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Patient Specific Stereolithographic Template Guided Resection Of Skull Bone Tumors

Adashvoev Kh.A.

Republican Specialized Scientific and Practical Medical Center of Neurosurgery, Uzbekistan

Khazratkulov R.B.

Republican Specialized Scientific and Practical Medical Center of Neurosurgery, Uzbekistan

Boboev J.I.

Republican Specialized Scientific and Practical Medical Center of Neurosurgery, Uzbekistan

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Abstract: Background: Although surgical techniques for the treatment of skull bone tumors have advanced considerably, there is still no unified or structured concept that defines the optimal surgical and reconstructive strategy for these lesions. Careful preoperative planning, particularly the digital design of resection margins and the fabrication of patient-specific stereolithographic templates based on MSCT data, offers surgeons the possibility of performing more accurate and aesthetically predictable operations.

Objective: This study aimed to assess the practical benefits of using patient-specific stereolithographic templates to determine the extent of bone resection in patients with skull bone tumors.

Methods: The analysis included 12 patients with skull bone tumors who underwent resection with the assistance of an individually manufactured stereolithographic guide. Each template was generated using three-dimensional CT data, allowing the surgical team to define resection lines with high precision before surgery. The main indication for intervention was aesthetic deformity. Postoperative evaluation involved follow-up CT imaging and assessment of both functional and cosmetic results.

Results: The planned resection boundaries were reproduced intraoperatively with high accuracy in all patients. Eight individuals underwent simultaneous cranioplasty. Implant positioning was performed without technical difficulties, achieving satisfactory symmetry and contour. No postoperative complications were observed, and all patients were discharged in stable condition.

Conclusion: The use of patient-specific stereolithographic templates helped shorten operative time while ensuring radical tumor removal. Immediate cranioplasty allowed for aesthetic restoration of cranial contours and eliminated the need for secondary procedures.

Keywords: Patient-specific template, skull bone tumors, preoperative virtual planning, stereolithography, simultaneous cranioplasty.

Introduction: The surgical management of skull bone tumors remains a challenging and clinically significant issue due to several factors, including the dense structure of the lesions, the complexity of cranial reconstruction, and the frequent extension of tumors into adjacent anatomical spaces such as the paranasal sinuses. Another key difficulty lies in the lack of a unified surgical strategy. Surgeons are often faced with a choice between radical tumor removal—with excision of all affected bone segments and the formation of large cranial defects—or more conservative resection, which aims to minimize complications but may leave residual disease.

Previous studies have shown that both oncological control and cosmetic outcomes have a substantial impact on long-term patient results [1,2]. Benign calvarial tumors typically present as firm, painless masses that may be discovered incidentally in the absence of neurological symptoms [3]. However, these lesions can grow to considerable size, causing mass effect on intracranial structures and resulting in cosmetic deformities. Total surgical excision remains the most effective treatment option, but it inevitably leads to extensive cranial defects, which in turn require additional reconstructive procedures [4,5].

Modern preoperative planning technologies offer new opportunities to address these challenges. Patient-specific stereolithographic templates, designed using CT-based three-dimensional reconstruction, allow surgeons to precisely determine the tumor resection margins. This improves the accuracy of radical resection and provides an optimal fit for the implant, as has been demonstrated in cases of intraosseous meningiomas [7,8]. Similar approaches may also be applied to other skull bone lesions, including osteomas, fibrous dysplasia, and related pathologies.

In our view, the use of patient-specific stereolithographic templates offers clear advantages over traditional surgical techniques by reducing operative time, improving radicality, and optimizing reconstructive outcomes. Minimizing the need for secondary procedures is especially important in patients with complex cranial anatomy and elevated surgical risk. This study aims to contribute additional clinical evidence supporting the growing body of literature on stereolithographic technology in craniofacial surgery.

