Development of a Prediction Model for Cranioplasty Implant Survival Following Craniectomy

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■ BACKGROUND: **Cranioplasty after craniectomy can result in high rates of postoperative complications. Although determinants of postoperative outcomes have been identified, a prediction model for predicting cranioplasty implant survival does not exist. Thus, we sought to develop a prediction model for cranioplasty implant survival after craniectomy.**

■ METHODS: **We performed a retrospective cohort study of patients who underwent cranioplasty following craniectomy between 2014 and 2020. Missing data were imputed using multiple imputation. For model development, multivariable Cox proportional hazards regression analysis was performed. To test whether candidate determinants contributed to the model, we performed backward selection using the Akaike information criterion. We corrected for overfitting using bootstrapping techniques. The performance of the model was assessed using discrimination and calibration.**

■ RESULTS: **A total of 182 patients were included (mean age, 43.0 ± 19.7 years). Independent determinants of cranioplasty implant survival included the indication for craniectomy (compared with trauma—vascular disease: hazard ratio [HR], 0.65 [95% confidence interval (CI), 0.36–1.17]; infection: HR, 0.76 [95% CI, 0.32–1.80]; tumor: HR, 1.40 [95% CI, 0.29–6.79]), cranial defect size (HR, 1.01 per cm^2 [95% CI, 0.73–1.38]), use of an autologous bone flap (HR, 1.63 [95% CI, 0.82–3.24]), and skin closure using staples (HR, 1.42 [95% CI, 0.79–2.56]). The concordance index of the model was 0.60 (95% CI, 0.47–0.73).**

■ CONCLUSIONS: **We have developed the first prediction model for cranioplasty implant survival after craniectomy. The findings from our study require external validation and deserve further exploration in future studies.**

INTRODUCTION

Craniectomy is a commonly performed neurosurgical procedure mainly used to alleviate medically refractory elevated intracranial pressure and, thus, prevent neurological deterioration following traumatic brain injury, massive stroke, or various other conditions.[1] With advances in medical and surgical care, more patients survive their initial insult and require subsequent cranioplasty to protect the dura and brain from physical insult and to restore cosmesis. Cranioplasty also contributes to neurological recovery by improving cerebral blood flow, cerebrospinal fluid hydrodynamics, and cerebral metabolic activity.[2,3] Therefore, cranioplasty can highly improve patients' quality of life.

Although often considered a routine surgery, high rates of postoperative complications have been reported following cranioplasty. Bone flap resorption rates range from 4% to 33% in adults and occur in ≤58% of pediatric patients. In addition, surgical site infections occur in 2%–24% of patients.[4,5] Eventually, these complications will often require removal of the cranioplasty implant and insertion of a new one, and revision surgery rates of 23% for autologous bone flaps and 12% for cranial implants have been reported.[6] These revision surgeries imply additional hospital stays, increasing healthcare costs, and exposure of patients to further potential complications.

Key words
- Autologous bone grafts
- Craniectomy
- Cranioplasty
- Prediction

Abbreviations and Acronyms
C-index: Concordance statistic
CI: Confidence interval
IQR: Interquartile range
MAR: Missing at random
TRIPOD: Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis

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Citation: World Neurosurg. (2023) 175:e693-e703.
https://doi.org/10.1016/j.wneu.2023.04.008

*Journal homepage: **www.journals.elsevier.com/world-neurosurgery***

*Available online: **www.sciencedirect.com***

Owing to the scarcity of sufficient evidence to identify the determinants of postoperative outcomes, cranioplasty is often performed according to institutional and personal preferences. An increased interest in studying such determinants has arisen, in attempts to guide clinical practice regarding operative and perioperative management.[7-21] Different determinants of bone flap resorption and surgical site infection have been reported, including patient age and cranial defect size.[7,10-12,15,17,20] Although these reports are useful to alert neurosurgeons to those determinants associated with postoperative complications, they are not suitable for predicting an individual patient's clinical course following cranioplasty. Predicting an individual patient's absolute risk of cranioplasty implant survival would help inform neurosurgeons and patients regarding the expected clinical course following cranioplasty, which is important for anticipating patients' concerns and improving their confidence in the clinical care provided. Furthermore, this could help assist neurosurgeons in the clinical management of these patients. Therefore, the purpose of the present study was to develop a prediction model for cranioplasty implant survival in patients undergoing cranioplasty following craniectomy.

