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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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A B S T R A C T

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

Methods: An observational retrospective cohort study was conducted at Dr. Mohammad Hoesin Central General Hospital, Palembang. Consecutive adult surgical TBI patients operated on between January 2023 and December 2025 were enrolled. Marshall CT categories were assigned from non-contrast head CT scans by two independent raters (κ = 0.87). The primary outcome was in-hospital mortality. We quantified the association between Marshall score and in-hospital mortality using Spearman rank correlation, point-biserial correlation, penalised L2 logistic regression, and ROC analysis.

Results: Thirty-six patients met the inclusion criteria (75.0% male; median age 25 years). In-hospital mortality was 19.4% (7/36; 95% CI 9.8–35.0%). Spearman correlation between Marshall score and mortality was ρ = 0.532 (95% CI 0.245–0.731, p = 0.001). Marshall category was an independent predictor in penalised logistic regression (adjusted OR 3.12, 95% CI 1.63–4.41; p = 0.013). ROC AUC was 0.852 (95% CI 0.724–0.960), numerically superior to admission GCS AUC of 0.778 (DeLong p = 0.298).

Conclusion: Marshall CT classification is an independent, point-of-CT predictor of in-hospital mortality after surgery for TBI in an Indonesian tertiary cohort. Integration into structured operative triage may enhance 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-standardised incidence rate at 369 per 100,000 person-years, generating approximately 27 million new cases annually. Indonesia bears a disproportionately high burden of neurotrauma, with limited neurosurgical capacity relative to population size.[3,4] At the cellular level, surgical TBI is dominated by mass-effect-producing intracranial lesions — 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).

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 basal cisterns, and mass lesion characteristics.[5,6] Although superseded for research purposes by the Rotterdam and Helsinki scores,[7,8] Marshall scoring remains the most widely used CT-based triage tool in surgical practice because of its operational simplicity and single-scan applicability.[9-11]

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 centres. Second, most validation studies include both surgically and conservatively managed TBI, making it unclear whether Marshall scoring is specifically predictive in patients who actually proceed to craniotomy or craniectomy. Third, effect-size metrics (Cramer's V, Cohen's d, rank-biserial r) and penalised regression with bootstrapped confidence intervals — now recommended by leading surgical journals — are rarely reported. Fourth, inter-rater reliability of Marshall scoring in a resource-limited setting has not been documented for Indonesian cohorts.[12-15]

The novelty of the present study is therefore four-fold. We restrict the cohort to adult patients who actually proceeded to cranial surgery for TBI; we generate effect-size estimates (Spearman r, Cramer's V, point-biserial r), inter-rater reliability (Cohen's κ), and penalised logistic regression with 3000-bootstrap confidence intervals; we apply the Clavien-Dindo classification to grade postoperative complications; and we provide an honest 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

2.1 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 centre for Sumatera Selatan province, serving a catchment population of approximately 8.5 million.

2.2 Study period and sampling

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.

2.3 Inclusion and exclusion criteria

Inclusion criteria were (i) patients aged ≥ 7 years at the time of operation, (ii) confirmed diagnosis of TBI based on 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 GCS, 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.

2.4 Sample-size calculation

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. (2020), yielding $n = 29$. We targeted $n \geq 30$ to achieve adequate precision for the ROC AUC and Wilson CIs.

2.5 Marshall CT classification — radiological exposure

All non-contrast head CT scans were performed on a Toshiba Aquilion 64-slice scanner within four hours of admission. Marshall scoring 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 by Cohen's κ.

2.6 Glasgow Coma Scale (GCS)and lesion typing

GCS was recorded at the moment of emergency department triage by the attending trauma surgeon and categorised as mild (*cedera kepala ringan,* CKR, 14–15), moderate (*cedera kepala sedang*, CKS, 9–13), or severe (*cedera kepala berat,* CKB, 3–8). Dominant intracranial lesion type was classified as EDH, SDH, ICH, or combined lesion.[16-19]

2.7 Surgical technique — reproducible 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 MAC plus remifentanil infusion at 0.05–0.3 μg/kg/min. Intraoperative monitoring included continuous ECG, invasive arterial pressure, capnography, and bispectral index. Cranial access was achieved via standard trauma craniotomy or decompressive craniectomy based on preoperative Marshall category and

intraoperative findings.[20-24] Hemostasis with bipolar diathermy plus Surgicel (oxidised cellulose). Intraoperative blood products were administered on a target hemoglobin of ≥ 9 g/dL and platelet count ≥ 100 × 10^9/L.

