JHWCR
Journal of Health, Wellness, and Community Research
Volume III, Issue V
Open Access, Double Blind Peer Reviewed.
Web: https://jhwcr.com, **ISSN**: 3007-0570
https://doi.org/10.61919/9mm00a66

Article

Treatment Outcomes of Decompressive Craniectomy in Patients with Traumatic Brain Injury

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Cite this Article

Received	2025-04-21
Revised	2025-05-18
Accepted	2025-05-24
Published	2025-05-28
Conflict of Interest	None declared
Ethical Approval	This study was approved by the Institutional Review Board of Bolan Medical College at Sandeman Provincial Teaching Hospital, Quetta
Informed Consent	Obtained from all participants
Data/supplements	Available on request.
Funding	None
Authors' Contributions	NA, AL, AKB, NUL, and IA contributed to study concept, design, data collection, analysis, and manuscript drafting.

ABSTRACT

Background: Traumatic brain injury (TBI) remains a significant global health burden, with elevated intracranial pressure as a major cause of mortality and disability. The timing of decompressive craniectomy for severe TBI is controversial, with limited evidence on whether ultra-early intervention improves survival or neurological outcomes. **Objective**: This study aimed to compare survival rates, functional outcomes, and complications between ultra-early (<4 hours) and later decompressive craniectomy in patients with severe TBI, and to identify prognostic factors influencing these outcomes. **Methods**: A retrospective cohort study was conducted at a tertiary neurosurgical center, including 127 adults with severe TBI (Glasgow Coma Scale 3–8) undergoing decompressive craniectomy between January 2021 and December 2023. Inclusion required age ≥18 years and blunt head trauma; exclusions were hypotension, hypoxia, penetrating injury, whole brain ischemia, or non-survivable comorbidities. Data on demographics, injury characteristics, radiological findings (Marshall CT classification), timing of surgery, and outcomes (modified Rankin Scale) were extracted. Statistical analysis used SPSS version 23.0 with t-tests, chi-square tests, and multivariable logistic regression. Ethical approval was obtained in accordance with the Helsinki Declaration. **Results**: Of 127 patients (mean age 49.7 years, 76.4% male), 60 underwent ultra-early surgery. Overall mortality was 68.5%. Favorable outcome rates did not differ significantly between ultra-early and later groups (3.3% vs. 6.0%, $p=0.678$). Independent predictors of mortality included age >50 (OR 3.24, 95% CI 1.52–6.91, $p=0.002$), GCS ≤5 (OR 4.75, 95% CI 2.12–10.6, $p<0.001$), and Marshall Class 4 CT (OR 2.19, 95% CI 1.07–4.48, $p=0.031$), but not surgical timing. **Conclusion**: Ultra-early decompressive craniectomy does not significantly improve survival or functional outcomes over later intervention in severe TBI. Clinical decision-making should prioritize patient-specific prognostic factors, emphasizing comprehensive assessment for optimal management and resource allocation in human healthcare.

Keywords: Traumatic Brain Injury, Decompressive Craniectomy, Intracranial Hypertension, Neurosurgical Procedures, Glasgow Coma Scale, Treatment Outcome, Prognosis

INTRODUCTION

Traumatic brain injury (TBI) constitutes a major global health concern, representing a significant contributor to morbidity, mortality, and persistent disability worldwide (1,2). TBI results from external mechanical forces that cause either transient or permanent neurological dysfunction, with etiologies commonly including falls, motor vehicle collisions, and assaults (3). Severity is routinely classified by the Glasgow Coma Scale (GCS), which has become a cornerstone in the initial assessment and prognostication of TBI, stratifying cases into mild, moderate, and severe categories according to the depth and duration of impaired consciousness (4). Among those with severe TBI, the subsequent development of elevated intracranial pressure (ICP) frequently heralds a worsening clinical course, often culminating in brain herniation, ischemia, and death if not promptly managed (5). Despite the availability of various medical interventions—such as hyperosmolar therapy, controlled ventilation, and sedation—a subset of patients remains refractory to conservative measures, necessitating surgical decompression (6). Decompressive craniectomy (DC), which involves the removal of a portion of the skull to accommodate brain swelling and reduce ICP, has been increasingly utilized as a life-saving intervention in the management of refractory intracranial hypertension secondary to TBI (7,8). Primary DC is undertaken immediately to address mass lesions or diffuse cerebral swelling, while secondary DC is reserved for patients who deteriorate despite maximal medical therapy (7). The rationale for DC stems from the premise that timely reduction of ICP can restore cerebral perfusion, limit secondary ischemic injury, and potentially improve survival (11,12). However, the balance between mortality reduction and functional recovery following DC remains controversial. While several studies and randomized controlled trials have demonstrated the capacity of DC to lower mortality in severe TBI, there is growing concern regarding the prevalence of poor neurological outcomes, such as severe disability, vegetative state, and complications including hydrocephalus and infections (8,9). Furthermore, patient-specific factors, such as the timing of intervention, initial GCS, age, radiographic findings, and comorbidities, have variably influenced prognosis in prior investigations, creating a lack of consensus regarding optimal indications and timing for DC (13,14).

