

Selection of Cranial Repair Materials Based on Preoperative Imaging Indicators and Analysis of Risk Factors for Complications

Peilin Zhu

The First Affiliated Hospital of Xi'an Jiaotong University

Yichang Wang

The First Affiliated Hospital of Xi'an Jiaotong University

Gang Bao

baogang1973@aliyun.com

The First Affiliated Hospital of Xi'an Jiaotong University

Research Article

Keywords: Cranioplasty, Titanium Mesh (Ti), Polyether Ether Ketone (PEEK), Postoperative Complications, Brain Collapse, Abnormal Volume Ratio

Posted Date: February 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8619362/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Selection of Cranial Repair Materials Based on Preoperative Imaging Indicators and Analysis of Risk Factors for Complications

Authors:

Peilin Zhu¹, Yichang Wang¹, Gang Bao^{1*}

Affiliations:

¹Department of Neurosurgery, The First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710000, China

*Corresponding author:

Gang Bao

Department of Neurosurgery, The First Affiliated Hospital of Xi'an Jiaotong University

No. 277, Yanta West Road, Xi'an 710000, China

Email: baogang1973@aliyun.com

Abstract

Background

Cranioplasty is a common neurosurgical procedure, yet managing postoperative complications remains a significant clinical challenge. A definitive consensus is lacking on the choice of repair materials and the factors influencing complications.

Objective

This study aimed to identify independent risk factors for complications following cranioplasty and to establish evidence-based criteria for the individualized selection between titanium mesh (Ti) and polyether ether ketone (PEEK), based on preoperative imaging indicators.

Methods

We included 211 patients who underwent cranioplasty (110 Ti, 101 PEEK) at our institution between January 2018 and May 2024. Demographic, imaging, and surgical data were collected. Univariate and multivariate logistic regression models identified risk factors for complications. Generalized Additive Models (GAM) and piecewise regression analysis were employed to characterize the nonlinear relationship between the abnormal volume ratio and the efficacy of material choice, and to identify critical thresholds.

Results

Age (OR=1.03, $P=0.010$) and brain collapse volume (OR=1.03, $P=0.042$) were independent risk factors for postoperative complications. GAM revealed a significant interaction between material type and abnormal volume ratio ($P=0.019$). Piecewise regression identified a key threshold: when the abnormal volume ratio exceeded 3.47%,

the number of complications was significantly lower in the Ti group than in the PEEK group ($P<0.05$).

Conclusion

Age and brain collapse volume are independent predictors of complications after cranioplasty. For patients with an abnormal volume ratio greater than 3.47%, selecting Ti may reduce postoperative complication risk.

Keywords

Cranioplasty; Titanium Mesh (Ti); Polyether Ether Ketone (PEEK); Postoperative Complications; Brain Collapse; Abnormal Volume Ratio

Introduction

Cranioplasty (CP) is a common neurosurgical procedure aimed at reconstructing the cranial contour. It not only improves cranial appearance but also facilitates neurological recovery¹, normalizes intracranial pressure, and alleviates disturbances in cerebrospinal fluid circulation.² Patients who have undergone decompressive craniectomy for conditions such as traumatic brain injury or cranial tumors are often left with skull defects, typically necessitating CP. However, determining the optimal implant material, surgical timing, and strategies to minimize postoperative complications remains a critical and nuanced challenge in clinical practice.³

The optimal timing for cranioplasty continues to be debated. Although CP is typically performed 3 to 6 months after the initial defect, some studies suggest that early repair benefits neurological recovery^{4,5}, while others associate early intervention with an increased risk of complications such as postoperative seizures⁶. Presently, there is no definitive consensus regarding the specific timing for CP. Retrospective studies indicate that the timing of CP may be less related to a rigid time window and more associated with patient-specific factors like the volume of brain collapse^{7,8}. The relationship between cranioplasty timing and postoperative complications therefore warrants further elucidation⁹.

Common complications following cranioplasty include seizures¹⁰, infection¹¹, graft exposure, epidural fluid collection¹², epidural hemorrhage¹³.

The primary materials currently used for cranioplasty implants include autologous bone, titanium mesh (Ti), polyether ether ketone (PEEK), and other synthetic materials¹⁴. Autologous bone grafts are limited by graft availability and unpredictable resorption¹⁵, particularly in patients with large cranial defects. Bone resorption often necessitates reoperation¹⁶, thus limiting the clinical application of autologous bone.

Titanium (Ti) alloys exhibit excellent corrosion resistance, wear resistance, and outstanding biocompatibility. However, Ti has disadvantages: it is susceptible to deformation under mechanical stress and lacks sufficient elasticity. Additionally, as a thermal conductor, Ti can induce scatter artifacts in conventional imaging modalities¹⁷.

Polyether Ether Ketone (PEEK) is a high-performance polymer known for its resistance to hydrolysis, high temperatures, and corrosion^{14,18}, conferring stable chemical properties. After 3D shaping, it provides a satisfactory aesthetic contour and demonstrates superior resistance to deformation. Its properties also include good thermal insulation and relatively low radiopacity. PEEK implants offer high mechanical strength¹⁹. Furthermore, the elastic modulus of PEEK is close to that of human cortical bone, potentially providing better protection for the brain during traumatic impact. Some evidence suggests a lower reoperation risk with PEEK compared to Ti²⁰. However, PEEK does not integrate with surrounding bone and does not unequivocally reduce complication rates^{21,22}. Its higher cost may also limit its widespread use.²³.

Despite the increasing use of PEEK, studies comparing the choice of cranioplasty materials to mitigate complications have yielded conflicting results^{24–27}. Therefore, this retrospective study aims to compare the complication rates between PEEK and Ti, identify potential predictors of complications, and inform material selection tailored to different clinical presentations.

