Decompressive Craniectomy
Surgical Techniques and Complication Avoidance

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KEYWORDS

• Traumatic brain injury • TBI • Craniectomy • Neurosurgery • Neurotrauma • Surgical techniques • Cranioplasty

KEY POINTS

- Position patient for full anatomic access of the frontal, temporal, and parietal lobes.
- Correlate external anatomy to bony landmarks to enable safe maximum access.
- A large dural opening is needed for adequate decompression.
- Use of wound drains can reduce post-operative intracranial pressure.

BACKGROUND

Following a neurologic insult such as severe traumatic brain injury (TBI) or ischemic stroke, therapy is directed at minimizing secondary neurologic injury through mechanisms such as ischemia and hypoxia.[1] Control of elevated intracranial pressure (ICP) is a critical element in the management of patients with these injuries.[2] Intracranial hypertension may result from an increase in volume in any of the cranial components (brain parenchyma, blood, and cerebrospinal fluid [CSF]) and may result from hydrocephalus, cerebral edema, and/or hemorrhage. Sustained ICP elevation can compromise cerebral perfusion, precipitate internal herniation, and result in irreversible neurologic injury. While first-line therapies such as patient positioning, analgesia, hyperosmolar therapy, CSF drainage, and sedation are employed to manage ICP, a subset of patients remains refractory to medical management.[3] Unilateral mass lesions or edema, such as from hemorrhagic or ischemic stroke, can affect uninjured brain by compression or herniation. In these cases, decompressive craniectomy (DC) may be considered to provide additional mechanical relief by way of expanding the cranial vault, thereby decreasing ICP and minimizing secondary brain injury.[3]

The evidence supporting the use of DC has evolved considerably over the past 2 decades, owing to the publication of several high-quality randomized controlled trials in both TBI and malignant middle cerebral artery infarction.[4–8] Owing to its widespread use, several techniques have been described, with some variation based on incision, craniectomy technique, and dural closure/lack thereof. In this article, the authors describe their preferred technique for the unilateral frontotemporoparietal craniectomy and review associated complications and strategies to avoid them.

PREOPERATIVE CONSIDERATIONS AND SURGICAL PLANNING

Preoperative planning for DC involves a comprehensive assessment of the patient's neurologic status, radiological findings, and overall medical condition. The evaluation begins with an assessment of ICP

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Abbreviations

CSF	cerebrospinal fluid
CT	computed tomography
DC	decompressive craniectomy
ICP	intracranial pressure
ICU	intensive care unit
TBI	traumatic brain injury
VP	ventriculoperitoneal

and neurologic deterioration despite optimal medical therapy. Imaging studies, primarily computed tomography (CT), are essential for determining the underlying pathology (eg, location of hemorrhage if present), extent of cerebral edema, midline shift, herniation, and ventricular effacement. In select cases, MRI or CT angiography may provide additional detail regarding infarct territory, vascular anatomy, and tissue viability.

Primary Versus Secondary Decompressive Craniectomy

When performed as part of the evacuation of a space occupying lesion, DC has been termed *primary DC*. If a craniectomy is performed after exhaustion of medical therapies for elevated ICP, it has been termed *secondary DC*. As the indications for each are different, outcomes after primary and secondary DC can vary. Primary DCs are performed typically on the side of the larger mass lesion. Site selection in secondary DC can be either the side of greater edema or opposite to midline shift, or can be on the nondominant hemisphere in generalized edema.