METHODS

Twelve patients with skull bone tumors operated on at the Republican Specialized Scientific and Practical Medical Center of Neurosurgery between 2022 and 2025 were included in the study. The most common localization of bone tumors was the fronto – orbital region (n = 8), followed by the parietal region (n = 3) and the occipital bone (n = 1). The age of the patients ranged from 12 to 57 years. Eleven patients were female and seven were male. One patient with fibrous dysplasia was diagnosed with McCune–Albright syndrome. The main clinical manifestations in most patients were local tumor-like swelling of the bone tissue with gradual progression over time, leading to cosmetic deformity, as well as local pain and/or headache. In patients with fibrous dysplasia of the cranio-orbital region, functional disorders were also observed, including ocular dystopia, limitation of eye movement, facial and orbital asymmetry, and narrowing of the visual field with decreased visual acuity. In isolated cases, signs of local mass effect on the brain were noted.

All patients underwent neuroimaging studies, including multislice computed tomography (MSCT) with three-dimensional reconstruction. In cases of cranio-orbital involvement, additional brain MRI, ophthalmological examination, and visual field assessment were performed. Based on the obtained DICOM data, preoperative virtual planning was carried out using specialized software to define the resection margins. For each patient, an individual stereolithographic template was produced using 3D printing technology.

Preoperative Planning and Template Fabrication. Preoperative MSCT scans with 0.6-mm slices were obtained using a spiral CT scanner for each patient (Fig.1). The MSCT data were digitally transferred from the scanner console to the planning workstation via the DICOM interface (Digital Imaging and Communications in Medicine). The images were processed using DVISIO software. The surgeon and a medical designer (engineer) performed surgical planning with specialized image processing software. BLENDER software was used to outline the bone tumor resection margins. The surgeon could dynamically modify the resection boundaries as well as the size and shape of the titanium implant using these data. Based on the 3D reconstruction of the MSCT images, virtual removal of the bone lesion was performed along the predefined resection margins using MESHMIXER and RHINOCEROS software (Fig.1). Following this planning stage, a stereolithographic plastic template was fabricated along the edges of the defect using a Creality Ender 3V3SE 3D printer to determine tumor resection margins intraoperatively. In addition, a stereolithographic skull model with a virtually created defect after simulated resection of the lesion was produced on a Creality K1C 3D printer to verify the accuracy of the resection template. All steps were checked and verified on stereolithographic models (Fig.2).

Surgical technique. All surgeries were performed under general anesthesia. A standard skin incision was made around the lesion, and the margins of the tumor were exposed. After skeletonizing the lesion, the sterile stereolithographic template was applied to define the exact resection margins. The unique shape and curvature of the template matched the resection edge like a “key in a lock,” preventing any displacement of the guide and ensuring the accuracy of the planned resection margins. Tumor resection was then performed along the defined borders. In eight cases, the resulting bone defect was reconstructed intraoperatively with a manually shaped titanium implant.

All patients underwent early postoperative CT scans of the skull to confirm the accuracy of tumor resection and the positioning of the implant.

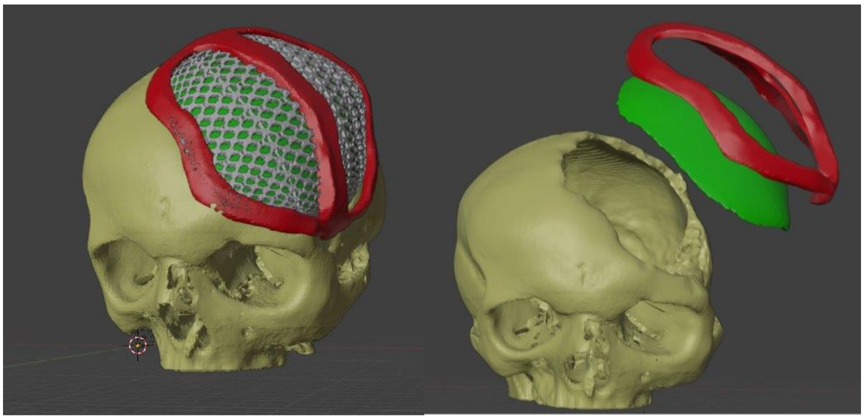


Fig.2. Based on the 3D reconstruction of the MSCT images, virtual removal of the bone lesion along the predefined resection margins using Meshmixer and Rhinoceros software.