Methods

Data Collection

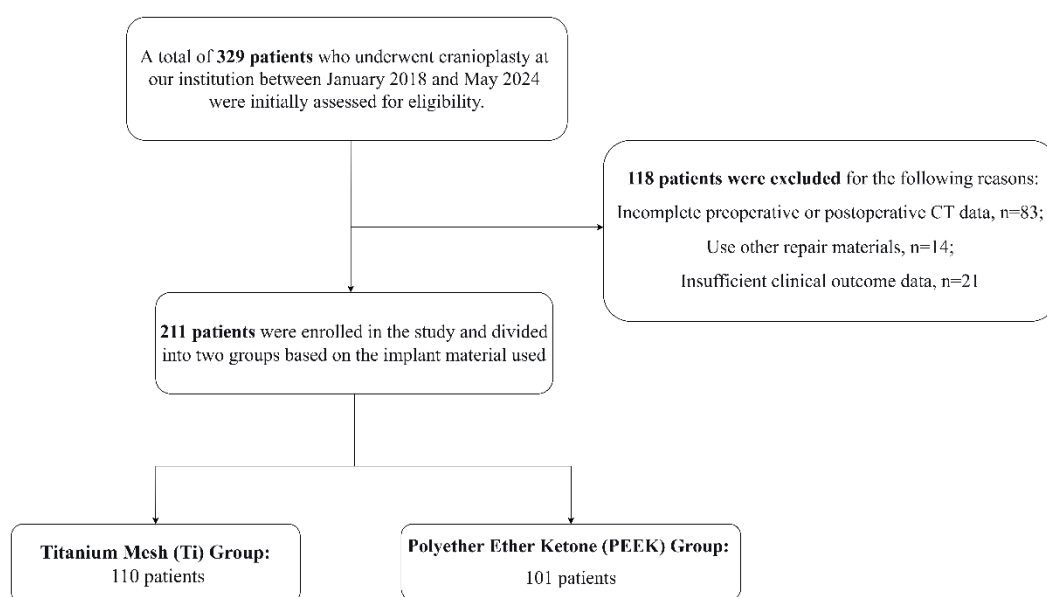


Figure 1. Flowchart of patient screening and grouping

This single-center retrospective cohort study initially screened 329 patients who underwent PEEK or Ti cranioplasty in the Department of Neurosurgery at The First Affiliated Hospital of Xi'an Jiaotong University between January 2018 and May 2024. Demographic data, imaging data, and postoperative complications were recorded and analyzed. After excluding 118 patients due to incomplete clinical information or imaging data, 211 patients were included in the final analysis (Figure1). Univariate and multivariate logistic regression models were used to analyze risk factors for complications following cranioplasty with PEEK or Ti.

Data were retrospectively collected from the electronic medical records system, encompassing patient demographics (age, sex), primary disease, skull defect characteristics (location, size), brain collapse volume, encephalocoe volume, abnormal brain volume ratio, surgical details (repair material, blood loss, operative time, postoperative drainage volume), and postoperative complications (surgical site infection, epidural hematoma, brain edema, scalp swelling, implant exposure, seizures, epidural/subdural fluid collection).

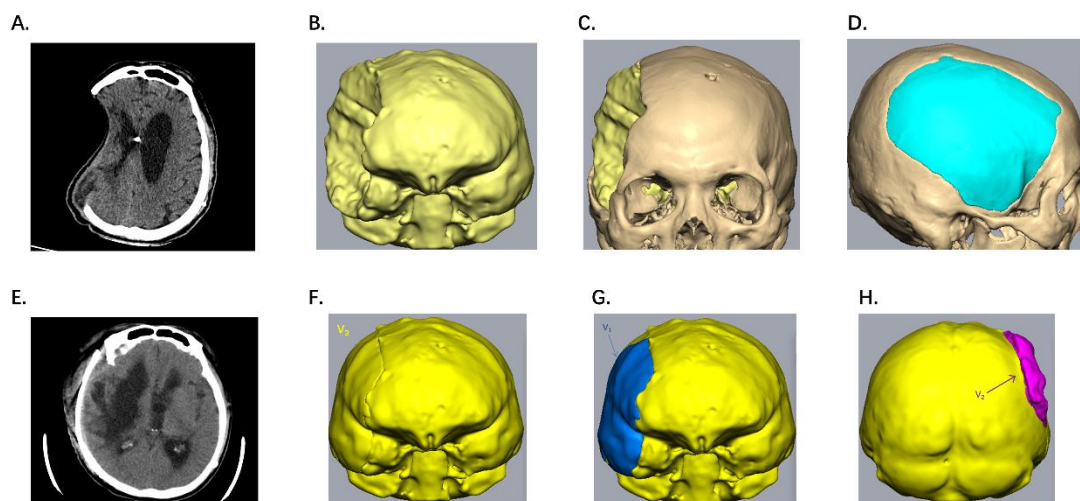


Figure 2. Schematic illustration of preoperative and postoperative cranial volume measurement.

(A) Preoperative CT scan; (B) Preoperative brain volume; (D) Skull defect size;

(E) Postoperative CT scan; (F) Ideal postoperative volume;

(G) Brain collapse volume (V_1); (H) Encephalocoe volume (V_2).

MIMICS and FreeForm software were utilized to generate 3D models from patient CT data. Preoperative CT scans (Figure2.A) and postoperative CT scans (Figure2.E) were modeled to calculate the preoperative cranial brain volume (Figure2.B), the postoperative ideal volume (V_3 ; Figure2.F), and the precise defect area (Figure2.D), among other parameters. The preoperative brain volume was compared against the postoperative ideal volume to derive the Brain Collapse Volume (V_1 ; Figure2.G) and

the Encephalocele Volume (V_2 ; Figure 2.H). The patient's abnormal brain volume ratio was calculated as $[(V_1 + V_2) / V_3]$.

