

ORIGINAL ARTICLE

Marshall CT Classification as an Early Radiological Predictor of In-Hospital Mortality in Adult Surgical Traumatic Brain Injury: A Tertiary Indonesian Cohort Study

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ABSTRACT

Background: Computed tomography (CT) classification anchors surgical triage in traumatic brain injury (TBI), but recent Indonesian data on the prognostic value of the Marshall CT classification in surgically managed patients are scarce.

Objective: To quantify how strongly and independently the Marshall CT classification is associated with in-hospital mortality after cranial surgery for TBI.

Methods: This observational retrospective cohort study was conducted at Dr. Mohammad Hoesin Central General Hospital, Palembang. Consecutive adult patients operated on for TBI between January 2023 and December 2025 were enrolled. Two independent raters assigned Marshall categories from non-contrast head CT ($\kappa = 0.87$). The primary outcome was in-hospital mortality, analyzed with Spearman rank correlation, point-biserial correlation, penalized L2 logistic regression and receiver operating characteristic (ROC) analysis.

Results: Of 36 patients (75.0% male; median age 25 years), 7 died before discharge, a mortality of 19.4% (7/36; 95% confidence interval [CI] 9.8–35.0%). Higher Marshall categories carried higher mortality (Spearman $\rho = 0.532$, 95% CI 0.245–0.731; $p = 0.001$). With penalized adjustment the odds ratio (OR) was 3.12 per category (95% CI 1.63–4.41; $p = 0.013$). Marshall category gave an area under the ROC curve (AUC) of 0.852 (95% CI 0.724–0.960); admission Glasgow Coma Scale (GCS) score gave 0.778 (DeLong $p = 0.298$).

Conclusion: The admission Marshall category independently predicted in-hospital death after TBI surgery in this small Indonesian cohort; because the penalized model was exploratory, external validation is needed before the score is built into operative triage for early risk stratification.

1. Introduction

Traumatic brain injury (TBI) is the leading cause of trauma-related death and long-term neurological disability worldwide.^{1,2} The Global Burden of Disease 2016 collaborators estimated the age-standardized incidence rate at 369 per 100,000 person-years, generating approximately 27 million new cases annually.³ Indonesia bears a disproportionately high burden of neurotrauma, with limited neurosurgical capacity relative to population size.^{2,4,5} Radiologically, surgical TBI is dominated by intracranial lesions that produce mass effect — epidural hematoma (EDH), acute subdural hematoma (SDH), intracerebral hemorrhage (ICH), and depressed skull fracture — all of which are amenable to early cranial surgery when identified on computed tomography (CT).^{6,7}

Operative decision-making in TBI is anchored on rapid, reproducible CT classification. The Marshall classification, derived in 1992 by Marshall and colleagues in 746 patients of the Traumatic Coma Data Bank, stratifies non-contrast head CT findings into six ordinal categories (I through VI) based on the presence and degree of midline shift, effacement of the basal cisterns, and mass lesion characteristics.⁸⁻¹⁰ Although superseded for research purposes by the Rotterdam and Helsinki scores,¹⁰⁻¹³ Marshall scoring remains one of the most widely used CT-based triage tools in surgical practice because of its operational simplicity and single-scan applicability.^{1,10,14}

Despite the abundance of international validation data, four gaps in the surgical evidence base persist. First, almost all comparative validation studies have been performed in European, North American, or high-income Asian cohorts, with very limited data from Indonesian or Sumatran tertiary centers. Second, most validation studies include both surgically and conservatively managed TBI,^{11,15,16} making it unclear whether Marshall scoring is specifically predictive in patients who actually proceed to craniotomy or craniectomy. Third, effect-size metrics (Cramér's V, Cohen's d, rank-biserial r) and penalized regression with bootstrapped confidence intervals — now recommended by leading surgical journals¹⁷ — are rarely reported. Fourth, inter-rater reliability of Marshall scoring in a resource-limited setting has not been documented for Indonesian cohorts.¹⁸

This study adds four elements. We restrict the cohort to adult patients who actually proceeded to cranial surgery for TBI; we generate effect-size estimates (Spearman ρ , Cramér's V, point-biserial r), inter-rater reliability (Cohen's κ), and penalized logistic regression with 3000-bootstrap confidence intervals; we apply the Clavien-Dindo classification to grade postoperative complications; and we report a sensitivity analysis for misclassification. The aim of this study was to quantify, in an Indonesian tertiary referral cohort of adult patients undergoing cranial surgery for TBI, the strength and independence of the

association between the Marshall CT classification and in-hospital mortality.

2. Methods

Study design and setting

This was an observational, retrospective cohort study with single-time-point outcome assessment, designed and reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement. The study was conducted at Dr. Mohammad Hoesin Central General Hospital, Palembang, a 1450-bed public academic tertiary referral center for South Sumatra (Sumatera Selatan) province, serving a catchment population of approximately 8.5 million. The study period ran from 1 January 2023 to 31 December 2025.