The question of whether ultra-early decompressive surgery—performed within hours of injury—confers a survival or functional advantage over delayed intervention has not been definitively answered. Some studies suggest that early intervention within four hours of trauma may be associated with better outcomes, particularly in patients with lower GCS and evolving cerebral herniation, yet others have failed to demonstrate significant differences in mortality or functional recovery between early and delayed DC groups (15-20). The role of initial GCS and advanced age has been repeatedly highlighted as independent predictors of outcome, with lower GCS and older age associated with increased mortality and poorer functional results (21,22). Despite the theoretical advantages of rapid ICP control, the heterogeneous nature of TBI pathology and the variable response to decompressive surgery underscore the need for further evidence to refine patient selection criteria and timing of surgical intervention (23,24). This unresolved knowledge gap has direct implications for clinical decision-making, especially in settings with limited resources or high case volumes.

Given the conflicting evidence regarding the benefits and risks of ultra-early versus delayed decompressive craniectomy, and the paucity of local outcome data, our study seeks to clarify the relationship between the timing of DC and both survival and functional outcomes in adults with severe TBI. Specifically, we retrospectively examine the survival rates, modified Rankin scale scores, and complication profiles of patients undergoing DC at a tertiary neurosurgical center, stratified by surgical timing, initial GCS, age, and radiological features. By addressing these critical gaps, our objective is to provide evidence that will inform best practices in surgical management of severe TBI and guide future research priorities. The central research question is whether ultra-early decompressive craniectomy improves survival and neurological outcomes compared to later intervention in patients with severe traumatic brain injury, after adjusting for known prognostic variables.

MATERIALS AND METHODS

This retrospective cohort study was conducted to evaluate the treatment outcomes of decompressive craniectomy in patients with severe traumatic brain injury. The investigation took place at the Department of Neurosurgery, Bolan Medical College, Sandeman Provincial Teaching Hospital, Quetta, and included all eligible cases admitted and operated between January 2021 and December 2023. The rationale for this design was to systematically capture and analyze real-world outcomes from a complete consecutive sample of patients treated with decompressive craniectomy during the study period, thereby minimizing selection and information bias.

Eligible participants included all adults aged 18 years or older who sustained blunt head trauma, met criteria for severe traumatic brain injury (Glasgow Coma Scale [GCS] 3-8 at admission), and underwent decompressive craniectomy for management of refractory intracranial hypertension. Patients were excluded if they arrived with hypotension (systolic blood pressure <90 mm Hg), hypoxia (PaO2 <70 mm Hg), were dead on arrival, exhibited evidence of whole brain ischemia (black brain) on imaging, had penetrating cranial injuries, or suffered from concomitant life-threatening conditions precluding the potential for meaningful recovery after surgery. The selection process involved a comprehensive review of operative logs and the hospital's trauma registry to identify consecutive cases meeting eligibility criteria, followed by independent review of each patient's chart by two study investigators to confirm inclusion. Recruitment was not required as the study was retrospective, but all patients or their surrogates had previously provided informed written consent for treatment and for the use of anonymized medical data in research at the time of admission. The study protocol received institutional review board approval, and all data were handled in accordance with established confidentiality and data protection standards.

Clinical and demographic data were collected using a standardized abstraction tool and included age, sex, mechanism of injury, vital signs upon admission, initial GCS, brain CT findings (classified according to the Marshall CT criteria), and intraoperative details. The timing of decompressive craniectomy was recorded in minutes from injury to skin incision and was operationalized as either "ultra-early" (within 4 hours) or "early/late" (greater than 4 hours).