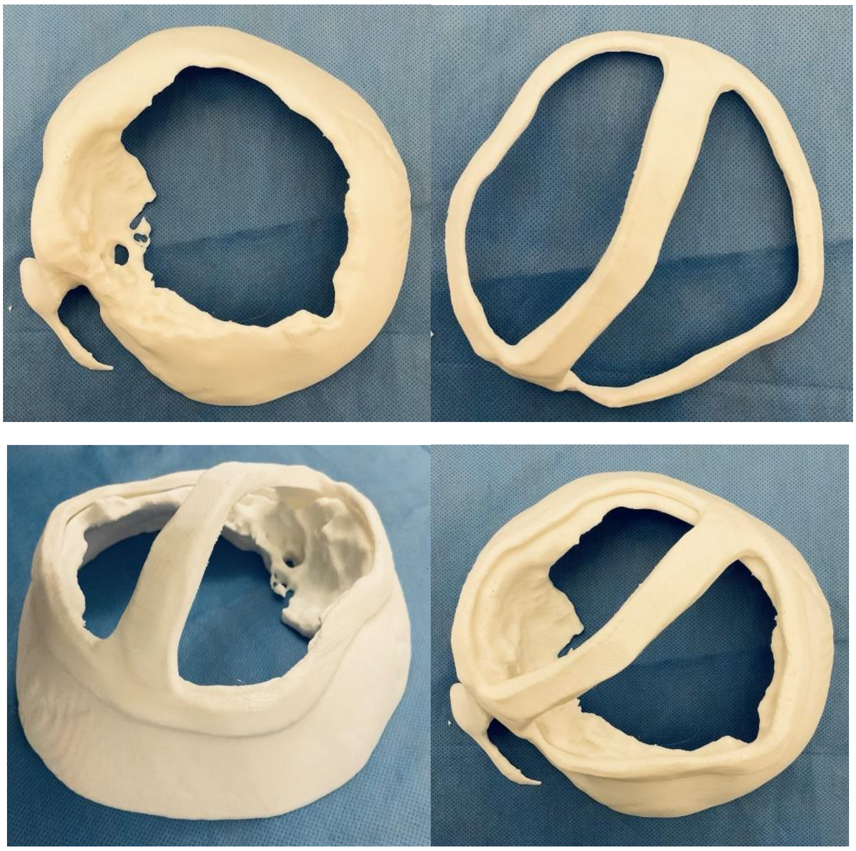


Fig.3. The stereolithographic skull model and stereolithographic plastic template were fabricated along the edges of the defect after simulated resection of the lesion using a Creality Ender 3V3SE 3D printer to determine tumor resection margins.

Case series.

Case 1. Patient A.X. 16y., male. Diagnosis: McCune–Albright syndrome.

The patient presented with complaints of facial deformity, disturbed facial proportions, nasal obstruction, asymmetry of the eyes with left-sided exophthalmos. Clinical examination revealed signs of precocious puberty. Café-au-lait macules were noted on the trunk and neck. The patient also reported pain in the chest region and the left leg. Imaging studies revealed a mass lesion of the left fronto-orbital bone with extension into the nasal cavity. MSCT of the chest and spine demonstrated multiple mass lesions involving the left ribs V5–V11 and the vertebral bodies of T9 and T11. All lesions were located on the left side of the body. The patient underwent planned resection of the mass involving the fronto-parieto-temporo-orbital bones with the use of stereolithographic modeling, followed by cranioplasty with a titanium mesh on the left side. Histopathological examination confirmed the diagnosis of fibrous dysplasia. In the postoperative period, the patient developed subflap hematoma without mass effect, which completely resolved within one month.