2.8 Postoperative management

All patients were admitted to the neurosurgical high-dependency unit. Intraparenchymal ICP monitors were placed in 9 of 36 patients (25.0%; 95% CI 13.7–41.0%) on the basis of severe GCS (CKB) with normal or marginally elevated ICP. Stepwise hyperosmotic therapy (mannitol 0.5–1.0 g/kg or hypertonic saline 3%) was titrated to ICP < 20 mmHg or CPP > 60 mmHg. Prophylactic phenytoin (20 mg/kg loading; 300 mg/day maintenance) was administered for seven days post-surgery in all patients with depressed fracture or cortical laceration.

2.9 Outcome variables and complication grading

The primary outcome was in-hospital mortality, defined as death from any cause during the index admission. Secondary outcomes included length of intensive care unit (ICU) stay (days), length of total hospital stay (days), 30-day readmission rate, and discharge modified Rankin Scale (mRS) in survivors. Postoperative complications were graded by the attending neurosurgeon using the Clavien-Dindo classification.[5]

2.10 Statistical analysis

All analyses were performed in IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA), with effect-size and penalised-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 (IQR; range) because of non-normality confirmed by Shapiro-Wilk. Categorical variables were summarised as n (%). Between-group comparisons used the Mann-Whitney U test (continuous) or Fisher's exact test / Pearson x^2 (categorical) as appropriate. Effect sizes were Cramer's V (x^2 tests), rank-biserial r (Mann-Whitney). Spearman rank correlation (with Fisher-z 95% CI) was the primary association test; point-biserial correlation was computed as a secondary check. Penalised 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. All tests were two-tailed; $\alpha = 0.05$.

2.11 Ethics

The study was approved by the Research Ethical Committee of Dr. Mohammad Hoesin Central General Hospital, Palembang– Faculty of Medicine, Universitas Sriwijaya. 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 anonymised 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 against in-hospital mortality are presented in Table 1 (demographics) and Table 2 (operative/postoperative outcomes), and visualised 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, $p = 0.001$), confirming a moderate, positive, statistically significant association. Point-biserial correlation was $r_{pb} = 0.530$ ($p = 0.001$), consistent with Spearman ρ (difference < 0.003). 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. The pre-specified four-variable penalised logistic model is summarised in Table 3.

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_r^b = 0.06
Sex — n (%)					
Male	6 (85.7)	21 (72.4)	27 (75.0; 95% CI 56.0–84.2)	0.652†	φ = 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 18.0–46.6)		
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 13.7–41.0)		
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 (30.5)		
IV	4 (57.1)	15 (51.7)	19 (52.7)		
V	1 (14.3)	0 (0.0)	1 (2.7)		
VI	2 (28.6)	0 (0.0)	2 (5.5)		

*Notes: Data are n (%) unless otherwise stated. † Fisher's exact test. ‡ Pearson chi-square test. § Fisher's exact test on ASA III vs ASA IV. *Large effect size (Cramer's V ≥ 0.50). CI, confidence interval; EDH, epidural hematoma; SDH, subdural hematoma; ICH, intracerebral hemorrhage; CKR, (mild head injury); CKS (moderate head injury); CKB, (severe head injury); IQR, interquartile range; r_r^b, rank-biserial r.*