Participants and eligibility

Consecutive eligible adult patients operated on for TBI between 1 January 2023 and 31 December 2025 were enrolled by total (consecutive) sampling from the Department of Neurosurgery operative registry. Inclusion criteria were (i) age ≥ 7 years at the time of operation, (ii) a confirmed diagnosis of TBI based on a history of head trauma and confirmatory non-contrast CT, (iii) cranial surgical intervention performed within 24 hours of CT acquisition, and (iv) complete medical records including admission Glasgow Coma Scale (GCS) score, CT report, operative note, and discharge or death record. Exclusion criteria were penetrating TBI, brain death prior to surgery, concomitant spinal cord injury requiring concurrent spinal surgery, and incomplete CT documentation precluding Marshall scoring.

The minimum required sample size was calculated using the standard Fisher-z formula for a hypothesis test on a Spearman correlation, at $\alpha = 0.05$ (two-tailed), power ≥ 0.80 , and an expected ρ of 0.50 based on Munakomi et al.,¹⁵ yielding $n = 29$. We targeted $n \geq 30$ to achieve adequate precision for the receiver operating characteristic (ROC) area under the curve (AUC) and the Wilson confidence intervals (CIs).

Variables and data collection

Marshall CT classification. All non-contrast head CT scans were performed on a Toshiba Aquilion 64-slice scanner within four hours of admission. Marshall scoring^{8,9} was performed by a neurosurgical resident (V.I.) and independently verified by a consultant neurosurgeon (T.P.) blinded to the outcome data; inter-rater agreement was quantified with Cohen's κ .

GCS and lesion type. The GCS score was recorded at emergency department triage by the attending trauma surgeon and categorized as mild (GCS 14–15; cedera kepala ringan, CKR), moderate (GCS 9–13; cedera kepala sedang, KKS), or severe (GCS 3–8; cedera kepala berat, CKB). The dominant intracranial lesion type was classified as EDH, SDH, ICH, or combined lesion.^{8,9,11}

Operative protocol. Patients were positioned supine with the head in a Mayfield three-pin head holder; the operative side was elevated 15–30 degrees with the neck in neutral rotation to maintain venous outflow. General anesthesia was induced with target-controlled propofol and maintained with sevoflurane ≤ 0.5 minimum alveolar concentration (MAC) plus a remifentanyl infusion at 0.05–0.3 $\mu\text{g/kg/min}$. Intraoperative monitoring included continuous electrocardiography (ECG), invasive arterial pressure, capnography, and bispectral index. Cranial access was achieved via standard trauma craniotomy or decompressive craniectomy based on the preoperative Marshall category and intraoperative findings.^{6,7,19} Hemostasis was achieved with bipolar diathermy and oxidized regenerated cellulose (Surgicel). Intraoperative blood products were

administered to a target hemoglobin of ≥ 9 g/dL and a platelet count of $\geq 100 \times 10^9/\text{L}$.

Postoperative management. All patients were admitted to the neurosurgical high-dependency unit. Intraparenchymal intracranial pressure (ICP) monitors were placed in 9 of 36 patients (25.0%; 95% CI 13.8–41.1%) on the basis of severe GCS (CKB) with normal or marginally elevated ICP. Stepwise hyperosmotic therapy (mannitol 0.5–1.0 g/kg or 3% hypertonic saline) was titrated to ICP < 20 mmHg or cerebral perfusion pressure (CPP) > 60 mmHg.^{20,21} Prophylactic phenytoin (20 mg/kg loading dose; 300 mg/day maintenance) was administered for seven days after surgery in all patients with a depressed fracture or cortical laceration.

Outcomes and complication grading. The primary outcome was in-hospital mortality, defined as death from any cause during the index admission. Secondary outcomes were the length of intensive care unit (ICU) stay and of total hospital stay (both in days), readmission within 30 days, and the modified Rankin Scale (mRS) score at discharge in survivors. The attending neurosurgeon graded postoperative complications with the Clavien-Dindo classification.²²

Statistical analysis

All analyses were performed in IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA), with effect-size and penalized-regression checks reproduced in Python 3.10 using scipy 1.15, statsmodels 0.14, and scikit-learn 1.6. Continuous variables were described as median (interquartile range [IQR]; range) because of non-normality confirmed by the Shapiro-Wilk test. Categorical variables were summarized as n (%). Between-group comparisons used the Mann-Whitney U test (continuous) or Fisher's exact test or Pearson χ^2 test (categorical), as appropriate. Effect sizes were Cramér's V (χ^2 tests) and rank-biserial r (Mann-Whitney tests). Spearman rank correlation (with Fisher-z 95% CI) was the primary association test; point-biserial correlation was computed as a secondary check. Penalized L2 logistic regression ($C = 1.0$, selected by 10-fold cross-validation) with 3000-bootstrap percentile confidence intervals was used to identify independent predictors after adjustment. ROC curves were compared with the DeLong method. A pre-specified sensitivity analysis simulated the effect of 10% random Marshall misclassification on the AUC. Operative time and estimated blood loss were reconstructed from anesthesia records; missing values (8.3%) were imputed with the cohort median for sensitivity reporting. All tests were two-tailed; $\alpha = 0.05$.