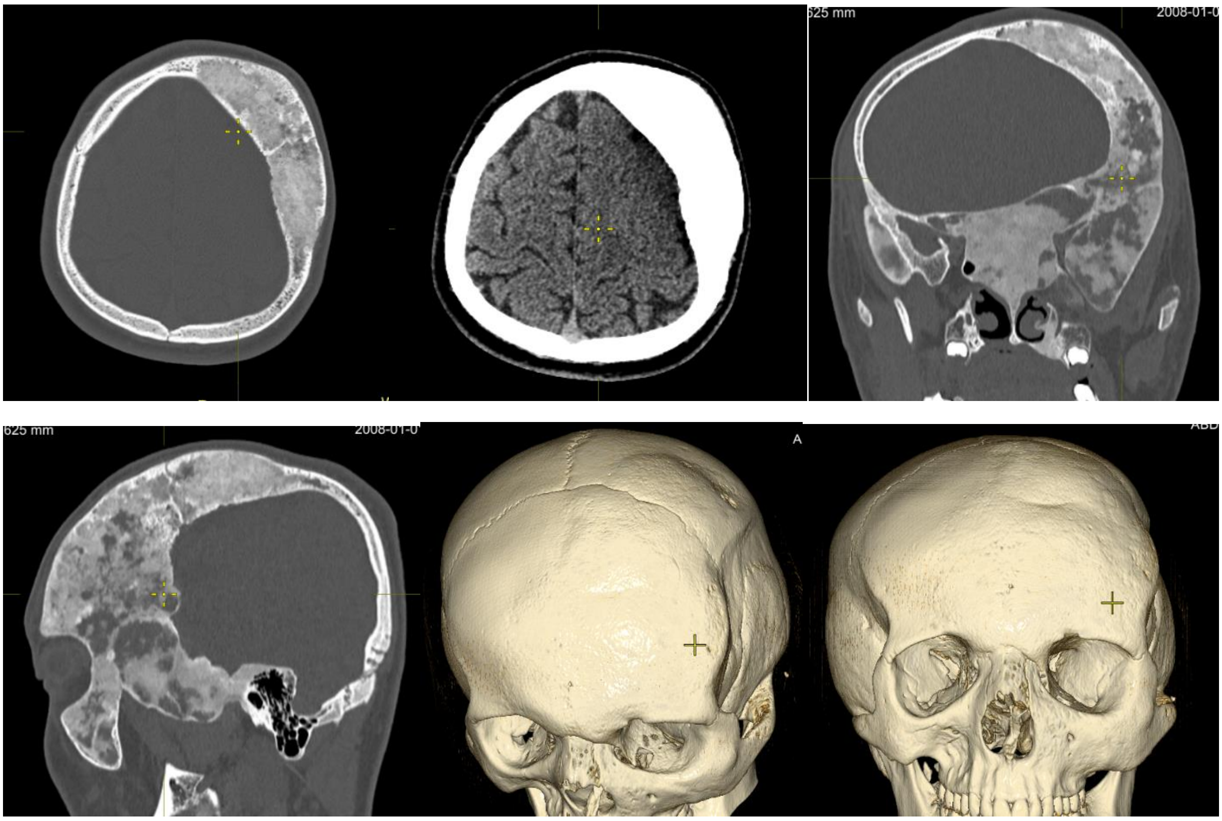
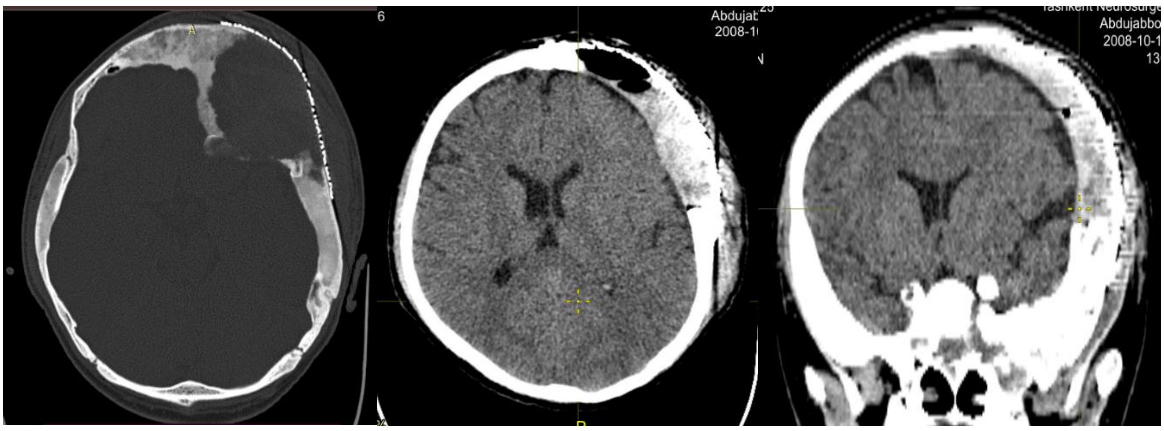


