Management of Skull Fractures and Calvarial Defects

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Abstract

Scalp and calvarial defects can result from a myriad of causes including but not limited to trauma, infection, congenital malformations, neoplasm, and surgical management of tumors or other pathologies. While some small, nondisplaced fractures with minimal overlying skin injury can be managed conservatively, more extensive wounds will need surgical repair and closure. There are many autologous and alloplastic materials to aid in dural and calvarial reconstruction, but no ideal reconstructive method has yet emerged. Different reconstructive materials and methods are associated with different advantages, disadvantages, and complications that reconstructive surgeons should be aware of. Herein, we discuss different methods and materials for the surgical reconstruction of calvarial defects.

Keywords

- scalp soft tissue repair
- dural repair
- skull fractures
- calvarial reconstruction

Scalp and calvarial defects can result from a myriad of causes including but not limited to trauma, infection, congenital malformations, neoplasm, and surgical management of tumors or other pathologies.[1] Up to 68% of falls and 75% of blunt object blows to the head have been associated with calvarial fractures.[2,3] While some small, nondisplaced fractures with minimal overlying skin injury can be managed conservatively, more extensive wounds will need surgical repair and closure. Herein, we discuss different methods and materials for the surgical reconstruction of calvarial defects.

Surgical Repair

Indications

Some fractures and cranial defects will require surgical intervention and should not be managed conservatively. In the case of nondisplaced fractures, simple soft tissue reconstruction or rearrangement may be all that is necessary to close the wound and/or stop a cerebrospinal fluid (CSF) leak. For larger wounds with missing calvarial bone, multilayer replacement of bony and soft tissue components is necessary. If there is a significant leakage of CSF, this should be addressed with dural repair or CSF diversion (through a lumbar drain or ventriculoperitoneal shunt) before cranial repair is performed.[1] Dural tears and persistent CSF leaks are associated with an increased risk of meningitis (8.6–41%) that increases with the persistence of the leak.[4] A repaired CSF leak has a comparatively lower cumulative risk of meningitis (7%). Next, expanding pneumocephalus necessitates immediate management, which can be accomplished with cranioplasty. Finally, wounds with missing dural, calvarial, or scalp tissue require surgical closure and replacement.

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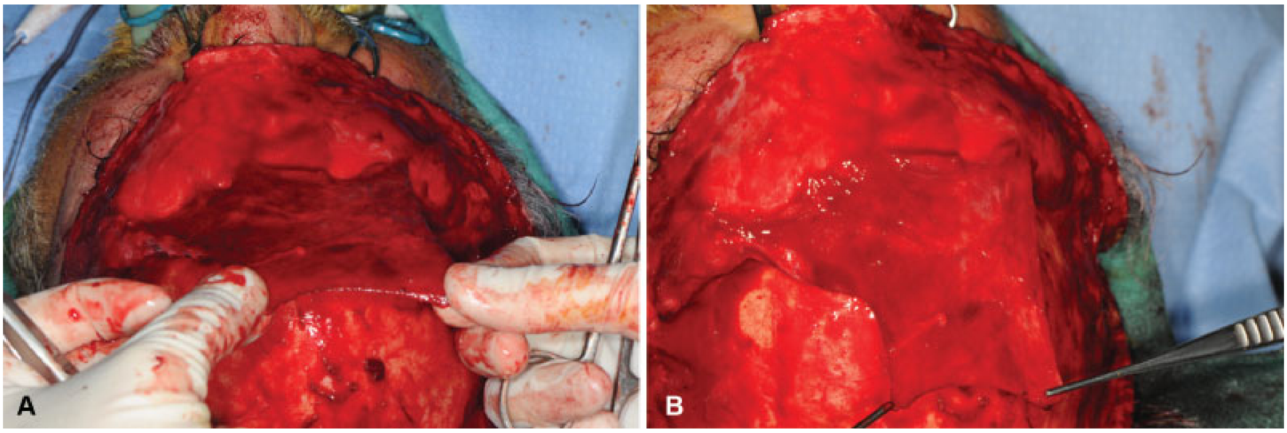

Fig. 1 (**A**) Coronal exposure of calvarium with the elevation of the pericranial flap. (**B**) Depiction of the pericranial flap on tension in situ showing the extent of potential coverage.

