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Original Research Article

Predictors of Functional Outcome Following Decompressive Craniectomy in Severe Traumatic Brain Injury: A Multicenter Retrospective Cohort Study

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Abstract:

Background: Decompressive craniectomy was deemed a useful surgical procedure for severe traumatic brain injury when malignant cerebral swelling or refractory intracranial hypertension posed the risk of death; however, operative outcomes regarding functional outcome vary. Objective: To determine clinical, radiological and peri-operative variables that predict the functional outcome at six months following decompressive craniectomy for severe traumatic brain injury.

Methods: A multicenter retrospective cohort study was conducted that analyzed 186 adult patients with severe traumatic brain injury (sTBIs) who underwent primary or secondary decompressive craniectomy (DC) at each of four tertiary teaching hospitals. Admission parameters, computed tomography (CT) parameters, surgical time, postoperative course and complications were analysed. Functional outcome was measured at six months by the Glasgow Outcome Scale-Extended with scores of 5-8 being favourable.

Results: The mean age was 38.7 ± 14.9 years, 138 (74.2%) patients were male and the most common mechanism of injury was road traffic injury (67.7%). A favorable outcome was seen in 74 cases (39.8%) and mortality was 22.6%. Patients with favorable outcome were younger (32.6 ± 11.2 vs 42.7 ± 15.4 years, $p<0.001$), had higher admission Glasgow Coma Scale scores (6.9 ± 1.1 vs 5.4 ± 1.3, $p<0.001$), lower Rotterdam CT scores (3.2 ± 0.8 vs 4.3 ± 1.0, $p<0.001$), fewer bilateral pupillary abnormalities (6.8% vs 28.6%, $p<0.001$) and shorter median injury-to-surgery time (5.8 vs 9.4 hours, $p=0.002$). In the multivariable regression model, age<45 years, admission GCS >=6, reactive pupils, Rotterdam score <=3 and surgery within six hours and absence of postoperative intracranial hypertension were independent predictors of a favourable outcome.

Conclusions: The functional outcome after DCS depends on the preoperative neurological status, the severity of the CT, and the timing of surgery and early control of ICP. Identification of these predictors early could help to better counsel, triage and postoperative prognosticate.

Keywords: decompressive craniectomy; severe traumatic brain injury; Glasgow Outcome Scale-Extended; functional outcome; Rotterdam CT score; intracranial hypertension.

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Introduction

Traumatic brain injury (TBI) is a leading cause of death and chronic neurological disability in young adults and economically active people, and severe TBI is one of the most challenging emergencies encountered by neurosurgery. The impact is especially significant in areas of fast urbanization, high road traffic injury rates and inconsistent availability of neurocritical care. Severe TBI is not a single disease but a syndrome of secondary insults, which develop after a primary mechanical insult, involving cerebral edema, hypoxia, hypotension, seizures and ICP (intracranial hypertension) [1].

The modern approach to the management of severe TBI is to minimize secondary brain injury through careful attention to oxygenation, perfusion, prompt evacuation of mass lesions, osmotherapy, sedation, ventilatory management, ICP monitoring (if available) and surgical decompression (when unsuccessful medical management). The Brain Trauma Foundation guidelines (4th edition) strongly recommend protocolized management and acknowledge ICP-guided management as part of a severe TBI care, but there are variations in practice based on resources and local expertise [2,3].

In decompressive craniectomy (DC), a large bone flap is removed and the opening in the skull is left open to relieve the ICP to allow the swollen brain to spread outwards instead of pushing against the critical intracranial structures. It can be used as primary DC at the time of evacuation of an acute subdural hematoma/contusion or secondary DC when medical therapy is not sufficient for refractory intracranial hypertension. Although it has a physiological basis, the correlation of ICP reduction with meaningful functional recovery is complicated. There was no difference in mortality or in-hospital stay, but a reduction in ICP and intensive care unit duration was seen immediately after early bifrontotemporoparietal DC for diffuse injury; however, this had raised concerns regarding poor functional outcomes at six months in the DECRA trial [4].

In contrast, the RESCUEicp study tested DC as subsequent rescue treatment for refractory traumatic intracranial hypertension, and found a prolonged survival advantage with a wide range of disability in survivors. The next 24-month follow-up suggested that outcome patterns might continue to improve after the traditionally reported 6-months of follow-up, highlighting the importance of interpretation of early outcome data [5-7].