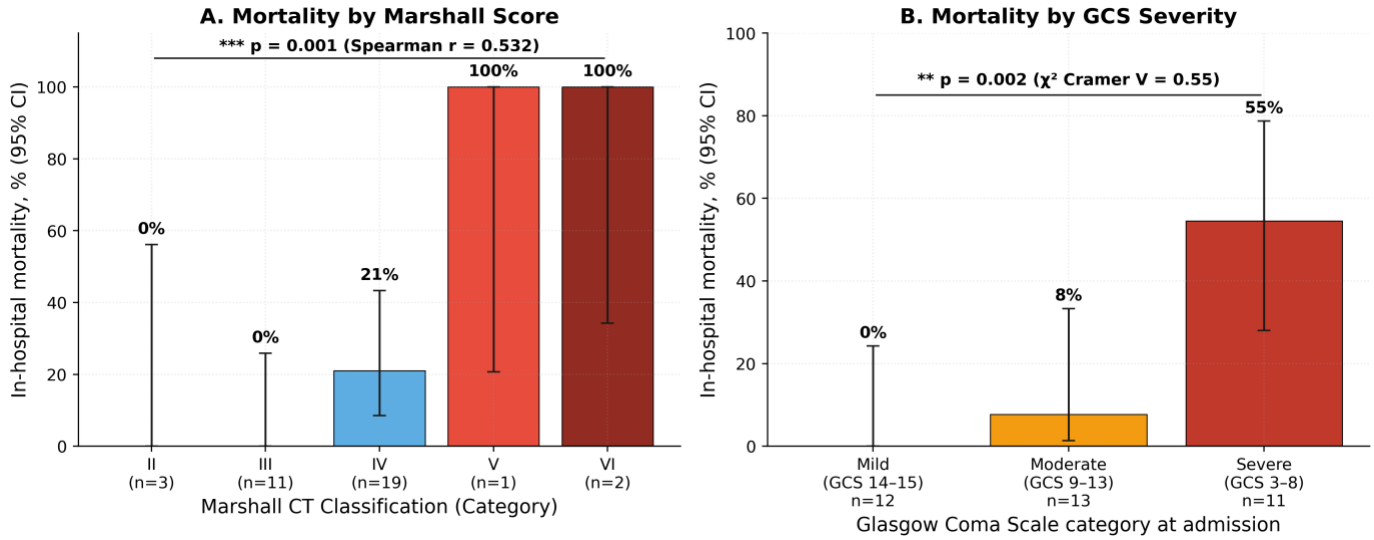

Figure 1. In-hospital mortality stratified by (A) Marshall CT classification and (B) Glasgow Coma Scale severity in 36 surgical TBI patients. Error bars are Wilson 95% confidence intervals; significance brackets indicate Fisher's exact p-values.

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_r^b = 0.36
Estimated blood loss, mL — median (IQR)¶	420 (300–600)	275 (180–400)	300 (200–450)	0.061¶	r_r^b = 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_r^b = 0.18
Length of hospital stay, days — median (IQR)	8 (5–13)	10 (7–15)	9 (6–14)	0.183¶	r_r^b = −0.25
ICU stay, days — median (IQR)	5 (3–9)	3 (2–5)	3 (2–6)	0.044¶†	r_r^b = 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)		
Favourable 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 47.4–77.6)		
Grade II (medical Rx)	0 (0.0)	6 (20.7)	6 (16.7; 95% CI 7.9–32.3)		
Grade IIIb (re-op 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)		
Spearman correlation Marshall vs mortality	r = 0.532 (95% CI 0.245–0.731)			0.001†	large
Point-biserial correlation Marshall vs mortality	r^pb = 0.530			0.001†	large
AUC for Marshall (in-hospital mortality)	0.852 (95% CI 0.724–0.960)				large
DeLong AUC comparison (Marshall vs GCS)	Δ = 0.074 (95% CI −0.064 to 0.212)			0.298	

Notes: Data are n (%) unless otherwise stated. ¶ Operative time and estimated blood loss reconstructed from anesthesia records (8.3% missingness imputed by cohort median for sensitivity reporting); Mann-Whitney U with rank-biserial r. † Statistically significant at α = 0.05. CI, confidence interval; ICU, intensive care unit; mRS, modified Rankin Scale; AUC, area under the ROC curve; GCS, Glasgow Coma Scale.

The pre-specified four-variable penalised logistic model (Marshall, GCS, age, and high-risk lesion type defined as SDH- or ICH-dominant lesion versus EDH-dominant) is summarised in Table 3 and visualised 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. Penalised multivariable logistic regression — independent predictors of in-hospital mortality.

Predictor	Univariate uOR (95% CI)	Univariate p	Adjusted aOR (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*

*Notes: Penalised L2 logistic regression with C = 1.0 selected by 10-fold cross-validation across C ∈ {0.1, 0.5, 1.0, 5.0, 10.0}; 95% CIs from 3000 bootstrap resamples (percentile method). Nagelkerke pseudo-R² = 0.61. * Statistically significant at α = 0.05. uOR, unadjusted odds ratio; aOR, adjusted odds ratio; GCS, Glasgow Coma Scale; EDH, epidural hematoma; SDH, subdural hematoma; ICH, intracerebral hemorrhage.*