Fig.3. Preoperative MSCT of the brain with 3D skull reconstruction.



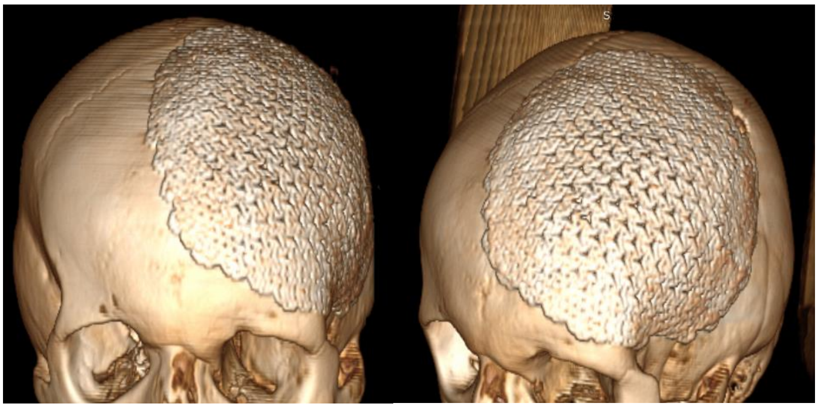


Fig. 4. Postoperative MSCT of the brain with 3D skull reconstruction.

Case 2. Patient R.M., female, born in 1962. Diagnosis: Expansile lesion of the right parietal bone with bony destruction.

The patient presented with complaints of a painful swelling in the right parietal region and persistent headache. Neurological examination revealed no focal neurological deficits. Local findings: a painful swelling was noted in the right parietal region. On palpation, the pain increased; the lesion had a firm to elastic consistency. Preoperative MRI and MSCT demonstrated an osteolytic lesion of the right parietal bone with extracranial extension into the overlying soft tissues and intracranial involvement of the dura mater. The imaging characteristics were highly suggestive of a malignant process, and a decision was made to perform resection of the lesion with immediate cranioplasty using polymethyl methacrylate (PMMA).

The patient underwent en bloc resection of the parietal bone tumor, guided by a stereolithographic surgical template, followed by defect reconstruction with PMMA cranioplasty. Histopathological examination confirmed the diagnosis of Langerhans cell histiocytosis. The postoperative period was uneventful, and the patient was discharged in good clinical condition. No early complications were observed.