Anesthesia and Perioperative Medication Management

Prior to proceeding with surgery, we ensure that the patient's coagulation parameters have been reviewed, any anticoagulation reversed if present, and type and screen performed with blood available. Furthermore, the patient should receive appropriate prophylactic anticonvulsants, as well as additional tier 1 ICP-reducing agents such as hypertonic solutions or sedation. Judicious use of mannitol is advised to ensure that the patient is hemodynamically stable during induction of anesthesia and for the duration of the procedure. Corticosteroids should be avoided.[9]

Operating Room Preparation and Informed Consent

Owing to the nature of its indications, the DC is most commonly an emergent procedure in which the care team has limited time to prepare operating room equipment as well as identify and consent a patient's surrogate decision-makers. It is standard practice at the authors' institution as well as several tertiary academic centers for the operating room staff to prepare and maintain an easily-accessible *emergency craniotomy cart*, which contains a basic set of tools necessary for the procedure such as hemostatic clips, electrocautery, drills, drains, and a bone flap-plating system in cases where placement/removal of hardware is necessary.

The patient/surrogate decision-makers should be informed in layman terms that this procedure entails removal of a portion of the skull to allow the injured brain more space to expand as well as remove any compressive lesions if applicable/present (eg, subdural hematoma) with the major objective being to improve control of refractory elevated ICP. Risks include but are not limited to intraoperative or postoperative bleeding, seizures, ischemic stroke, hydrocephalus, infection, neurologic deficit, and death.

SURGICAL TECHNIQUE

Patient Positioning

Patient positioning is a critical determinant of safety, exposure, and surgical efficiency in DC. The procedure is generally performed with the patient in the supine or lateral position on a standard operating table. The authors use a horseshoe head holder, rather than fixed pin head holder immobilization. If the head is immobilized with pins, it is important to coordinate timing with the anesthesiology team so that they can anticipate and prepare for the stimulation imparted by the pinning. Note that a rigid pin head holder is often not feasible when severe comminuted skull fractures are present and may limit wound drain tunneling access.

A critical aspect of patient positioning is adequate positioning of the head to permit the exposure necessary to perform a wide craniectomy. Proper positioning of the head relative to the rest of the body optimizes surgical access while minimizing venous congestion, cervical strain, and the risk of secondary injury. To permit this, a large towel roll or gel bump—approximately the size of the patient's thigh—is placed beneath the patient's shoulder and the head is rotated 90° with the entire lateral aspect of the operative side accessible. In this position, the anterior–posterior axis of the head should be parallel with the floor, allowing unobstructed access to the temporal, parietal, and frontal regions. Elevation of the head by 15 to 30° facilitates venous drainage and contributes to the reduction of ICP intraoperatively. If a cervical collar is present, this is removed after positioning while holding stability;

attention is given to neck alignment to prevent secondary injury especially in cases in which a cervical spine injury has not yet been ruled out. The arms, elbows, hips, and heels are padded and the patient is secured to the table using tape or peelable straps.

Once the patient is securely positioned, the hair is shaved to expose the entire operative side, extending to slightly past midline, with planned exit sites for the drains away from the incision.

Incision and Exposure

The standard incision for a unilateral frontotemporoparietal craniectomy is the reverse question mark incision (**Fig. 1**A). This begins at the level of the zygoma approximately 1 cm anterior to the tragus, curves superiorly above the auricle until approximately 3 cm past the pinna before turning superiorly toward the vertex anterior and parallel to the lamboid suture, then extending anteriorly toward the actual or anatomic hairline edge. The skin incision should be larger than the intended craniectomy, while avoiding the pinna.[10]

In order to find the midline, a straight line tracing from nasion to inion can be helpful. In the authors' practice, the incision extends along midline, as this permits wide bony exposure and allows identification of the sagittal suture while planning the margins of the craniectomy. The incision is furthermore designed to maximize exposure of the frontal, temporal, and parietal regions while preserving the vascular supply of the scalp.

Several alternatives to the question mark incision have been described, including the retroauricular and Kempe (*T*) incisions (**Fig. 1**B, C). N-shaped and cloverleaf approaches have also been described.[11] The goal of the retroauricular incision is to maximize the safety of the occipital branch of the superficial temporal artery.[11,12] A Kempe incision is proposed to maximize the extent of bony exposure to facilitate wide decompression, while N-shaped and cloverleaf incisions may be incorporated with standard pterional incisions.[11,13] Superiority of an incision type has not been clearly demonstrated. In choosing an incision type, the typical facility and surgeon for cranioplasty is a consideration. An unconventional incision left to outside surgeons for cranioplasty with inadequate surgeon communication may create difficulties for that outside surgeon and potential patient complications.

