

Comparison of autologous and custom-made titanium cranioplasty following decompressive craniectomy for traumatic brain injury: A 7-year clinical experience

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ABSTRACT

BACKGROUND: Traumatic brain injury (TBI) is one of the common reasons for decompressive craniectomy (DC). The management of DC must include cranioplasty procedures. Although both procedures may cause several complications, postoperative outcomes are of greater concern for patients. The timing of cranioplasty (CP) and the type of CP material are the main parameters evaluated retrospectively in this report in terms of their impact on postoperative complications and cosmetic results.

METHODS: A total of 47 patients who underwent autologous cranioplasty (n=22) or custom-made titanium cranioplasty (n=25) due to TBI between January 2017 and January 2024 in our department were retrospectively analyzed. The groups were compared in terms of demographic characteristics, complication rates, and operative parameters. Cosmetic results and one-year mortality rates were also reported. The Odom criteria were used for the assessment of cosmetic results.

RESULTS: Baseline characteristics and overall complication rates did not differ significantly between the groups. Blood loss was significantly lower in titanium cranioplasty compared to autologous cranioplasty (126.2±47.9 ml vs. 215.5±35.6 ml, p<0.001). The highest complication rate was observed in cranioplasties performed 3–6 months after DC. In the early period (<3 months), autologous grafts were associated with significantly more complications than titanium (5/7 vs. 0/7, p=0.021). Cosmetic outcomes were significantly better with titanium, while timing had no effect on cosmetic results. One-year mortality rates were similar between the groups.

CONCLUSION: The timing of cranioplasty and the type of cranioplasty material may influence postoperative outcomes in patients with TBI. Titanium plates could be a preferable option for early cranioplasty if autologous bone cannot be used for reconstruction, whereas late cranioplasty appears to be associated with fewer complications overall. Further studies are needed to support these findings.

Keywords: 3D implant; titanium; cranioplasty; traumatic brain injury; decompressive craniectomy.

INTRODUCTION

Traumatic brain injury (TBI) refers to injury of the cerebral parenchyma and can result from several types of head trauma.

^[1] It is one of the major causes of morbidity and mortality

worldwide.^[2] TBI is most commonly associated with motor vehicle accidents and falls, but it can also occur in the context of large-scale disasters such as earthquakes or explosions during military operations. Other risk factors include mining accidents, construction site incidents, and infrastructure col-

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lapses.^[3] Due to the risk of complications, decompressive craniectomy (DC) is often performed in emergency situations to reduce intracranial pressure (ICP) caused by TBI, making a cranioplasty procedure after DC necessary.^[4-7] DC involves removal of the affected portion of the skull. If the removed portion of the skull is intact, it can be stored in the patient's anterior abdominal wall or frozen and preserved under sterile conditions at -80°C.^[5,6,8] Otherwise, allogenic materials such as titanium can be used to reconstruct the calvarial defect. Custom-made titanium implants offer well-established biocompatibility, good cosmetic outcomes, and low infection rates.^[9,10] Nevertheless, autologous bone grafts are the most commonly used option, with bone resorption being the most frequent complication, often leading to increased infection rates and the need for revision cranioplasty.^[11]

In this study, we analyzed patients with TBI who underwent DC followed by cranioplasty. A retrospective evaluation was conducted to assess the impact of using autologous bone and titanium plates for cranioplasty on patient outcomes and complication rates.

MATERIALS AND METHODS

Patient Population

A total of 47 patients with TBI who were admitted to our department between January 2017 and January 2024 were included in this study. All patients were divided into two groups according to the type of cranioplasty material used: the autologous cranioplasty (AC) group (n=22) and the custom-made titanium cranioplasty (TC) group (n=25). The decision to perform DC was based on clinical and radiological criteria. Clinically, DC was considered in patients with refractory intracranial hypertension, unresponsive pupils, or rapid neurological deterioration. Radiologically, indications included significant midline shift (>5 mm), cerebral edema, space-occupying lesions, or signs of herniation. The decision was made by the attending neurosurgeon in the context of each patient's overall clinical status.

The decision to perform cranioplasty in the early (<3 months), intermediate (3–6 months), or late (>6 months) period was based on clinical stability, neurological recovery, absence of infection, soft tissue condition, and logistical factors such as implant availability and surgical prioritization. Patients with satisfactory wound healing and stable general condition were considered for early cranioplasty, whereas those requiring further recovery or delayed implant production were scheduled for later procedures.

Patients were included in the study if they met the following criteria:

1. Underwent DC due to TBI;
2. Subsequently underwent cranioplasty (with autologous bone or a titanium plate) at the same center;
3. Were ≥18 years of age.

Patients were excluded if they met any of the following criteria:

1. Had a history of craniectomy due to tumors, vascular malformations, infections, or congenital cranial defects;
2. Underwent bilateral DC;
3. Had missing or incomplete clinical or imaging data;
4. Underwent revision cranioplasty with only data available from the revision surgery.

Baseline characteristics such as sex, age, chronic diseases (hypertension, diabetes mellitus), presence of scalp deformity, and preoperative Glasgow Coma Scale (GCS) score; operative parameters such as operation time, blood loss, cranial defect area (CDA), DC region (DCR), use of a ventriculoperitoneal (VP) shunt, and the time interval between DC and cranioplasty; and postoperative outcomes such as length of hospital stay, presence of postoperative complications, and one-year mortality rate were recorded. The Odom criteria (excellent, good, fair, or poor) were used to evaluate postoperative cosmetic satisfaction.

All patients underwent cranial computed tomography (CT) at the time of admission and both before and after the cranioplasty procedures. The CDA were defined in a three-dimensional (3D) environment using CT images obtained before and after cranioplasty.

