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Cost-effective 3D reconstruction of skull defects

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ABSTRACT

Cranial defects following decompressive craniectomy or tumour resection can result in major cosmetic, protective, and neurological deficits, including the "syndrome of the trephined". While patient-specific PEEK and titanium implants offer excellent anatomical and functional results, their high-cost limits accessibility in many healthcare systems. This study describes a cost-effective cranioplasty technique that uses in-house 3D-printed skull models or templates to pre-contour standard titanium mesh implants. We report three representative cases of large cranial defects secondary to tumour resection, complex infection with decompressive craniectomy, and severe traumatic brain injury. In each case, preoperative CT data were used to generate a patient-specific 3D model, which guided precise shaping of the implant and restoration of the native cranial curvature. This workflow combines the affordability and availability of conventional materials with the accuracy of computer-aided planning, minimises intraoperative modelling time, and reduces the need for expensive industrial patient-specific implants. Our early experience suggests that 3D-assisted contouring of standard implants is a robust and accessible strategy for restoring cranial integrity and improving cosmetic outcomes in resource-constrained settings.

1. INTRODUCTION

Cranioplasty is one of the oldest neurosurgical procedures, dating back to antiquity. Historically performed mainly to protect the underlying brain, modern cranioplasty serves three critical functions: cosmetic restoration, mechanical protection, and the restoration of physiological hydrodynamics and intracranial pressure [1]. The latter is particularly relevant in the "syndrome of the trephined" (sinking skin flap syndrome), in which atmospheric pressure acting on an unshielded brain leads to neurological deterioration, headaches, and focal deficits [2]. Once cerebral edema has subsided and the patient survives the initial insult, the resulting cranial defect frequently necessitates secondary reconstruction to restore both appearance

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decompressive craniectomy,
skull reconstruction

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and neurophysiological function [3]. Beyond these structural and hemodynamic effects, restoring cranial integrity may also facilitate recovery of higher-order cognitive and language functions, in line with contemporary neurolinguistic and cognitive perspectives on brain plasticity [14].

The choice of material for cranioplasty remains a matter of debate, balancing biocompatibility, mechanical strength, aesthetic outcome, radiological behavior, and cost [4]. Autologous bone has long been considered the gold standard, but its use is limited by high resorption rates and infection risk, often necessitating flap disposal [5]. Synthetic alternatives such as titanium mesh, PEEK, and PMMA have therefore become indispensable. Titanium mesh is widely used due to its high strength, biocompatibility, and low infection rates compared to autologous grafts [6]. However, conventional intraoperative contouring of titanium mesh for large or complex defects is technically demanding and may result in suboptimal cosmetic results or sharp edges that risk scalp breakdown. Patient-specific implants (PSI) manufactured from PEEK or titanium provide excellent anatomical accuracy but are expensive and frequently inaccessible in low- and middle-income settings [7,8].

Three-dimensional (3D) printing has emerged as a promising strategy to bridge this gap. Using preoperative CT imaging, a virtual model of the skull and defect can be generated; from this, 3D-printed anatomical models or templates enable preoperative or extracorporeal shaping of standard materials (titanium mesh or PMMA), thereby reducing cost while preserving the advantages of patient-specific reconstruction [9–11]. Moreover, casting or contouring the implant away from the brain avoids the exothermic polymerization risks associated with intraoperative PMMA molding [10].

Infection risk and optimal timing of cranioplasty remain crucial considerations. Many authors advocate reconstruction 3–6 months after craniectomy to allow for resolution of brain edema and scalp healing, although earlier cranioplasty (within 12 weeks) may help mitigate the syndrome of the trephined in selected patients [12].

In this context, the aim of our study is to describe an in-house, cost-effective 3D-assisted cranioplasty workflow using 3D-printed skull models or templates to contour standard titanium mesh implants, and to illustrate its application through three representative cases of large cranial defects of different etiologies.