Statistical Analysis

All statistical analyses were performed using R software (version 4.2.2). Continuous variables were compared using independent samples t-tests or Mann-Whitney U tests. Categorical variables were analyzed using Chi-square tests or Fisher's exact tests. Multicollinearity among variables from univariate analysis was assessed using Variance Inflation Factor (VIF) and Tolerance. Variable selection was performed using a combination of stepwise regression, LASSO regression, Random Forest variable importance ranking, and the Boruta algorithm. Selected variables were incorporated into the multivariate analysis model. A P-value < 0.05 was considered statistically significant.

To investigate potential nonlinear interactions between the repair material and the abnormal volume ratio, a Generalized Additive Model (GAM) was constructed. The model included material type as a factor variable, the abnormal volume ratio as a smooth term, and an interaction smooth term between material type and the abnormal volume ratio. Model significance was assessed via likelihood ratio tests. To identify the clinical threshold where material selection efficacy diverges, piecewise regression analysis was performed on the abnormal volume ratio, guided by GAM results. A grid search method identified the optimal inflection point, and hypothesis testing compared groups on either side of this point.

Results

Basic Information of Patients and Details of Surgeries

Table 1: Patient demographics and baseline characteristics

Characteristic	Cranial repair materials		p-value
	PEEK N = 101 ¹	Ti N = 110	
Sex			0.007
female	19 (19%)	39 (35%)	
male	82 (81%)	71 (65%)	
Age	41 (31, 54)	51 (40, 59)	<0.001
Primary Disease			0.006
Brain Tumor	2 (2.0%)	9 (8.2%)	
Cerebrovascular Disease	30 (30%)	48 (44%)	

Characteristic	Cranial repair materials		p-value
	PEEK N = 101 ¹	Ti N = 110	
Skull Lesion	1 (1.0%)	0 (0%)	0.900
Traumatic Brain Injury	68 (67%)	53 (48%)	
Skull defect side			
both	6 (5.9%)	5 (4.5%)	
left	52 (51%)	57 (52%)	
right	43 (43%)	48 (44%)	0.547
Skull defect size, cm ²	190 (137, 234)	201 (141, 237)	
Brain volume, cm ³	1,396 (1,292, 1,479)	1,350 (1,256, 1,433)	
Operative time, minutes	3.00 (2.50, 3.00)	2.50 (2.00, 3.00)	
Blood loss, mL	100 (50, 150)	100 (50, 200)	
Postoperative drainage volume	100 (80, 150)	150 (100, 200)	<0.001

¹n (%); Median (IQR)

²Pearson's Chi-squared test; Wilcoxon rank sum test; Fisher's exact test

The baseline characteristics of patients undergoing cranial repair with PEEK (n=101) and Ti (n=110) are summarized in Table 1. The groups differed significantly in several demographic and clinical characteristics. Patients in the Ti group were significantly older (49 ± 14 vs. 41 ± 15 years, $P < 0.001$) and had a higher proportion of females (35.5% vs. 18.8%, $P = 0.007$). Significant differences were also noted in primary disease distribution ($P = 0.006$), with traumatic brain injury being more prevalent in the PEEK group (67.3% vs. 48.2%) and cerebrovascular disease more common in the Ti group (43.6% vs. 29.7%). The Ti group had significantly lower brain volume ($1,339 \pm 140$ vs. $1,396 \pm 143$ cm³, $P = 0.004$) and higher postoperative drainage volume (162 ± 87 vs. 122 ± 69 mL, $P < 0.001$). No significant differences were found in skull defect side distribution ($P = 0.900$), defect size ($P = 0.680$), operative time ($P = 0.365$), or blood loss ($P = 0.078$).

A general overview of postoperative complications

Table 2: Postoperative Complications of Patients

Characteristic	Cranial repair materials		p-value
	PEEK N = 101	Ti N = 110	
Overall complications, n (%)			0.240 ¹
	78 (77.2%)	92 (83.6%)	
Complications number, Median (Q1, Q3)	2.00 (1.00, 3.00)	2.00 (1.00, 3.00)	0.407 ²

Characteristic	Cranial repair materials		p-value
	PEEK N = 101	Ti N = 110	
Intracranial fluid accumulation disorders, n (%)			0.020 ¹
cerebral edema	35 (34.7%)	36 (32.7%)	
hydrocephalus	3 (3.0%)	15 (13.6%)	
Exposure of implant, n (%)			>0.999 ³
	1 (1.0%)	2 (1.8%)	
Infection, n (%)			0.174 ³
Intracranial Infection	0 (0.0%)	1 (0.9%)	
wound infection	2 (2.0%)	7 (6.4%)	
Scalp swelling, n (%)			0.307 ¹
	37 (36.6%)	33 (30.0%)	
Epilepsy, n (%)			0.685 ³
	2 (2.0%)	4 (3.6%)	
Delayed wound healing, n (%)			0.123 ³
	0 (0.0%)	4 (3.6%)	
Pneumatosis, n (%)			0.640 ¹
	51 (50.5%)	52 (47.3%)	
Subcutaneous effusion, n (%)			0.017 ¹
	36 (35.6%)	23 (20.9%)	
Epidural hematoma, n (%)			0.102 ¹
	30 (29.7%)	22 (20.0%)	

¹Pearson's Chi-squared test

²Wilcoxon rank sum test

³Fisher's exact test

175

176 Skull defects are often caused by traumatic brain injury, and post-traumatic
177 hydrocephalus is one of the common complications²⁸. Chronic hydrocephalus can
178 persist for months to years. Cranioplasty is typically performed 3 to 6 months after the
179 initial defect, meaning the timing of postoperative complications can overlap with the
180 natural history of hydrocephalus.