METHODS

The present study was performed in accordance with the TRIPOD (transparent reporting of a multivariable prediction model for individual prognosis or diagnosis) statement, a set of recommendations for the reporting of studies developing and validating a prediction model.[22,23]

Study Design and Study Population

For the development of the model, we performed a retrospective cohort study to identify all consecutive patients who underwent cranioplasty after craniectomy from January 1, 2014 to December 31, 2020 at the University Medical Center Utrecht, the Netherlands. Patients were eligible for inclusion if a minimum of 1 year of follow-up data were available. Patients were excluded if they had undergone cranioplasty for the treatment of craniosynostosis or had required skull base reconstruction. Our institution's medical research ethics committee reviewed and approved the present study (approval no. 22/519). All identified patients, except for 3, provided written informed consent. Sharing of the current data for further research will be considered on request.

Surgical Techniques

Patients underwent craniectomy for evacuation of an intracranial mass lesion resulting from traumatic brain injury, treatment of otherwise medically refractory raised intracranial pressure, or bone flap infection.[1] The interval between craniectomy and cranioplasty depended on the patient's general health status and preference, treating neurosurgeon's expert opinion, and availability of the operating room. Before the cranioplasty procedure, patients received a prophylactic dose of cefazolin 2000 mg or clindamycin 600 mg. A wound drain was inserted according to surgeon preference. In the case of subsequent autologous cranioplasty, the removed bone flaps were preserved under sterile conditions in a freezer at −80°C or subcutaneously in an abdominal pocket. The surgical incision was closed using absorbable subcutaneous sutures and either skin sutures or staples. When present, the wound drain was removed within the first 3 days. A clinical follow-up visit was scheduled at 6 weeks after the cranioplasty procedure. All further follow-up visits were planned individually via the outpatient clinic.

Outcome and Candidate Determinants

The primary outcome measure was cranioplasty implant survival, assessed by the interval between the date of cranioplasty and date of revision surgery. Revision surgery was defined as any subsequent surgery performed to remove the cranioplasty implant and replace it with a new one, either during the same procedure or at a later stage. The secondary outcome measures included the incidence of postoperative complications, including bone flap resorption (in the case of autologous cranioplasty) and surgical site infection. Bone flap resorption could vary from thinning of the rim of the autologous bone flap to bone lysis through the tabula externa and tabula interna, measured on conventional skull radiographs and/or computed tomography scans. Surgical site infection was defined as a culture-positive wound swab or underlying fluid tap requiring surgical removal of the cranioplasty implant and antibiotic therapy. A prior examination of the literature and expert opinion guided the selection of candidate determinants. Both patient- and cranioplasty procedure-associated variables that were hypothesized to influence cranioplasty implant survival were included. Each candidate determinant was clearly defined before a review of the medical records to limit measurement bias. These included the indication for craniectomy, Glasgow coma scale score at craniectomy, syndrome of the trephined, cranial defect size (in cm^2), interval between craniectomy and cranioplasty (in days), age at cranioplasty (in years), cranioplasty implant material, presence of wound drainage or cerebrospinal fluid drainage (ventriculoperitoneal shunt or lumboperitoneal shunt) at cranioplasty, and method of skin closure after cranioplasty. When infection was the indication for craniectomy (i.e., removal of an infected autologous bone flap that was reinserted intraoperatively during craniotomy), the cranioplasty procedure was postponed until the patient had finished the antibiotic therapy and all signs of infection had resolved.

Statistical Analysis

Normally distributed continuous variables are presented as the mean ± standard deviation. Non-normally distributed continuous variables are presented as the median and corresponding interquartile range (IQR). Categorical variables are presented as numbers and corresponding percentages.

We performed χ^2 tests and Fisher's exact tests to test for differences in 1) postoperative complication and revision surgery rates between autologous bone flaps and cranial implants; 2) surgical site infection rates between patients who had undergone skin closure with sutures versus skin closure with staples and between patients who had undergone cranioplasty <12 weeks after craniectomy versus ≥12 weeks after craniectomy; and 3) proportions of the method of skin closure (sutures vs. staples) between the different treating neurosurgeons. P values < 0.05 were taken to indicate statistically significant differences.

Table 1. Baseline Patient Characteristics* ($n = 182$)