2. Methods / 3D-assisted cranioplasty workflow

Preoperative thin-slice skull CT scans were exported in DICOM format, processed in dedicated 3D reconstruction software ([software name]) for segmentation of the cranial vault and defect, and mirrored from the intact side to restore native curvature. The resulting 3D model was exported as an STL file and printed on a desktop FDM 3D printer using PLA filament, either as a full-scale skull or local template depending on defect morphology and surgeon preference. After sterilization according to institutional protocol, the models were used pre- or intraoperatively to contour standard titanium mesh on the back table, ensuring close adaptation to the cranial curvature and smooth edges. All procedures were performed by the same neurosurgical team, and demographic, radiological, operative, and early clinical and cosmetic outcomes were prospectively recorded.

3. Case reports

3.1. Case 1 – Infectious etiology with decompressive craniectomy

A 20-year-old male presented to the Emergency Department with intense headache and left-sided hemiparesis. He had a known history of frontal sinusitis. Preoperative imaging identified a life-threatening intracranial infectious process consisting of a right frontal subdural empyema, a parasagittal subdural empyema, and a left epidural abscess. Due to the severity of the infection and intractable intracranial hypertension, the patient underwent a life-saving decompressive craniectomy with evacuation of the empyemas and cranialization of the frontal sinus. The craniectomy was extended to allow adequate decompression of the edematous brain.

After complete resolution of the infection and clearance for reconstruction, restoration of the cranial vault was prioritized. Given the patient's young age and the extensive fronto-temporo-parietal defect, achieving an optimal cosmetic result was essential. To avoid the prohibitive costs of PEEK PSIs, a cost-effective 3D-assisted reconstruction was chosen. A patient-specific 3D anatomical model of the skull defect was generated from CT data and printed in PLA. This model served as a template for shaping a titanium mesh implant preoperatively on the back table. This hybrid technique combined the affordability of standard titanium mesh with the precision of computer-assisted design and eliminated many of the irregularities associated with free-hand bending.

Postoperative CT demonstrated restoration of the cranial contour, with the implant perfectly adapted to the bone margins and providing rigid protection of the underlying brain. The herniation seen on preoperative imaging was reversed. The patient was discharged with improved neurological status, and his hemiparesis resolved over the following weeks. At 6-month follow-up, there were no implant-related complications or infections.

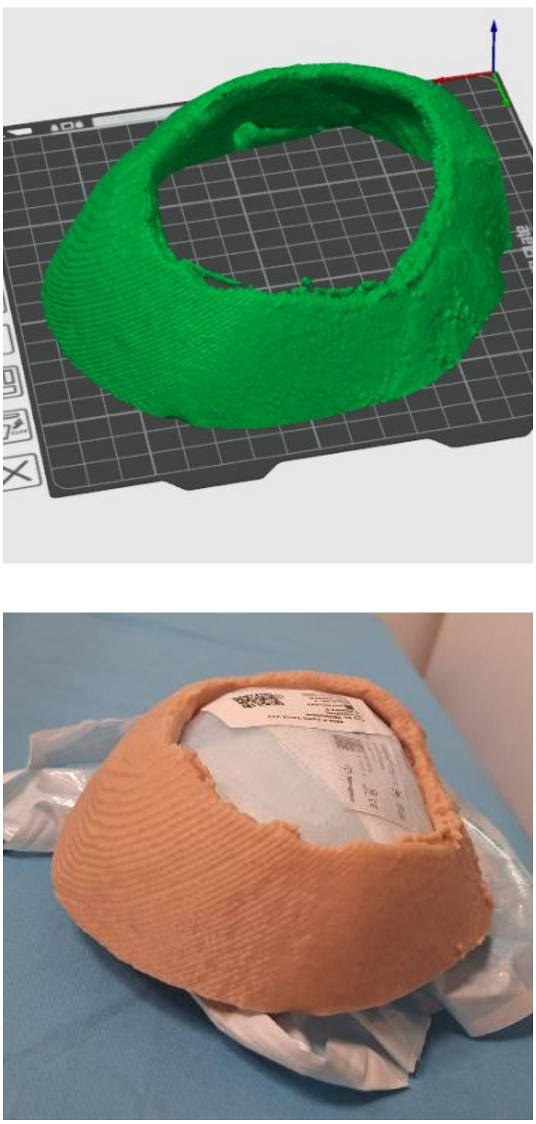

Figure 1. 3D-printed mold on which the titanium mesh was shaped to match the patient-specific cranial curvature.