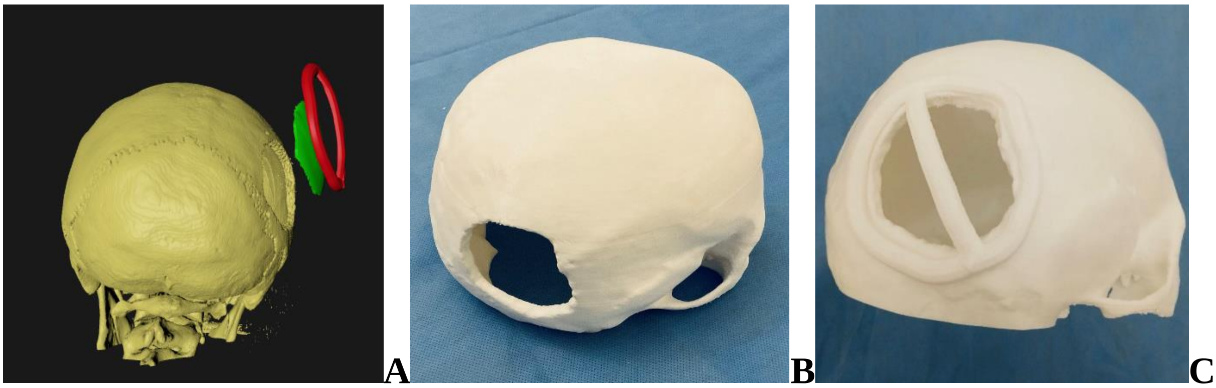


Fig. 5. Virtual removal of the bone tumor along the predefined resection margins (A). The stereolithographic skull model and stereolithographic plastic template were fabricated along the edges of the defect after simulated resection (B,C)