After the incision is planned and marked, the skin is prepared in the usual surgical sterile fashion and drapes are placed. The skin is infiltrated with local anesthetic, opened sharply with a blade, and further developed down to bone with monopolar electrocautery. Raney clips are applied to the scalp edges to maintain hemostasis. The scalp and pericranium are dissected from the skull with a periosteal elevator. The scalp flap is raised subperiosteally with careful dissection to maintain tissue/vessel viability and minimize the risk of necrosis and surgical site infection, either at the time of craniectomy or subsequent cranioplasty.[14] The temporalis muscle can be either raised with Bovie electrocautery along the entire length or by raising the temporalis with Bovie along the superior temporal line and then using blunt periosteal elevator inferiorly down to zygoma. The former technique has superior hemostasis at the possible cost of decreased blood supply from the deep

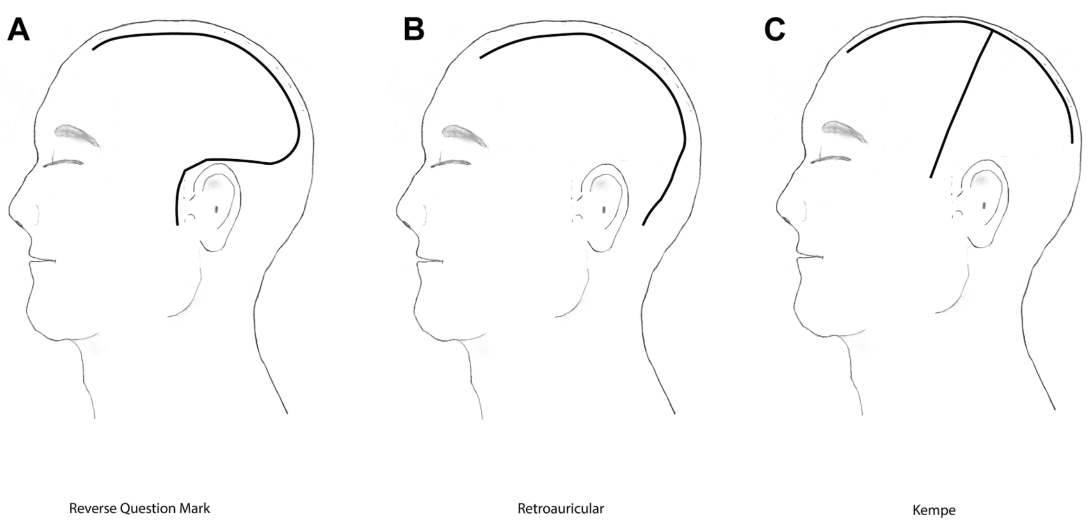

Fig. 1. Common incisions for unilateral frontotemporoparietal craniectomy: (*A*) Reverse question-mark incision; (*B*) Retroauricular incision; and (*C*) Kempe (T) incision.

temporal muscular arteries. Exposure can be maximized and maintained using fishhooks or other retractors so as to permit adequate visualization for the eventual decompression. The authors apply fishhook retraction at the base of the retracted scalp flap as well as along the temporalis muscle above the inferior portion of the squamous temporal bone.