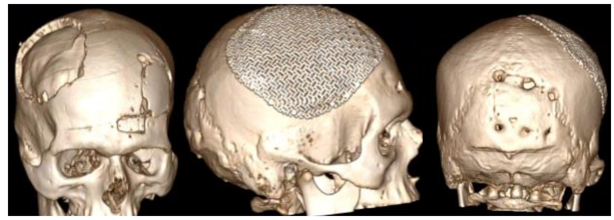

Figure 2. Preoperative and postoperative CT images demonstrating cranial reconstruction with a titanium mesh implant.

3.2 Case 2 – Tumor-related cranial defect

A 71-year-old male was admitted to the Neurosurgery Department following an episode of right-sided focal motor seizures that secondarily generalized. On admission, the patient was conscious and cooperative (GCS 14) but reported headache and vertigo. Native and contrast-enhanced CT scans revealed a large, mixed-density parasagittal mass in the left fronto-parietal region. Imaging showed an extra-axial lesion with nodular components and a fluid element, exerting mass effect with compression of the left lateral ventricle. The tumor infiltrated the calvarial bone and the superior sagittal sinus, necessitating removal of the involved bone flap during surgery. [13]

To address the resulting cranial defect, a titanium mesh implant was used. The mesh was contoured intraoperatively to replicate the natural curvature of the fronto-parietal region and to achieve a precise fit with the surrounding bone margins. Postoperative CT confirmed appropriate implant positioning, restoration of the cranial vault, and a symmetrical aesthetic profile. The postoperative course was uneventful. The patient was discharged in good general condition, without new neurological deficits, and with a highly satisfactory cosmetic result.

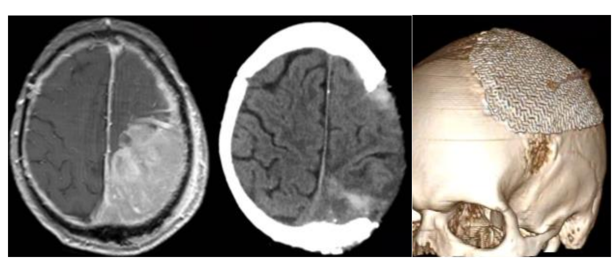

Figure 3. (left) Preoperative contrast-enhanced MRI demonstrating an intracranial mass with intraosseous extension; (center) postoperative CT scan following tumor ablation and craniectomy; and (right) 3D reconstruction of the cranial defect with a contoured titanium mesh implant.

3.3 Case 3 – Traumatic brain injury with extensive cranial defect

A 41-year-old male was admitted to the Emergency Department after a scooter accident with polytrauma. On arrival, he was intubated and sedated. Initial CT imaging revealed a devastating craniocerebral injury: a right parieto-temporo-occipital epidural hematoma exerting significant mass effect, an acute fronto-temporo-parieto-occipital subdural hematoma, and a midline shift of approximately 13 mm. Multiple skull fractures involved the parietal and temporal bones.

Emergency surgery was performed with evacuation of the hematomas and a large right-sided fronto-temporo-parietal decompressive craniectomy. Although the life-saving procedure was successful, follow-up CT scans in the subacute phase showed herniation of brain parenchyma through the craniectomy site, progression of edema, and distortion of cerebral architecture. Given the magnitude and irregular morphology of the defect, free-hand intraoperative contouring of a reconstruction implant would have been difficult and prone to cosmetic asymmetry.

Using the patient's CT data, a 3D model of the skull was generated and printed. This model was used preoperatively to precisely pre-contour a titanium mesh implant, matching the patient's individual cranial curvature. Intraoperatively, the pre-shaped mesh required only minimal adjustments and was fixed flush with the bone margins. This approach reduced operative time and provided rigid protection against atmospheric pressure, effectively reversing the sinking skin flap and parenchymal herniation. The reconstruction restored the symmetry of the skull and stabilized the previously herniated brain tissue.

The patient was discharged in good general condition, and his subsequent course was favorable, with progressive neurological improvement and complete recovery at 6-month follow-up, without implant-related complications.