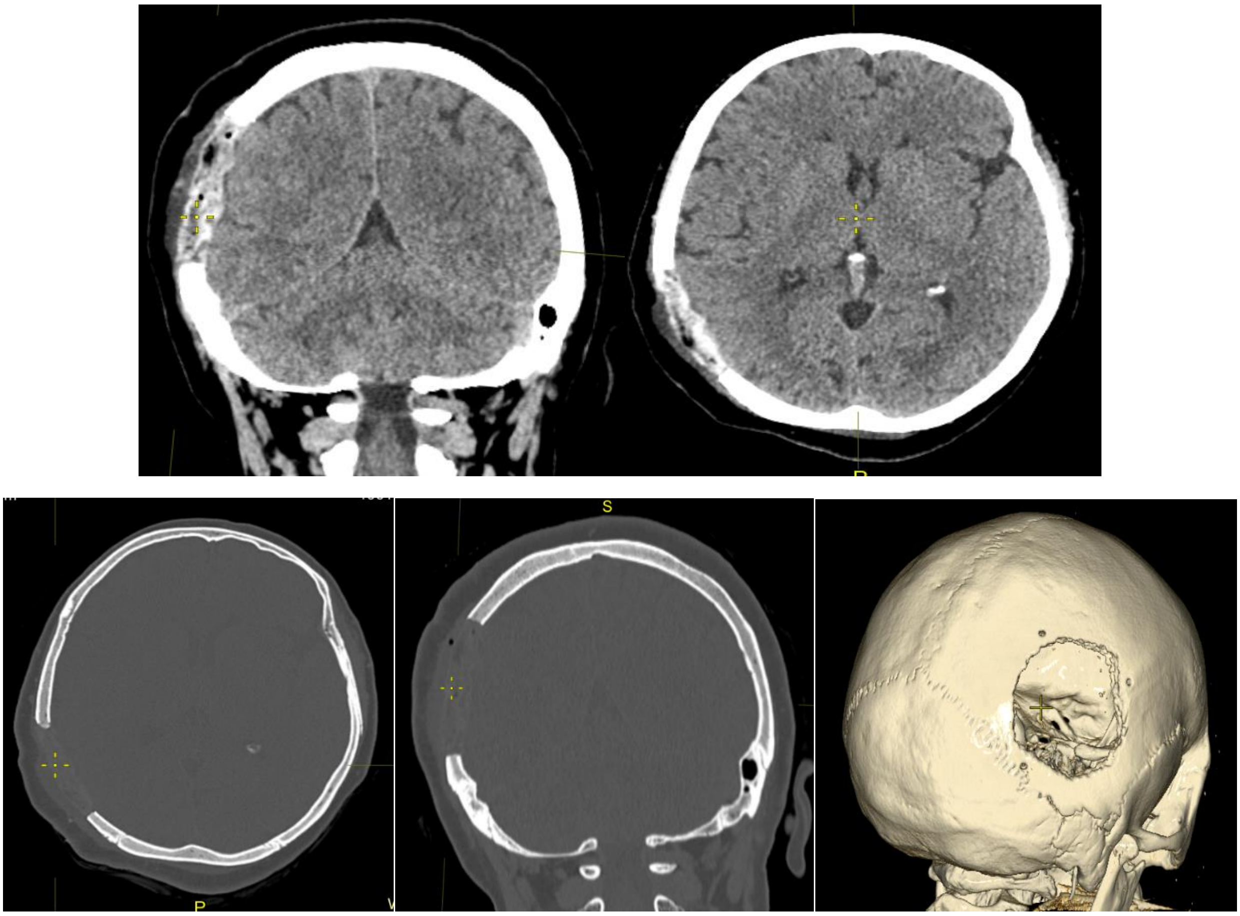


Fig. 6. Postoperative MSCT of the brain with 3D skull reconstruction. Bone tumor is deleted en-block total and performed cranioplasty with PMMA.

RESULTS

All 12 patients successfully underwent surgical resection of skull bone tumors using patient-specific stereolithographic templates. Histological examination revealed fibrous dysplasia (FD) in 4 cases, eosinophilic granuloma in 4, osteoma in 3, and hemangioma in 1 case. One patient with fibrous dysplasia was diagnosed with McCune–Albright syndrome.

Simultaneous cranioplasty was performed in 8 patients using titanium mesh. Adaptation of the implants to the bone defects was precise in all cases, and no additional intraoperative adjustments were required. Postoperative cosmetic results were rated as good or excellent by both surgeons and patients. The mean operative time was 122 minutes (range, 95–165 min), which was significantly shorter compared with procedures performed without preoperative template guidance. No intraoperative complications were observed. The postoperative period was uneventful, with no signs of infection, implant displacement, or neurological deficits.

All patients underwent early postoperative MSCT, which confirmed the accuracy of tumor resection and correct positioning of the implants. During a follow-up period ranging from 6 to 24 months, which included assessment of wound healing, cosmetic outcomes, and the presence of early postoperative complications. The tumor recurrence or late complications were not documented. All patients reported satisfactory functional and cosmetic outcomes.

DISCUSSION

The surgical management of skull bone tumors has historically varied among countries and centers, particularly regarding the extent of bone resection and the optimal reconstruction techniques. The optimal resection margins for skull tumors and the best reconstructive strategies remain a subject of ongoing debate [8]. Bloch and McDermott first described so-called “in situ” cranioplasty for the excision and reconstruction of hyperostotic meningiomas of the calvaria. The same principle can be applied to other skull lesions, including metastatic tumors and fibrous dysplasia [1]. Immediate reconstruction in a single-stage procedure avoids the need for a second surgery and reduces the risks associated with large cranial defects. Early cranioplasty has also been associated with improved neurological recovery, which may be attributed to the restoration of cerebrospinal fluid dynamics and resolution of the "syndrome of the trephined." Today, computer-assisted implant fabrication is a widely accepted option for cranial defect reconstruction [9].

Preoperative virtual planning and the use of CAD/CAM technologies have expanded the possibilities of achieving excellent cosmetic and functional results in skull tumor surgery. These methods eliminate the need for traditional reconstruction or two-stage procedures, which is particularly important in large or complex craniofacial tumors. Simultaneous tumor resection and cranial reconstruction using preoperatively designed stereolithographic (STL) 3D models have already been reported in cases of fibrous dysplasia and intraosseous meningiomas [7,10,11]. Schebesch et al. also described simultaneous tumor resection and craniofacial reconstruction, with the resection modeled on a 3D skull and a corresponding titanium plate fabricated preoperatively.