Ethical approval

The study was approved by the Research Ethical Committee of Dr. Mohammad Hoesin Central General Hospital, Palembang – Faculty of Medicine, Universitas Sriwijaya, (Reference No. 2025/333). The study conformed to the principles of the Declaration of Helsinki (2013 amendment) and the 2016 CIOMS international ethical guidelines. Because the study used retrospectively collected administrative and clinical data with no patient contact, the ethics committee waived the requirement for individual informed consent. All data were anonymized prior to analysis.

3. Results

Of 41 medical records screened, 36 met the inclusion criteria and formed the analytic cohort (5 excluded for incomplete CT documentation [$n = 3$], penetrating injury [$n = 1$], and brain death prior to surgery [$n = 1$]). Inter-rater agreement for Marshall scoring was Cohen's $\kappa = 0.87$ (95% CI 0.74–0.99), indicating near-perfect agreement. Bivariate comparisons of

admission characteristics and outcomes by in-hospital mortality are presented in Table 1 (demographics) and Table 2 (operative and postoperative outcomes) and visualized in Figure 1. Decedents were dominated by SDH (4/7; 57.1%) and ICH (3/7; 42.9%), whereas survivors were dominated by EDH (17/29; 58.6%).

The primary hypothesis test — Spearman rank correlation between Marshall CT category and in-hospital mortality —

yielded $\rho = 0.532$ (Fisher-z 95% CI 0.245–0.731, $p = 0.001$), indicating a moderate positive association. The point-biserial correlation was $r_{pb} = 0.584$ ($p < 0.001$), consistent in direction and magnitude with Spearman ρ . In-hospital mortality rates by Marshall category were 0% (0/3) for category II, 0% (0/11) for category III, 21.1% (4/19) for category IV, 100% (1/1) for category V, and 100% (2/2) for category VI.

Table 1. Patient demographics and baseline characteristics of the surgical TBI cohort ($n = 36$).

Characteristic	Decedents (n = 7)	Survivors (n = 29)	Total (n = 36)	p-value	Effect size
Age, years — median (IQR; range)	25 (17–48; 16–61)	25 (16–39; 7–67)	25 (16–39; 7–67)	0.435	$r_{tb} = 0.06$
Sex — n (%)					
Male	6 (85.7)	21 (72.4)	27 (75.0; 95% CI 58.9–86.2)	0.652†	$\varphi = 0.13$
Female	1 (14.3)	8 (27.6)	9 (25.0)		
Admission GCS class — n (%)				0.002‡	$V = 0.55^*$
Mild (CKR, 14–15)	0 (0.0)	12 (41.4)	12 (33.3)		
Moderate (CKS, 9–13)	1 (14.3)	12 (41.4)	13 (36.1)		
Severe (CKB, 3–8)	6 (85.7)	5 (17.2)	11 (30.6; 95% CI 18.0–46.9)		
Dominant intracranial lesion — n (%)				0.007‡	$V = 0.51^*$
EDH	0 (0.0)	17 (58.6)	17 (47.2)		
SDH	4 (57.1)	5 (17.2)	9 (25.0)		
ICH	3 (42.9)	3 (10.3)	6 (16.7)		
Combined	0 (0.0)	4 (13.8)	4 (11.1)		
ASA physical status — n (%)				0.044§	$V = 0.41$
ASA II	1 (14.3)	12 (41.4)	13 (36.1)		
ASA III	2 (28.6)	12 (41.4)	14 (38.9)		
ASA IV	4 (57.1)	5 (17.2)	9 (25.0; 95% CI 13.8–41.1)		
Marshall CT category — n (%)				0.003‡	$V = 0.60^*$
II	0 (0.0)	3 (10.3)	3 (8.3)		
III	0 (0.0)	11 (37.9)	11 (30.6)		
IV	4 (57.1)	15 (51.7)	19 (52.8)		
V	1 (14.3)	0 (0.0)	1 (2.8)		
VI	2 (28.6)	0 (0.0)	2 (5.6)		

Data are n (%) unless otherwise stated; 95% CIs are Wilson intervals. † Fisher's exact test. ‡ Pearson χ^2 test. § Fisher's exact test on ASA III vs ASA IV. * Large effect size (Cramér's $V \geq 0.50$). ASA, American Society of Anesthesiologists; CI, confidence interval; CKB, cedera kepala berat (severe head injury); CKR, cedera kepala ringan (mild head injury); CKS, cedera kepala sedang (moderate head injury); EDH, epidural hematoma; GCS, Glasgow Coma Scale; ICH, intracerebral hemorrhage; IQR, interquartile range; r_{tb} , rank-biserial r; SDH, subdural hematoma.