Dural Repair

Tears in the dura should be repaired in a layered and watertight fashion before proceeding with calvarial repair to mitigate the risk of CSF leak and restore normal intracranial homeostasis. A pericranial flap, either pedicled or free, provides thin, pliable, yet robust tissue for dural closure (►**Fig. 1A**, **B**). Often it is used in combination with synthetic dural materials (refer to Jaskolka and Olavarria[1]). Use of pericranium for dural reconstruction can also aid IN calvarial repair, as it has osteoconductive properties.[1]

Calvarial Repair

Reconstruction of calvarial defects has two main goals: (1) restoration of a barrier between cranial contents and external elements and (2) cosmetic restoration of the contour of the skull and its overlying tissue.[5] Recreation of the calvarial barrier has been shown to improve CSF dynamics.[6,7] Furthermore, inadequate functional closure and repair is associated with persistent headaches, fatigue, dizziness, and psychological distress.[5]

There are many materials that can be used for successful cranial reconstruction, both autologous and synthetic. The ideal material is strong enough to protect intracranial contents, malleable to recreate the natural contour of the skull, relatively lightweight, and capable of osseous integration with native calvarium. Furthermore, it should be durable over time, resistant to infection, inflammation, and biological breakdown, and should allow artifact-free imaging evaluation.[1,8,9] An ideal material has yet to be found. No single material or reconstructive method has proven superior to others, and, thus, a variety of methods and materials are used for cranioplasty in modern times.

Autologous Bone

Autologous reconstruction has, historically, been the gold standard for skull defects.[8] There are many sources of "spare" bone to use for autologous reconstruction. Split-thickness calvarium and rib are common, though iliac crest, pelvis, and tibial bone have also been described.[8,10] Advantages of autologous bone include the ability for osteogenesis. It can be safely used in pediatric patients.[1] Furthermore, given its native source, it is unlikely to incite inflammation and has a small risk of infection. In case infection is present, autologous bone can be salvaged through debridement, whereas synthetic grafts would require complete removal and replacement.[5]

Disadvantages of autologous bone include donor-site morbidity.[5] Care must be taken when harvesting a split-calvarial graft not to damage the inner table or sagittal sinus. In some cases, a full-thickness craniotomy can be created, the harvested bone split into inner and outer tables after harvest, and then the donor site reconstructed with the inner table at the same time the outer table is used for a different site.[1] A full-thickness harvest can allow larger sections of graft bone to be harvested intact and may be suitable for the reconstruction of slightly larger defects, but, in general, autologous calvarial bone cannot be used to fully reconstruct very large cranial gaps. Also, the donor bone can be difficult to shape and cannot always recreate the natural contour and curve of the skull, which can lead to unfavorable cosmetic outcomes. Finally, while osteogenesis, osteoconduction, and osteoinduction can occur, bone resorption is also possible.[1] Some studies suggest that the membranous bone undergoes less resorption than the endochondrial bone.[2,11]

There are also disadvantages of using autologous ribs. Harvest of split-thickness rib can cause chest wall instability or violation of the pleura, albeit rarely. Furthermore, these grafts are also limited by their size; they may not provide enough tissue for the reconstruction of larger calvarial defects and are prone to resorption over time, the extent of which is variable.

In the senior author's experience, rib is best used in pediatric patients, whereas the iliac crest can better recreate the curve of the calvarium in adults.