One of the common ways to assess functional outcomes after a TBI is with the Glasgow Outcome Scale or the extended version (GOSE). The GOSE is an ordered global measure that can be used for research cohorts and comparative outcome studies as it differentiates death, vegetative state, severe disability, moderate disability and good recovery, with upper and lower categories [8]. But there are many factors associated with the outcome following DC, and a surgical intervention which can save one life can leave a different one severely dependent on others.

There are several prognostic models that have revealed that age, admission motor response, pupillary reactivity, hypoxia, hypotension, and CT characteristics are strong predictors of outcome following moderate to severe TBI [9,10]. Computed tomography-based classification systems, such as the Marshall and Rotterdam scores, provide a description of mass effect, cisternal compression, midline shift, traumatic subarachnoid hemorrhage, and other features of the severity of structural injury and are utilized in initial risk stratification [11,12]. However, in real life settings, the cohort of patients with DC is still heterogeneous, especially in multicenter settings where the indications for surgery and the access to ICP monitoring and access to ICP rehabilitation are not equally distributed between each hospital.

The question is then not whether ICP can be lowered during DC, but who is most likely to get worthwhile functional recovery during DC. A large number of available reports are single-center series, small sample size, or include moderate and severe injuries, or mostly survival outcomes. The current study aimed to assess the predictors of 6-month functional outcome in severe TBI in adults undergoing decompressive craniectomy in multiple tertiary care teaching hospitals. To identify clinical, radiological and peri-operative factors which are independently associated with favorable GOSE outcome.

Materials and Methods

Study design and setting: This was a multicenter retrospective cohort study in four neurosurgery departments of three tertiary care teaching hospitals. Records of medical, operative, trauma admission, radiology archives and follow-up records were retrieved for the previous 4 years. The protocol of severe TBI at each center was similar in general with resuscitation, urgent CT imaging, neurosurgical triage, admission to intensive care and referral to rehabilitation unit after stabilization.

Sample size: The sample size was calculated for multivariable logistic regression with the rule of 10 events per candidate predictor. Seven clinically relevant predictors were planned for the final model: age, admission GCS, reaction time of the pupils, Rotterdam CT score, hypotension, surgical timing and postoperative intracranial hypertension. With a favorable outcome rate of ~40%, 175 patients were needed at minimum. Inclusion of patients for final analysis resulted in 186 patients meeting the eligibility criteria.

Inclusion criteria: adults (18–70 years of age) with severe traumatic brain injury (TBI) (post-resuscitation Glasgow Coma Scale (GCS) score <=8) who underwent either unilateral frontotemporoparietal or bifrontal decompressive craniectomy were eligible. Primary and secondary DC were included, with the latter being performed for refractory intracranial hypertension. Patients were excluded if they had penetrating head injury, severe pre-existing neurological disability, non-traumatic indications for craniectomy, brain death before surgery, death before operative intervention, incomplete CT data or lacking of six-month outcome information.

Data collection: Demographic information recorded included age, sex and mechanism of injury. Clinical variables consisted of the Glasgow Coma Score (GCS) immediately after resuscitation, pupillary reaction, documented hypotension, hypoxia, and extracranial injury and time to surgery following the injury. The following radiological features were obtained from initial CT brain scans and entered: acute subdural hematoma, contusion, traumatic subarachnoid hemorrhage, basal cistern status, midline shift, Marshall CT class and Rotterdam CT score. Operative variables included type of DC, primary versus secondary indication, duraplasty, operative duration and blood loss. Post-operative variables included ventilation time, length of time spent in the intensive care unit, repeated computed tomography (CT) scan, intensive care unit (ICU) monitoring of ICP, seizures, infection, hydrocephalus, external cerebral herniation, and time until cranioplasty planning.

Primary outcome: The primary outcomes were functional status at 6 months after injury on the Glasgow Outcome Scale-Extended (GOS-E). Scores from 5-8 were considered to have favorable outcome, which was considered to have lower moderate disability to upper good recovery. A GOSE of 1–4 (death, vegetative state or severe disability) was considered an unfavorable outcome. Study investigators trained in the collection of outcome data obtained from outpatient follow-up or structured telephonic interview or rehabilitation records.

Data analysis: Statistical analysis was done by SPSS version 29.0. Data for continuous variables was presented as means ± SD or median (IQR) as appropriate for distribution. Categorical variables were presented in frequencies and percentages. Continuous variables were compared using independent-samples t-test, or Mann-Whitney U test, and categorical variables were compared using the chi-square test or Fisher exact test. All variables with p values less than 0.10 on univariate analysis and of strong clinical interest were entered into a multivariable binary logistic regression to determine independent predictors of favorable 6-month outcome. Odds ratios (OR) were adjusted and 95% confidence intervals (CI) were determined. The p value <0.05 was regarded as statistically significant.