181

182 Table 2 presents the baseline characteristics stratified by cranial repair material, with
183 101 patients in the PEEK group and 110 in the Ti group. There were no statistically
184 significant differences between groups in the incidence of overall complications (77.2%
185 vs 83.6%, $P=0.240$), median number of complications (2.00 vs 2.00, $P=0.407$), implant
186 exposure (1.0% vs 1.8%, $P>0.999$), infection (2.0% vs 7.3%, $P=0.174$), scalp swelling
187 (36.6% vs 30.0%, $P=0.307$), epilepsy (2.0% vs 3.6%, $P=0.685$), delayed wound healing
188 (0.0% vs 3.6%, $P=0.123$), pneumatosis (50.5% vs 47.3%, $P=0.640$), or epidural

hematoma (29.7% vs 20.0%, $P=0.102$). However, significant differences were observed in intracranial fluid accumulation disorders ($P=0.020$), particularly hydrocephalus (3.0% vs 13.6%), and subcutaneous effusion (35.6% vs 20.9%, $P=0.017$).

Identification of Independent Risk Factors for Overall Complications.

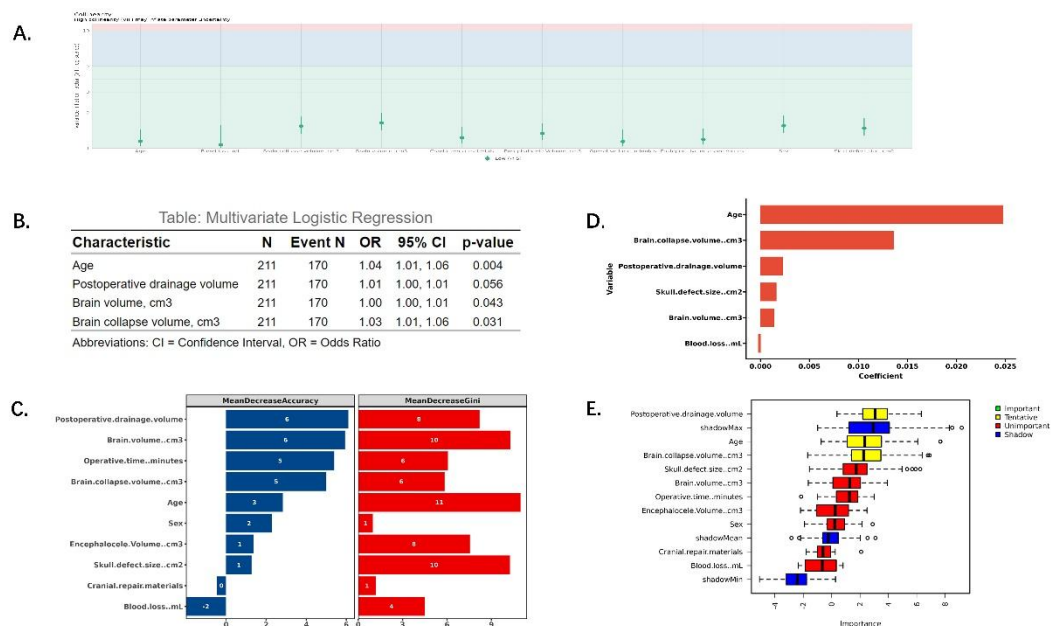


Figure 3. Variable selection and multicollinearity assessment for overall complication risk.

Four variable selection methods were employed to identify factors influencing overall complications: (1) Stepwise regression (Figure3.B); (2) LASSO regression (Figure3.D); (3) Random Forest ranking (Figure3.C); (4) Boruta algorithm (Figure3.E). Multicollinearity was assessed and found to be low ($VIF < 5$, Figure3.A). The selected variables—Age, Postoperative drainage volume, Skull defect size, and Brain collapse volume—were included in a multivariate logistic regression model to identify independent risk factors.

Table 3: Univariate and multivariate analysis of influencing factors (Logistic regression)

[illegible]

Characteristic	Univariable					Multivariable				
	N	Event N	OR	95% CI	p-value ¹	N	Event N	OR	95% CI	p-value ¹
female	58	45	—	—						
male	153	125	1.29	0.60, 2.67	0.501					
Cranial repair materials										
PEEK	101	78	—	—						
Ti	110	92	1.51	0.76, 3.03	0.242					
Age	211	170	1.03	1.01, 1.06	0.007**	211	170	1.03	1.01, 1.06	0.010**
Blood loss, mL	211	170	1.00	0.99, 1.00	0.664					
Postoperative drainage volume	211	170	1.00	1.00, 1.01	0.110	211	170	1.00	1.00, 1.01	0.133
Operative time, minutes	211	170	1.18	0.78, 1.81	0.434					
Skull defect size, cm²	211	170	1.01	1.00, 1.01	0.027*	211	170	1.00	1.00, 1.01	0.305
Brain volume, cm³	211	170	1.00	1.00, 1.00	0.086					
Encephalocoele Volume, cm³	211	170	1.00	0.99, 1.01	0.464					
Brain collapse volume, cm³	211	170	1.03	1.01, 1.07	0.014*	211	170	1.03	1.00, 1.06	0.042*
Abnormal Volume Ratio (%)	211	170	1.05	0.93, 1.21	0.448					

¹*p<0.05; **p<0.01; ***p<0.001

Abbreviations: CI = Confidence Interval, OR = Odds Ratio

Null deviance = 208; Null df = 210; Log-likelihood = -93.5; AIC = 197; BIC = 214; Deviance = 187; Residual df = 206; No. Obs. = 211

210

211 Univariate analysis showed that age, skull defect size, and brain collapse volume were
212 significantly associated with the occurrence of postoperative complications.
213 Multivariate analysis revealed that age was significantly associated with the overall risk
214 of complications (adjusted odds ratio 1.03; 95% confidence interval 1.01 - 1.06; *P*=
215 0.010), indicating a 3% increase in the odds of complications for each additional year
216 of age. Similarly, a larger brain collapse volume was associated with a higher likelihood
217 of complications (adjusted odds ratio 1.03; 95% confidence interval 1.00 - 1.06; *P*=
218 0.042). In contrast, postoperative drainage volume (adjusted odds ratio 1.00; 95%
219 confidence interval 1.00 - 1.01; *P*= 0.133) and skull defect size (adjusted odds ratio
220 1.00; 95% confidence interval 1.00 - 1.01; *P*= 0.305) did not show statistically
221 significant associations with overall complications.