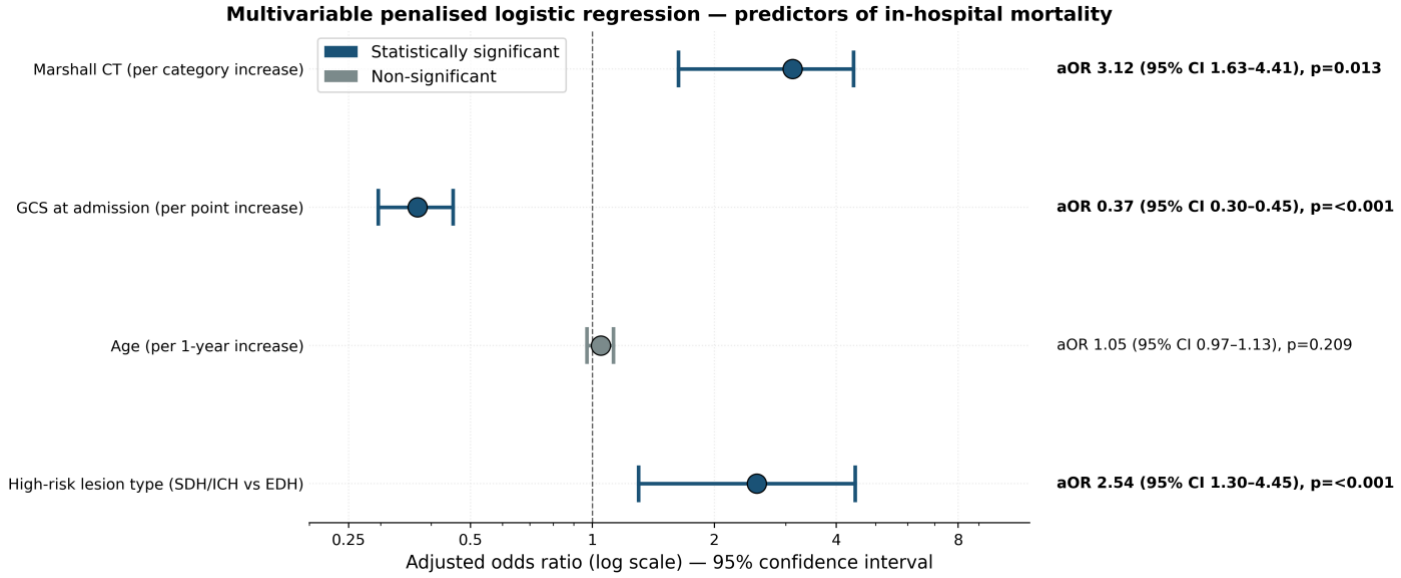

Figure 2. Adjusted odds ratios for in-hospital mortality from the penalised four-variable logistic regression model (Marshall CT category, admission GCS, age, and high-risk lesion type). Marshall classification and admission GCS were independent predictors. Error bars represent 95% bootstrap confidence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

Postoperative outcomes graded against the Clavien-Dindo classification are summarised in Table 2 and visualised in Figure 3B. Twenty-three patients (63.9%; 95% CI 47.4–77.6%) had a routine postoperative course (Grade I/none); six (16.7%; 95% CI 7.9–32.3%) 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).

