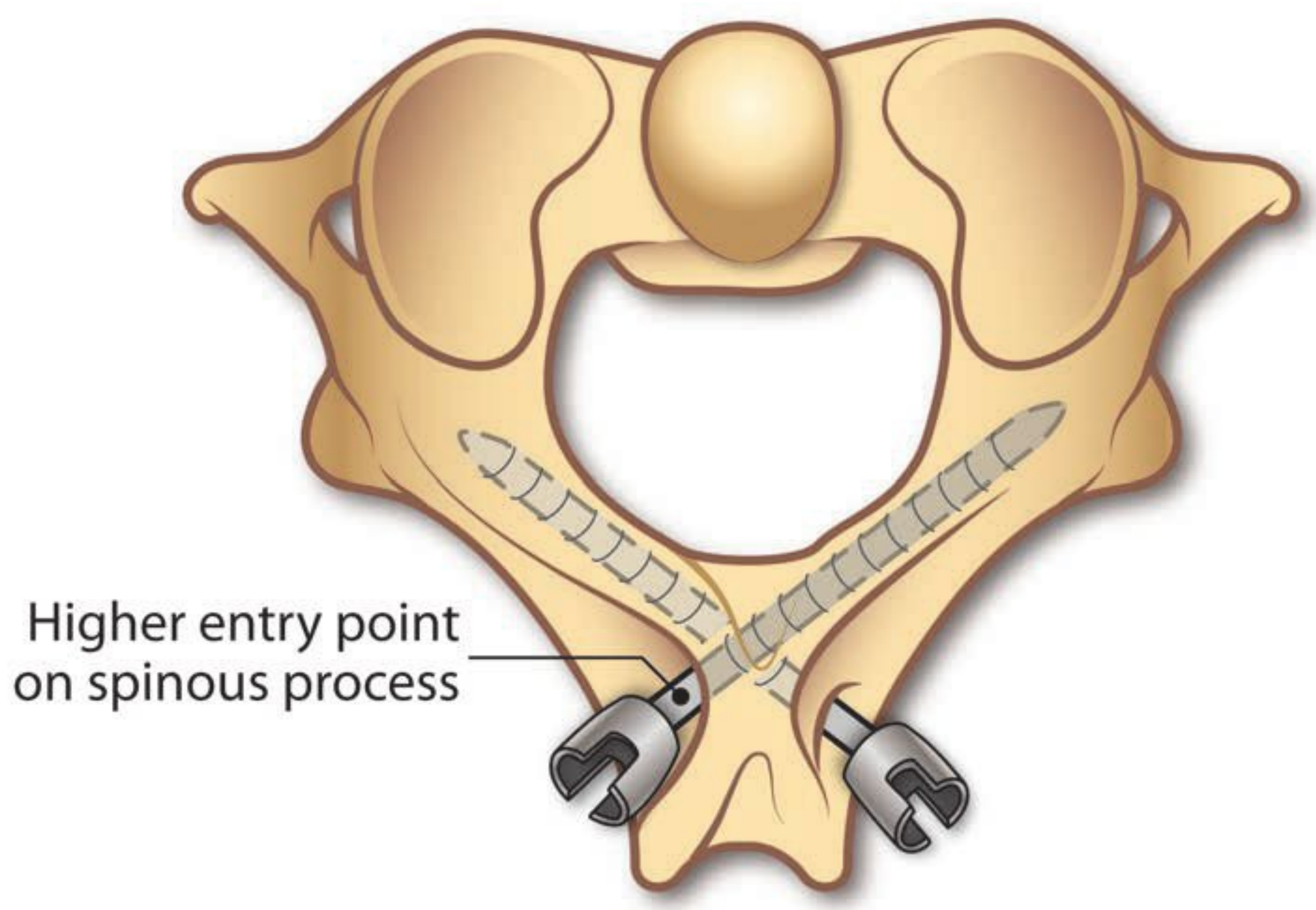


Figure	Procedural Steps
Fig. 29.10	**After subperiosteal dissection of the C2 posterior arch, the entry point will be identified at the base of the spinous process (i.e., the spinolaminar line), contralateral to the lamina intended for fixation. The lamina itself will define the screw trajectory; make a slight dorsal angulation to avoid vertebral canal breach. When using this technique bilaterally, one entry point must be higher than the other so that one screw will not intersect with the other. The lamina must be thick enough to allow the placement of 3.5 mm screws. Frequently, the anatomy requires a hybrid construct with different instrumentation on left and right. The C2 translaminar screw head location in longer constructs may require offset fixation and may pose occasional rod bending challenges.**

Atlantoaxial Arthrodesis

Technique: Brooks and Jenkins[15] (Fig. 29.11)