222

223 Identifying Independent Risk Factors for the Number of 224 Complications

225

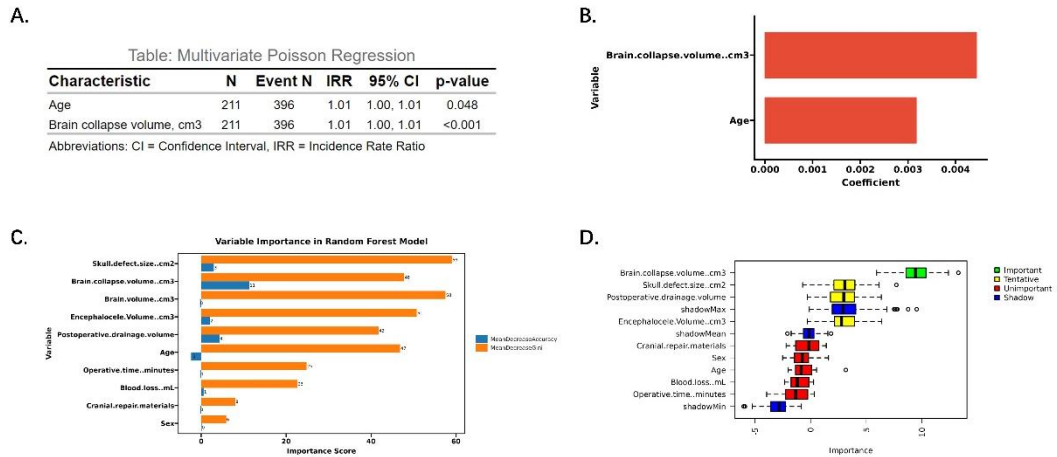


Figure 4. Variable selection process for analyzing the number of complications.

To identify factors influencing the number of complications, the same four variable selection methods were applied (Figure4). Age and Brain collapse volume were selected and included in a multivariate Poisson regression model.

Table 4: Univariate and multivariate analysis of influencing factors (Poisson regression)

Characteristic	Univariable					Multivariable				
	N	Event N	IRR	95% CI	p-value ¹	N	Event N	IRR	95% CI	p-value ¹
Sex										
female	58	108	—	—						
male	153	288	1.01	0.81, 1.27	0.924					
Cranial repair materials										
PEEK	101	197	—	—						
Ti	110	199	0.93	0.76, 1.13	0.454					
Age	211	396	1.01	1.00, 1.02	0.016*	211	396	1.01	1.00, 1.01	0.048*
Operative time, minutes	211	396	1.03	0.91, 1.16	0.633					
Blood loss, mL	211	396	1.00	1.00, 1.00	0.721					
Postoperative drainage volume	211	396	1.00	1.00, 1.00	0.957					
Skull defect size, cm²	211	396	1.00	1.00, 1.00	0.037*					
Brain volume, cm³	211	396	1.00	1.00, 1.00	0.231					
Encephalocele Volume, cm³	211	396	1.00	1.00, 1.00	0.209					
Brain collapse volume, cm³	211	396	1.01	1.00, 1.01	<0.001***	211	396	1.01	1.00, 1.01	<0.001***
Abnormal Volume Ratio (%)	211	396	1.02	0.99, 1.06	0.178					

¹*p<0.05; **p<0.01; ***p<0.001

Abbreviations: CI = Confidence Interval, IRR = Incidence Rate Ratio

Null deviance = 269; Null df = 210; Log-likelihood = -350; AIC = 706; BIC = 716; Deviance = 251; Residual df = 208; No. Obs. = 211

As shown in Table 4, univariate regression analysis indicated that age, skull defect size, and brain collapse volume were significantly correlated with the number of

complications. Multivariate regression analysis revealed significant associations between patient characteristics and complication risk. Each one-year increase in age was associated with a slight elevation in the risk of complications (IRR, 1.01; 95% CI, 1.00 - 1.01; $P= 0.048$). Similarly, each 1 cm³ increase in brain collapse volume was associated with a significant increase in the risk of complications (IRR, 1.01; 95% CI, 1.00 - 1.01; $P< 0.001$). These findings suggest that both increasing age and larger brain collapse volume independently increase the risk of complications.

The Exploration of Material Selection

Due to high multicollinearity ($VIF > 5$) among imaging indicators such as brain collapse volume, encephalocele volume, and the abnormal volume ratio, and to avoid the impact of multicollinearity on the stability of parameter estimates, only the brain collapse volume, which had relatively lower collinearity, was included as a representative variable in the multivariate logistic regression model.

However, given another important objective of this study was to establish clinically applicable individualized material selection criteria, we further investigated the interaction between the repair material and the composite indicator—the abnormal volume ratio—which comprehensively reflects the degree of abnormality in the cranial content. We employed Generalized Additive Models and piecewise regression analysis to explore this nonlinear relationship. This method is insensitive to collinearity among variables and can intuitively display the trend of material effect changes with continuous variables.

Table 5: Multivariable Negative Binomial Regression Analysis with Interaction Effects

Characteristic	N	Event N	IRR ¹	95% CI ¹	p-value
Sex					
female	58	108	Reference	Reference	
male	153	288	1.05	0.84, 1.34	0.663
Cranial.repair.materials					
PEEK	101	197	Reference	Reference	
Ti	110	199	1.14	0.84, 1.56	0.405
Abnormal.Volume.Ratio...	211	396	1.05	1.00, 1.10	0.031
Age	211	396	1.01	1.00, 1.02	0.007
Skull.defect.size..cm ²	211	396	1.00	1.00, 1.00	0.078

Characteristic	N	Event N	IRR ¹	95% CI ¹	p-value
Cranial.repair.materials * Abnormal.Volume.Ratio...	211	396			
Ti * Abnormal.Volume.Ratio...	110	199	0.92	0.86, 0.99	0.019