Alloplastic Materials

Alloplastic implants have essentially replaced autologous bone as the modern gold standard reconstructive material for calvarial defects given that they lack donor-site morbidity and can be very precisely shaped for optimal and individualized reconstruction. There are many types of synthetic materials with many advantages. First, they can be made to cover any size defect and can be precisely shaped to exactly recreate

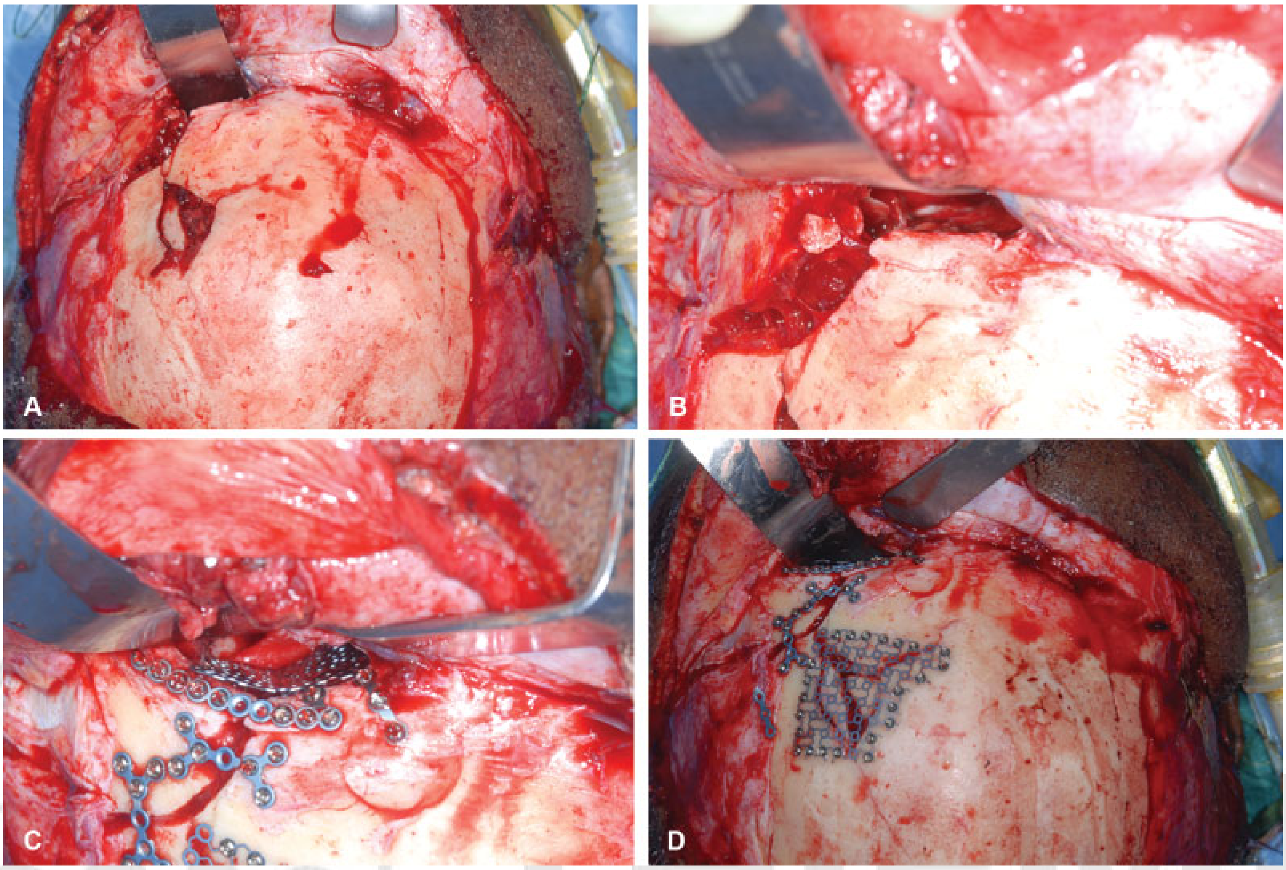

Fig. 2 (**A**) Calvarial fracture extending to the frontal sinus and left orbital roof, with displacement of the fracture segment. (**B**) View of the comminuted displaced frontal sinus and orbital roof component of the fracture, (**C**) Reconstitution of the sinus wall/orbital roof as well as multiple skull fractures with a combination of titanium mesh and plating. (**D**) Internal fixation of fracture segments with the application of well-contoured titanium mesh overlying calvarial fracture fragments.