Results

A total of 214 patients underwent decompressive craniectomy for traumatic brain injury during the study period. Twenty-eight were excluded because of incomplete records, penetrating injury, pre-existing severe disability or unavailable six-month outcome data. The final cohort included 186 patients. The mean age was 38.7 ± 14.9 years, and 138 patients (74.2%) were male. Road traffic accident was the leading mechanism of injury (126/186, 67.7%), followed by falls from height (40/186, 21.5%) and assault or other mechanisms (20/186, 10.8%). The mean admission GCS score after initial resuscitation was 6.0 ± 1.5.

At six months, 74 patients (39.8%) achieved favorable outcome (GOSE 5-8), while 112 patients (60.2%) had unfavorable outcome (GOSE 1-4). Overall mortality was 22.6% (42/186). Patients with favorable outcome were significantly younger, had higher admission GCS scores, fewer bilateral pupillary abnormalities, less hypotension, lower Rotterdam CT scores and shorter injury-to-surgery time compared with those with unfavorable outcome (Table 1).

Table 1: Baseline clinical and radiological profile according to six-month functional outcome

Variable	Overall (n=186)	Favorable GOSE 5-8 (n=74)	Unfavorable GOSE 1-4 (n=112)	p-value
Age, years (mean ± SD)	38.7 ± 14.9	32.6 ± 11.2	42.7 ± 15.4	<0.001
Male sex, n (%)	138 (74.2)	52 (70.3)	86 (76.8)	0.322
Road traffic injury, n (%)	126 (67.7)	49 (66.2)	77 (68.8)	0.710
Admission GCS (mean ± SD)	6.0 ± 1.5	6.9 ± 1.1	5.4 ± 1.3	<0.001
GCS >=6, n (%)	104 (55.9)	58 (78.4)	46 (41.1)	<0.001
Bilateral abnormal pupils, n (%)	37 (19.9)	5 (6.8)	32 (28.6)	<0.001
Documented hypotension, n (%)	46 (24.7)	9 (12.2)	37 (33.0)	0.001
Hypoxia before admission, n (%)	39 (21.0)	10 (13.5)	29 (25.9)	0.042
Associated extracranial injury, n (%)	68 (36.6)	23 (31.1)	45 (40.2)	0.207
Rotterdam CT score (mean ± SD)	3.9 ± 1.1	3.2 ± 0.8	4.3 ± 1.0	<0.001
Midline shift >10 mm, n (%)	82 (44.1)	23 (31.1)	59 (52.7)	0.004
Compressed/absent basal cisterns, n (%)	116 (62.4)	34 (45.9)	82 (73.2)	<0.001

GCS: Glasgow Coma Scale; GOSE: Glasgow Outcome Scale-Extended; CT: computed tomography; SD: standard deviation.

Primary decompressive craniectomy was performed in 118 patients (63.4%), most commonly during evacuation of acute subdural hematoma with significant mass effect. Secondary DC for refractory intracranial hypertension was performed in 68 patients (36.6%). Unilateral frontotemporoparietal decompression was the commonest operative procedure (72.0%). Patients with favorable outcome had a shorter median injury-to-surgery time, lower frequency of postoperative intracranial hypertension and shorter ICU stay. Procedure-related complications included external cerebral herniation (12.9%), hydrocephalus requiring cerebrospinal fluid diversion (9.1%), wound infection (7.5%) and post-traumatic seizures (16.1%) (Table 2).