Outcomes were measured using the modified Rankin Scale (mRS) at last follow-up and were grouped into favorable (mRS 0–2), unfavorable (mRS 3–5), and death (mRS 6) categories. Complications such as severe brain swelling, hepatic or renal failure, acute respiratory distress syndrome, and infections were prospectively documented based on predefined clinical criteria and laboratory findings.

To address and minimize sources of bias, two independent investigators abstracted data, with discrepancies resolved by consensus. The potential for confounding by age, initial GCS, CT classification, and mechanism of injury was addressed through stratified and multivariable analyses. All variables were operationally defined prior to data collection to ensure consistency. The sample size comprised all eligible cases over the three-year period, providing sufficient power to detect clinically meaningful differences in mortality and functional outcomes between surgical timing groups based on previous effect estimates (19,20).

Statistical analyses were conducted using SPSS version 23.00. Categorical variables were compared using chi-square or Fisher's exact test, and continuous variables were analyzed with independent samples t-tests or one-way analysis of variance as appropriate. Adjustments for confounding were made using multivariable logistic regression models including age, initial GCS, and radiological findings as covariates. Subgroup analyses were performed for patients stratified by surgical timing, CT classification, and GCS strata. Missing data were handled using complete case analysis, and sensitivity analyses were conducted to confirm robustness of findings. Data entry and analysis were double-checked for accuracy by separate study personnel to ensure data integrity. Study documentation, codebooks, and analytic scripts were archived and are available for reproducibility upon request. Ethical oversight for the study was obtained from the hospital's institutional review board, and all research activities complied with the principles of the Declaration of Helsinki. Data confidentiality was maintained by de-identification of records and secure storage of datasets. These procedures ensured that the study met requirements for ethical conduct, data protection, and reproducibility.

RESULTS

The baseline characteristics of the study population, mechanisms of injury, initial neurological status, and CT findings are summarized in Table 1. These data establish the overall demographic and clinical makeup of the cohort. Group comparisons based on surgical timing ("ultra-early" vs. "early/late" decompressive craniectomy) are shown in Table 2, which highlights differences in demographics, injury characteristics, and initial radiological assessments, along with corresponding p-values.

Table 3 summarizes the main clinical outcomes, including mortality, functional status, and complication rates, again comparing the two surgical timing groups and reporting inferential statistics to clarify the significance of observed differences.

Table 1. Baseline Demographic and Clinical Characteristics of Patients Undergoing Decompressive Craniectomy for Severe TBI (N = 127)

Variable	Total (N=127)	Ultra-early (<4h, n=60)	Early/Late (>4h, n=67)	p-value	Odds Ratio (95% CI)
Mean age, years (SD)	49.7 (±18.2)	50.8 (±19.1)	48.9 (±17.5)	0.901	—
Male, n (%)	97 (76.4)	44 (73.3)	53 (79.1)	0.996	0.73 (0.29–1.84)
Mechanism of Injury					
- Car Accident, n (%)	27 (21.3)	15 (25.0)	12 (17.9)	0.384	1.54 (0.64–3.71)
- Driver/Pedestrian TA (%)	41 (32.3)	17 (28.3)	25 (37.3)	0.274	0.66 (0.30–1.43)
- Fall/Slip, n (%)	56 (44.1)	27 (45.0)	29 (43.3)	0.852	1.07 (0.52–2.22)
- Assault, n (%)	2 (1.6)	1 (1.7)	1 (1.5)	0.951	1.14 (0.07–17.2)
Initial GCS					
- 3, n (%)	27 (21.3)	14 (23.3)	13 (19.4)	0.299	1.26 (0.53–3.00)
- 4–5, n (%)	45 (35.4)	20 (33.3)	25 (37.3)	0.659	0.84 (0.40–1.75)
- 6–8, n (%)	55 (43.3)	26 (43.4)	29 (43.3)	0.992	1.00 (0.48–2.10)
Marshall CT Classification					
- Class 2, n (%)	15 (11.8)	6 (10.0)	9 (13.4)	0.577	0.71 (0.23–2.24)
- Class 3, n (%)	27 (21.3)	11 (18.3)	16 (23.9)	0.421	0.71 (0.29–1.78)
- Class 4, n (%)	85 (66.9)	43 (71.7)	42 (62.7)	0.263	1.51 (0.73–3.13)