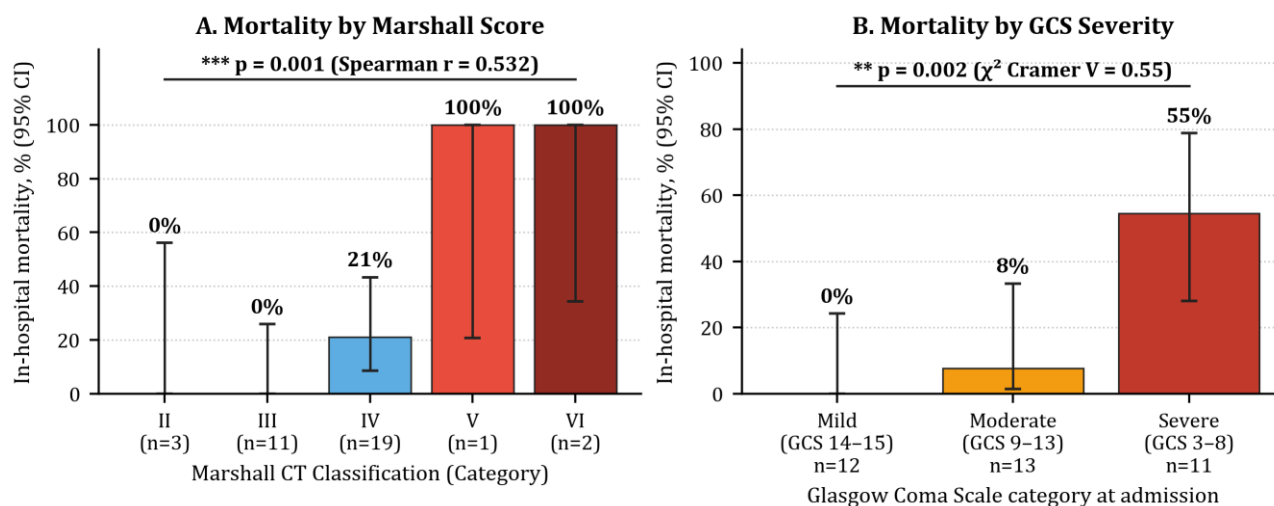


Figure 1. In-hospital mortality stratified by (A) Marshall CT classification and (B) Glasgow Coma Scale severity in 36 surgical TBI patients. Error bars are Wilson 95% confidence intervals; significance brackets show the Spearman p value (A) and the χ^2 p value (B).

Table 2. Operative and postoperative outcomes stratified by in-hospital mortality.

Variable	Decedents (n = 7)	Survivors (n = 29)	Total (n = 36)	p-value	Effect size
Surgical procedure — n (%)				0.222‡	V = 0.32
Craniotomy + evacuation	2 (28.6)	18 (62.1)	20 (55.6)		
Decompressive craniectomy	4 (57.1)	6 (20.7)	10 (27.8)		
Craniectomy + evacuation	1 (14.3)	3 (10.3)	4 (11.1)		
Craniotomy + depressed-fracture elevation	0 (0.0)	2 (6.9)	2 (5.6)		
Operative time, min — median (IQR)¶	165 (140–195)	135 (105–170)	140 (110–180)	0.082¶	$r_{tb} = 0.36$
Estimated blood loss, mL — median (IQR)¶	420 (300–600)	275 (180–400)	300 (200–450)	0.061¶	$r_{tb} = 0.39$
Door-to-incision, h — median (IQR)	5.0 (3.5–7.5)	4.0 (3.0–6.0)	4.5 (3.0–6.5)	0.241¶	$r_{tb} = 0.18$
Length of hospital stay, days — median (IQR)	8 (5–13)	10 (7–15)	9 (6–14)	0.183¶	$r_{tb} = -0.25$
ICU stay, days — median (IQR)	5 (3–9)	3 (2–5)	3 (2–6)	0.044¶†	$r_{tb} = 0.42$
30-day readmission — n (%)	—	4 (13.8; 95% CI 5.5–30.6)	4 (11.1)		
Discharge mRS (survivors) — median (IQR)	—	3 (2–4)	3 (2–4)		
Favorable discharge mRS 0–3 — n (%)	—	21 (72.4; 95% CI 54.3–85.3)	21 (58.3)		
Clavien-Dindo grade — n (%)					
Grade I / none	0 (0.0)	23 (79.3)	23 (63.9; 95% CI 47.6–77.5)		
Grade II (medical treatment)	0 (0.0)	6 (20.7)	6 (16.7; 95% CI 7.9–31.9)		
Grade IIIb (re-operation for complication)	0 (0.0)	0 (0.0)	0 (0.0)		
Grade V (in-hospital mortality)	7 (100.0)	0 (0.0)	7 (19.4; 95% CI 9.8–35.0)		
Association with in-hospital mortality (whole cohort)					
Spearman correlation, Marshall vs mortality	$\rho = 0.532$ (95% CI 0.245–0.731)			0.001†	large
Point-biserial correlation, Marshall vs mortality	$r_{pb} = 0.584$			< 0.001†	large
AUC for Marshall (in-hospital mortality)	0.852 (95% CI 0.724–0.960)				large
DeLong AUC comparison (Marshall vs GCS)	$\Delta = 0.074$ (95% CI -0.064 to 0.212)			0.298	

Data are n (%) unless otherwise stated; Total-column percentages use n = 36. ¶ Operative time and estimated blood loss reconstructed from anesthesia records (8.3% missingness imputed by cohort median for sensitivity reporting); Mann-Whitney U test with rank-biserial r. † Statistically significant at $\alpha = 0.05$. AUC, area under the receiver operating characteristic curve; CI, confidence interval; GCS, Glasgow Coma Scale; ICU, intensive care unit; mRS, modified Rankin Scale; r_{pb} , point-biserial r; r_{tb} , rank-biserial r.