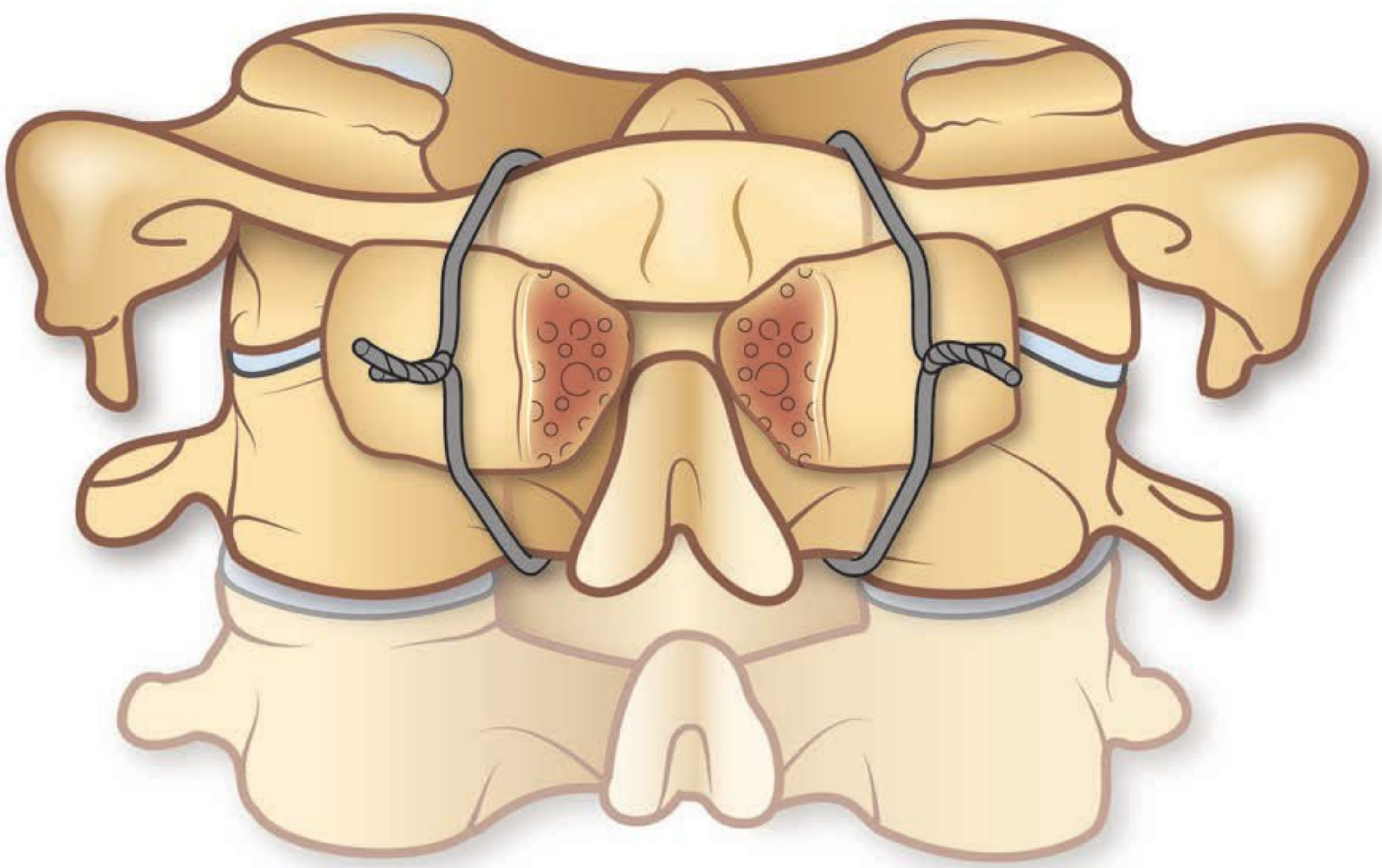


Figure	Procedural Steps	Pearls
Fig. 29.11	**Brooks and Jenkins fixation. C1-C2 sublaminar wires are secured over bilateral interposition bone grafts to provide a measure of stability. A standard midline longitudinal posterior approach is used to expose the arch of the atlas and lamina/spinous process of the axis. Two double 20-gauge wires should be inserted under each side of the posterior arch of C1 and the lamina of C2. Two tricortical structured bone autografts are harvested from the iliac crest and shaped to the size of the posterior space between C1 and C2. The wires, once positioned, are tightened over the graft.**	• Postoperative rigid immobilization is required with a Minerva cast or halo brace. • Despite the appearance and the feeling of being very stable at placement, the wiring constructs lack the rigidity and stability of the Harms or transarticular configurations.[16]

Technique: Gallie[17] (Fig. 29.12)