Characteristic	Value
Male sex	96 (52.7)
Age at craniectomy (years)	42.5 ± 19.7
Age at cranioplasty (years)	43.0 ± 19.7
Age group at cranioplasty (years)	
<18	22 (12.1)
18–50	73 (40.1)
>50	84 (46.2)
Indication for craniectomy	
Trauma	70 (38.5)
Vascular disease	68 (37.4)
Infection	42 (23.1)
Tumor	2 (1.1)
GCS score at craniectomy	
≤8	86 (47.3)
>8	89 (48.9)
Cranial defect size (cm^2)	82.0 ± 31.5
Cranial defect size group (cm^2)	
<75	57 (31.3)
≥75	116 (63.7)
Laterality	
Unilateral	177 (97.3)
Bilateral	5 (2.7)
Syndrome of the trephined	6 (3.3)
Interval between craniectomy and cranioplasty (weeks)	20.4 (15.8–29.2)
Interval between craniectomy and cranioplasty categories (weeks)	
<12	19 (10.4)
≥12	160 (87.9)
Cranial reconstruction material	
Autologous bone flap	121 (66.5)
Glass-fiber reinforced composite	36 (19.8)
MMA	16 (8.8)
PMMA	6 (3.3)
PEEK	2 (1.1)
Custom-made porous hydroxyapatite	1 (0.5)
Wound drain placed after cranioplasty	48 (26.4)
Skin closure after cranioplasty	
Sutures	133 (73.1)
Staples	39 (21.4)
In-hospital complications	9 (4.9)
EDH	4 (2.2)
Wound leakage	2 (1.1)
Hydrocephalus	1 (0.5)
Epidural fluid	2 (1.1)
Presence of CSF drainage	11 (6.0)
Before cranioplasty procedure	5 (2.7)
During cranioplasty procedure	4 (2.2)
After cranioplasty procedure	2 (1.1)
Follow-up after craniectomy (years)	5.6 (4.3–7.0)
Follow-up after cranioplasty (years)	5.1 (3.9–6.5)

Data presented as *n* (%), mean ± standard deviation, or median (interquartile range).
GCS, Glasgow coma scale; MMA, methyl methacrylate; PMMA, polymethyl methacrylate; PEEK, polyetheretherketone; EDH, epidural hematoma; CSF, cerebrospinal fluid.
*Values before multiple imputation shown; data were missing for age at craniectomy (1.1%), age at cranioplasty (1.6%), GCS score at craniectomy (3.8%), cranial defect size (4.9%), interval between craniectomy and cranioplasty (1.6%), wound drainage (2.7%), skin closure (5.5%), in-hospital complications (1.6%), presence of CSF drainage (1.6%), follow-up after craniectomy (1.1%), and follow-up after cranioplasty (1.6%).

Missing data were imputed using multiple imputation, creating 5 imputed datasets. To study the association between cranioplasty implant survival and candidate determinants, we performed multivariable Cox proportional hazards regression analysis for all 5 imputed datasets. The functional form of the continuous candidate determinants was assessed using martingale residuals. To test whether the candidate determinants contributed to the model, we performed backward selection using the Akaike information criterion. The proportional hazards assumption was assessed using the scaled Schoenfeld residuals test. Prediction models developed using multivariable regression can be overfitted to the development cohort and thus overestimate the effect sizes when applied to different patient populations.[24-26] We corrected for this by applying a shrinkage factor to the regression coefficients determined using bootstrapping techniques.[26] The regression coefficients of each imputed dataset were pooled using Rubin's rules.[27] The estimated effect sizes of the independent determinants from the model are expressed as hazard ratios with their corresponding 95% confidence intervals (CIs). To assess the model's performance, we estimated its discrimination and calibration. Discrimination indicates the model's ability to correctly distinguish between patients with and without revision surgery, and we evaluated this performance measure using the concordance statistic (C-index).[24,25] The C-index of each imputed dataset was pooled using Rubin's rules.[27] Calibration is an indicator of the measure of agreement between predicted and observed cranioplasty implant survival, and we evaluated this with a 1-year calibration plot.[24,25] To study the influence of our missing data on the outcome, we performed a sensitivity analysis that included only patients with complete data.

Table 2. Out-of-Hospital Complications and Revision Surgery After Cranioplasty

Variable	Autologous Bone Flaps (n = 121)*	Cranial Implants (n = 61)†	P Value‡
Total patients with complication	60 (49.6)	9 (14.8)	< 0.001
Bone flap resorption	46 (38.0)	0 (0.0)	< 0.001
Surgical site infection	16 (13.2)	5 (8.2)	0.316
Mechanical complications	3 (2.5)	2 (3.3)	1.000
Hydrocephalus	1 (0.8)	1 (1.6)	1.000
Implant exposure	1 (0.8)	1 (1.6)	1.000
Pain	0 (0.0)	1 (1.6)	0.335
First revision surgery	56 (46.3)	10 (16.4)	< 0.001

Data presented as *n* (%).
*Five patients experienced both resorption and infection, 1 patient experienced both resorption and hydrocephalus, 1 patient experienced both resorption and mechanical complications.
†One patient experienced both infection and hydrocephalus, which explains the discrepancy between the number of patients with complications and the stratified number of complications.
‡The χ^2 test or Fisher exact test (for cell counts <5) was used for differences in proportions.