Surgical planning and the production of titanium plates were performed at the Medical Design and Production Center of our institution. CT data were transferred via the Digital Imaging and Communications in Medicine (DICOM) interface and processed using the Mimics Innovation Suite (Materialise, Belgium) to design the implant in a 3D environment. The titanium plate was produced using selective laser melting (M2 Wallet, Concept Laser, Germany) with medical-grade Ti6Al4V (grade 23 ELI). A patient-specific skull model was also created to assess the fit prior to sterilization and surgical use.

This study was approved by the Ethics Committee for Non-Interventional Scientific Research of Gülhane Training and Research Hospital (Date: 24.01.2024, No: 2024/23) and was conducted in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.^[12] All patients or their families provided informed consent for cranial surgery. Consent for the use of patients' images was obtained directly from the patients. The study was conducted in accordance with the Declaration of Helsinki.

Cranioplasty Procedures

Autologous cranioplasty was performed for patients with preserved bone grafts, while custom-made TC was used for those without. Hemostasis was achieved at each stage of the procedure. A Hemovac drain was placed at an appropriate distance at the end of the operation, and the layers were closed anatomically. The operation was completed without complications.

Autologous Cranioplasty

The patient was placed in the supine position. The CDA and the autologous bone graft, which had been stored in the anterior abdominal wall, the lateral thigh region, or frozen and stored under sterile conditions during the previous surgery, were prepared. After skin disinfection, the surgical field was isolated with sterile covers. The skin and subcutaneous tissue were incised along the previous incision, taking the defect margins into account. The scalp was separated from the dura using a scalpel, dissector, and surgical scissors. The borders of the CDA and the intact bone were clearly identified. The autologous bone grafts were then carefully retrieved from the previous storage site through the skin and subcutaneous tissue. The dura was attached to the bone graft at specific points using silk suspension sutures. The bone graft was fixed to the intact bone tissue with mini plates and screws (Fig. 1).

Custom-Made Titanium Cranioplasty

The CDA, scalp deformities, and the 3D-printed sample model of the patient were photographed for documentation. The patient was placed in the supine position according to the defect location. After skin cleaning, the surgical field was isolated with sterile covers. The skin and subcutaneous tissue were incised along the previous incision, taking the defect margins into account. The scalp was separated from the dura using a scalpel, dissector, and surgical scissors. The borders of the CDA and intact bone structures were clearly identified. The compatibility of the titanium plate with the defect area was verified. The dura was attached to the titanium plate at

specific points using silk suspension sutures. After confirming that the defect was successfully closed, the titanium plate was fixed to the intact bone tissue using the predesigned number and size of mini plates and screws (Fig. 2).

The patient presented in Figure 2 had sustained a traumatic brain injury during the earthquakes that occurred in south-eastern Türkiye on February 6, 2023. A custom-made titanium cranioplasty was performed following decompressive craniectomy. According to the Odom criteria, the cosmetic result was classified as “excellent,” and satisfactory functional recovery was also achieved.

Statistical Analysis

Data normality was assessed using the Shapiro-Wilk test. The chi-squared (χ^2) test and Fisher's exact test were used to compare categorical variables, while the independent samples t-test and Mann-Whitney U test were used to compare continuous variables. For normally distributed continuous variables, descriptive statistics were presented as means $\pm$ standard deviations (SD), whereas categorical variables were expressed as numbers and percentages. To evaluate the relationship between the timing of cranioplasty and the presence of complications, both general and stratified analyses were performed. Pairwise comparisons were conducted to assess the significance between time intervals. A p value of <0.05 was considered statistically significant. Data analyses were performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA).

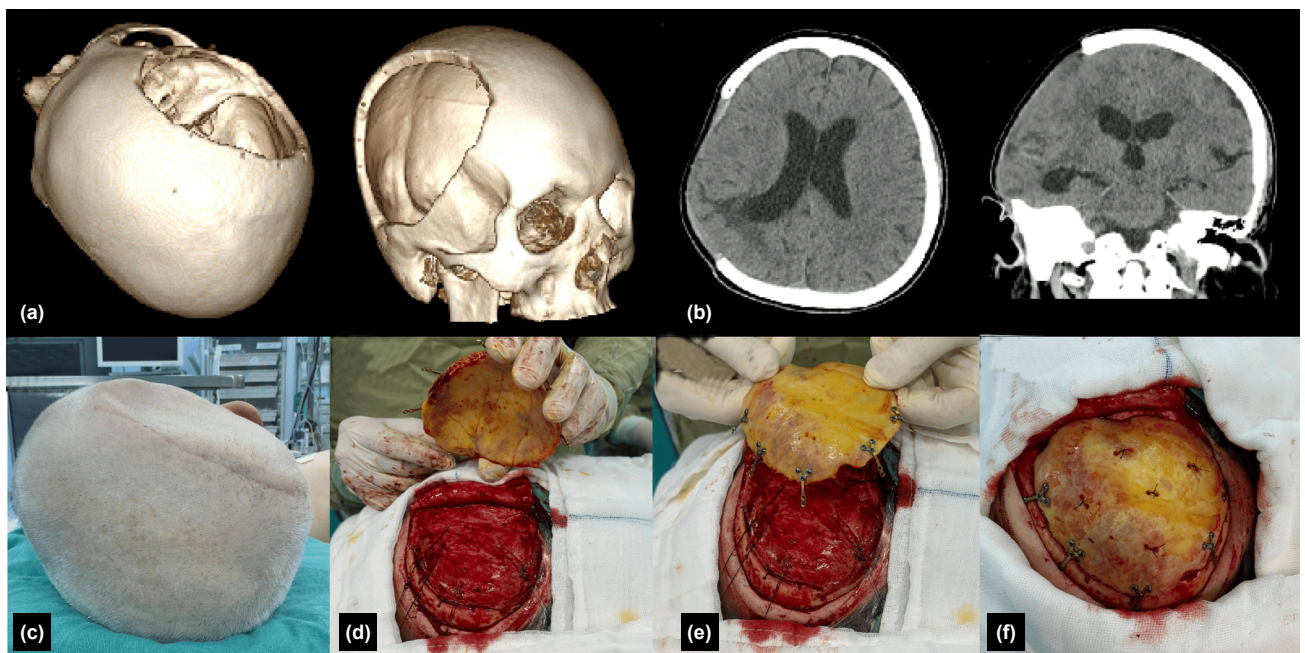


Figure 1. Autologous cranioplasty. **a)** 3D images of the patient's cranial defect area. **b)** Computed tomography (CT) images showing the craniectomy site before cranioplasty. **c)** Cranial defect area with previous incision scars. **d)** Autologous bone graft and defect area. **e)** Attachment of the dura to the bone graft using silk suspension sutures. **f)** Fixation of the bone graft with titanium plates and screws.