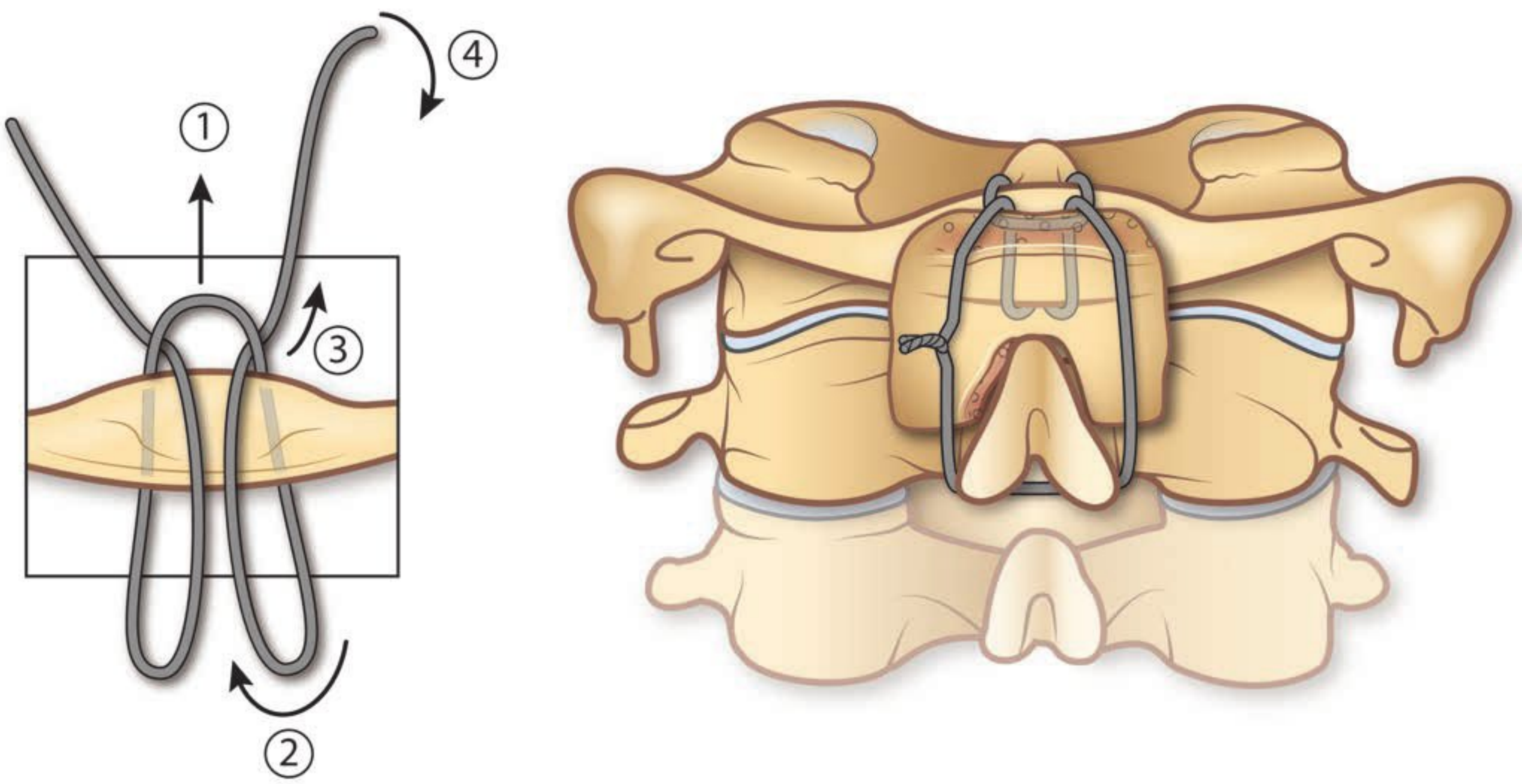


Figure	Procedural Steps	Pearls
Fig. 29.12	**Gallie fixation. A posterior wire construct is bolstered with a notched interposition bone graft shaped to fit above the lamina of C2 and over the C1 posterior arch.** **The posterior arch of the atlas and the lamina of C2 are exposed no further than 1.5 cm lateral to the midline in order to prevent injury to the vertebral arteries. A wire loop is passed upward under the arch of the atlas (1). Then, the free ends of the wire are passed into the loop, notching the arch of C1 (2, 3). An interpositional, notched corticocancellous graft is harvested from the iliac crest and shaped to fit the space above the lamina of C2 and over the arch of C1. The free ends (4) of the wires are passed over the graft, securing it. One end will pass around or through the spinous process of C2 and then should be twisted and tightened to the other end. Postoperative rigid immobilization is required with a Minerva cast or halo brace.**	• This technique avoids the need for sublaminar C2 wires, which may be advisable in cases of congenital or acquired spinal stenosis. • This technique is one of the least stable constructs, which could result in wire breakage and delayed deformity. • Also, because the wire is sublaminar at C1 and around the spinous process at C2, overtightening of the wires will cause a posterior translation of C1 on C2. • Multiple other wiring techniques have been described, including Sonntag's modified Gallie technique.[18]

Technique: Posterior C1–C2 Transarticular Screw Fixation (Fig. 29.13a, b)