Figure 4. Postoperative CT 3D reconstructions (left and center) and intraoperative aspect (right).

4. Discussions

Reconstruction of large cranial defects is a multidimensional challenge that requires balancing functional restoration, cosmetic outcome, and economic feasibility. In many healthcare systems, particularly those with constrained resources, the high cost of industrial patient-specific implants represents a major barrier to optimal reconstruction. Our case series shows that combining in-house 3D printing with standard titanium mesh allows patient-specific restoration of cranial anatomy while maintaining affordability.

Titanium mesh remains an attractive material due to its mechanical strength, biocompatibility, and relatively low infection rates compared to autologous bone [6]. However, free-hand intraoperative contouring of mesh for large and complex defects is technically demanding and can result in irregular contours, "temporal hollowing," or palpable step-offs. By using 3D-printed models or templates derived from preoperative CT data, we were able to restore the native cranial curvature more reliably. In the presented cases, postoperative imaging confirmed a close anatomical fit and satisfactory cranial symmetry, with results comparable to those reported for high-end PSIs [7–11].

From a cost perspective, 3D-assisted contouring of standard implants offers a substantial economic advantage. The material cost of a 3D-printed PLA model and titanium mesh is typically only a fraction of that of a custom-made PEEK or titanium PSI, while still providing individualized reconstruction. This is particularly relevant in high-risk situations such as infectious etiologies or patients with a history of empyema, where implant removal may be required. In such scenarios, discarding an expensive PSI represents a significant financial loss, whereas replacing a standard titanium mesh contoured on a new 3D model is more acceptable from a health-economic standpoint.

Infection remains one of the most feared complications of cranioplasty, with reported rates between 4% and 12% [7,12]. In our small series, no implant-related infections occurred, including in the patient with a history of intracranial empyema. Although our follow-up is limited, this suggests that

3D-assisted use of standard materials does not carry an inherently higher infectious risk compared with more expensive alternatives, provided appropriate patient selection, timing, and perioperative management are observed.

The present work has several limitations. It is a small, single-center case series without a control group of conventional cranioplasties or industrial PSIs. Follow-up is relatively short, and functional outcomes were not quantified using standardized scales. Furthermore, we did not perform a formal cost-effectiveness analysis, which would be valuable to objectively compare this approach with commercial patient-specific solutions. Nevertheless, our experience supports the concept that in-house 3D printing can meaningfully expand access to individualized cranial reconstruction, particularly in centers where resources are limited but basic 3D printing infrastructure is available.

5. Conclusion

Cost-effective 3D-assisted cranioplasty using in-house 3D-printed models or templates to contour standard titanium mesh implants represents a robust and accessible alternative to expensive industrial patient-specific implants. In our small case series, this approach enabled accurate restoration of cranial anatomy, satisfactory cosmetic results, and adequate protection of the brain, without early implant-related complications. From a risk–benefit perspective, it is particularly appealing in resource-constrained settings and in patients at increased risk of infection, where the potential need for implant removal must be weighed against cost. We advocate the development and integration of simple in-house 3D printing workflows in neurosurgical centers, so that “cost-effective” reconstruction can remain synonymous with “clinically effective” rather than “low quality”.

Table 1. Overview of the three 3D-assisted cranioplasty cases.

Parameter	Case 2	Case 1	Case 3
Age / Sex	71 / M	20 / M	41 / M
Etiology	Parasagittal extra-axial tumor with bone and sinus invasion	Intracranial infection (subdural empyema, epidural abscess)	Severe TBI with acute EDH + SDH and skull fractures
Defect location	Left fronto-parietal	Fronto-temporo-parietal	Right fronto-temporo-parietal
Decompressive craniectomy	No	Yes	Yes
3D printing use	Anatomical model	3D skull model for pre-contouring	3D skull model for pre-contouring
Implant material	Titanium mesh	Titanium mesh	Titanium mesh
Early outcome	Good cosmetic result, no new deficits	Hemiparesis resolved, no reinfection	Restored cranial symmetry, no early complications
Follow-up	3 months, no complications	6 months, no complications	6 months, no complications

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