¹IRR = Incidence Rate Ratio, CI = Confidence Interval

Null deviance = 269; Null df = 210; Log-likelihood = -350; AIC = 714; BIC = 737; Deviance = 251; Residual df = 204; No. Obs. = 211

To investigate the interaction between the type of repair material and the abnormal volume ratio, the product term (interaction term) of the material type and the abnormal volume ratio was incorporated into the multivariate regression model (Table 5). The significance of the interaction term was assessed via the likelihood ratio test. Multivariable negative binomial regression analysis revealed that male sex was not significantly associated with complication rates (IRR 1.05, 95% CI 0.84–1.34, *P*=0.663) when compared to females, while Ti repair material showed no statistically significant difference from PEEK in complication incidence (IRR 1.14, 95% CI 0.84–1.56, *P*=0.405). Abnormal volume ratio demonstrated a significant positive association with complications (IRR 1.05, 95% CI 1.00–1.10, *P*=0.031), as did increasing age (IRR 1.01, 95% CI 1.00–1.02, *P*=0.007), whereas skull defect size did not reach statistical significance (IRR 1.00, 95% CI 1.00–1.00, *P*=0.078). A significant interaction effect was observed between Ti and abnormal volume ratio (IRR 0.92, 95% CI 0.86–0.99, *P*=0.019), indicating a modifying effect on complication risk.

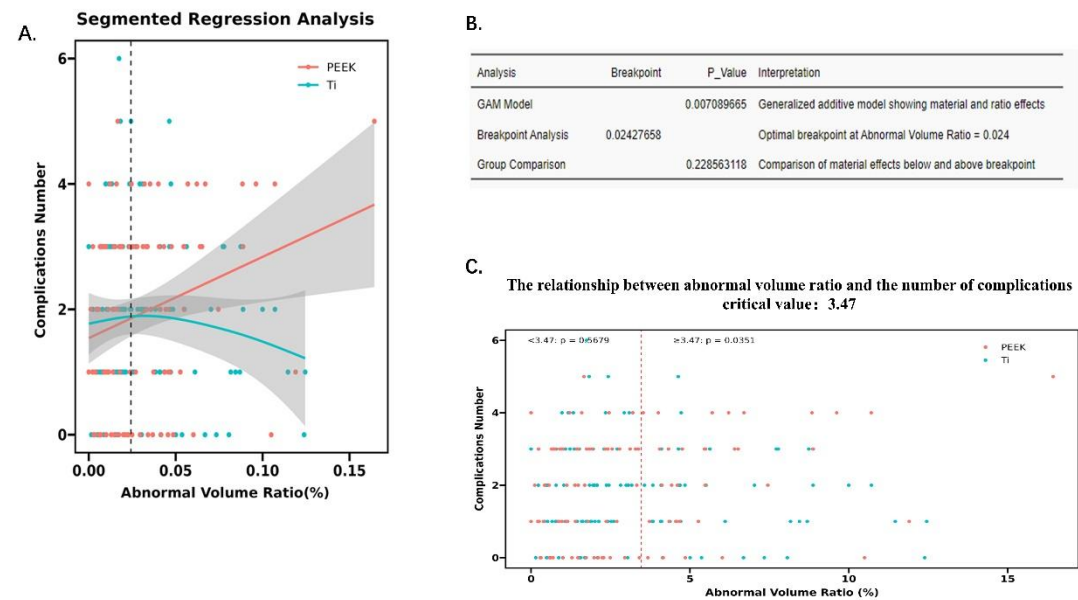


Figure 5. Interaction between implant material and abnormal volume ratio on complications.
(A) GAM smoothing plot; (B) Inflection point analysis at 2.42%;
(C) Clinical decision threshold at 3.47%.
Despite not being included in the previous multivariate regression model due to

collinearity concerns, we found the abnormal volume ratio to be a highly valuable composite indicator for clinical decision-making. As shown in Figure5.A, GAM analysis of the joint effect of Cranial repair materials and Abnormal Volume Ratio on Complications number showed a statistically significant interaction between material type and the abnormal volume ratio ($P=0.019$). The plot suggests that for PEEK, the number of complications shows an increasing trend at lower abnormal volume ratios (0.00 - 0.10), with a notable increase around an abnormal volume ratio of approximately 0.10. In contrast, the number of complications for the Ti material shows a gradually decreasing trend across the range of abnormal volume ratios (0.00 - 0.15), being significantly lower than PEEK around an abnormal volume ratio of 0.10. Overall, the number of complications appears lower and more stable with Ti material, while PEEK material shows higher complication numbers. These results suggest that the abnormal volume ratio is an important factor when selecting cranial repair materials. Inflection point analysis (Figure5.B) found that the optimal inflection point for the lowest complication risk was at an Abnormal Volume Ratio of 2.42%. Further comparison of material effects between groups below and above this inflection point (abnormal volume ratio $<2.42\%$ vs $\geq 2.42\%$) showed no statistically significant difference ($P=0.229$), indicating that material choice did not significantly differentiate the effect on complication numbers on either side of this optimal point. This result suggests that an abnormal volume ratio of 0.024 (2.42%) might serve as a clinical decision threshold, but the differential effect of material choice on either side of this threshold requires validation with larger samples. To find a threshold with clinical decision-making significance, further investigation revealed that when the Abnormal Volume Ratio exceeded 3.47% (Figure5.C), a significant difference in the effect of the two materials emerged. Clinically, this suggests recommending Ti for cranial repair in patients with an Abnormal Volume Ratio greater than 3.47%.

Conclusions

Cranioplasty aims not only to restore anatomy but also to minimize risks and optimize neurological outcomes. Analyzing data from 211 patients, this study identified independent risk factors for complications and proposed, for the first time, a quantitative criterion based on the preoperative "abnormal volume ratio" for individualized selection between Ti and PEEK.