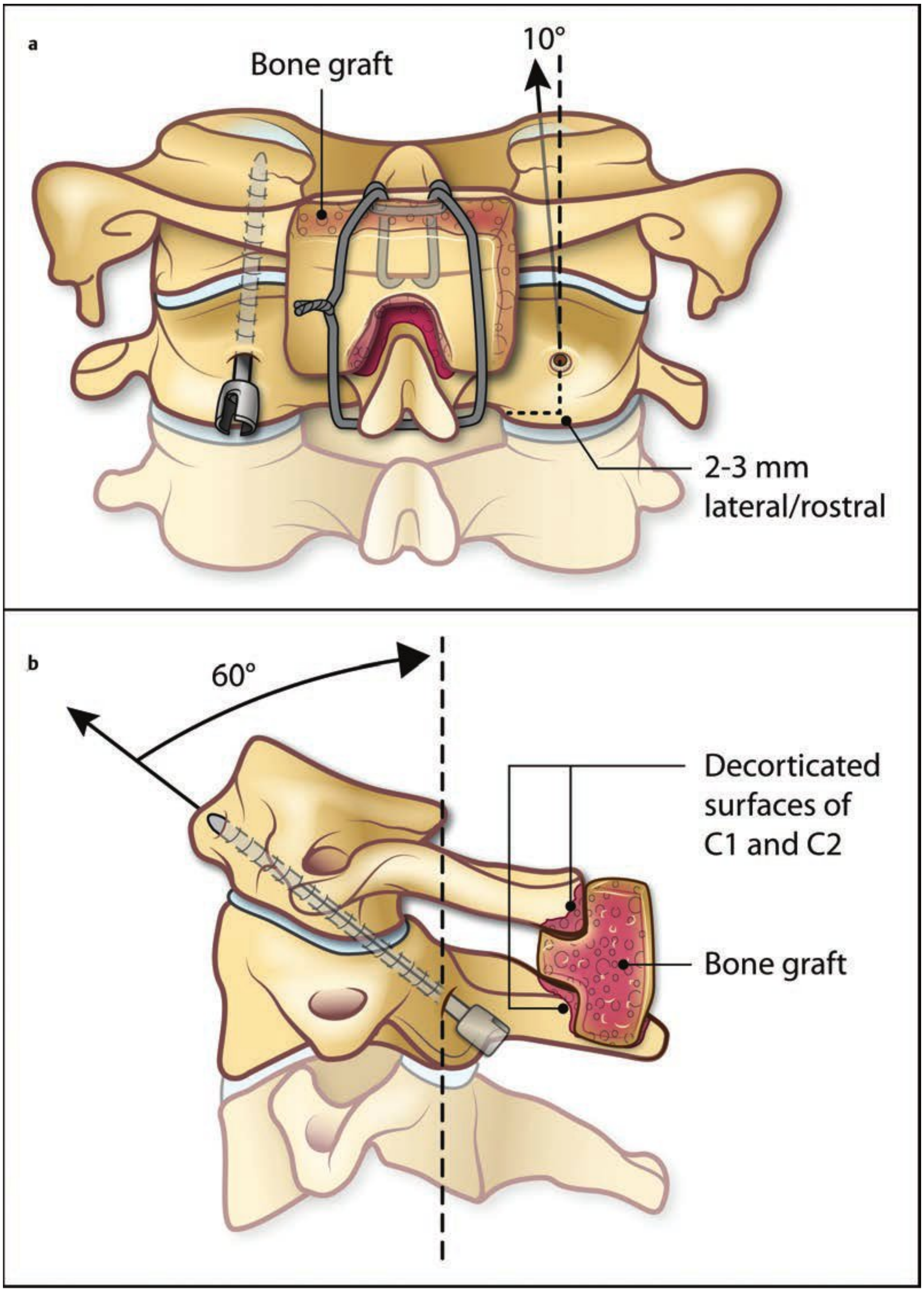


Figure	Procedural Steps	Pearls
Fig. 29.13	**Reduction of C1–C2 to anatomic or near anatomic alignment must be achieved preoperatively and confirmed with radiographs. A CT of the upper cervical spine is mandatory to rule out an aberrant position of the vertebral artery. Slight flexion of the neck helps the exposure. A routine midline longitudinal posterior approach is performed to expose the posterior elements of C1 to C3. Identification of the C2–C3 facet joint will determine the entry point: 2 to 3 mm lateral and 2 to 3 mm rostral to the inferior, medial portion of the C2–C3 facet joint. (a) A small angulation of 10–15 degrees to medial is also made. (b) Lateral view fluoroscopy is used to direct the trajectory toward the C1 posterior tubercle (approximately 60 degrees), running just below and parallel to the dorsal aspect of the pars interacrticularis. The assistant will use a towel clamp on the spinous process of C2 to manually reduce the C1–C2 articulation before the drill crosses the joint.**	• Frequently, a separate stab incision is made caudal to the operative opening to allow the proper angulation of the drill bit. • Tapping with an appropriately sized tap is recommended, especially with grossly unstable spines to prevent distraction of the C1–C2 joint space.
	Once the screw is in place and reduction is achieved, the contralateral screw is placed, keeping the same reduction. Each screw should pass through four cortical surfaces (the entry point just above the inferior C2 face, each surface of the C1–2 joint space, and the anterior C1 lateral mass), making it a very strong construct. If a vertebral artery injury is suspected, continue placing the working screw and abort placement on the contralateral side.	• A unilateral transarticular screw, married with contralateral wire construct, is preferable where a suspected or known preexisting vertebral artery injury is present.
	If there is no concern for an arterial injury, then proceed with placement of the contralateral screw with the same technique. The arthrodesis is reinforced with a corticocancellous bone graft harvested from the iliac crest and fixed with sublaminar wires around the posterior elements of C1 and C2.	• There is no need for halo or Minerva cast postoperatively. A rigid cervical collar only is used.