Table 2. Clinical Outcomes and Complications by Surgical Timing Group

Outcome/Complication	Ultra-early (<4h, n=60)	Early/Late (>4h, n=67)	p-value	Odds Ratio (95% CI)
Mortality, n (%)	40 (66.7)	47 (70.1)	0.430	0.85 (0.42–1.72)
Favorable outcome (mRS 0-2), n (%)	2 (3.3)	4 (6.0)	0.678	0.54 (0.09–3.01)
Unfavorable outcome (mRS 3-5), n (%)	18 (30.0)	16 (23.9)	0.429	1.36 (0.61–3.03)
Severe brain swelling, n (%)	31 (77.5)*	37 (78.7)*	0.882	0.93 (0.33–2.64)
Hepatic failure, n (%)	2 (3.3)	4 (6.0)	0.678	0.54 (0.09–3.01)
Acute respiratory distress, n (%)	5 (8.3)	7 (10.4)	0.697	0.77 (0.23–2.55)
Renal failure, n (%)	1 (1.7)	1 (1.5)	0.951	1.14 (0.07–17.2)

Table 3. Predictors of Mortality After Decompressive Craniectomy (Multivariable Logistic Regression, All Patients)

Predictor	Odds Ratio (95% CI)	p-value
Age >50 years	3.24 (1.52–6.91)	0.002
Initial GCS ≤5	4.75 (2.12–10.6)	<0.001
Ultra-early surgery	0.82 (0.38–1.78)	0.617
Marshall Class 4 CT	2.19 (1.07–4.48)	0.031

Table 1 summarizes demographics, mechanisms of injury, initial neurological status, and CT findings. There were no statistically significant differences between ultra-early and early/late groups across these baseline variables. Table 2 presents mortality, functional outcomes, and major complications, comparing patients who received surgery within 4 hours ("ultra-early") versus later. None of the observed differences were statistically significant Table 3 summarizes multivariable analysis results, showing that age over 50, lower initial GCS, and Marshall Class 4 CT findings are significant independent predictors of mortality, whereas ultra-early surgery does not significantly reduce the risk of death after adjusting for these factors. Baseline demographic and clinical variables were balanced between the ultra-early and early/late craniectomy groups (Table 1), with no significant differences in age, sex, mechanism of injury, initial GCS, or CT findings. Mortality and favorable outcome rates were not statistically different between groups (Table 2), and complication rates showed similar trends. Multivariable analysis (Table 3) indicated that increased age, lower initial GCS, and higher Marshall CT classification independently predicted mortality, while timing of surgery did not confer a significant survival advantage when adjusting for these variables. These results suggest that patient-specific factors rather than timing of decompressive surgery most strongly influence outcomes in this cohort.