RESULTS

Baseline Characteristics

A total of 182 consecutive patients underwent cranioplasty following craniectomy within the study period (Table 1). The mean age at cranioplasty was 43.0 ± 19.7 years (range, 0.7–83.4 years), and 22 patients (12.1%) were aged <18 years. The mean cranial defect size was 82.0 ± 31.5 cm² (range, 7.9–231.4 cm²); 116 patients (63.7%) had a defect of ≥75 cm². The median interval between craniectomy and cranioplasty was 20.4 weeks (IQR, 15.8–29.2 weeks; range, 23 days to 1.7 years). For 160 patients (87.9%), this interval was >12 weeks. The most frequently used

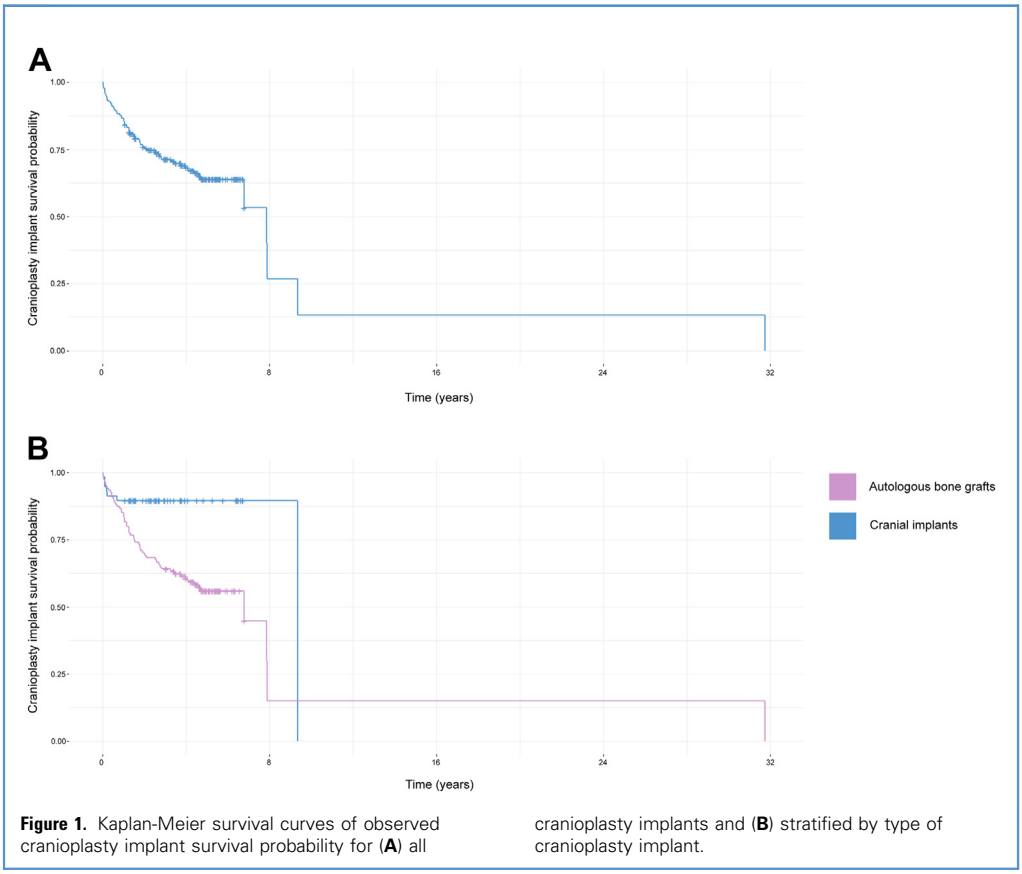

Figure 1. Kaplan-Meier survival curves of observed cranioplasty implant survival probability for (**A**) all cranioplasty implants and (**B**) stratified by type of cranioplasty implant.