First, our findings confirm that patient-specific factors significantly influence surgical risk. Multivariate analyses identified advanced age and larger brain collapse volume as independent risk factors, consistent with previous reports^{7,29}. Advanced age may correlate with diminished healing capacity and more comorbidities, while significant brain collapse often indicates severe initial insult and disturbed cerebrospinal fluid dynamics, complicating recovery.

Secondly, and most notably, this study reveals a significant interaction between material properties and the patient's intracranial state. While the main effect analysis showed no

overall difference in complication rates between PEEK and Ti—aligning with some literature^{24,25}, GAM and piecewise regression demonstrated that material performance is highly dependent on the preoperative "abnormal volume ratio." Specifically, Ti demonstrated a significant advantage in controlling complication numbers when the abnormal volume ratio exceeded 3.47%. This finding may explain the conflicting conclusions in prior studies, which may have included patient populations with differing distributions of brain collapse severity.

Regarding the reasons for the superior performance of Ti in patients with a high abnormal volume ratio, we speculate it may be related to the following mechanisms: First, compared to PEEK, Ti typically offers better porosity and fluid permeability, which might be more conducive to the drainage and absorption of postoperative subcutaneous or epidural fluid collections. The trend towards a higher rate of subcutaneous effusion in the PEEK group observed in this study and previous research^{30,31} supports this speculation. Second, PEEK material is generally stiffer and often thicker than Ti. In cases of severe brain collapse where significant postoperative brain re-expansion is anticipated, PEEK implants might exert a greater "mass effect" on the brain tissue, potentially interfering with cerebrospinal fluid circulation and brain tissue repositioning. Ti, due to its better compliance, might better adapt to these dynamic changes in the intracranial environment.

The clinical implication of our findings is the potential to advance material selection from a primarily empirical practice towards a more individualized and quantitative approach. For most patients with a low abnormal volume ratio, both PEEK and Ti are viable options, with PEEK potentially favored for its rigidity and reduced imaging artifacts, balanced against cost and patient factors. However, for patients with an abnormal volume ratio > 3.47%—those with large defects and severe brain collapse at highest risk—our data strongly support selecting Ti to reduce the overall complication burden.

This study has limitations. Its single-center retrospective design introduces potential selection bias. Data loss from patient dropout may have influenced results. Although statistically derived, the proposed 3.47% threshold for the abnormal volume ratio requires validation in prospective, multi-center, larger-scale studies. Future research should also investigate the influence of defect location on material performance and complications.

Declarations

Funding

This study was supported by the Project Supported by Natural Science Basic Research Program of Shaanxi (Program No.2024JC-YBQN-0914), Natural Science Basic

364 Research Program of Shaanxi (Program No.2021JC-YB-1786)

365 **Authors' contributions**

366 Peilin Zhu contributed to conceptualization, data curation, formal analysis,
367 investigation, methodology, validation, visualization, and writing – original draft and
368 review. Yichang Wang contributed to data curation, formal analysis, investigation,
369 methodology, software, validation, visualization, and writing – original draft. Gang Bao
370 contributed to conceptualization, funding acquisition, project administration, resources,
371 supervision, validation, and writing – review & editing.

372 **Acknowledgement**

373 The authors appreciate the input of all members of the Department of Neurosurgery,
374 Center of Translational Medicine of the First Affiliated Hospital of Xi'an Jiaotong
375 University

376 **Ethics Approval and consent to participate**

377 This retrospective study was conducted in accordance with the ethical standards of the
378 Declaration of Helsinki and was approved by the Ethics Committee of The First
379 Affiliated Hospital of Xi'an Jiaotong University (approval no. 2020G-142). The
380 requirement for informed consent was waived due to the retrospective nature of the
381 study Clinical trial number: not applicable.

382 **Competing Interests**

383 The authors declare that they have no conflicts of interest regarding the publication of
384 this paper

385 **Availability of data and materials**

386 The data that support the findings of this study are available from the corresponding
387 author upon reasonable request, subject to institutional and ethical restrictions.

388 **Consent for publication**

389 Not applicable. All data presented in this study have been anonymized and contain no
390 personally identifiable information.

Abbreviations

The following abbreviations are used throughout this manuscript to enhance readability. Key statistical and methodological terms, material designations, and clinical/imaging-related acronyms are abbreviated after their first full mention in the text. A comprehensive list is provided in the table below for reference.

Statistical & Methodological Terms: AIC (Akaike Information Criterion), BIC (Bayesian Information Criterion), CI (Confidence Interval), GAM (Generalized Additive Model), IRR (Incidence Rate Ratio), IQR (Interquartile Range), LASSO (Least Absolute Shrinkage and Selection Operator), OR (Odds Ratio), VIF (Variance Inflation Factor).

Materials & Procedures: CP (Cranioplasty), PEEK (Polyether Ether Ketone), Ti (Titanium Mesh).

Clinical & Imaging Terms: CSF (Cerebrospinal Fluid), CT (Computed Tomography), 3D (Three-Dimensional).

References

1. Cranioplasty Following Severe Traumatic Brain Injury: Role in Neurorecovery | Current Neurology and Neuroscience Reports. <https://link.springer.com/article/10.1007/s11910-021-01147-6>.
2. Sh, H. *et al.* Effects of Cranioplasty on Cerebral Blood Flow Following Decompressive Craniectomy: A Systematic Review of the Literature. *Neurosurgery* **81**, (2017).
3. H, M. *et al.* Cranioplasty: A Multidisciplinary Approach. *Frontiers in surgery* **9**, (2022).
4. Jg, M. *et al.* Early Cranioplasty is Associated with Greater Neurological Improvement: A Systematic Review and Meta-Analysis. *Neurosurgery* **82**, (2018).
5. K, T., Id, R., A, K. S. & C, Y. R. Role of timing of cranioplasty in improving Neurological functional outcome. *The British journal of oral & maxillofacial surgery* **62**, (2024).
6. Z, Y., X, H. & C, Y. The incidence and treatment of seizures after cranioplasty: a systematic review and meta-analysis. *British journal of neurosurgery* **32**, (2018).