the natural contour of the calvarium. Furthermore, they are not prone to resorption and can be very durable over time. Common synthetics used for calvarial reconstruction today include titanium mesh, polymethylmethacrylate (PMMA), hydroxylapatite, and polyetheretherketone (PEEK).[5]

Titanium Mesh

Titanium is easily malleable, noncorrosive, and relatively inert, with a minimal risk of infection or inflammation.[12,13] It has the highest biomechanical strength of any alloplastic implant used today, which confers maximum stability and resistance to future injury.[8] Furthermore, it can be specifically customized and shaped preoperatively for an individual patient to aid in intraoperative implantation and long-term cosmesis (►**Figs. 2A–C** and **3A**, **B**).[14] Patient-specific implants are relatively expensive compared with titanium sheets shaped by hand or autologous bone. Also, a titanium implant can cause significant scatter and artifact on computed tomography (CT) and magnetic resonance

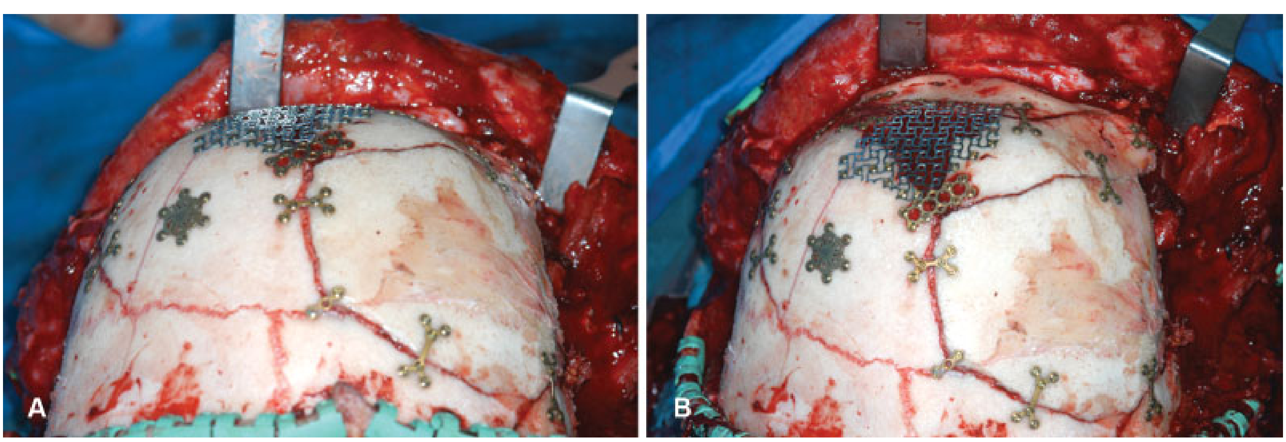

Fig. 3 (**A**) Use of titanium mesh and multiple miniplate and box-plate configurations in the fixation of fracture components; note contour of mesh with native calvarium. (**B**) Titanium mesh application to avulsed calvarial segment with the surrounding miniplate fixation.

imaging (MRI), potentially limiting the quality of postoperative imaging surveillance of disease.[8] Finally, titanium mesh requires significant tissue coverage superficial to the implant, as simple skin coverage is associated with high rates of exposure and extrusion.[15] The risk of extrusion can be mitigated by rotation or replacing muscle over the titanium implant, or through lipotransfer.[16]