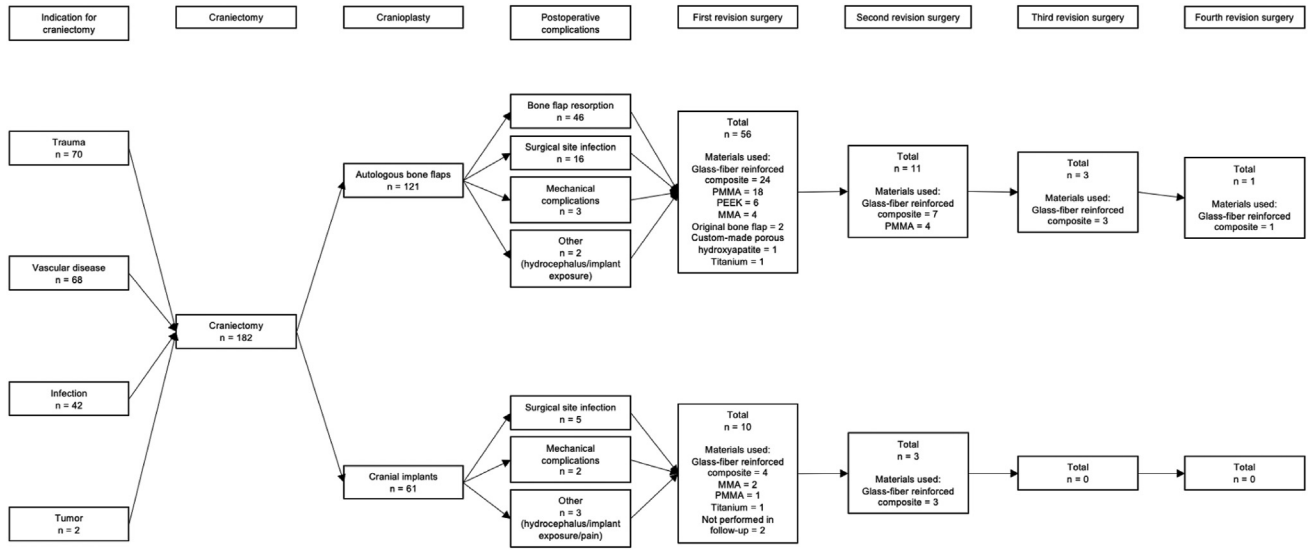

Figure 2. Flowchart of postoperative complications and subsequent revision surgeries following cranioplasty. MMA, methyl methacrylate; PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate).

cranioplasty technique was replacement of the autologous bone flap in 121 cases (66.5%), followed by a glass fiber-reinforced composite in 36 cases (19.8%). For 133 cases (73.1%), sutures were used as the method of skin closure. Of the 24 different treating neurosurgeons, 9 (37.5%) always used sutures and never used staples, and 15 (62.5%) used both sutures and staples. The median follow-up after cranioplasty was 5.1 years (IQR, 3.9–6.5 years; range, 1.1–37.9 years).

Postoperative Complications and Revision Surgeries

The out-of-hospital postoperative complications stratified by the cranioplasty implant material are presented in Table 2. The total complication rate differed significantly between the autologous bone flap and cranial implant groups (60 of 121 [49.6%] and 9 of 61 [14.8%], respectively; $P < 0.001$). A total of 66 patients (36.3%) required a first revision surgery (second cranioplasty implant). This rate also differed significantly between the 2 groups, with 56 in the autologous bone graft group (46.3%) and 10 in the cranial implant group (16.4%; $P < 0.001$), for an absolute risk reduction of 29.9%. Thus, we would need to treat 4 patients with a cranial implant instead of an autologous bone flap to prevent 1 revision surgery. The surgical site infection rate also differed significantly between those who had undergone skin closure with sutures or skin closure with staples (9 of 133 [6.8%] and 10 of 39 [25.6%], respectively; $P < 0.001$). The surgical site infection rate did not differ significantly between those who had undergone cranioplasty <12 weeks after craniectomy versus ≥12 weeks after craniectomy (1 of 19 [5.3%] and 20 of 160 [12.5%], respectively; $P = 0.704$). The Kaplan-Meier curves of observed cranioplasty survival probability are shown in Figure 1. A flowchart of postoperative complications and subsequent revision surgeries is presented in Figure 2. A second revision surgery (third cranioplasty implant) was necessary for 14 patients (7.7%). Subsequently, 3 patients (1.6%) had required a third revision surgery and 1 (0.5%) had required a fourth revision surgery.

Table 3. Univariable and Multivariable Cox Proportional Hazards Regression Analysis of Determinants of Cranioplasty Implant Survival From Final Model

Predictor	Univariable	Multivariable*
Indication for craniectomy		
Trauma	Reference	NA
Vascular disease	0.52 (0.29–0.92)	0.65 (0.36–1.17)
Infection	0.35 (0.16–0.77)	0.76 (0.32–1.80)
Tumor	2.57 (0.61–10.82)	1.40 (0.29–6.79)
Cranial defect size per cm^2	1.01 (1.00–1.02)	1.01 (0.73–1.38)
Cranioplasty implant material		
Cranial implant	Reference	NA
Autologous bone graft	2.47 (1.26–4.87)	1.63 (0.82–3.24)
Skin closure		
Sutures	Reference	NA
Staples	1.62 (0.95–2.75)	1.42 (0.79–2.56)

Data presented as hazard ratios (95% confidence intervals).
NA, not applicable.
*The initial regression coefficients were corrected for overfitting with bootstrapping techniques.