Craniectomy

Successful decompression requires precise identification of cranial landmarks to guide burr hole placement. Multiple burr holes are placed along the margins of the craniectomy to allow careful dissection of the dura prior to further drilling, and the exact number of burr holes is at the discretion of the surgeon. In our practice, at least 5 burr holes are placed: frontal, parietal, posterior temporoparietal, keyhole, and low temporal (**Fig. 2**A–E). Burr holes are drilled with either perforator or round drill bit. The frontal burr hole is typically placed just lateral to the midline and posterior at the anatomic hairline to access the anterior cranial fossa. Burr holes near the vertex are placed at least 2 cm off of the visible saggital suture. Posterior parietal burr hole is similarly placed ipsilateral to the sagittal suture to facilitate superior and posterior decompression. A posterior temporoparietal burr hole is placed well inside of the lamboid suture. The keyhole burr hole is positioned at the pterion, providing access to the frontal and temporal lobes. If using a perforator, care should be taken at this step to avoid directing the burr hole anteriorly, to avoid the orbit. The temporal burr hole is placed at the posterior root of the zygomatic arch, which is usually at the bottom extent of the exposure.

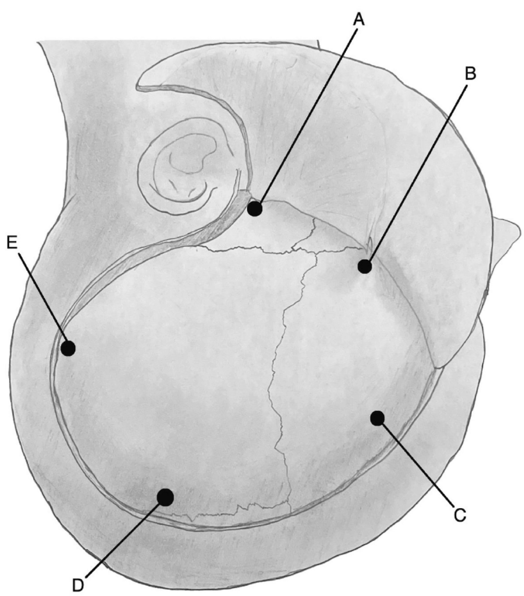

Fig. 2. The authors' preferred burr hole locations: low temporal (A), keyhole (B), frontal (C), parietal (D), and posterior temporoparietal (E).

Burr holes serve as entry points for the craniotome and must be strategically placed to allow smooth traversal between holes while avoiding injury to bridging veins and the dural sinuses. Incorrect placement may lead to cortical contusion and/or inadequate decompression. Preoperative imaging and surface landmarks, including the pterion, coronal suture, sagittal suture, and zygoma, are key. After burr hole placement, the dura is carefully dissected from the undersurface of the skull using Woodson dental or equivalent instruments.

At this point, the margins of the craniectomy are carefully planned and marked with either a marker or monopolar electrocautery. Essentially, a straight line can be traced from the inferior temporal burr hole to the pterion burr hole to the anterior frontal burr hole, with a slight anterior swing between the pterion burr hole and anterior frontal burr hole. Between the inferior temporal and posterior temporoparietal burr holes, an attempt is made to stay as low as possible along the middle fossa floor for at least 5 cm prior to curving up toward the posterior temporoparietal burr hole. Incorporating a wide area for the decompression is essential. The dimensions of the bone flap are directly correlated with the effectiveness of decompression: in TBI, a frontotemporoparietal flap measuring at least 12 $\times$ 15 cm is recommended. The effect of craniectomy size (12 $\times$ 15 cm vs a smaller 8 $\times$ 6 cm flap) on mortality and functional outcome has been the subject of multiple studies—most notably 2 randomized controlled trials—found that larger craniectomy was associated with lower rates of mortality and higher rates of good neurologic outcome at 1 year, with reduced rates of perioperative complications.[15,16]