Polymethylmethacrylate

Polymethylmethacrylate is a synthetic polymer of acrylic acid that, when originally mixed, forms a paste that can be shaped to fit any defect before hardening. It is the most frequently used allogenic cranioplastic material[17,18], and it is radiolucent and nonferromagnetic.[1] It produces less artifact on CT imaging than titanium or hydroxylapatite[19] and is safe for postoperative MRI.[1] It can withstand physical stresses similar to native bone, and it is stable and inert and is associated with minimal inflammation.[20,21] When initially mixed, PMMA undergoes an exothermic reaction and can become very hot, around 70°C[22], and has the potential to burn tissue if not constantly irrigated with cool saline or removed from tissue contact all-together while hardening.[8] PMMA implants can be prefabricated in a patient-specific fashion to avoid this risk. When healing, a fibrous capsule typically develops around PMMA implants; they do not integrate with surrounding tissue.[1] As such, PMMA prevents bony ingrowth and is not a good choice for pediatric calvarial reconstruction. Furthermore, PMMA is also associated with a 5% rate of infection and is prone to fracture.[5] To mitigate the risk of fracture, PMMA can be applied on top of a titanium mesh for improved stability and strength.[5]

Medpor (Porex Surgical Inc.) is a polymer similar to PMMA that is composed of high-density polyethylene. Unlike PMMA, it can allow tissue ingrowth, which enhances its structural stability and minimizes its risk of infection.[1]

Hydroxylapatite

Hydroxylapatite is another synthetic material useful in calvarial reconstruction. It is both biocompatible and osteoconductive; it tends to remodel bone over time.[8] Hydroxylapatite cement, or "bone cement," is a puttylike substance that can be molded to fit various calvarial defects, but it is not suitable and a standalone material for the reconstruction of large defects.[8] It can be combined with titanium mesh, however, for improved rigidity and strength and to cover larger defects ($> 25\,cm^2$).[23] It is a porous substance that allows bony ingrowth, and it undergoes isothermic hardening; there is no risk of tissue burn injury with its application.[8] It can be used superficial to a different reconstruction to aid in bone shaping, contouring, and camouflage of partial-thickness reconstructions.[1] Furthermore, it is capable of expanding with a growing calvarium, and, thus, it is an option for pediatric reconstruction.

Hydroxylapatite has a relatively high rate of complications when used as a single-substance calvarial reconstruction material, specifically infection and instability, compared with other materials.[24] As such, it should be avoided in the reconstruction of the frontal sinus, beneath a coronal skin incision, or in patients who will undergo postoperative radiotherapy.[25] Hydroxylapatite is prone to fragmentation over time, however, and as such is best suited to smaller defects.[26] Also, hydroxylapatite should never be placed directly on the dura.[1] Similarly, because of its risk of infection, it should not be placed in contact with the frontal sinus or aerodigestive tract.[1]

Polyetheretherketone

Polyetheretherketone implants are made from an inert semicrystalline powder that develops strength similar to that of the cortical bone.[5,27] It can be easily made with a 3D printer, thus providing a feasible patient-specific implant. It confers minimal artifact on imaging after implantation and is very lightweight. It does not allow osseointegration or expansion with bony growth, however, and the literature on its long-term results and durability is currently limited.[8]

Technologic Navigation and Modeling

Advancements in intraoperative navigation and preoperative specific implant development over the past two decades have changed the ease with which large calvarial defects are reconstructed and have improved their long-term cosmesis. While "freehand" reconstruction is often adequate for small calvarial defects, optimal cosmetic reconstruction of larger defects requires precise shaping of the skull, either with intraoperative navigation with mirroring, a patient-specific implant, or both.[8] Creating a perfect patient-specific implant can be difficult for immediate reconstruction after extirpation of a malignancy, as the exact bony defect cannot be predicted. In these cases, patients may require two separate surgeries to achieve the best end result.[8]