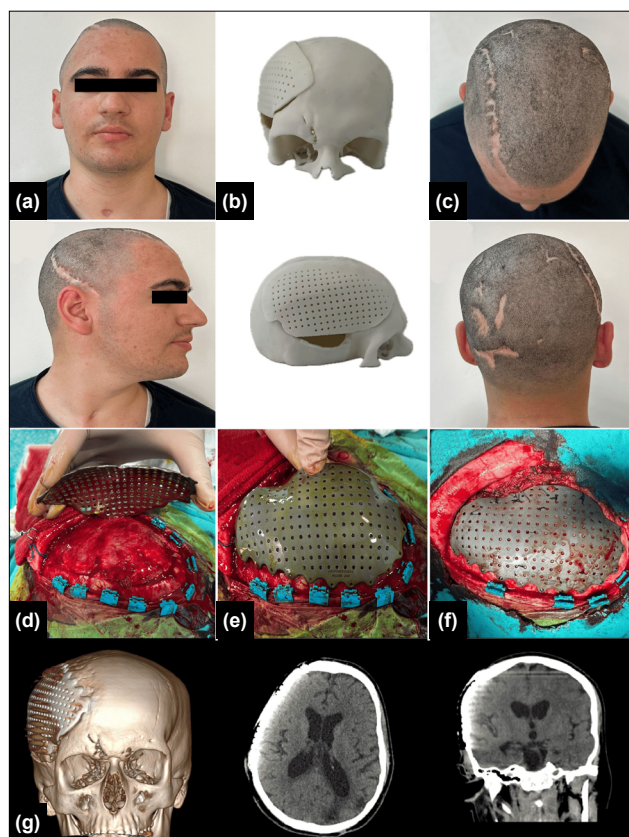


Figure 2. Titanium cranioplasty. **a)** Preoperative images of the patient from anterior and lateral views showing cranial deformity due to craniectomy. **b)** Sample kit produced using a 3D printer. **c)** Preoperative images of the patient from superior and posterior views showing previous incision scars and scalp deformities. **d)** Titanium plate and cranial defect area. **e)** Intraoperative demonstration of the fit between the implant and the defect area. **f)** Attachment of the dura to the implant using silk suspension sutures and fixation of the implant with pre-designed plates and screws. **g)** Postoperative 3D and computed tomography (CT) images showing successful closure of the defect area.

RESULTS

Baseline Characteristics of Patients

A total of 47 patients with TBI resulting from various traumatic events were examined, with a median age of 45 years

(range: 13-86), of whom 24 (51.1%) were female. Twenty-two (46.8%) patients underwent AC and 25 (53.2%) underwent TC. No significant differences were found between the groups in terms of age (49.8 ± 22.5 vs. 46 ± 23.5 years, $p=0.55$), sex (female: 50% vs. 52%, $p=0.89$), hypertension (54.5% vs. 32%, $p=0.12$), diabetes mellitus (31.8% vs. 24%, $p=0.55$), pre-operative GCS score (13.8 ± 2.4 vs. 13.7 ± 2.4 , $p=0.84$), or scalp deformity (50% vs. 53.2%, $p=0.68$) (Table 1).

Operative Parameters

There were no significant differences between the groups in terms of operation time (104.0 ± 27.7 min. vs. 104 ± 27.7 min., $p=0.80$), DCR (54.5% vs. 48%, $p=0.65$), CDA (46.4 ± 13.1 vs. 49.5 ± 12.4 , $p=0.41$), use of VP shunt (4.6% vs. 8%, $p=1.0$), or length of hospital stay (7.3 ± 2.4 days vs. 7.7 ± 2.1 days, $p=0.59$). Blood loss was significantly greater in the AC group than in the TC group (215.5 ± 35.6 ml vs. 126.2 ± 47.9 ml, $p<0.001$) (Table 2).

Complications and Mortality

Postoperative complications occurred in 19 patients (40.4%) overall, while resorption was observed only in the AC group (four patients, 18.2%). All affected patients subsequently underwent revision cranioplasty with 3D custom-made TC. Overall, two patients experienced dehiscence (one [4.5%] in the AC group and one [4%] in the TC group). No surgical intervention was required for the patient with AC who developed dehiscence, whereas skin revision was performed afterwards for the patient with TC. Surgical site infection occurred in three patients overall (two [9.1%] in the AC group and one [4%] in the TC group). Autologous grafts were removed from these patients, while the patient in the TC group did not require implant removal. Three patients developed postoperative hydrocephalus: one (4.5%) in the AC group and two (8%) in the TC group, and all of them underwent VP shunt surgery. Postoperative hemorrhage occurred in three patients (two [9.1%] in the AC group and one [4%] in the TC group). Two patients with AC had subdural hematomas, and the patient with TC had an intracerebral hematoma. None of the patients required surgical intervention for postoperative hematoma. Seizures occurred in four patients overall (two [9.1%] in the AC group and two [8%] in the TC group) and

Table 1. Baseline characteristics at admission

	All (n=47)	Autologous Cranioplasty (n=22)	Titanium Cranioplasty (n=25)	P-value
Age, years, mean $\pm$ SD	47.8 $\pm$ 22.8	49.8 $\pm$ 22.5	46 $\pm$ 23.5	0.55
Sex, women, n (%)	24 (51.1)	11 (50)	13 (52)	0.89
Hypertension, n (%)	20 (42.6)	12 (54.5)	8 (32)	0.12
Diabetes mellitus, n (%)	13 (27.7)	7 (31.8)	6 (24)	0.55
Scalp deformity, n (%)	25 (53.2)	11 (50)	14 (56)	0.68
Preoperative GCS, mean $\pm$ SD	13.7 $\pm$ 2.3	13.8 $\pm$ 2.4	13.7 $\pm$ 2.4	0.84

GCS: Glasgow Coma Scale; SD: Standard deviation.