Technique: Harms Posterior C1-C2 Fusion with Polyaxial Screw and Rod Fixation[14] (Fig. 29.14a, b)

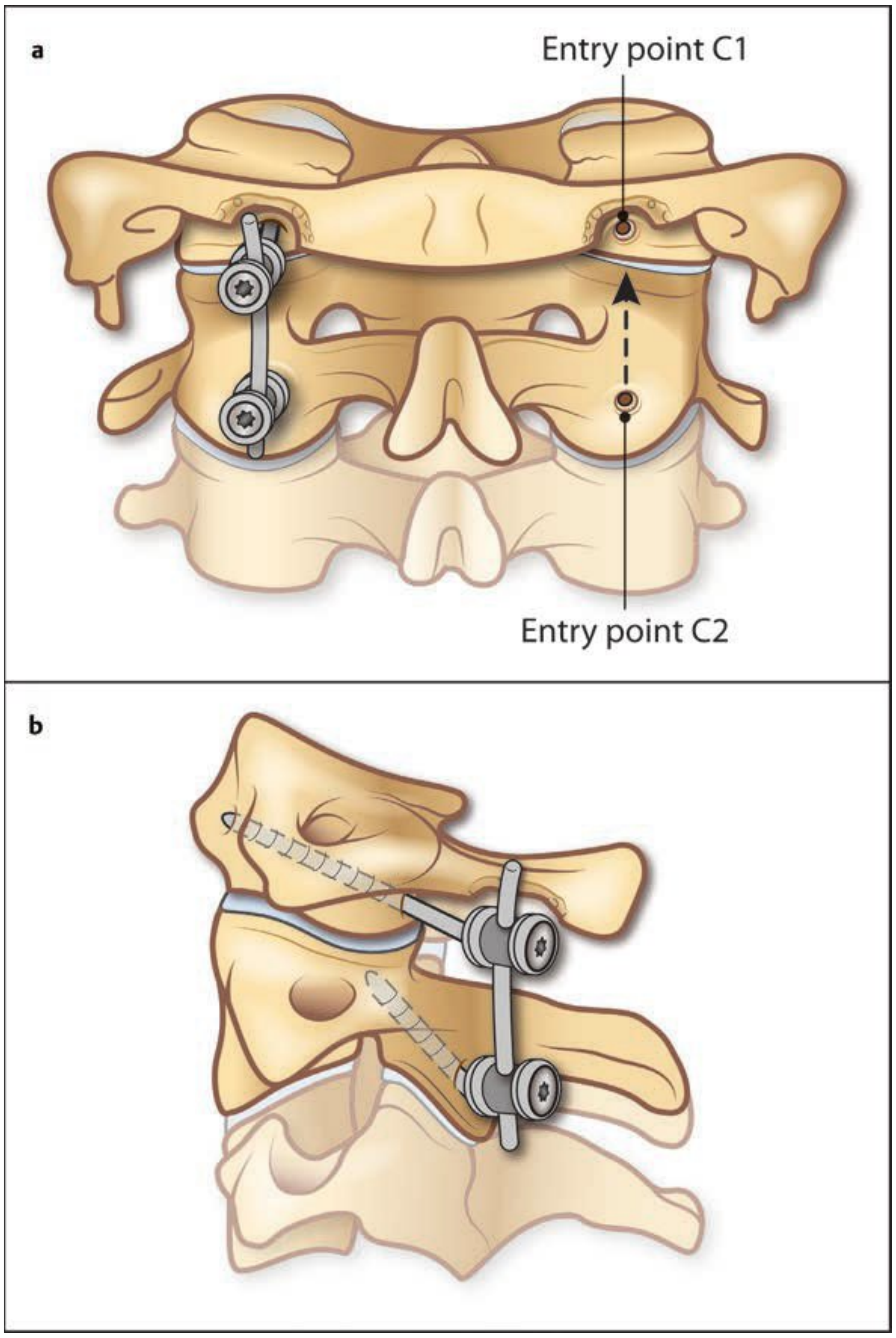


Figure	Procedural Steps
Fig. 29.14	**Harms posterior C1–C2 fusion with polyaxial screw and rod fixation. C1 lateral mass fixation is coupled with C2 pars or pedicle screws. The construct is held together with a rod, providing rigid fixation bilaterally.** **A standard midline longitudinal posterior approach is used to expose the C1–C2 complex. First, 3.5-mm polyaxial screws are inserted in the lateral masses of C1. Next, polyaxial screws are placed bilaterally into the C2 pars interarticularis or pedicle (as described above). Manipulation of the implants allows reduction of C1 onto C2 when necessary. A 3.2- to 3.5-mm rod is placed to connect the screws and provide rigid fixation. Bone graft is then placed over the decorticated posterior elements for definitive fusion. Intraoperative reduction of subluxation can be achieved with placement of the screws either recessed or proud in spite of their polyaxial nature.** **(a) Figure demonstrates the desired entry point and (b) the optimal screw trajectory.**

Subaxial Cervical Posterior Arthrodesis

Technique: Interspinous Wiring Arthrodesis (Fig. 29.15)