The bone flap is typically removed using a craniotome, joining the burr holes in a continuous fashion. Typically, the burr holes nearest the superior sagittal sinus are connected last, as this allows quicker access to the sinus in case of an inadvertent injury. The sphenoid wing at the inferior margin of the craniectomy is usually not amenable to the craniotome, owing to its width and depth. This can either be taken down with a standard matchstick or ball-tipped drill bit and/or carefully fractured from the surrounding bone at the final stage of bone flap removal. The bone flap is elevated from the surrounding skull using an instrument such as Penfield 3 to dissect it from the underlying dura. The bone flap is then removed in one piece and passed off the field. Following removal of the bone flap, the craniectomy can be extended inferiorly down the temporal bone to decompress the middle fossa. Sharp edges are rongeured and waxed as needed to prevent dural strangulation and cortical injury. Preservation of the bone flap for future cranioplasty requires sterile handling, often involving storage in a deep-freeze facility or, now less commonly, a subcutaneous abdominal pocket. If the bone flap has been contaminated as a result of an open traumatic scalp laceration through galea, it may be discarded in some surgeons' practice or intensively disinfected with antiseptic solution prior to storage. Operative cultures at index surgery have not proven effective in predicting infection at autologous cranioplasty.[17]

Dural Opening and Expansion

Bone removal alone is insufficient for effective decompression; the dura must be opened to allow cerebral expansion and primary dural closure should not be performed.[3,10] Prior to opening the dura, the authors tack the dural edges to the surrounding bone using 4-0 Nurolon or equivalent suture in order to reduce the risk of postoperative epidural hematoma. Careful attention is paid to hemostasis at this point due to the numerous vessels present on the dura, which themselves may be injured. These are coagulated with bipolar electrocautery. The authors coagulate the entire visible length of the middle meningeal artery and its branches. A stellate or curvilinear dural incision is then performed in order to maximize cortical decompression while minimizing the risk of tearing or strangulation. The authors use a stellate incision. The initial durotomy is delicately made with an 11-blade, and then extended with scissors. It is possible to cause a cortical laceration at this stage as the intracranial hypertension usually compresses the plane between the pial surface and the dura. One can reduce this risk by placing a cottonoid or Telfa patty beneath the dura as the dural incision is extended. Bleeding from the dural edges can be controlled with either mechanical compression or bipolar electrocautery. At this point, if subdural hematoma is present (such as in the case of trauma), this can be evacuated with irrigation in the standard fashion.

Hemostasis

Achieving meticulous hemostasis is a critical component of DC, as uncontrolled bleeding can compromise cerebral perfusion, prolong operative time, and increase the risk of postoperative complications. Bleeding can originate from several sources, including the scalp, diploic veins within the skull, dural vessels, and, rarely, cortical surfaces. Bone bleeding, particularly from diploic channels, is controlled using bone wax, which is applied sparingly to avoid excessive local inflammation, interference with cortical tissue, and seeding with infectious agents.

Dural bleeding frequently occurs along the edges of the incision or at arachnoid adhesions. As previously mentioned, bipolar cautery provides precise coagulation while minimizing collateral thermal injury to the underlying cortex. Adjunctive hemostatic agents, such as oxidized cellulose, gelatin sponges, or fibrin sealants, are commonly employed in cases of persistent oozing. Their use is particularly valuable in patients with coagulopathy or in those on antiplatelet therapy.

Parenchymal bleeding is rare but may result from inadvertent cortical laceration during dural opening or manipulation. Gentle retraction and avoidance of excessive pressure are critical for minimizing parenchymal injury. In some cases, hemostatic agents may be applied directly to cortical surfaces, though care must be taken to avoid creating mass effect or compressing the underlying brain. Throughout the procedure, coordination with anesthesia is essential to maintain hemodynamic stability, optimize mean arterial pressure, and correct any coagulopathy that could exacerbate bleeding.