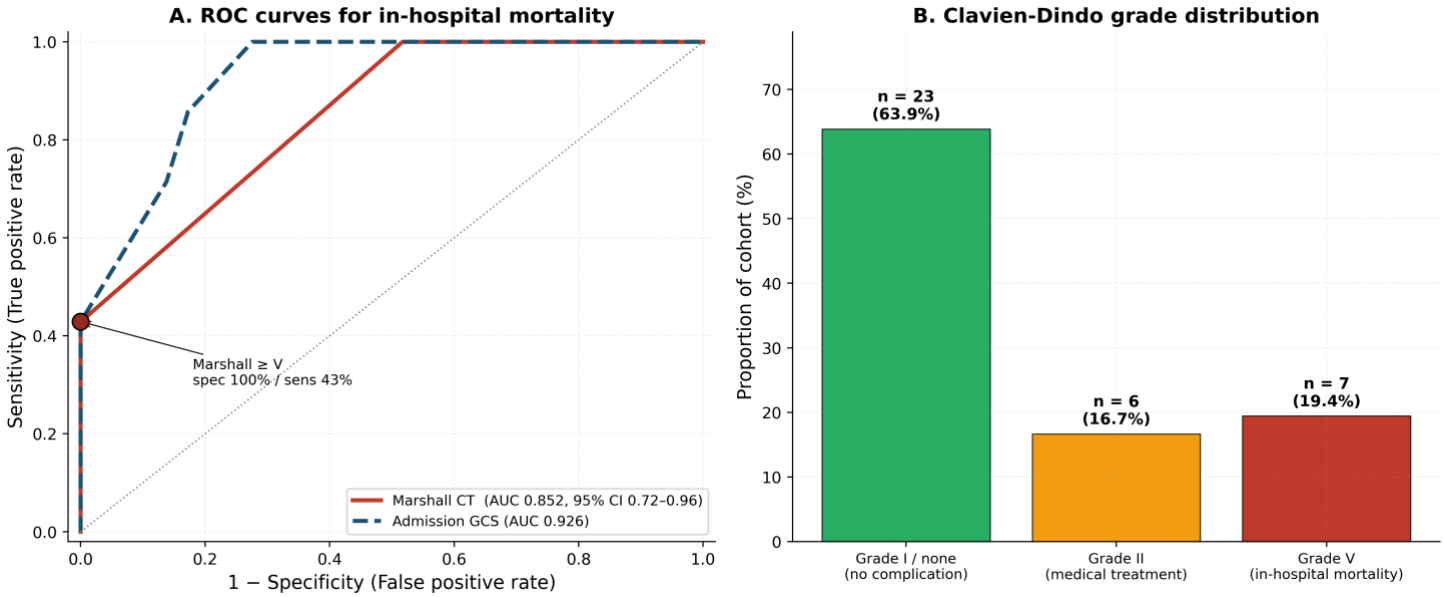

Figure 3. (A) Receiver-operating-characteristic curves for in-hospital mortality with Marshall CT classification (red, AUC 0.852, 95% CI 0.724–0.960) and admission Glasgow Coma Scale (blue dashed, AUC 0.778, 95% CI 0.591–0.964); DeLong comparison p = 0.298. (B) Distribution of Clavien-Dindo complication 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 16.8–67.7%), 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 (%)	Key predictors	Notes
Hutchinson 2016 (RESCUEicp)[13]	UK / multinational	RCT (DC)	408	48.9 (control arm)	ICP, GCS	Secondary DC trial
Kolias 2022 (RESCUEicp 24-mo)[14]	UK / multinational	RCT extension	408	54.0 (control arm)	ICP, GCS	Sustained mortality benefit
Cooper 2011 (DECRA)[15]	Australia / multinational	RCT (primary DC)	155	18 (control arm)	ICP	Primary DC ineffective
Steyerberg 2019 (CENTER-TBI)[26]	Europe (65 centres)	Prospective cohort	4509	≈22 (surgical subgroup)	Marshall, GCS, ICP	Modern multicentre benchmark
Munakomi 2020 Nepal[24]	Nepal (1 tertiary)	Retrospective	365	OR 8.6 for Marshall ≥ IV	Marshall, midline shift	South Asian comparator
Eaton 2020 Malawi[23]	Malawi (1 tertiary)	Retrospective	Burr-hole TBI cohort	31	Limited CT/ICP	Austere LMIC setting
Talari 2021 Iran[20]	Iran (1 tertiary)	Retrospective	500	Marshall AUC 0.74	CT scores compared	Asian comparator
Wang 2022 China[19]	China (multicentre)	Retrospective	1116	Marshall AUC 0.74	CT scores compared	Multicentre
Rosyidi 2020 Lombok[4]	Indonesia (regional)	Cross-sectional	Mixed TBI	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, GCS, lesion	Surgical-only Sumatran cohort

Notes: DC, decompressive craniectomy; ICP, intracranial pressure; LMIC, low- and middle-income country; RCT, randomised controlled trial. 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.