Soft Tissue Repair

All calvarial repairs require complete soft tissue coverage of the overlying scalp to complete the reconstruction. In some cases, primary closure or local tissue rearrangement is possible. Also, smaller defects can be allowed to heal by secondary intention, perhaps aided by a synthetic wound matrix. In general, skin-only soft tissue closure should be avoided, as it is associated with increased rates of implant extrusion.[16] Lipotransfer can help mitigate this risk. Tissue expanders can increase the amount of available local tissue to cover a wound, but they can be tedious and time-intensive, requiring multiple visits over several weeks prior to eventual reconstruction. They are also associated with dermal and subcutaneous thinning, which can be cosmetically unappealing and may risk implant exposure. Thus, for large soft tissue defects, free tissue transfer is an excellent option. A radial forearm free flap (RFFF) can provide a large amount of thin, pliable tissue with a long pedicle for anastomosis to the superficial temporal vessels or even neck vessels. Harvest of a free latissimus dorsi muscle flap can allow tissue coverage of near-complete scalp soft tissue defects. The muscle can then be covered with a skin graft. Pedicle length of a latissimus dorsi is shorter than an RFFF and may require pedicle extension through vein grafting to reach donor vessels in the neck.

Postoperative Care

Patients should be evaluated frequently in the few weeks after reconstruction and then at increasing intervals. Acute complications can be severe and are best managed if caught early, but late complications can arise several years after initial reconstruction; therefore, long-term follow-up is important. Not surprisingly, in general, larger and more complex reconstructions are more likely to develop complications than smaller, simpler reconstructions.[1]

Acute Complications

The most severe acute complications arise from neurologic injury during or before surgery and include seizures, hydrocephalus, CSF leakage, and significant swelling or bleeding causing rising intracranial pressures.[1] Some seromas and hematomas can be observed and treated medically with longer-duration antibiotic therapy, but large fluid collections may require aspiration or other drainage.

Cerebrospinal fluid leak can also be managed conservatively, initially. Often, postoperative CSF leaks will resolve within a few days with conservative management including elevation of the head of the bed and sinus precautions (stool softeners, no sneezing, no bending over).[28] Intracranial pressure should be maintained within a normal range ($<$ 20 mm Hg).[1] Occasionally, acetazolamide can be given or a lumbar drain or ventriculostomy be placed to decrease intracranial pressure and allow healing and sealing of the fistula.[28] A persistent leak requires surgical closure, however, to mitigate the risk of meningitis.[4] Elevated intracranial pressure can also contribute to bone resorption and poor healing at the craniotomy site.[1] A multilayer closure is advantageous in preventing and managing CSF leak. Vascularized tissue is preferable, and local tissue transfer and free tissue transfer have been demonstrated to have fewer complications than regional tissue transfer.[4,29] In some cases, when local tissue transfer has failed, intracranial free tissue transfer, such as from a fascia-only radial forearm flap or muscle-only rectus flap, lends the best protection against persistent CSF leak.[4]

Delayed Complications

Implant infection, extrusion, and exposure can occur years after the initial reconstruction. Similarly, poor integration of autologous materials with resorption can take months to arise. Also, reconstruction materials can migrate over time, and patient dissatisfaction with the cosmetic appearance of the reconstruction can develop.

Conclusions (Counseling Recommendations, Management Algorithm)

Overall, the repair of dural, calvarial, and scalp defects should include a multilayer water-tight closure with intra- and postoperative antibiotic prophylaxis for infection. Patients should be monitored frequently in the acute postoperative period and then at increasing intervals for several years after surgery to observe for complications. We propose the management algorithm in ►Fig. 4 to aid in intraoperative reconstruction. First, if there is dural injury, a pericranial flap and adjuvant dural synthetic materials should be used to seal the wound. Next, the calvarial bone should be replaced. Small wounds ($< 6\,cm^2$) should be reconstructed with split-calvarial bone or, for