The combination of intraoperative navigation and STL 3D models provides the best results because navigation can help define the location and size of skin incisions and refine resection margins. In our setting, due to the lack of intraoperative navigation systems, we relied on dedicated virtual planning software. This allowed us to preoperatively determine precise resection margins based on anatomical landmarks, remove the tumor segment virtually, and generate a 3D defect model. A patient-specific titanium allograft was then designed to match the resection margins with high accuracy.

Compared with intraoperative free-hand modeling, this technique offers several advantages [12]. Operative time is significantly reduced, which is particularly valuable in high-risk patients. The pre-shaped implant fits the defect precisely, and virtual 3D modeling allows for accurate determination of resection margins based on anatomy. As a result, cosmetic outcomes are highly favorable. In our series, the models were produced in an in-house 3D laboratory, which also reduced implant fabrication costs. Importantly, this approach minimizes complications by enabling detailed visualization of critical anatomical structures such as dural venous sinuses, thereby reducing the risk of injury during craniotomy [13,14].

Although various complications have been reported after cranioplasty—including graft rejection, infection, or skin and muscle atrophy with exposure of the implant—these events are not specific to simultaneous procedures and can also occur after staged interventions. Furthermore, several studies have demonstrated that early cranioplasty is associated with improved motor and cognitive function [22], supporting the rationale for simultaneous surgery.

A wide range of biomaterials can be used for cranioplasty, including hydroxyapatite (HA), polymethylmethacrylate (PMMA), titanium, and emerging new materials [15]. Titanium implants have proven to be particularly advantageous in simultaneous procedures, as they allow precise coverage and adjustment of the resection margins. By contrast, other biomaterials often require additional intraoperative shaping to achieve an optimal fit.

There has also been considerable debate regarding the nature of the tumors suitable for single-stage reconstruction. Traditionally, simultaneous cranioplasty has been performed mainly in benign lesions, where complete excision is potentially curative. In malignant tumors, adjuvant therapy is often required after resection. Radiation therapy can damage small vessels, cause fibrosis, and lead to soft-tissue atrophy and ulceration [16,17]. To minimize radiation-induced ulceration, skin dose should be minimized [18]. When high atomic number materials are present in the beam path, dose distribution may be altered, resulting in areas of over- or underdosage [19,20]. Titanium [22] and hydroxyapatite [20] have similar dose distribution characteristics, allowing safe postoperative radiation if necessary [18]. Moreover, implants with approximately 30% porosity provide better tissue ingrowth and lower infection rates [21]. Based on these data, simultaneous procedures may also be feasible for selected malignant lesions, provided that surgery is performed promptly after the final diagnostic workup to avoid tumor progression.

A limitation of our study is the small number of patients, which reflects the rarity of skull bone tumors and the infrequency of cranio-orbital reconstruction. This also explains the lack of consensus regarding the optimal approach to simultaneous tumor resection and cranioplasty with virtual surgical planning. Reported approaches vary in modeling techniques, manufacturing methods, and materials. A common challenge is the objective assessment of cosmetic outcomes. In our series, cosmetic results were based on patient self-assessment, which may be subjective.

LIMITATION

The small patient cohort and limited follow-up remain important limitations, underscoring the need for larger prospective studies.

CONCLUSION

This study confirms that the use of patient-specific stereolithographic templates in the surgical treatment of skull bone tumors significantly enhances the precision and efficiency of operative management. Preoperative virtual planning based on high-resolution MSCT allows accurate definition of resection margins and reliable implant preparation prior to surgery. Simultaneous cranioplasty with pre-shaped titanium mesh or PMMA ensures precise anatomical reconstruction, shortens operative time, and delivers excellent cosmetic outcomes while eliminating the need for a second surgical stage.

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