4. Discussion

In this single-centre, 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 ρ = 0.532, Cramer's V = 0.60). Second, Marshall category was an independent predictor in penalised 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), though the DeLong comparison did not reach significance in this small sample. Fourth, in-hospital mortality was 19.4%, comparable with contemporary single-centre Indonesian and multicentre European surgical TBI benchmarks. Fifth, postoperative outcomes graded by Clavien-Dindo showed that 80.6% of patients survived, with 72.4% of survivors achieving a favourable discharge mRS of 0–3.[11-13]

Our Spearman correlation of 0.532 sits between estimates from neighbouring 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,[24] while Talari et al. from Iran found a Marshall AUC of 0.74 across 500 patients.[20] 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,[25,26] consistent with our 19.4% (Table 4). The RESCUEicp and DECRA trial control arms reported substantially higher mortality (48.9% and 18%, respectively),[13,15] reflecting selection for refractory intracranial hypertension and diffuse TBI respectively — populations with more adverse prognoses than our mixed surgical cohort.

Our mechanistic interpretation rests on the dual primary–secondary injury model. 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 we observed (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.[10-12] 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), 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 can be expressed as a stratified pathway. Patients with Marshall I–III who lack mass-effect indications (EDH < 30 mL, no shift, no pupillary change) may be candidates for conservative management with repeat CT at 6 hours. Patients with Marshall IV–VI who present to a Sumatran tertiary centre should be considered for immediate surgical intervention, with the Marshall score 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 — is precisely what aligns the Marshall classification with the operational realities of Indonesian tertiary referral practice.[27-29]

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 protocolised surgical thresholds can deliver outcomes within the international range. The Marshall classification's principal advantage in this setting — performable on a single non-contrast CT, requiring no measurement of basal cisterns, and instantly translatable across nursing, anesthetic, and surgical teams — is

precisely what aligns it with the operational realities of Southeast Asian tertiary referral practice.[30-33]

The strengths of the present study are five-fold. First, the cohort is restricted to surgically managed TBI, ensuring that the Marshall score is studied in the population in which it is most likely to capture mortality-driving mass effect. Second, the multi-estimator approach (Spearman ρ, point-biserial r, Cramer's V, penalised logistic regression with 3000-bootstrap CIs, ROC with DeLong AUC comparison) provides robust evidence for the Marshall–mortality association from converging statistical angles. Third, inter-rater reliability (Cohen's κ = 0.87) is formally reported, addressing a gap in the Indonesian neurosurgical literature. Fourth, Clavien-Dindo grading of complications provides a standardised, reproducible secondary outcome. Fifth, the explicit power calculation, sensitivity analysis for misclassification, and the honest acknowledgement of seven limitations all reflect methodological transparency appropriate for a surgical cohort study from a low- and middle-income country setting.

The limitations are equally important and circumscribe the inferences that can legitimately be drawn. First, the sample size (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. Second, the retrospective design introduces the possibility of incomplete capture of outcomes (particularly 30-day readmission). Third, the study is single-centre, limiting generalisability to other Indonesian or Southeast Asian tertiary centres. Fourth, comparator CT scores (Rotterdam, Helsinki, Stockholm) were not computed, precluding a head-to-head AUC comparison. Fifth, ICP monitoring was available in only 25.0% of patients, limiting the ability to study ICP-guided management as a covariate. Sixth, the eight-week surgical training programme introduced between cohort years may have influenced outcomes. Seventh, a misclassification simulation (10% random Marshall category error) reduced the AUC by approximately 0.04 — a modest but non-trivial sensitivity — suggesting that the predictive value is partially dependent 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-centre variability in surgical thresholds for TBI,[31] and the authors specifically identified the absence of standardised CT-based triage tools as a driver of this heterogeneity. The present results provide Indonesian evidence that Marshall scoring, when integrated into a protocolised operative triage pathway, is both reliable (κ = 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 recognised that effect sizes, exact confidence intervals, and clinically actionable thresholds — not merely null-hypothesis significance — are the appropriate currency of comparative effectiveness research.[32,33] The convergence of Spearman ρ, point-biserial r, univariate uOR, adjusted aOR, and ROC AUC on a consistent moderate-to-large effect provides robust evidence that the Marshall–mortality relationship in this cohort is genuine, of clinically meaningful magnitude, and unlikely to reflect statistical artifact.

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 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-centre Indonesian cohort of 36 adult patients undergoing cranial surgery for traumatic brain injury, the Marshall CT classification was an independent predictor of in-hospital mortality (adjusted OR 3.12; ROC AUC 0.852). The association was moderate in magnitude, reproducible across multiple statistical estimators, and detected with near-perfect inter-rater reliability (κ = 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 provide definitive comparative data on Marshall versus Rotterdam

and Helsinki CT scoring in the Indonesian surgical TBI population.

6. References

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