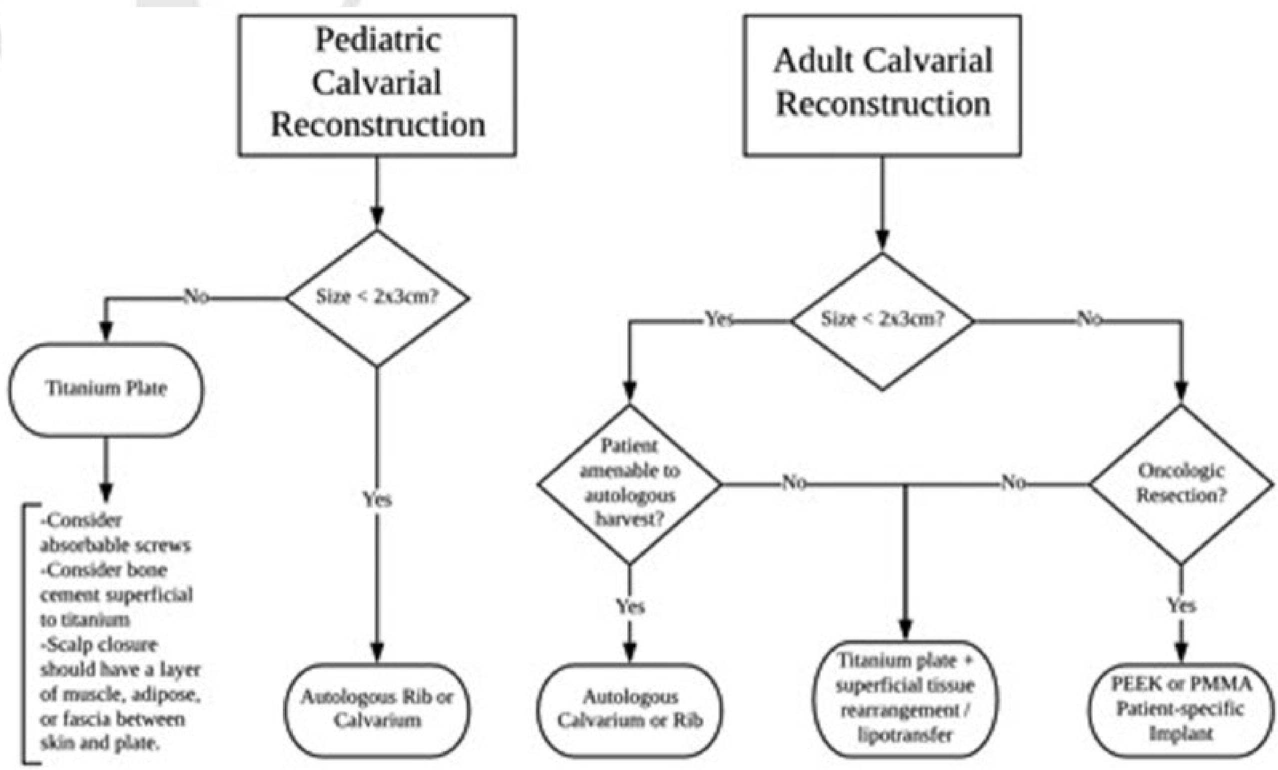

Fig. 4 Algorithm for the management of pediatric and adult calvarial defects.

children, autologous rib. Larger wounds in children should be closed with titanium plates, perhaps covered by Medpor or hydroxylapatite. Muscle, adipose, or other tissue should be layered beneath the skin for the final soft tissue closure. Larger wounds in adults can be optimally approached with patient-specific prefabricated PEEK or PMMA implants; these are preferable in oncological resections when postoperative imaging will be needed for disease monitoring. Titanium plates, which are more feasible, can also be used, but they should be covered by adequate soft tissue.

Conflicts of Interest
None.

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