Table 2. Operative parameters and postoperative outcomes

	All (n=47)	Autologous Cranioplasty (n=22)	Titanium Cranioplasty (n=25)	P-value
Operation time, min, mean±SD	103.1±27.0	104.0±27.7	104.0±27.7	0.80
Blood loss, ml, mean±SD	168.0±61.7	215.5±35.6	126.2±47.9	<0.001
CDA, cm ² , mean±SD	48.1±12.7	46.4±13.1	49.5±12.4	0.41
DCR, right, n (%)	24 (51.1)	12 (54.5)	12 (48)	0.65
VP shunt, n (%)	3 (6.4)	1 (4.6)	2 (8)	1.0*
Time interval, n (%)				0.94
Early (<3 months)	14 (29.8)	7 (31.8)	7 (28)	
Intermediate (3-6 months)	17 (36.2)	8 (36.4)	9 (36)	
Late (>6 months)	16 (34)	7 (31.8)	9 (36)	
Length of hospital stay, days, mean±SD	7.5±2.2	7.3±2.4	7.7±2.1	0.59
Presence of postoperative complication, n (%)	19 (40.4)	12 (54.5)	7 (28)	0.06
Resorption	4 (8.5)	4 (18.2)	0	
Dehiscence	2 (4.3)	1 (4.5)	1 (4)	
Seizure	4 (8.5)	2 (9.1)	2 (8)	
Surgical site infection	3 (6.4)	2 (9.1)	1 (4)	
Postoperative hemorrhage	3 (6.4)	2 (9.1)	1 (4)	
Postoperative hydrocephalus	3 (6.4)	1 (4.5)	2 (8)	
One-year mortality, exitus, n (%)	5 (10.6)	3 (13.6)	2 (8)	0.65*

CDA: Cranial defect area; DCR: Decompressive craniectomy region; VP: Ventriculoperitoneal shunt; SD: Standard deviation. *Fisher's exact test.

Table 3. Comparison of postoperative complications according to time interval and cranioplasty material

Time Interval	Autologous Cranioplasty (Yes/No)	Titanium Cranioplasty (Yes/No)	P-value
Early (<3 months)	5/2	0/7	0.021
Intermediate (3-6 months)	6/2	5/4	0.620
Late (>6 months)	1/6	2/7	1.000

GCS: Glasgow Coma Scale; SD: Standard deviation.

represented the second most common complication. Time intervals (early: <3 months; intermediate: 3–6 months; and late: >6 months) were compared between the AC and TC groups. In the AC group, 31.8% of patients underwent early cranioplasty, 36.4% intermediate, and 31.8% late. Similarly, in the TC group, 28.0% underwent early cranioplasty, 36.0% intermediate, and 36.0% late. There was no statistically significant difference in the timing distribution between the two groups ($p=0.94$). Mortality was observed in 10.6% of patients overall (13.6% vs. 8%, $p=0.65$) (Table 2).

When the data were stratified by material and time interval (Table 3), complications were significantly more frequent in the AC group during the early period (<3 months) compared

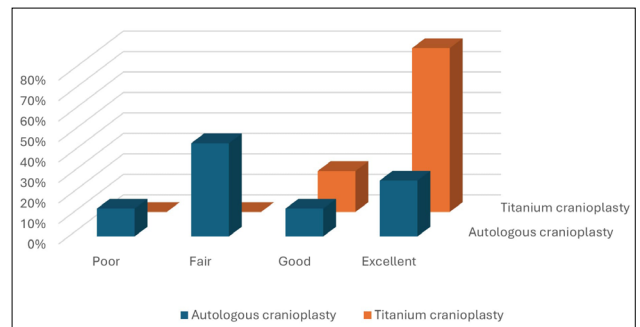


Figure 3. Comparison of cosmetic results between groups. Titanium cranioplasty provided significantly better cosmetic results than autologous cranioplasty.

Table 4. Comparison of postoperative complications according to time interval

Time Interval			
Presence of complication	Early(<3 months) (n=14)	Intermediate (3–6 months) (n=17)	Late (>6 months) (n=16)
No, n (%)	9 (64.3)	6 (35.3)	13 (81.2)
Yes, n (%)	5 (35.7)	11 (64.7)	3 (18.8)
			P-value
Pairwise comparison	Early vs. Intermediate	0.21	
	Intermediate vs. Late	0.02	

Table 5. Comparison of cosmetic results and time interval between groups

	Autologous Cranioplasty	Titanium Cranioplasty	P value
Cosmetic result			
Poor, n (%)	3 (13.6)	0 (0)	<0.001
Fair, n (%)	10 (45.5)	0 (0)	
Good, n (%)	3 (13.6)	5 (20)	
Excellent, n (%)	6 (27.3)	20 (80)	
Time interval			
<3 months, n (%)	7 (31.8)	7 (28)	0.94
3-6 months, n (%)	8 (36.4)	9 (36)	
>6 months, n (%)	7 (31.8)	9 (36)	

to the TC group (5/7 vs. 0/7, $p=0.021$). No significant differences were observed in the intermediate (3–6 months) or late (>6 months) periods between the AC and TC groups ($p=0.620$ and $p=1.000$, respectively).