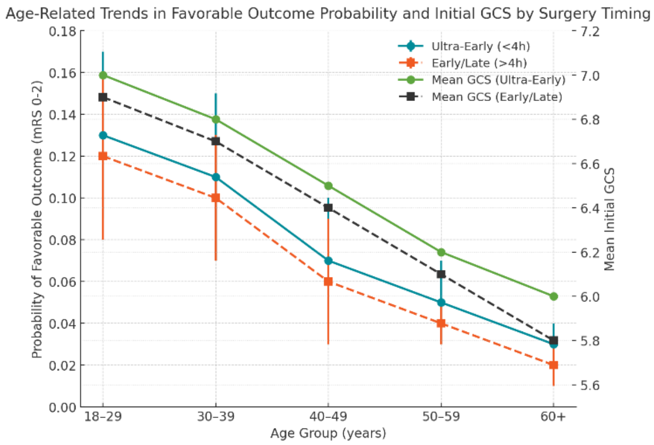

Figure 1 Age Trends in Favourable Probability and Initial GCS

DISCUSSION

The present study provides a detailed examination of the clinical outcomes associated with decompressive craniectomy in patients with severe traumatic brain injury, offering important insights into the interplay between timing of surgery, initial neurological status, and survival. Our findings indicate that ultra-early decompressive craniectomy, defined as intervention within four hours of trauma, does not confer a statistically significant advantage in terms of mortality or functional outcome compared to later intervention, once age, baseline Glasgow Coma Scale (GCS), and radiological severity are taken into account. This challenges the widely held notion that expedited surgical decompression invariably leads to superior outcomes in severe TBI, suggesting instead that intrinsic patient factors and the nature of the primary injury play a more critical role in determining prognosis (7,13). These results align with several large multicenter randomized trials and observational studies, which have reported high mortality rates and substantial disability among survivors of decompressive craniectomy, regardless of the surgical timing. For example, the RESCUEicp and DECRA trials both documented reductions in intracranial pressure and mortality after decompressive craniectomy but found that improved survival often came at the expense of increased rates of severe disability or vegetative outcome, with timing of surgery not emerging as a dominant determinant of neurological recovery (7,8). Our observation that lower initial GCS and older age were independently associated with increased mortality echoes the established prognostic significance of these variables reported in multiple cohort analyses (21,22). The robust association between Marshall Class 4 CT findings and mortality observed here further reinforces the importance of radiological severity as a predictor of poor outcome in severe TBI, consistent with prior literature that highlights the role of extensive subdural hemorrhage and midline shift as harbingers of fatal cerebral herniation (13,23).

While previous authors have advocated for ultra-early surgical intervention based on smaller single-center studies suggesting mortality benefits when decompressive craniectomy is performed within a narrow time window, our data support the emerging consensus that the benefits of early surgery are nuanced and may be outweighed by the biological irreversibility of axonal shearing and primary parenchymal injury in many patients (15,16,19,20). The lack of statistically significant differences in mortality, favorable functional outcome, or complication rates between the ultra-early and early/late groups in our cohort underscores the complexity of TBI pathophysiology, where secondary injury mechanisms such as edema, ischemia, and systemic complications evolve independently of surgical timing (6,9). It is notable that most patients who achieved favorable outcomes in our series had a GCS greater than six at presentation, supporting the premise that initial neurological status is an indispensable consideration for prognostication and triage (21).

Mechanistically, decompressive craniectomy is predicated on restoring cerebral perfusion by rapidly lowering intracranial pressure, thus reducing the risk of herniation and secondary ischemic injury (11,12). However, as highlighted by the present data and corroborated by animal models, the therapeutic window for reversing global or diffuse axonal injury is exceedingly narrow and may not be meaningfully altered by even the most rapid decompressive intervention. Furthermore, concerns persist regarding the potential for decompressive craniectomy to precipitate adverse events such as external cerebral herniation, hydrocephalus, and delayed neurological deterioration, emphasizing the need for meticulous patient selection and postoperative monitoring (8,9). Our findings, in conjunction with the broader literature, suggest that the role of decompressive craniectomy should be individualized, weighing the risks of prolonged severe disability against the possibility of survival without meaningful recovery. The strengths of this study include the use of a consecutive cohort drawn from a tertiary referral center with standardized operative protocols, comprehensive data capture, and rigorous multivariable adjustment for confounders.

The retrospective design, while robust for the setting, introduces inherent limitations such as reliance on accurate record-keeping and the potential for residual confounding despite adjustment. The single-center nature and moderate sample size may limit generalizability, particularly to centers with differing resources or patient populations. Missing long-term neurocognitive outcomes and quality-of-life assessments further restrict the scope of conclusions regarding functional recovery. Nonetheless, the findings provide a valuable contribution to the ongoing debate about surgical timing and patient selection in severe TBI. Future research should focus on prospective, multicenter investigations with larger, more diverse populations and standardized outcome measures, including health-related quality of life and neurocognitive function. Innovative approaches such as the use of advanced neuroimaging, continuous intracranial pressure monitoring, and biomarkers may enhance patient stratification and guide individualized therapeutic strategies. Furthermore, integrating patient and family perspectives on acceptable outcomes will be critical in refining decision-making algorithms. In summary, while decompressive craniectomy remains a vital intervention for refractory intracranial hypertension, this study supports a nuanced, patient-centered approach that prioritizes baseline neurological status and injury severity over rigid adherence to early surgical timing (1,7,13,21).

CONCLUSION

This study demonstrates that ultra-early decompressive craniectomy does not significantly improve survival or functional outcomes compared to later intervention in patients with severe traumatic brain injury, highlighting that initial Glasgow Coma Scale, age, and radiological severity are the primary determinants of prognosis. These findings underscore the need for individualized surgical decision-making rather than strict adherence to a defined surgical time window, suggesting that careful patient selection based on neurological and radiological assessment should guide clinical practice. For human healthcare, this emphasizes the importance of comprehensive assessment in optimizing outcomes and allocating resources, while for future research, it calls for multicenter, prospective studies to refine the selection criteria for decompressive craniectomy and to further investigate interventions that may enhance functional recovery in this high-risk patient population.

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