Duraplasty

Some have argued in favor of onlay or sutured duraplasty, including in consensus conference statements.[10] In the author's practice, the dural leaflets are reflected back overlying the brain, no onlay is used, and the dura is not primarily closed. It is important to ensure that if expansile duraplasty is performed, that excessive absorbant graft or other foreign material is avoided, thereby minimizing the risk for mechanical compression and surgical site infection.[10]

Drains and Closure

Placement of a subgaleal drain is a standard adjunct in DC, primarily to prevent fluid accumulation beneath the scalp flap. It is the author's practice to place 2 drains, one below the reflected dural flaps and one above. Accumulation of blood or serous fluid can increase local pressure, compromise flap perfusion, and contribute to wound dehiscence or delayed healing. The drain is typically tunneled away from the primary incision and connected to low-pressure, bulb suction or gravity. Proper tunneling minimizes the risk of infection by reducing communication between the skin surface and the subgaleal space. Secure fixation of the drain (such as with a stitch) is essential to prevent displacement, which may result in loss of suction, fluid accumulation, or local pressure on the scalp flap. The decision regarding the duration of drainage is guided by several factors, such as the degree of bleeding, presence of antiplatelet/anticoagulant use, postoperative imaging findings, and drain output. The authors typically leave drains in for at least 48 hours after surgery. In the event of suspected CSF drainage occurring through a wound drain, the drain can be transitioned to gravity drainage or bile bag to avoid excessively low ICP. *It is essential that elevated ICP be well controlled prior to discontinuing functioning wound drains after DC.*

Closure following DC is intended to protect the brain, minimize infection risk, and preserve tissue integrity for future cranioplasty. After achieving hemostasis, thorough irrigation to reduce contamination risk, and completing any duraplasty (if pursued), the scalp is closed in layers. The temporalis muscle can be loosely approximated with sutures at the fascia or left open. The galea is typically reapproximated with inverted interrupted absorbable sutures such as 2-0 or 3-0 Vicryl or equivalent, closely spaced. The galea closure requires special attention as it may be the primary barrier to an external CSF leak. Proper galeal closure also helps to reduce tension on the overlying skin as well as local hemostasis. The skin is then closed using either sutures or staples, depending on surgeon preference and flap characteristics. Following conclusion of the case, the patient is generally admitted or returned to the intensive care unit (ICU), often remaining intubated.

Adjunctive Procedures

If not already in place, a ventriculostomy or ICP monitor should be placed on the contralateral side using standard landmarks following completion and closure of the craniectomy. Ventriculostomy placement is often complicated by the fact that the ventricles may have moved from initial imaging studies due to relief of midline shift or other intraoperative developments. Ventriculostomy placement may be aided by a postoperative CT scan. ICP monitoring after DC for TBI is essential, as 36% of patients may have elevated ICP even after the index procedure as reported in one series.[18]

COMPLICATIONS

Dural Sinus Injury

Venous sinus injury is the most feared complication during DC and most commonly occurs while drilling the medial extent of the craniectomy. In trauma, it is also possible for an occult dural venous sinus injury, typically associated with skull fracture, to be *uncovered* during elevation of the bone flap.[19] Sinus injury is suggested by brisk, profuse bleeding while operating near the sinus and, if allowed to proceed uncontrolled, may rapidly progress to hemodynamic instability secondary to blood loss and/or venous air embolism. In order to minimize the likelihood of a dural sinus injury, it is important to identify cranial landmarks prior to drilling, particularly the sagittal suture, and to cut the medial margin of the bone flap last. Prior to bone flap removal, it is also advised to have wet sponges readily available to provide tamponade in the event of injury while strategies for more definitive repair are planned. Scrub technicians should be familiar with quick conversion from craniotome with footplate to bare straight router bit for placing tack-up sutures. Immediately upon recognition of an injury, the field should be flooded with saline irrigation, and the patient should be placed in the Trendelenburg position in order to minimize the risk of venous air embolism.[20]

In the event of an injury, several techniques for repair exist: for example, direct primary repair, dural tack-up suturing, dural flap, autologous patch graft, and ligation.[21] The repair technique selected depends on the extent and location of the injury. Most typically, a rapid application of closely spaced tack-up suturing along with gelatin sponges is sufficient for hemostasis. Regardless of the technique selected for repair, particular attention must be paid postoperatively to monitor for cerebral venous sinus thrombosis and its complications.