When analyzed independent of material (Table 4), complication rates varied significantly across time intervals. The intermediate period (3–6 months) had the highest complication rate (64.7%), followed by the early period (35.7%) and late period (18.8%). The difference between the intermediate and late periods was statistically significant ($p=0.02$), while the early vs. intermediate comparison did not reach significance ($p=0.21$).

Cosmetic Results

According to the Odom criteria, outcomes were rated as excellent in 26 patients (55.3%), good in eight (17%), fair in 10 (21.3%), and poor in three (6.4%) overall. A significant difference was observed in cosmetic outcomes according to the type of cranioplasty material ($p<0.001$), but not according to the time interval between DC and cranioplasty ($p=0.94$). Whether surgery was performed before 3 months, between 3-6 months, or after 6 months did not significantly affect cosmetic results ($p=0.501$). Patients who underwent

TC had better cosmetic outcomes according to the Odom criteria, whereas those with AC more often had poor results (Table 5, Fig. 3).

DISCUSSION

Traumatic brain injury remains one of the most common causes of mortality and morbidity worldwide.^[2] Although most TBIs are associated with motor vehicle accidents, falls, and assaults, large-scale disasters such as earthquakes may also cause TBI, particularly due to building collapses and entrapment under debris.^[13,14] However, in clinical practice, the etiology of TBI does not significantly alter the surgical approach once DC is required. The increase in ICP resulting from TBI is a condition that needs to be alleviated by DC as a last-line of intervention.^[7,15-17] Once the increased ICP has been relieved, cranioplasty procedures must be performed to restore skull integrity.^[4-7,17] Cranioplasty following DC can help facilitate the hydrodynamics of cerebrospinal fluid (CSF) and cerebral blood flow (CBF), thereby improving neurological status.^[4-8,17]

Both DC and cranioplasty procedures are inevitably associated with complications, which may depend on the time

interval between DC and cranioplasty.^[4-8,17-23] Tomar et al.^[8] reported postoperative complications in 7 of 31 patients (22.6%) who underwent AC. The overall complication rates were reported as 18.75% and 26.66% for early (<3 months) and late (>3 months) cranioplasty, respectively, with no statistically significant difference. Resorption occurred in only two patients, both in the late cranioplasty group. A systematic review revealed an increased risk of postoperative hydrocephalus following early cranioplasty (<3 months), although early intervention has been suggested to improve CSF hydrodynamics and clinical recovery.^[5,24] Early cranioplasty is often considered for patients with neurological deterioration due to loss of skull integrity, such as in sinking skin flap syndrome (SSFS). This condition results from an imbalance of atmospheric pressure and impaired cerebrospinal fluid dynamics and is particularly associated with postural neurological deficits and cognitive slowing.^[25,26] None of the patients in this study had this condition.

Schuss et al.^[6] reported that among 243 patients who underwent AC after DC, early cranioplasty (<2 months) was associated with a significantly higher overall complication rate than late cranioplasty (>2 months) (25.9% vs. 14.2%). Fifty percent of the early cranioplasty patients in that study had TBI, which may explain the higher complication rate observed in the early period. According to a multicenter study,^[4] early cranioplasty was associated with an increased risk of postoperative hydrocephalus and a significant risk of postoperative seizures, in contrast to the findings of Ozoner et al.,^[27] who reported that late cranioplasty carries a risk of postoperative hydrocephalus in TBI patients (80% vs. 20%).

We conducted this study in patients with TBI, and postoperative complications were observed in 40.4% of cases (19 out of 47 patients). We did not find any significant differences in terms of complication rates between the AC and TC groups. While the overall complication rate was highest in the 3–6-month group, the late cranioplasty (>6 months) group had the lowest rate, regardless of the type of cranioplasty material. These findings indicate that late cranioplasty may be a safer option for patients with TBI. In contrast, some studies have reported that the optimal timeframe for cranioplasty following DC is 3-6 months.^[6,23] Cerebral recovery after severe to mild TBI occurs most rapidly within this period.^[28,29] Altering this timeframe may negatively affect postoperative recovery and increase the incidence of complications. In the current literature, rare but life-threatening events such as paradoxical herniation have also been reported, particularly in cases of late cranioplasty, where the skull defect fails to protect the brain from external pressure gradients.^[30] Although we did not observe such cases in our series, this complication highlights the critical importance of individualized timing decisions based on radiological and clinical findings rather than rigid temporal protocols.

Subgroup analysis revealed that early cranioplasty using autologous bone was associated with significantly higher com-

plication rates compared to titanium implants. Given this increased risk, TC appears to be a safer and more reliable option in early cranioplasty scenarios. Nevertheless, autologous bone grafts should still be considered the first-line material due to their biocompatibility and cost-effectiveness, particularly when the graft is well preserved and structurally intact. However, if the autologous bone is compromised—for example, due to improper preservation, fragmentation, infection, or substantial resorption—the use of custom-made titanium implants represents a highly viable and preferable alternative. This approach not only reduces complication rates but also offers enhanced structural integrity and superior cosmetic outcomes, particularly in patients with TBI, in whom tissue healing may be impaired due to skin breakdown and damage to the bone itself. DC has also been shown to impair wound healing in TBI patients, which may influence the choice of cranioplasty material.^[6,31] Therefore, alternative cranioplasty materials such as titanium should be considered. Previous studies have reported surgical site infection rates of up to 10% in autologous cranioplasty and 4–8% in titanium-based cranioplasty, which is consistent with our findings.^[10,11,32-34] Notably, the relatively small sample size of our study may limit the generalizability of these results.