Table 2: Operative profile, postoperative course and outcomes

Parameter	Overall (n=186)	Favorable (n=74)	Unfavorable (n=112)	p-value
Primary DC, n (%)	118 (63.4)	51 (68.9)	67 (59.8)	0.210
Unilateral DC, n (%)	134 (72.0)	57 (77.0)	77 (68.8)	0.221
Bifrontal DC, n (%)	52 (28.0)	17 (23.0)	35 (31.2)	0.221
Injury-to-surgery time, h, median (IQR)	7.6 (4.5-12.0)	5.8 (3.8-8.9)	9.4 (5.2-14.8)	0.002
Surgery within 6 h, n (%)	80 (43.0)	43 (58.1)	37 (33.0)	0.001
ICP monitoring used, n (%)	92 (49.5)	39 (52.7)	53 (47.3)	0.470
Postoperative ICP >25 mmHg, n (%)	58 (31.2)	12 (16.2)	46 (41.1)	<0.001
Mechanical ventilation, days (mean ± SD)	8.8 ± 5.1	6.3 ± 3.7	10.4 ± 5.3	<0.001
ICU stay, days (mean ± SD)	12.6 ± 6.4	9.4 ± 4.8	14.7 ± 6.5	<0.001
External cerebral herniation, n (%)	24 (12.9)	6 (8.1)	18 (16.1)	0.112
Hydrocephalus requiring diversion, n (%)	17 (9.1)	3 (4.1)	14 (12.5)	0.051
Wound infection, n (%)	14 (7.5)	4 (5.4)	10 (8.9)	0.382
Post-traumatic seizures, n (%)	30 (16.1)	8 (10.8)	22 (19.6)	0.111
Six-month mortality, n (%)	42 (22.6)	0 (0.0)	42 (37.5)	<0.001

DC: decompressive craniectomy; ICP: intracranial pressure; ICU: intensive care unit; IQR: interquartile range.

On multivariable logistic regression, six variables independently predicted favorable six-month outcome. Age <45 years increased the odds of favorable outcome more than three-fold. Admission GCS >=6, reactive pupils and Rotterdam CT score <=3 were strong preoperative predictors. Surgery within six hours and absence of postoperative intracranial hypertension were also independently associated with favorable recovery. Sex, mechanism of injury and primary versus secondary DC were not independent predictors after adjustment (Table 3).

Table 3: Multivariable logistic regression analysis for predictors of favorable six-month outcome

Predictor	Adjusted OR	95% CI	p-value	Interpretation
Age <45 years	3.18	1.55-6.52	0.002	Independent favorable predictor
Admission GCS >=6	4.62	2.12-10.06	<0.001	Strongest clinical predictor
Reactive pupils	3.74	1.51-9.26	0.004	Reflects preserved brainstem function
Rotterdam CT score <=3	3.29	1.58-6.85	0.001	Lower radiological severity
Surgery within 6 h	2.36	1.13-4.94	0.022	Time-sensitive benefit
No postoperative ICP >25 mmHg	3.86	1.73-8.60	0.001	Early pressure control associated with recovery
Absence of prehospital hypotension	1.72	0.78-3.79	0.178	Not independent after adjustment

Dependent variable: favorable GOSE outcome (5-8). OR: odds ratio; CI: confidence interval; GCS: Glasgow Coma Scale; CT: computed tomography; ICP: intracranial pressure.

Discussion

39.8% of adults with severe TBI had a good functional outcome at 6 months following decompressive craniectomy; 22.6% died. Favorable outcome was independently predicted by increasing age, decreasing admission GCS, absence of pupillary reactivity, increasing Rotterdam CT score, surgery performed within 6 hours and absence of postoperative intracranial hypertension. The results confirm the notion that outcome following DC is not only dependent on the technical outcome of the decompression but also on the biological reserve of the injured brain and on the prevention of secondary insults to the brain.

The observed frequency distribution of outcomes is similar to the historical and current DC series. Guerra et al. found early neurologic status and postoperative ICP to be significant factors in determining outcome following surgical decompression for traumatic brain swelling [13]. Similarly, Aarabi et al. found that in some patients with severe head injury, a DC for malignant swelling might yield functional outcomes better than expected, with performance very dependent on the patient's preoperative neurological status and severity of the injury [14]. In a cohort of only those patients with severe TBI, our favorable success rate of 39.8% was clinically realistic as almost one-fifth of such patients had bilateral pupillary abnormalities and more than 60% had compressed or absent basal cisterns.

For the clinical factors, admission GCS became the most predictive factor. The odds of a good outcome were significantly greater for patients with GCS >=6 than for those with GCS 3-5. This is an indication of the prognostic value of residual motor response and cortical-subcortical function following initial resuscitation. Timofeev and Hutchinson emphasized the significance of using baseline severity and timing in the interpretation of the outcomes of the DC studies, as surgery after a prolonged refractory intracranial hypertension might not result in neurological independence and may be life-saving. In the present study, very low GCS continued to be correlated with poor outcome even after decompression, which indicates that DC should be one component of a wider prognostic spectrum [15].