- 418 7. Huo, H. *et al.* Optimal Timing of Cranioplasty After Decompressive Craniectomy: Timing or
419 Collapse Ratio. *Operative Neurosurgery* **27**, 715–723 (2024).
- 420 8. Chen, R. *et al.* Optimal Timing of Cranioplasty and Predictors of Overall Complications After
421 Cranioplasty: The Impact of Brain Collapse. *Neurosurgery* **93**, 84–94 (2023).
- 422 9. Malcolm, J. G. *et al.* Complications following cranioplasty and relationship to timing: A
423 systematic review and meta-analysis. *Journal of Clinical Neuroscience* **33**, 39–51 (2016).
- 424 10. Zhang, J. & Chen, J. Seizures and epilepsy following cranioplasty. *Seizure* **69**, 76 (2019).
- 425 11. S, T., T, K., K, S. & H, K. Predictive factors for bone flap infection after cranioplasty. *Journal*
426 *of clinical neuroscience : official journal of the Neurosurgical Society of Australasia* **98**, (2022).
- 427 12. D, R., R, B. & P, K. Epidural Fluid Collections After Cranioplasty. *Neurology India* **70**, (2022).
- 428 13. Ritter, L. *et al.* Complication rates after autologous cranioplasty following decompressive
429 craniectomy. *Acta Neurochir (Wien)* **166**, 380 (2024).
- 430 14. Alkhaibary, A. *et al.* Cranioplasty: A Comprehensive Review of the History, Materials, Surgical
431 Aspects, and Complications. *World Neurosurgery* **139**, 445–452 (2020).
- 432 15. T, C., T, R., H, C. & M, V. Infection-related failure of autologous versus allogenic cranioplasty
433 after decompressive hemicraniectomy - A systematic review and meta-analysis. *Brain & spine*
434 **3**, (2023).
- 435 16. Gerstl, J. V. E. *et al.* Complications and cosmetic outcomes of materials used in cranioplasty
436 following decompressive craniectomy—a systematic review, pairwise meta-analysis, and
437 network meta-analysis. *Acta Neurochir* **164**, 3075–3090 (2022).
- 438 17. Wiggins, A., Austerberry, R., Morrison, D., Ho, K. M. & Honeybul, S. Cranioplasty With
439 Custom-Made Titanium Plates—14 Years Experience. *Neurosurgery* **72**, 248 (2013).

- 440 18. Zhang, J. *et al.* The application of polyetheretherketone (PEEK) implants in cranioplasty. *Brain*
441 *Research Bulletin* **153**, 143–149 (2019).
- 442 19. Papia, E., Brodde, S. A. C. & Becktor, J. P. Deformation of polyetheretherketone, PEEK, with
443 different thicknesses. *Journal of the Mechanical Behavior of Biomedical Materials* **125**,
444 104928 (2022).
- 445 20. Punchak, M. *et al.* Outcomes following polyetheretherketone (PEEK) cranioplasty: Systematic
446 review and meta-analysis. *Journal of Clinical Neuroscience* **41**, 30–35 (2017).
- 447 21. Thien, A., King, N. K. K., Ang, B. T., Wang, E. & Ng, I. Comparison of Polyetheretherketone
448 and Titanium Cranioplasty after Decompressive Craniectomy. *World Neurosurgery* **83**, 176–
449 180 (2015).
- 450 22. Henry, J., Amoo, M., Taylor, J. & O'Brien, D. P. Complications of Cranioplasty in Relation to
451 Material: Systematic Review, Network Meta-Analysis and Meta-Regression. *Neurosurgery* **89**,
452 383 (2021).
- 453 23. Binhammer, A., Jakubowski, J., Antonyshyn, O. & Binhammer, P. Comparative Cost-
454 Effectiveness of Cranioplasty Implants. *Plast Surg (Oakv)* **28**, 29–39 (2020).
- 455 24. Yao, S. *et al.* Outcome and risk factors of complications after cranioplasty with
456 polyetheretherketone and titanium mesh: A single-center retrospective study. *Front Neurol* **13**,
457 926436 (2022).
- 458 25. Chen, K. *et al.* Clinical Outcomes After Cranioplasty With Titanium Mesh,
459 Polyetheretherketone, or Composite Bone Cement: A Retrospective Study. *J Craniofac Surg*
460 **34**, 2246–2251 (2023).
- 461 26. Bader, E. R., Kobets, A. J., Ammar, A. & Goodrich, J. T. Factors predicting complications

462 following cranioplasty. *Journal of Cranio-Maxillofacial Surgery* **50**, 134–139 (2022).

463 27. Zhu, S. *et al.* Complications following titanium cranioplasty compared with nontitanium
464 implants cranioplasty: A systematic review and meta-analysis. *Journal of Clinical*
465 *Neuroscience* **84**, 66–74 (2021).

466 28. Qiu, X. *et al.* The compensatory mechanism and clinical significance of hydrocephalus after
467 cranioplasty. *Front Neurol* **13**, 1075137 (2023).

468 29. Sun, S., Li, J., Deng, Y., Gong, S. & Tao, M. Analysis of Causes of Complications and
469 Prognostic Factors After Titanium Mesh Ultra-Early Cranioplasty Following Decompressive
470 Craniectomy for Craniocerebral Trauma. *World Neurosurgery* **191**, e144–e150 (2024).

471 30. Ji, T. *et al.* Subgaleal Effusion and Brain Midline Shift After Cranioplasty: A Retrospective
472 Study Between Polyetheretherketone Cranioplasty and Titanium Cranioplasty After
473 Decompressive Craniectomy. *Front Surg* **9**, 923987 (2022).

474 31. S, Z. *et al.* The Correlative Factors and Probable Mechanism of Epidural Fluid Collection After
475 Cranioplasty. *The Journal of craniofacial surgery* **31**, (2020).

476