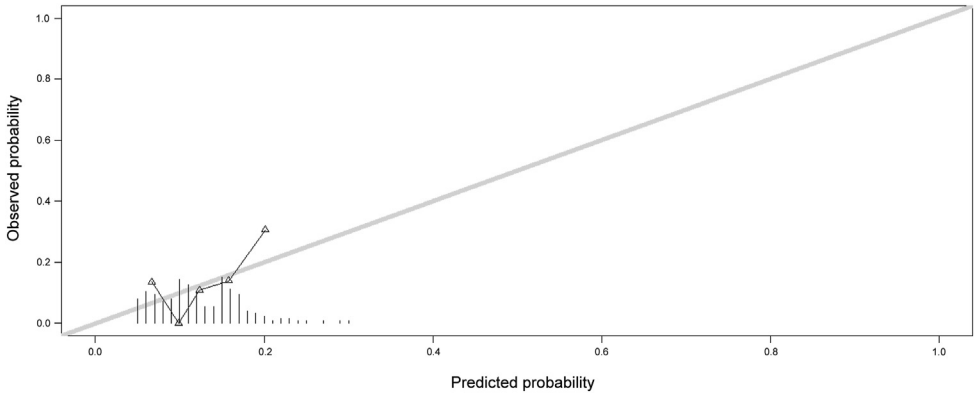

Figure 3. Calibration plot of observed versus predicted implant survival probability at 1 year following cranioplasty.

Model Development and Performance

The results from the final model are presented in **Table 3**. The indication for craniectomy, cranial defect size, cranioplasty implant material, and method of skin closure after cranioplasty were independent determinants of cranioplasty implant survival. The martingale residuals showed that cranial defect size could be analyzed as a linear determinant (**Supplementary Figure 1**). The scaled Schoenfeld residuals test showed that the proportional hazards assumption was not violated ($P > 0.05$ for all; **Supplementary Table 1**). After shrinkage of the regression coefficients, the C-index of the final model was 0.60 (95% CI, 0.47–0.73). The calibration plot of observed and predicted implant survival probability at 1 year after cranioplasty is presented in **Figure 3**. In the sensitivity analysis of only patients with complete data, the independent determinants of cranioplasty implant survival remained the same; however, the corresponding C-index was 0.68 (95% CI, 0.61–0.75).

To calculate an individual patient's absolute predicted implant survival probability at 1 year after cranioplasty, the original regression equation provided in **Supplementary Table 2** can be used. Thus, a patient who required craniectomy for vascular disease with a cranial defect size of 80 cm^2 that has been reconstructed using an autologous bone flap followed by skin closure using staples will have a risk of revision surgery of 6.9% at 1 year after cranioplasty.

DISCUSSION

Although cranioplasty is a routine procedure in neurosurgical practice, it is associated with high rates of postoperative complications and subsequent revision surgeries. We have developed the first prediction model for cranioplasty implant survival. We found that the indication for craniectomy, cranial defect size, cranioplasty implant material, and method of skin closure after following cranioplasty were independent determinants of cranioplasty implant survival.

Over the years, an increased interest has arisen in studying the determinants of postoperative complications after cranioplasty[7-21] The reported determinants of bone flap resorption and surgical site infection include age and cranial defect size.[7,10-12,15,17,20] Although the findings from these studies are important to alert neurosurgeons to those determinants associated with postoperative complications, they are not suitable for predicting individual patients' clinical course following cranioplasty. In general, prediction models to help neurosurgeons in optimizing individual patients' outcomes after neurosurgical interventions have been increasingly reported.[28-36] Our prediction model adds to this growing research domain in the neurosurgical field.

Although the results from our prediction model should not be interpreted causally, they are largely in agreement with the results from previous studies reporting on risk factors for postoperative complications following cranioplasty.[6,7,37-40] The relatively high resorption rate of cryosterilized autologous bone grafts is likely an important contributing factor to our results. Resorption often results in removal and replacement of the autologous bone flap, increasing the risk of revision surgery after the use of this material.[6,37] A recent meta-analysis by Malcolm et al[6] showed that autologous bone grafts required significantly more revision surgeries than cranial implants, primarily because of bone flap resorption. Furthermore, a larger cranial defect size has been reported to increase bone flap resorption rates, possibly due to a wide gap between the cranioplasty implant and cranial defect contour.[7,38,39]

Various studies in different surgical specialties have suggested that the use of sutures for skin closure results in lower postoperative surgical site infection rates than the use of staples.[41-44] In our cohort, we observed a statistically significant difference in the surgical site infection rate between sutures and staples, which could be an important contributing factor to the higher risk of revision surgery associated with staples. In addition, we found that the method of skin closure differed significantly between the treating neurosurgeons in our center, suggesting that the higher risk of revision surgery could also be related to the treating neurosurgeons' operative techniques rather than solely the skin closure type. Craniectomy for vascular disease or infection was associated with a lower risk of revision surgery compared with

craniectomy for trauma. In contrast, craniectomy for tumor increased the risk of revision surgery. A recent study by Bader et al[40] reported similar results, showing that craniectomy for cerebral infarction was associated with a decreased risk of revision surgery compared with other indications for craniectomy.