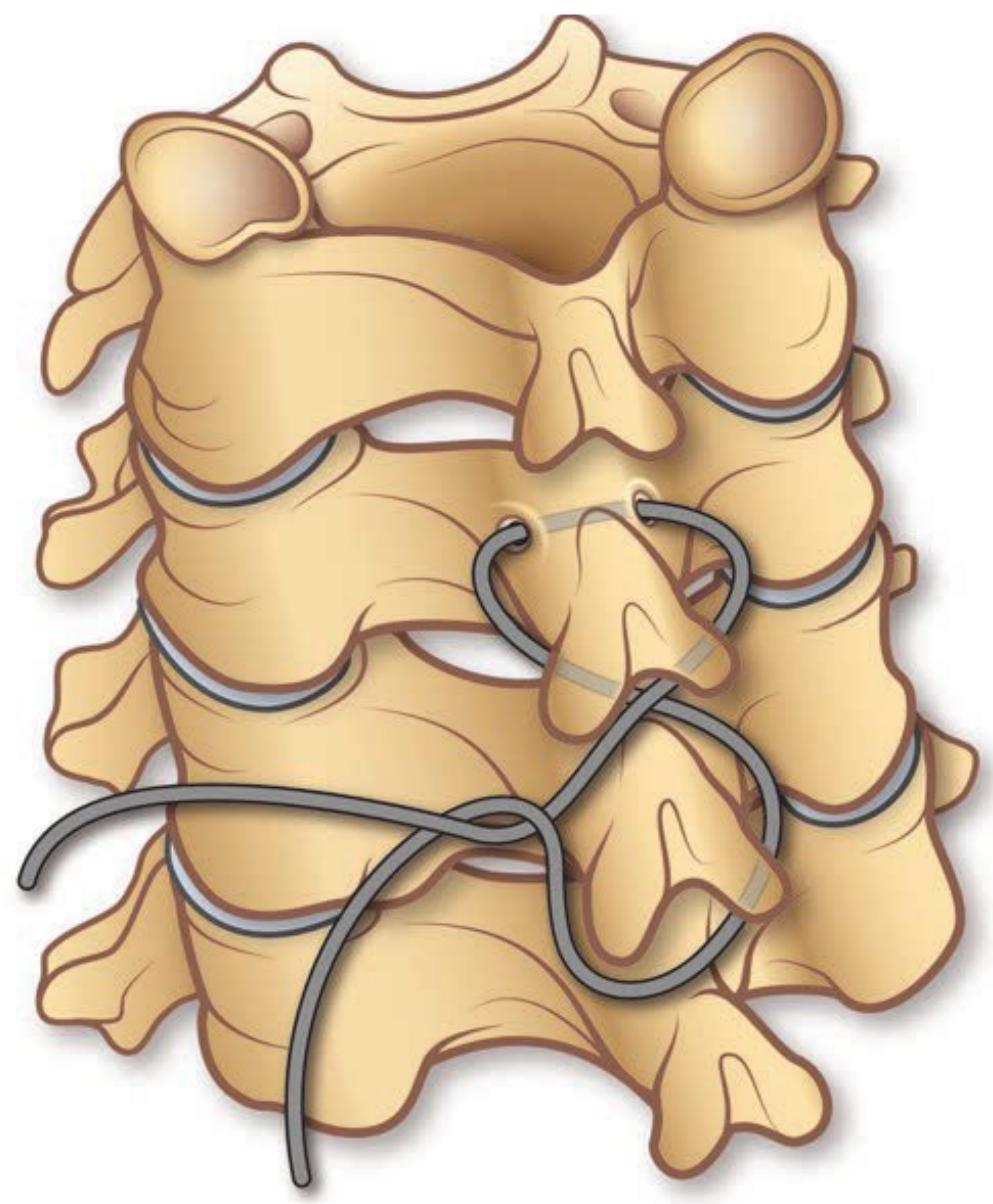


Figure	Procedural Steps	Pearls
Fig. 29.15	**A posterior midline longitudinal approach is performed to exposure the level of injury; subperiosteal exposure of the laminae and spinous processes is made. A through-and-through hole is made with a sharp towel clip at the base of each spinous process to be fused. A wire is passed through the hole at the base of the spinous process above. Then, the free ends of the wire are drawn caudally and crisscrossed at the level of the interspinous space, before passing through the spinous process of the level below, to create a figure-of-eight pattern. The free ends of the wire are cinched and secured. Decortication of the lamina and spinous processes is performed with a bur. Corticocancellous bone grafts are placed over the laminae. Rigid external immobilization is used.**	• With the advent of titanium cable systems, a simple loop fixation of the spinous processes may provide an easy adjunct to the more complex lateral screw fixation. • The Rogers interspinous wiring and the spinous process loop constructs should not be used for stand-alone fixation, but are ideal as a tension band to augment anterior constructs.

Technique: Posterior Arthrodesis with Lateral Mass Screw Fixation (Fig. 29.16a–c)