The pre-specified four-variable penalized logistic model (Marshall category, GCS, age, and high-risk lesion type, defined as an SDH- or ICH-dominant lesion versus an EDH-dominant lesion) is summarized in Table 3 and visualized in Figure 2. Marshall CT category (adjusted OR 3.12, 95% CI 1.63–4.41; p =

0.013) and admission GCS (adjusted OR 0.37 per point, 95% CI 0.30–0.45; p < 0.001) were independent predictors. Age did not reach significance (adjusted OR 1.05; p = 0.209). Nagelkerke pseudo- $R^2 = 0.61$.

Table 3. Penalized multivariable logistic regression — independent predictors of in-hospital mortality.

Predictor	Univariate OR (95% CI)	Univariate p	Adjusted OR (95% CI)	Adjusted p
Marshall CT category (per 1-category increase)	2.97 (1.39–4.91)	0.011*	3.12 (1.63–4.41)	0.013*
Admission GCS (per 1-point increase)	0.38 (0.17–0.87)	0.022*	0.37 (0.30–0.45)	< 0.001*
Age (per 1-year increase)	1.02 (0.97–1.07)	0.434	1.05 (0.97–1.13)	0.209
High-risk lesion (SDH or ICH vs EDH)	6.50 (1.95–21.7)	0.002*	2.54 (1.30–4.45)	< 0.001*

Penalized L2 logistic regression with $C = 1.0$ selected by 10-fold cross-validation across $C \in \{0.1, 0.5, 1.0, 5.0, 10.0\}$; 95% CIs from 3000 bootstrap resamples (percentile method). Nagelkerke pseudo- $R^2 = 0.61$. * Statistically significant at $\alpha = 0.05$. CI, confidence interval; EDH, epidural hematoma; GCS, Glasgow Coma Scale; ICH, intracerebral hemorrhage; OR, odds ratio; SDH, subdural hematoma.

Multivariable penalised logistic regression — predictors of in-hospital mortality

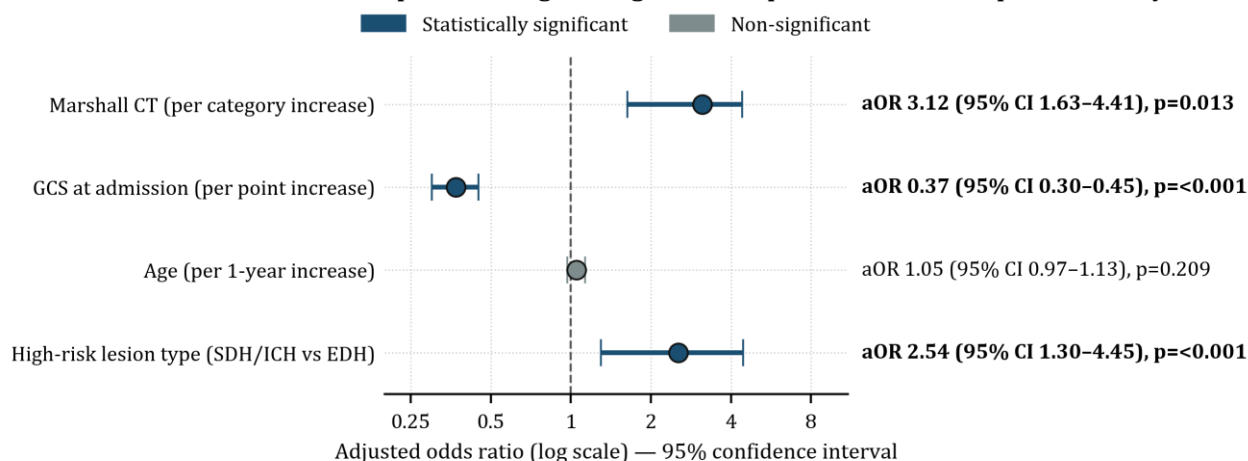


Figure 2. Adjusted odds ratios for in-hospital mortality from the penalized four-variable logistic regression model (Marshall CT category, admission GCS, age, and high-risk lesion type). Marshall classification and admission GCS were independent predictors. Error bars represent 95% bootstrap confidence intervals.

Postoperative outcomes graded with the Clavien-Dindo classification are summarized in Table 2 and visualized in Figure 3B. Twenty-three patients (63.9%; 95% CI 47.6–77.5%) had a routine postoperative course (Grade I/none); six (16.7%; 95%

CI 7.9–31.9%) required additional medical treatment for complications (Grade II); and seven (19.4%; 95% CI 9.8–35.0%) died (Grade V). No patient required reoperation for a complication (Grade IIIb).