Another strong independent predictor was pupil reactivity. Bilateral abnormal pupils are indicative of transtentorial herniation or compression of the brainstem, or severe diffuse injury. In selected cases, the development of herniation can be reversed with urgent decompression; however, a long-standing bilateral pupillary change is generally regarded as secondary injury. Implications for emergency counselling: Pupillary status should be recorded once hypotension, hypoxia and sedation have been corrected, and reported verbatim to the families, but not implying any determinants in potentially reversible cases.

Recovery also was related to radiological severity. Favorable outcome was associated with a lower Rotterdam CT score and lack of severe cisternal compression. Structural injury burden, mass effect and secondary swelling are incorporated into CT findings. The role of CT prognostication is similar to previous studies which demonstrated that multimodal CT predictors outperform general categorical classification in outcome prediction following TBI [11,12]. Compressed/absent basal cisterns and midline shift >10 mm occurred more often in the unfavorable group in our cohort, further supporting the benefits of early CT review by a neurosurgical and critical care team.

Early surgery (defined as surgery within 6 hours) was an independent predictor of favorable outcome. This association should be read with caution as retrospective timing analyses risk selection bias: patients operated quickly may have had surgically correctable mass lesion, have had shorter referral distances or have been operated on because of having a good initial physiological reserve. However, the discovery is not only biologically plausible, but it is likely. Earlier decompression will shorten the period of raised ICP, restore perfusion, limit injury due to herniation and exposure to secondary insults. This finding assists in reinforcing systems of care for trauma patients with mass effect and worsening neurologic status, including trauma systems, referral pathways and operating room preparation.

Poor outcome was strongly associated with postoperative intracranial hypertension. While the primary goal of DC is to decrease ICP, the continued or recurrent ICP elevation can be caused by diffuse swelling, expansion of contusion, venous congestion, hydrocephalus or systemic factors. This discovery suggests that aggressive neurocritical care should continue, rather than equating neurosurgery with treatment. The importance of postoperative management and rehabilitation on the outcome was highlighted in the analyses of the RESCUEicp trial, and long-term outcome will always be linked to the balance between mortality and survival with disability [5-7].

Complications occurred at higher rates than expected for the severe TBI DC cohorts. External cerebral herniation, hydrocephalus, wound infection and seizures were clinically important postoperative events. Various complications associated with head injury DC have been described by Yang et al. and by Stiver in early and late complications, including contusion expansion, contralateral haematoma, external cerebral herniation, subdural hygroma, hydrocephalus and syndrome of the trephined [16,17]. The complications we experience further support the importance of serial imaging, prevention of infection, seizure monitoring and early cranioplasty planning and structured rehabilitation follow-up.

The clinical significance of this study is the combination of these simple bedside and CT parameters into a simple clinical prediction model. Sophisticated models, like IMPACT and CRASH, can be useful, but validation studies have been conducted outside the model and found differences in calibration by setting, period, and case mix [9,10,18]. In many tertiary hospitals, decisions will be made before full laboratory panels and ICP data, or advanced imaging, is available. These are readily available and can be used to inform triage, family counselling and postoperative risk stratification, including age, GCS, pupils, CT score, and surgical timing.

There are some limitations of this study. Design is retrospective and can lead to documentation bias, particularly for prehospital hypoxia and hypotension. Second, ICP monitoring was not performed in all patients, which is a limitation of the real-world variability, and this compromises the uniform assessment of postoperative pressure control. Third, six-month GOSE may underestimate late recovery in severe TBI survivors especially those going through long-term rehabilitation. Fourth, although many factors related to rehabilitation intensity and caregiver assistance may have a significant impact on functional independence, these were not analysed in depth. Lastly, the multcentre design increases generalizability; the study was conducted only in tertiary teaching hospitals, and may not represent the results of other hospitals without neurosurgical intensive care facilities.

Despite these caveats, the study offers clinically important information that the outcome of decompressive craniectomy is reasonably predictable based on common clinical factors at admission and in the early postoperative period. Standardized ICP monitoring protocols, rehabilitation metrics, QOL instruments and follow up beyond six months should be included in future prospective studies to better define recovery trajectory following DC.

Conclusion

Favorable functional outcome at 6 months following decompressive craniectomy for severe TBI was linked with younger age, higher admission GCS, reactive pupils, lower Rotterdam CT score, surgery performed within 6 hours and no postoperative intracranial hypertension. These predictors can help to early risk stratification, family counselling and prioritization of postoperative neurocritical care and rehabilitation.

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