Postoperative Hemorrhage

Even in the absence of intraoperative sinus injury, hemorrhage can be encountered either intraoperatively or postoperatively and may even necessitate reoperation. Hemorrhage may be either intra- or extra-axial; such as in the case of ipsilateral subgaleal hematoma, contralateral subdural hematoma, or hemorrhagic transformation of infarct. Retrospective series report a postoperative hemorrhage rate of 20% to 50%.[22,23] As mentioned previously, paying close attention to hemostasis at the conclusion of the case and taking preventative measures such as dural tack-up sutures, electrocautery, thorough inspection of the operative field prior to definitive closure, and drain placement may minimize the risk of postoperative ipsilateral hematoma formation.

Standard postoperative ICU management should include serial neurologic examinations to identify deterioration early, and it is the authors' practice to obtain a postoperative noncontrast

CT scan soon after the conclusion of the procedure, either immediately up exiting the operating room or shortly thereafter.

Seizures

Postoperative seizures may occur due to cortical irritation, contusions, or underlying diagnosis, emphasizing the importance of anticonvulsant prophylaxis in high-risk patients. Patients undergoing DC are already at high risk for seizures due to the presence of stroke or severe TBI, with series reporting an incidence of epilepsy of 20% to 50% following craniectomy for these pathologies.[24,25]

Trephination Syndrome and Hydrocephalus

Delayed complications can arise weeks to months postoperatively and include hydrocephalus, syndrome of the trephined, and extra-axial fluid collections. Hydrocephalus may develop due to persistently impaired CSF absorption or obstruction of CSF pathways following cerebral herniation, dural manipulation, or cortical injury.[26] Subdural hygromas may additionally form secondary to CSF accumulation beneath the dural repair. The syndrome of the trephined is a poorly understood condition characterized by neurologic deterioration and cognitive changes after craniectomy.[27]

Cranioplasty is central to the management of trephination syndrome, extra-axial hygroma, and, in many cases, hydrocephalus.[22,28,29] In patients who require hospital-hospital transfer or facility placement prior to cranioplasty, a plan for cranioplasty timing, indications for accelerated cranioplasty, and location of own bone or custom implant with plan for transport if needed urgently should be communicated to the patient's receiving facility or hospital. In patients who are expected to require permanent CSF diversion postcraniectomy, several prior studies have demonstrated poorer outcomes in simultaneous cranioplasty and ventriculoperitoneal (VP) shunt placement, largely driven by an increased rate of infection and epidural hematoma.[30,31] Furthermore, in patients undergoing staged procedures, shunt placement prior to cranioplasty is associated with worse outcomes[31] and is recommended against in consensus statements[32] and systematic review.[33] For this reason, the authors advocate for cranioplasty prior to VP shunt placement if the latter is expected to be required.

SUMMARY

Craniectomy remains a critical, life-saving intervention for patients with refractory intracranial hypertension and should be in the operative armamentarium of every neurosurgeon. A thorough understanding of surgical anatomy, careful preoperative planning, meticulous operative technique, wide decompression, and vigilance during postoperative monitoring are essential for optimizing outcomes. The procedure carries a significant risk of complications that can impact short-term and long-term outcomes. By adhering to these principles, neurosurgeons can maximize the therapeutic benefit of the DC while minimizing complications.

CLINICS CARE POINTS

- External landmarks can be used to guide an incision that will accommodate the needed 12cm (vertical) by 15cm (horizontal) craniectomy. A large incision, larger than the planned craniectomy, can reduce stress on the incision at cranioplasty.
- Identification of bony sutures intraoperatively can avoid dural venous sinuses.
- Existing dural sinus injury, typically associated with skull fractures, can be uncovered with the craniectomy.
- Control of bleeding intraoperatively requires identification of the type of bleeding and immediate appropriate treatment.
- A stellate dural incision taken to the bone edges can avoid parenchymal injury from swelling against fixed dural edges.

DISCLOSURE

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