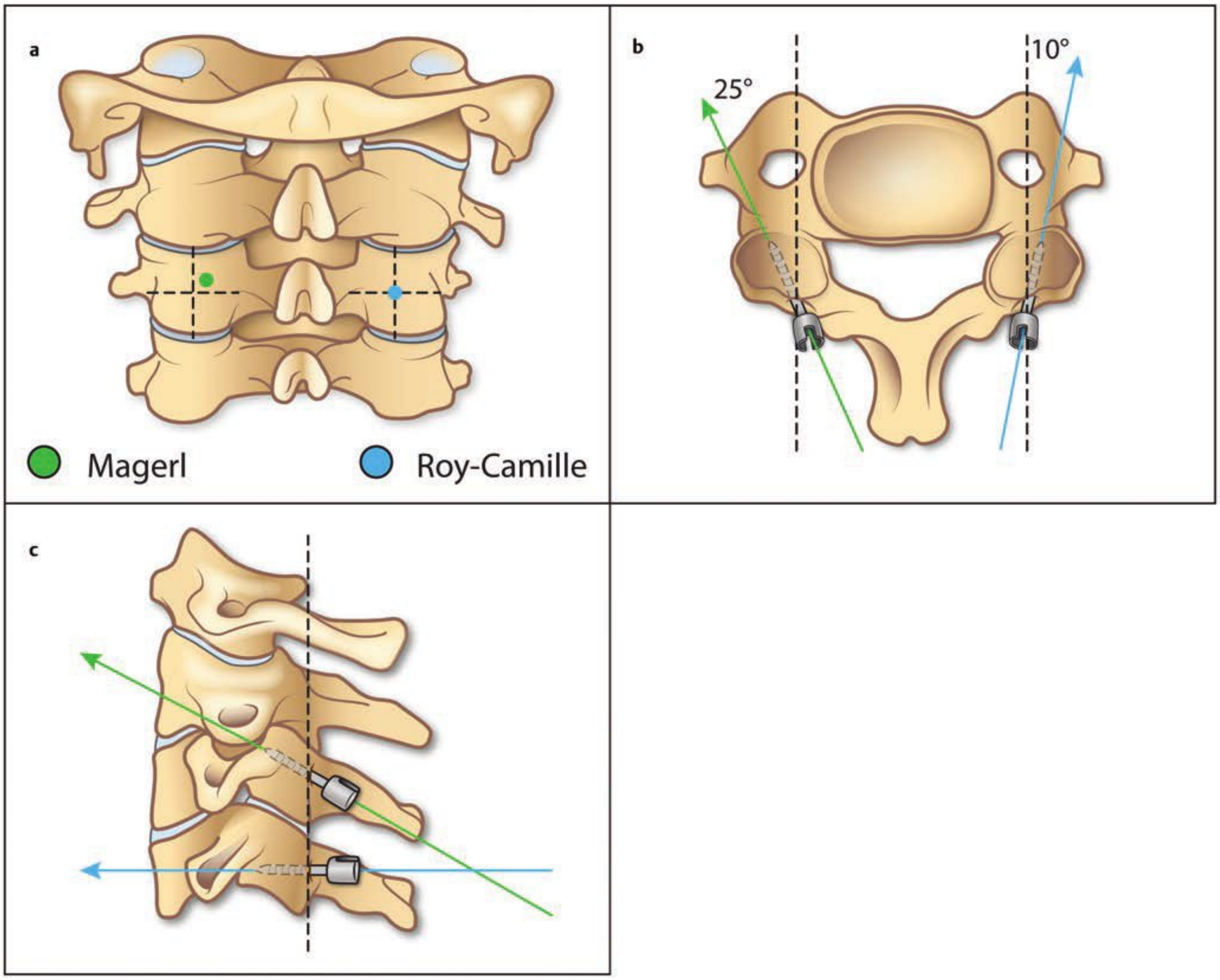


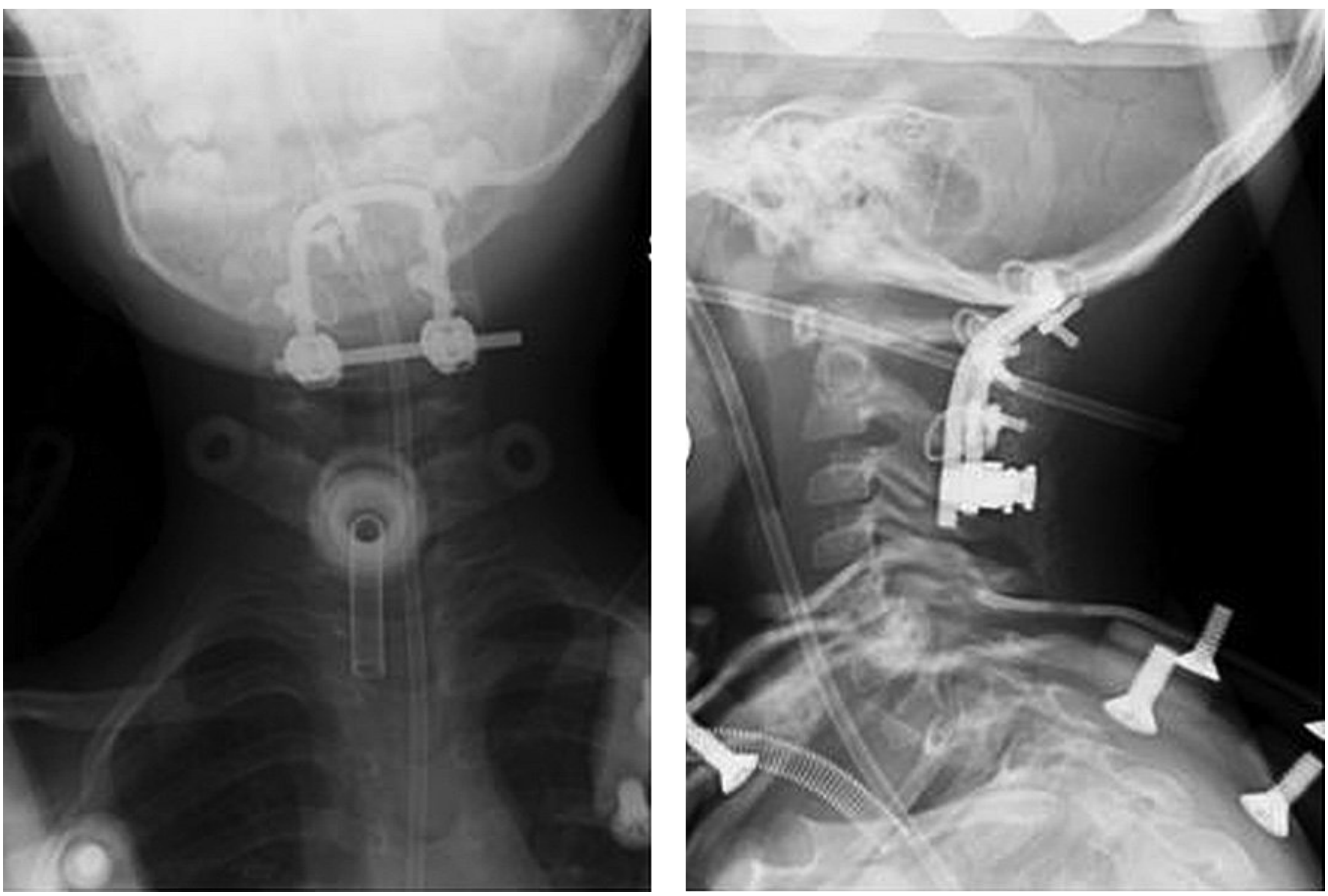
Figure	Procedural Steps
Fig. 29.16	**Several techniques to achieve lateral mass fixation have been described. Most differ with respect to the entry point and angulation of trajectory. The most popular are the Roy-Camille and the Magerl techniques.[19–21]. (a) The entry point for the Roy-Camille technique is at the intersection of two perpendicular lines that equally divide the lateral mass into four quadrants. The drill is directed perpendicular to the posterior wall of the vertebral body on sagittal view and 10 degrees lateral on coronal view. Magerl's entry point is 1 mm medial and rostral to the same center point of the posterior surface of the lateral mass. (b, c) The trajectory is oriented parallel to the adjacent facet joint (about 45 to 60 degrees rostral) and 25 degrees lateral. Placing the monopolar blade into the joint space may assist the operator with the proper orientation in the sagittal plane. Careful use of variable drill bits allows for the placement of bicortical screws when extra fixation is desired. Screw heads are then connected with longitudinal rods. A rigid cervical collar is used postoperatively.**

Closing

- The musculature and fascia are reapproximated with 2-0 absorbable sutures.
- Subcutaneous tissue is closed with 3-0 absorbable suture in an inverted, interrupted fashion.
- The skin is closed with a subcuticular, running monofilament absorbable suture.

Postoperative Management

- All these instrumentation techniques in children require a protective external orthosis (collar). The collar is used not only to limit motion but also to limit the activity of energetic children. While patients treated with wiring techniques typically require a rigid external orthosis, patients with constructs that use screws at each of the levels may not require a rigid collar. Specific recommendations are noted in the text accompanying the description of each arthrodesis procedure. For the occipitocervical arthrodesis that is detailed in this chapter, the use of a soft cervical collar is recommended. In that case, there is no need for halo orthosis unless bone quality is poor or a metabolic disorder with a high nonunion rate develops.