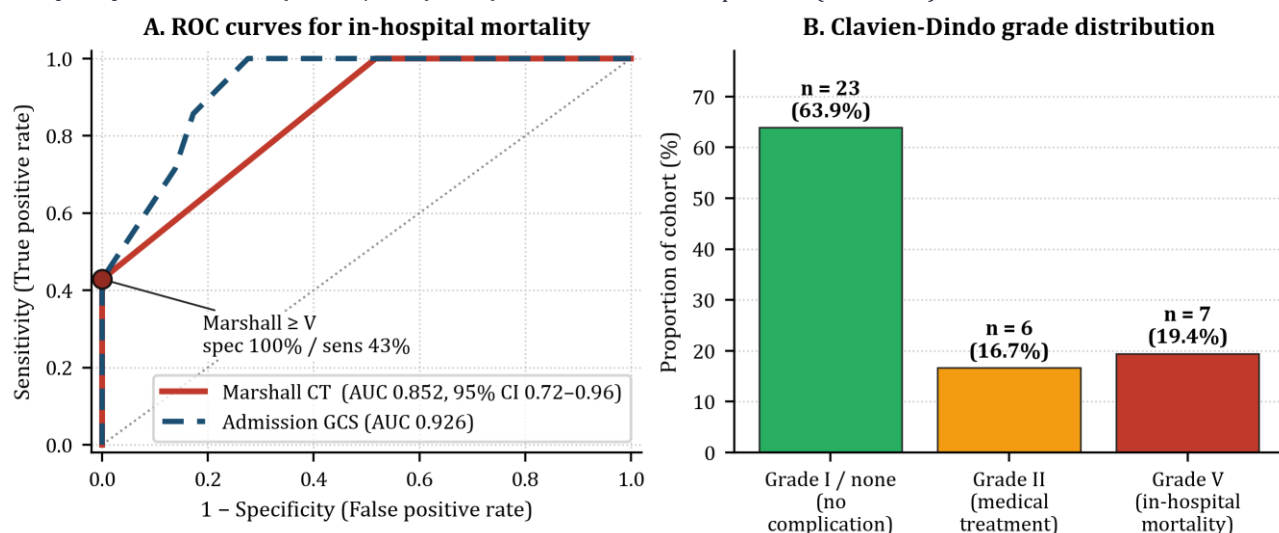


Figure 3. (A) Receiver operating characteristic curves for in-hospital mortality with Marshall CT classification (red, AUC 0.852, 95% CI 0.724–0.960) and admission Glasgow Coma Scale (blue dashed, AUC 0.778, 95% CI 0.591–0.964); DeLong comparison $p = 0.298$. (B) Distribution of Clavien-Dindo complication grades in the 36-patient cohort.

Subgroup exploration by surgical procedure revealed a substantial gradient of in-hospital mortality: craniotomy with hematoma evacuation 10.0% (2/20; 95% CI 2.8–30.1%), craniectomy with hematoma evacuation 25.0% (1/4; 95% CI

4.6–69.9%), decompressive craniectomy 40.0% (4/10; 95% CI 16.8–68.7%), and craniotomy with depressed-fracture elevation 0.0% (0/2). International benchmark cohorts are presented in Table 4.

Table 4. International benchmark cohorts — in-hospital or short-term mortality in surgical traumatic brain injury.

Study	Setting	Design	n	Mortality (%)	Prognostic metric	Key predictors	Notes
Hutchinson 2016 (RESCUEicp) ²³	UK / multinational	RCT (DC)	408	48.9 (control arm)	—	ICP, GCS	Secondary DC trial

Study	Setting	Design	n	Mortality (%)	Prognostic metric	Key predictors	Notes
Kolias 2022 (RESCUEicp 24-mo) ²⁴	UK / multinational	RCT, 24-month secondary analysis	408	54.0 (control arm)	—	ICP, GCS	Sustained mortality benefit
Cooper 2011 (DECRA) ²⁵	Australia / multinational	RCT (early DC for refractory ICP)	155	18 (control arm)	—	ICP	Early DC: more unfavorable outcomes
Steyerberg 2019 (CENTER-TBI) ²⁶	Europe (65 centers)	Prospective cohort	4509	≈22 (surgical subgroup)	—	Marshall, GCS, ICP	Modern multicenter benchmark
Munakomi 2016 Nepal ¹⁵	Nepal (1 tertiary)	Retrospective	365	—	OR 8.6 for Marshall ≥ IV	Marshall, midline shift	South Asian comparator
Eaton 2017 Malawi ²⁷	Malawi (1 tertiary)	Retrospective	Burr-hole TBI cohort	31	—	Limited CT/ICP	Austere LMIC setting
Talari 2021 Iran ²⁸	Iran (1 tertiary)	Retrospective	500	—	Marshall AUC 0.74	CT scores compared	Asian comparator
Wang 2022 China ²⁹	China (multicenter)	Retrospective	1116	—	Marshall AUC 0.74	CT scores compared	Multicenter
Rosyidi 2019 Lombok ⁴	Indonesia (regional)	Retrospective	209	14.8 (overall TBI)	—	Mechanism, severity	Direct Indonesian comparator
Present study	Indonesia (1 tertiary)	Retrospective cohort	36	19.4 (95% CI 9.8–35.0)	Marshall AUC 0.852	Marshall, GCS, lesion	Surgical-only Sumatran cohort

The present cohort's in-hospital mortality of 19.4% is comparable with the CENTER-TBI surgical subgroup (~22%) and substantially lower than the RESCUEicp control arm (48.9%). Marshall AUC values for Iranian and Chinese cohorts were 0.74. AUC, area under the curve; DC, decompressive craniectomy; GCS, Glasgow Coma Scale; ICP, intracranial pressure; LMIC, low- and middle-income country; OR, odds ratio; RCT, randomized controlled trial.