Yeap et al.^[34] reported that the most common etiologic factor for bone resorption is trauma. The cranioplasty procedure itself can lead to complications such as loss of skin quality, deterioration of the skin's blood supply, and reopening of the incision line due to scar tissue formation at the surgical site.^[29,35,36] Consequently, with advancements in software technology and 3D printing, the use of 3D custom-made titanium implants has become increasingly feasible. First, a 3D template is designed based on the patient's CT images using specialized software and then produced with a 3D printer. The 3D template assists the surgeon in assessing the compatibility between the defect area and the titanium implant, helping to avoid unnecessary costs and additional intraoperative shaping of the implant. However, this process involves specific costs and requires expertise at each stage, from production to surgery, which can be considered a limitation in daily neurosurgical procedures.

Another problem encountered in cranioplasty surgeries is the reduction in the volume and quality of the skin covering the defect, which increases in direct proportion to the size of the CDA.^[36] In this study, there was no significant difference in CDA between the AC and TC groups. Therefore, CDA was not a significant parameter influencing the postoperative complication rate in this study.

In a randomized controlled trial^[11] comparing custom-made titanium and AC, the one-year mortality rates did not differ from our findings. When the follow-up period was extended to two years, it was reported that the use of titanium instead of autologous bone reduced the need for revision cranioplasty. The one-year mortality rate observed in our study was not statistically significant.

We used the Odom criteria to evaluate patients' cosmetic satisfaction. Compared with the AC group, the TC group demonstrated significantly better outcomes, whereas the AC group showed mostly poor results. For the reconstruction of skull defects, 3D custom-made titanium implants provide well-established cranial symmetry and optimal aesthetic outcomes.^[9,10,35,37] The effectiveness of this approach has been demonstrated by its ability to produce favorable cosmetic results, reduce infection rates, and minimize the need for subsequent cranioplasty procedures. This may be because titanium inhibits the colonization of microorganisms, as it does not provide a nutrient medium for them compared with other materials and cannot form a biofilm layer due to its perforated structure.^[10,11,22,34,35] Following TBI, increased cerebral vulnerability, resulting from ongoing edema, disrupted autoregulation, and impaired brain compliance—may reduce the safety of using autologous bone.^[6,38] The restoration of cerebral and scalp functions may take time; therefore, custom-made titanium implants can be considered the most preferable alloplastic material. Moreover, we did not find any significant association between cosmetic outcomes and the time interval between DC and cranioplasty; however, the use of titanium as a cranioplasty material was associated with significantly better cosmetic results.

Limitations

This study has several limitations. First, we did not include other alloplastic materials used in cranioplasty for comparison. Second, the sample size of our study is relatively small compared with that of several other studies, which could lead to some complexity in determining statistical significance. Third, this is a retrospective, single-center study; therefore, patient selection bias, institutional preferences, and surgical experiences may limit the generalizability of the findings. Lastly, cosmetic outcomes were evaluated using the Odom criteria, which are inherently subjective and may vary depending on the evaluator's perspective.

CONCLUSION

Traumatic brain injury can result in unfavorable conditions affecting the patient's scalp and bone. To ensure optimal management following DC due to TBI, both the timing of cranioplasty and the choice of cranioplasty material play crucial roles. Based on the findings of this study, two main considerations can be proposed. First, while autologous bone grafts remain the first-line choice, custom-made titanium implants may serve as a reliable alternative in early cranioplasty when the graft is not well preserved or carries a high risk of resorption or fragmentation, owing to their lower complication rates and superior structural integrity. Second, regardless of the material used, late cranioplasty (≥ 6 months) appears to be associated with the lowest overall complication rates. Therefore, both timing and material selection should be carefully considered during surgical planning, with individualized decisions tailored to patient-specific factors. Further large-scale prospective

studies are warranted to support these observations.

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Ethics Committee Approval: This study was approved by the Non-Interventional Scientific Research of Gülhane Training and Research Hospital Ethics Committee (Date: 24.01.2024, Decision No: 2024/23).

Peer-review: Externally peer-reviewed.

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REFERENCES

1. Heegaard W, Biros M. Traumatic brain injury. *Emerg Med Clin North Am* 2007;25:655-78, viii. [\[CrossRef\]](#)
2. Ozoner B. Cranioplasty Following Severe Traumatic Brain Injury: Role in Neurorecovery. *Curr Neurol Neurosci Rep* 2021;21:62. [\[CrossRef\]](#)
3. Chu Z gang, Yang Z gang, Dong Z hui, Chen T wu, Zhu Z yu, Shao H. Comparative study of earthquake-related and non-earthquake-related head traumas using multidetector computed tomography. *Clin Sao Paulo Braz* 2011;66:1735-42. [\[CrossRef\]](#)
4. Vreeburg RJG, Singh RD, van Erp IAM, Korhonen TK, Yue JK, Mee H, et al. Early versus delayed cranioplasty after decompressive craniectomy in traumatic brain injury: a multicenter observational study within CENTER-TBI and Net-QuRe. *J Neurosurg* 2024;141:895-907.
5. Xu H, Niu C, Fu X, Ding W, Ling S, Jiang X, et al. Early cranioplasty vs. late cranioplasty for the treatment of cranial defect: A systematic review. *Clin Neurol Neurosurg* 2015;136:33-40. [\[CrossRef\]](#)
6. Schuss P, Vatter H, Marquardt G, Imöhl L, Ulrich CT, Seifert V, et al. Cranioplasty after decompressive craniectomy: the effect of timing on postoperative complications. *J Neurotrauma* 2012;29:1090-5. [\[CrossRef\]](#)
7. Svedung Wettervik T, Lenell S, Enblad P, Lewén A. Decompressive Craniectomy in Traumatic Brain Injury-Craniectomy-Related and Cranioplasty-Related Complications in a Single Center. *World Neurosurg* 2021;148:e508-17. [\[CrossRef\]](#)
8. Tomar K, Roy ID, Kumar Singh A, Yadav Rekha C. Role of timing of cranioplasty in improving Neurological functional outcome. *Br J Oral Maxillofac Surg* 2024;62:944-9. [\[CrossRef\]](#)
9. Park EK, Lim JY, Yun IS, Kim JS, Woo SH, Kim DS, et al. Cranioplasty Enhanced by Three-Dimensional Printing: Custom-Made Three-Dimensional-Printed Titanium Implants for Skull Defects. *J Craniofac Surg* 2016;27:943-9. [\[CrossRef\]](#)
10. Williams LR, Fan KF, Bentley RP. Custom-made titanium cranioplasty: early and late complications of 151 cranioplasties and review of the literature. *Int J Oral Maxillofac Surg* 2015;44:599-608. [\[CrossRef\]](#)
11. Honeybul S, Morrison DA, Ho KM, Lind CRP, Geelhoed E. A randomised controlled trial comparing autologous cranioplasty with custom-made titanium cranioplasty: long-term follow-up. *Acta Neurochir (Wien)* 2018;160:885-91. [\[CrossRef\]](#)
12. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting

- observational studies. *J Clin Epidemiol* 2008;61:344-9. [CrossRef]
13. Igarashi Y, Matsumoto N, Kubo T, Yamaguchi M, Nakae R, Onda H, et al. Prevalence and Characteristics of Earthquake-Related Head Injuries: A Systematic Review. *Disaster Med Public Health Prep* 2022;16:1253-8. [CrossRef]
 14. Lu-Ping Z, Rodriguez-Llanes JM, Qi W, van den Oever B, Westman L, Albela M, et al. Multiple injuries after earthquakes: a retrospective analysis on 1,871 injured patients from the 2008 Wenchuan earthquake. *Crit Care* 2012;16:R87. [CrossRef]
 15. Cooper DJ, Rosenfeld JV, Murray L, Arabi YM, Davies AR, D'Urso P, et al. Decompressive Craniectomy in Diffuse Traumatic Brain Injury. *New England Journal of Medicine* 2011;364:1493-502. [CrossRef]
 16. Skoglund TS, Eriksson-Ritzén C, Jensen C, Rydenhag B. Aspects on Decompressive Craniectomy in Patients with Traumatic Head Injuries. *Journal of Neurotrauma* 2006;23:1502-9. [CrossRef]
 17. Gerstl JVE, Rendon LF, Burke SM, Doucette J, Mekary RA, Smith TR. Complications and cosmetic outcomes of materials used in cranioplasty following decompressive craniectomy-a systematic review, pairwise meta-analysis, and network meta-analysis. *Acta Neurochir (Wien)* 2022;164:3075-90. [CrossRef]
 18. Gooch MR, Gin GE, Kenning TJ, German JW. Complications of cranioplasty following decompressive craniectomy: analysis of 62 cases. *Neurosurg Focus* 2009;26:E9. [CrossRef]
 19. Ng ZY, Ang WJJ, Nawaz I. Computer-designed polyetheretherketone implants versus titanium mesh ($\pm$ acrylic cement) in alloplastic cranioplasty: a retrospective single-surgeon, single-center study. *J Craniofac Surg* 2014;25:e185-189. [CrossRef]
 20. Maegele M, Schöchl H, Menovsky T, Maréchal H, Marklund N, Buki A, et al. Coagulopathy and haemorrhagic progression in traumatic brain injury: advances in mechanisms, diagnosis, and management. *The Lancet Neurology* 2017;16:630-47. [CrossRef]
 21. Kurland DB, Khaladj-Ghom A, Stokum JA, Carusillo B, Karimy JK, Gerzanich V, et al. Complications Associated with Decompressive Craniectomy: A Systematic Review. *Neurocrit Care* 2015;23:292-304. [CrossRef]
 22. Lindner D, Schlothofer-Schumann K, Kern BC, Marx O, Müns A, Meixensberger J. Cranioplasty using custom-made hydroxyapatite versus titanium: a randomized clinical trial. *J Neurosurg* 2017;126:175-83. [CrossRef]
 23. Mraček J, Mork J, Dostal J, Tupy R, Mrackova J, Priban V. Complications Following Decompressive Craniectomy. *J Neurol Surg A Cent Eur Neurosurg* 2021;82(5):437-45. [CrossRef]
 24. Paredes I, Castaño-León AM, Munarriz PM, Martínez-Perez R, Cepeda S, Sanz R, et al. Cranioplasty after decompressive craniectomy. A prospective series analyzing complications and clinical improvement. *Neurocirugia (Astur)* 2015;26:115-25. [CrossRef]
 25. Santander X, Hidalgo YG, Flores JC, Gómez-Jordana B. Sinking skin syndrome in a decompressive craniectomy series: Clinical and radiological features. *Surg Neurol Int* 2022;13:422. [CrossRef]
 26. Bateman EA, VanderEnde J, Sequeira K, MacKenzie HM. Postural neurologic deficits after decompressive craniectomy: A case series of sinking skin flap syndrome in traumatic brain injury. *NeuroRehabilitation* 2021;49:663-72. [CrossRef]
 27. Ozoner B, Kilic M, Aydin L, Aydin S, Arslan YK, Musluman AM, et al. Early cranioplasty associated with a lower rate of post-traumatic hydrocephalus after decompressive craniectomy for traumatic brain injury. *Eur J Trauma Emerg Surg* 2020;46:919-26. [CrossRef]
 28. Carroll EL, Outtrim JG, Forsyth F, Manktelow AE, Hutchinson PJA, Tenovuo O, et al. Mild traumatic brain injury recovery: a growth curve modelling analysis over 2 years. *J Neurol* 2020;267:3223-34. [CrossRef]
 29. Wilkins TE, Beers SR, Borrasso AJ, Brooks J, Mesley M, Puffer R, et al. Favorable Functional Recovery in Severe Traumatic Brain Injury Survivors beyond Six Months. *J Neurotrauma* 2019;36:3158-63. [CrossRef]
 30. Taheri M, Ghazvini MH, Javadnia P. Paradoxical brain herniation following decompressive craniectomy: A case series and systematic review of literature. *Int J Surg Case Rep* 2024;125:110477. [CrossRef]
 31. Archavlis E, Carvi Y, Nievas M. The impact of timing of cranioplasty in patients with large cranial defects after decompressive hemicraniectomy. *Acta Neurochir (Wien)* 2012;154:1055-62. [CrossRef]
 32. van de Vijfeijken SECM, Münker TJAG, Spijker R, Karssemakers LHE, Vandertop WP, Becking AG, et al. Autologous Bone Is Inferior to Alloplastic Cranioplasties: Safety of Autograft and Allograft Materials for Cranioplasties, a Systematic Review. *World Neurosurg* 2018;117:443-52.e8. [CrossRef]
 33. Birgersson U, Wettervik TS, Sundblom J, Linder LKB. The role of autologous bone in cranioplasty. A systematic review of complications and risk factors by using stored bone. *Acta Neurochir* 2024;166:438. [CrossRef]
 34. Yeap MC, Tu PH, Liu ZH, Hsieh PC, Liu YT, Lee CY, et al. Long-Term Complications of Cranioplasty Using Stored Autologous Bone Graft, Three-Dimensional Polymethyl Methacrylate, or Titanium Mesh After Decompressive Craniectomy: A Single-Center Experience After 596 Procedures. *World Neurosurg* 2019;128:e841-50. [CrossRef]
 35. Kayhan S, Kırmızıgöz Ş, Kırık A, Tehli Ö, İzci Y. Revision Cranioplasty with Three-dimensional Custom-made Titanium Implants in Patients with Failed Cranioplasty. *World Neurosurg* 2024;191:e465-72. [CrossRef]
 36. Tehli O, Kırmızıgöz Ş, Evleksiz D, İzci Y, Kutlay M, et al. Simultaneous Closure of Bilateral Cranial Defects Using Custom-Made 3D Titanium Implants: A Single Institution Series. *Turk Neurosurg* 2023;33:386-92. [CrossRef]
 37. Tehli O, Dursun AM, Temiz C, Solmaz I, Kural C, Kutlay M, et al. Computer-based surgical planning and custom-made titanium implants for cranial fibrous dysplasia. *Neurosurg* 2015;11:213-9. [CrossRef]
 38. Posti JP, Yli-Olli M, Heiskanen L, Aitasalo KMJ, Rinne J, Vuorinen V, et al. Cranioplasty After Severe Traumatic Brain Injury: Effects of Trauma and Patient Recovery on Cranioplasty Outcome. *Front Neurol* 2018;9:223. [CrossRef]