We found that the GCS score at craniectomy, syndrome of the trephined, interval between craniectomy and cranioplasty, patient age at cranioplasty, and presence of wound drainage or cerebrospinal fluid drainage at cranioplasty were not independent determinants of cranioplasty implant survival. However, this finding does not indicate that these factors do not play a role in the development of postoperative complications following cranioplasty but, rather, that they did not contain predictive information for predicting cranioplasty implant survival beyond the other determinants in our model.

We adjusted for our missing data using multiple imputation, because we believe our missing data were either missing at random (MAR) or missing not at random. When missing data are MAR, it is advisable to use multiple imputation because this leads to valid effect estimates, including a measure of uncertainty.[45,46] When missing data are missing not at random, no straightforward method is available to obtain valid effect estimates, and the only possibility is to perform a sensitivity analysis that includes only those patients with complete data to evaluate the influence of the missing data on the outcome. In our sensitivity analysis, the determinants in the model remained the same, suggesting that our missing data did not have an important influence on which determinants are associated with cranioplasty implant survival. However, the model based on our complete case analysis showed better performance than the model based on multiple imputation (C-index, 0.68 [95% CI, 0.61–0.75] and C-index, 0.60 [95% CI, 0.47–0.73], respectively). However, we believe these results are less valid because our missing data were likely MAR, and, in such cases, it is not recommended to use a complete case analysis.

Implications

The current prediction model allows for the prediction of an individual patient's absolute risk of cranioplasty implant survival, which should help inform neurosurgeons and patients regarding the expected clinical course following cranioplasty. This is important to allow neurosurgeons to anticipate patients' concerns and improve their confidence in the clinical care provided. Furthermore, the use of our model could help assist neurosurgeons in the clinical management of these patients. However, the current prediction model is designed as a research tool and should not be widely implemented in clinical practice before external validation in different prospective cohort studies. In general, external validation is essential for deciding whether the performance of a prediction model will be maintained when applied to new patient populations.[25] Moreover, the development of other models with the same outcome but using different populations and pooling their results could lead to more accurate model predictions. Furthermore, prediction models should be used to inform, not for direct decision-making, in clinical practice. We support a multidimensional approach for clinical decision-making regarding craniectomy and cranioplasty, in which model predictions are complemented by clinical experience and patient preference.

Study Strengths and Limitations

An important strength of our study is that we have developed the first prediction model for cranioplasty implant survival in patients undergoing cranioplasty following craniectomy. In addition, instead of only reporting determinants of the outcome, we combined those into a prediction model and assessed its performance. Our prediction model showed fair discrimination, with a C-index of 0.60, and fair calibration between the observed and predicted implant survival probability at 1 year after cranioplasty. Second, the independent determinants in our prediction model are all readily available at cranioplasty, allowing for simple estimation of individual patients' cranioplasty implant survival probability. Finally, we optimized model development using appropriate methodological techniques, including correcting for overfitting using bootstrapping techniques and imputing missing data using multiple imputation. Our study also has limitations. The main limitation was the retrospective nature of our study and the corresponding small sample size. For the development of a prediction model, one would ideally use a large prospective cohort study. However, such a study design and sample size are practically and financially infeasible for cohorts of patients undergoing cranioplasty following craniectomy. Second, although we included a wide range of candidate determinants, other clinical factors that might predict for cranioplasty implant survival were unmeasured in our study. Third, although our model includes a clinically relevant outcome, it does not elucidate the underlying reason for the need of revision surgery. Finally, we categorized the cranioplasty implant material as either autologous bone flaps or cranial implants, instead of stratifying the cranial implants into the different material types. However, this was practically unattainable because the numbers per type were low.

CONCLUSIONS

In the present study, we developed the first prediction model for cranioplasty implant survival following craniectomy. This model is a good starting point to help inform neurosurgeons and patients regarding the expected clinical course following cranioplasty. The findings from our study require external validation and deserve further exploration in future studies.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Vita M. Klieverik: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Pierre A. Robe:** Conceptualization, Supervision, Writing – review & editing. **Marvick S.M. Muradin:** Supervision, Writing – review & editing. **Peter A. Woerdeman:** Conceptualization, Supervision, Writing – review & editing.