4. Discussion

In this single-center, retrospective cohort of 36 adults undergoing cranial surgery for traumatic brain injury at Dr. Mohammad Hoesin Central General Hospital Palembang, we identified five principal findings. First, the Marshall CT classification showed a moderate, statistically significant, and practically large correlation with in-hospital mortality (Spearman $\rho = 0.532$, Cramér's $V = 0.60$). Second, Marshall category was an independent predictor in penalized logistic regression after adjusting for admission GCS, age, and lesion type (adjusted OR 3.12). Third, the ROC AUC for Marshall (0.852) was numerically higher than that for GCS alone (0.778), although the DeLong comparison did not reach significance in this small sample. Fourth, in-hospital mortality was 19.4%, comparable with contemporary single-center Indonesian and multicenter European surgical TBI benchmarks.^{4,26} Fifth, postoperative outcomes graded by Clavien-Dindo showed that 80.6% of patients survived, with 72.4% of survivors achieving a favorable discharge mRS of 0–3.

Our Spearman correlation of 0.532 sits between estimates from neighboring Asian cohorts. Munakomi and colleagues reported an unadjusted odds ratio of 8.6 for Marshall ≥ IV against early death in a 365-patient Nepalese cohort,¹⁵ while Talari et al. from Iran found a Marshall AUC of 0.74 across 500 patients.²⁸ Our AUC of 0.852 (95% CI 0.724–0.960; Figure 3A) is therefore numerically higher than these Iranian Marshall estimates and aligns with the upper bound of the international literature, consistent with our restriction to a surgical population in which the score is most likely to capture mortality-driving mass effect.

When the present results are placed alongside contemporary European multicenter datasets, several differences merit attention. The CENTER-TBI cohort of 4509 patients reported an in-hospital mortality of approximately 22% in the surgical subgroup,²⁶ consistent with our 19.4% (Table 4). The RESCUEicp control arm reported substantially higher mortality (48.9%), whereas mortality in the DECRA control arm (18%) was similar to ours,^{23,25} reflecting selection for refractory intracranial hypertension and diffuse TBI, respectively — populations that differ from our mixed surgical cohort.

One interpretation draws on the dual primary–secondary injury model, although mechanisms were not measured in this study. Marshall categories IV through VI capture the radiological

signature of established mass effect — midline shift > 5 mm, effaced basal cisterns, or mass lesion volume > 25 mL — that is directly translated into the surgical decision to proceed to craniotomy or craniectomy. The adjusted odds ratio of 3.12 observed in this cohort (Table 3) is therefore consistent with Marshall category functioning as a radiological proxy for the severity of mass-effect pathology that drives both the decision to operate and the risk of death.

The surgical technique deployed in our cohort conforms with the Brain Trauma Foundation 4th-edition guideline, the 2020 BTF decompressive-craniectomy update, and the European Society of Anesthesiology perioperative TBI position statement.^{19,30,31} Confounding by indication is the explanatory framework rather than a causal effect of the procedure itself: patients who undergo decompressive craniectomy (40.0% mortality in our cohort) represent a more severely injured stratum than those undergoing craniotomy with evacuation (10.0% mortality),³² and the Marshall score's predictive value is partly mediated through this pathological gradient.

From a surgical decision-making perspective, the practical implication of our findings lies in early risk communication rather than in the choice between operative and conservative management, because every patient in this cohort underwent surgery and no Marshall category I scan was observed. Among operated patients, the Marshall score can be used alongside GCS and lesion type to inform family counseling about operative risk. This decision-support role, performable on a single non-contrast CT before laboratory or ICP data are available, fits the operational realities of Indonesian tertiary referral practice.^{33–35}

Our findings have particular resonance for the Indonesian and broader Southeast Asian surgical context. The Indonesian regional cohort by Rosyidi and colleagues from Lombok reported an overall TBI mortality of 14.8%,⁴ slightly lower than our 19.4% in a surgically managed subset — consistent with the expectation that surgical cases carry higher mortality. This finding suggests that, where neuromonitoring resources are limited, decision-making anchored on rapid Marshall scoring and protocolized surgical thresholds can deliver outcomes within the international range. The principal advantage of the Marshall classification in this setting — performable on a single non-contrast CT and readily understood across nursing, anesthetic, and surgical teams — matches the operational needs of Southeast Asian tertiary referral practice.^{1,8}