ORİJİNAL ÇALIŞMA - ÖZ

Travmatik beyin hasarında dekompresif kraniyektomi sonrası otolog ve özel yapım titanyum kraniyoplastinin karşılaştırılması: 7 yıllık klinik deneyim

AMAÇ: Travmatik beyin hasarı (TBH), dekompresif kraniyektominin (DK) en sık uygulanma sebeplerinden biridir. Dekompresif kraniyektominin yönetimi kraniyoplasti prosedürlerini de içermelidir. Her iki prosedür de çeşitli komplikasyonlara sebep olabileceği de, kozmetik sonuçlar gibi kraniyoplasti sonrası postoperatif sonuçlar, hastalar için önem arz etmektedir. Kraniyoplastinin zamanlaması ve kullanılan kraniyoplasti materyali, bu çalışmada kozmetik ve postoperatif sonuçlar adına retrospektif olarak değerlendirilen esas parametrelerdir.

GEREÇ VE YÖNTEM: Ocak 2017 ve Ocak 2024 tarihleri arasında, travmatik beyin hasarı dolayısıyla kliniğimizde otolog kraniyoplasti (n=22) ve özel yapım titanyum kraniyoplasti (n=25) operasyonları geçiren toplam 47 hasta retrospektif olarak analiz edildi. Hastalar demografik özellikleri, komplikasyon oranları ve operasyonel parametreler bazında karşılaştırıldı. Kozmetik sonuçlar ve 1 yıllık mortalite oranları da ayrıca rapor edildi. Kozmetik sonuçların değerlendirilmesinde Odom kriterleri kullanıldı.

BULGULAR: Gruplar arasında, temel özellikler ve genel komplikasyon oranları anlamlı farklılık göstermemiştir. Kan kaybı titanyum kraniyoplastide otolog kraniyoplastiye kıyasla anlamlı olarak daha düşüktür (126.2 ± 47.9 ml ve 215.5 ± 35.6 ml, $p < 0.001$). En yüksek komplikasyon oranı DK'den 3-6 ay sonra yapılan kraniyoplastilerde gözlenmiştir. Erken dönemde (< 3 ay), otolog greftler titanyumdan, anlamlı olarak daha fazla komplikasyonla ilişkilendirilmiştir (5/7 ve 0/7, $p = 0.021$). Kozmetik sonuçlar titanyum ile anlamlı derecede daha iyi iken, zamanlamanın kozmetik sonuçlar üzerine etkisi olmamıştır. 1 yıllık mortalite oranları gruplar arasında benzerdir.

SONUÇ: Kraniyoplastinin zamanlaması ve kraniyoplasti materyali TBH hastalarında ameliyat sonrası sonuçları etkileyebilir. Otolog kemik rekonstrüksiyon için kullanılamıyorsa, titanyum plaklar erken kraniyoplastide tercih edilebilir bir seçenek olabilirken, geç kraniyoplasti genel olarak daha az komplikasyonla ilişkili görünmektedir. Bu bulguları desteklemek için daha fazla çalışmaya ihtiyaç vardır.

Anahtar sözcükler: Dekompresif kraniyektomi; kraniyoplasti; titanyum; travmatik beyin hasarı; 3D implant.

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