- If the child is kept in a rigid collar, the neck and jaw line must be monitored carefully for skin breakdown.
- The rigid collar, if employed, is typically worn for the first 6–8 weeks after surgery and then gradually discontinued or replaced with a soft one.
- The surgical drain is removed after 48 hours or when output has decreased to a minimum. Because dural tears are common in the occiput–C1–C2 dislocations, the use of a drain may be limited.
- Postoperative intravenous prophylactic antibiotics are terminated after 24 hours.
- Imaging (either plain X-ray or a CT) is performed in the immediate postoperative period. Further imaging is done with plain films at intervals of 2 weeks, 1 month, 3 months, and 6 months after surgery. At that point, a CT is performed to assess for fusion.
- Postoperative imaging (**Fig. 29.17a, b**).



a b

Fig. 29.17a, b (**a**) AP and (**b**) lateral radiographs showing the final occipitocervical construct.

Special Considerations

SCIWORA

SCIWORA is a term used almost exclusively in children. It is an outdated term that was used previously to describe a child presenting with a clinical spinal cord injury—absent any obvious fracture or subluxation on plain radiographs or CT imaging. In young children, the supporting musculoligamentous structures and joints can absorb forces by stretching and moving, respectively. However, this excess laxity can place the fragile and intolerant spinal cord at risk for injury. High quality MRI can almost always identify the ligamentous and spinal cord injury in children who were previously designated as SCIWORA.

Halo Application

The application of halos in the pediatric population poses special challenges. Due to the thin caliber of the skull, pins must be placed under less pressure; usually more than four pins are required for adequate fixation. Pins need to be monitored closely for infection and skull perforation (see Chapter 11).

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