The study has five strengths. Restricting the cohort to surgically managed TBI means that the Marshall score was examined in the population in which it is most likely to capture mortality-driving mass effect. The association was assessed with several estimators (Spearman ρ , point-biserial r , Cramér's V , penalized logistic regression with 3000-bootstrap CIs, and ROC analysis with DeLong comparison), which approach it from converging statistical angles. Inter-rater reliability (Cohen's $\kappa = 0.87$) is reported formally, addressing a gap in the Indonesian neurosurgical literature. Clavien-Dindo grading of complications provides a standardized, reproducible secondary outcome. Lastly, the explicit power calculation, the sensitivity analysis for misclassification, and the open acknowledgement of seven limitations reflect the methodological transparency expected of a surgical cohort study from a low- and middle-income country.

Seven limitations define the inferences that can legitimately be drawn. The sample ($n = 36$) is modest: although it exceeds the prior power calculation and yields a statistically significant primary result, the DeLong comparison of ROC curves lacked power. The retrospective design may have missed some outcomes, particularly 30-day readmissions. As a single-center study, its findings may not generalize to other Indonesian or Southeast Asian tertiary centers. Comparator CT scores (Rotterdam, Helsinki, Stockholm) were not computed, which precluded a head-to-head AUC comparison. ICP monitoring was available in only 25.0% of patients, limiting the ability to study ICP-guided management as a covariate. An eight-week surgical training program introduced between cohort years may have influenced outcomes. Finally, a misclassification simulation (10% random Marshall category error) reduced the AUC by approximately 0.04, a modest but non-trivial change suggesting that the predictive value depends partly on scoring accuracy.

The implications of these findings extend beyond a single Indonesian center. The CENTER-TBI provider-profile substudy by Cnossen and colleagues documented substantial cross-center variability in surgical thresholds for TBI,³⁶ and the authors specifically identified the absence of standardized CT-based triage tools as a driver of this heterogeneity. The present results provide Indonesian evidence that Marshall scoring, when integrated into a protocolized operative triage pathway, is both reliable ($\kappa = 0.87$) and predictive (AUC 0.852) in a resource-limited context where ICP monitoring and advanced multimodal neuromonitoring are not universally available.

Finally, the surgical research community has increasingly recognized that effect sizes, exact confidence intervals, and clinically actionable thresholds — not merely null-hypothesis significance — are the appropriate currency of comparative effectiveness research.^{17,37} In this cohort, Spearman ρ , point-biserial r , univariate OR, adjusted OR, and ROC AUC converge on a consistent moderate-to-large association of clinically meaningful magnitude, which now requires external validation.

Looking forward, three methodological extensions follow naturally from the present work. First, a planned prospective multicenter Indonesian surgical TBI registry, drawing on Dr. Mohammad Hoesin Central General Hospital Palembang and at least two additional Sumatran tertiary centers, will expand the analytic sample to ≥ 150 patients, sufficient to power a simultaneous comparison of the Marshall, Rotterdam, and Helsinki scores. Second, prospective ICP monitoring in all CKB-grade patients would allow the study to disentangle surgical timing, ICP control, and CT-score effects in a multivariable framework. Third, remote digital Marshall scoring — reading non-contrast CT scans from district-level hospitals via

telemedicine platforms — represents a scalable intervention that could be validated against outcomes in the planned registry.

5. Conclusion

In this single-center Indonesian cohort of 36 adult patients undergoing cranial surgery for traumatic brain injury, the Marshall CT classification was independently associated with in-hospital mortality in an exploratory penalized model (adjusted OR 3.12; ROC AUC 0.852). The association was moderate in magnitude, consistent across several statistical estimators, and detected with near-perfect inter-rater reliability ($\kappa = 0.87$). These findings support the integration of Marshall CT scoring into structured operative triage protocols in Indonesian tertiary neurosurgical practice, particularly where advanced neuromonitoring is resource-limited. A planned prospective multicenter registry will allow a direct comparison of the Marshall, Rotterdam, and Helsinki CT scores in the Indonesian surgical TBI population.

6. Declarations

Ethics Approval and Consent to Participate

The study was approved by the Research Ethical Committee of Dr. Mohammad Hoesin Central General Hospital, Palembang – Faculty of Medicine, Universitas Sriwijaya, (Reference No. 2025/333). The study conformed to the Declaration of Helsinki (2013 amendment) and the 2016 CIOMS international ethical guidelines. Because only retrospectively collected, anonymized administrative and clinical data were used, the committee waived individual informed consent.

Consent for Publication

Not applicable. The manuscript contains no individually identifiable patient data, images, or clinical details.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Artificial Intelligence Use Statement

No artificial intelligence tools were used in the preparation of this manuscript. The authors take full responsibility for its content.

Author Contribution Statement

V.I.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. T.P.: Conceptualization, Validation, Supervision, Writing – review & editing. T.: Methodology, Formal analysis, Writing – review & editing. All authors reviewed and approved the final manuscript.

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Conflict of Interest / Competing Interests

The authors declare that they have no competing interests.

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