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Conflict of interest statement: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 20 March 2023; accepted 3 April 2023

Citation: World Neurosurg. (2023) 175:e693-e703. https://doi.org/10.1016/j.wneu.2023.04.008

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

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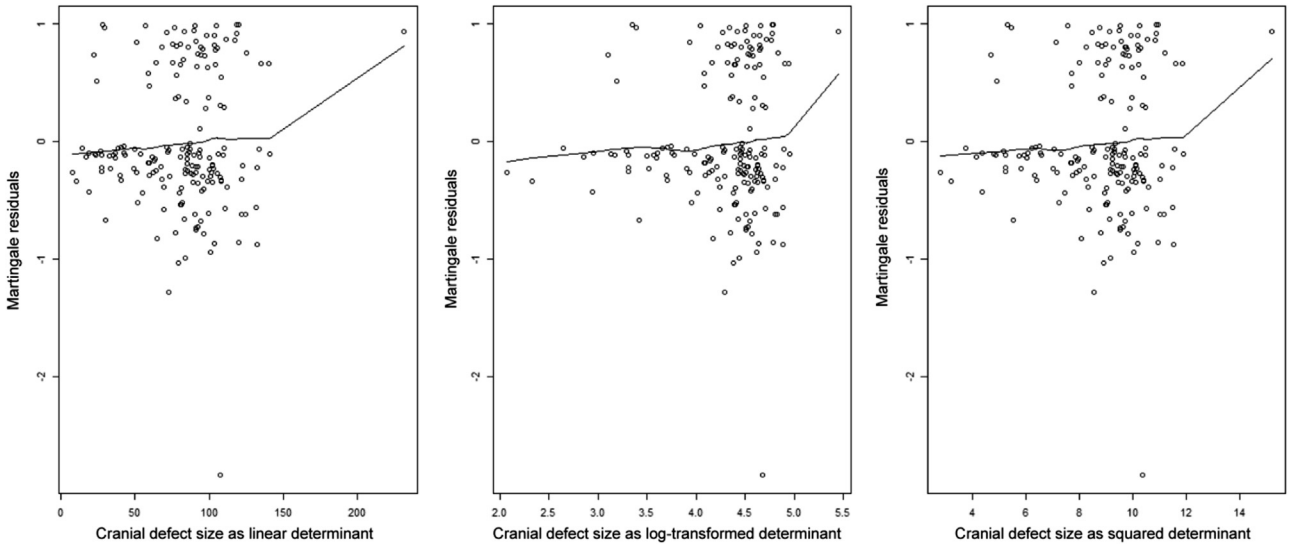

Supplementary Figure 1. Martingale residuals plots of a model without the determinant cranial defect size plotted against the determinant cranial defect size.

Supplementary Table 1. Scaled Schoenfeld residuals test p -values, tested against different time scales

		KM	time Log-transformed time
	Linear time scale	scale	scale
Indication for craniectomy	0.05	0.36	0.27
Cranial defect size	0.27	0.23	0.32
Cranioplasty implant material	0.32	0.26	0.27
Skin closure	0.10	0.23	0.18

Supplementary Table 2. Original regression equation of the final model

Linear predictor (LP)
−0.428 (if craniectomy for vascular disease) − 0.272 (if craniectomy for infection) + 0.337 (if craniectomy for tumor) + 0.006 (per cm^2 in cranial defect size) + 0.487 (if autologous bone graft) + 0.351 (if skin closure following cranioplasty using staples)
Mean LP
1.470
Estimating individual patients' absolute risk of revision surgery at 1 year following cranioplasty is based on the following formula: $1 - S(t)^{\exp(LP - \text{mean LP})}$, where $S(t)$ is the baseline survival probability at 1 year and LP is the linear predictor of the regression coefficients of the final model, corrected for the averages of the regression coefficients (mean LP). The baseline survival probability at 1 year is 0.8792839 and LP should be filled in according to predictor status.
As an example on how to use this formula: consider a patient that required craniectomy for vascular disease, with a cranial defect size of 80 cm^2 that has been reconstructed using an autologous bone flap followed by skin closure using staples. In this instance, the LP is filled in as follows:
−0.428 (for craniectomy for vascular disease) + 0.006*80 (for cranial defect size of 80 cm^2) + 0.487 (for autologous bone graft) + 0.351 (for skin closure using staples) = 0.89
$1 - S(t)^{\exp(LP - \text{mean LP})}$
$S(t) = 0.8792839$ LP = 0.89 Mean LP = 1.470
$1 - 0.8792839^{\exp(0.89 - 1.470)} = 1 - 0.8792839^{\exp(-058)} = 1 - 0.8792839^{0.55989836656} = 1 - 0.93050344678 = 0.06949655321 = 6.9\%$
This patient will have a risk of revision surgery at 1 year following cranioplasty of 6.9%.