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Research Article

Comprehensive Review of Traumatic Brain Injury Scoring Systems in Emergency Medicine: Evolution, Comparative Performance, Emerging Models, and Clinical Applications

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Abstract

Background: Evaluation of injury severity and prognosis in TBI must be fast, yet scoring systems have different purposes, predictors, outcomes, validation populations, and clinical value.

Methods: This structured narrative review compiled knowledge about well-established and novel scoring systems assessing TBI severity and prognosis. PubMed/MEDLINE, Scopus, Web of Science, and Embase databases were systematically searched from the publication of major scoring systems up until December 2025, with further citation chasing. The comparison of the systems was performed by population, clinical setting, outcome, predictive ability, reliability, validation, and limitations of each.

Results: GCS, Marshall, Rotterdam, RTS, TRISS, FOUR, and APACHE II are still clinically useful; the Helsinki and Stockholm scoring systems add to CT-based characterization of TBI. IMPACT and CRASH utilize both clinical and radiological variables for formal prognostication, GOS-E is a functional outcome measure and BIG is useful for risk stratification of mild TBI pathways. Modern AI/ML models exhibit promising discriminatory ability, yet calibration, validation, reproducibility and generalizability are their shortcomings.

Conclusion: No single tool applies to all scenarios; GCS and RTS facilitate initial assessment. While, CT-based scores add radiologic information after neurologic examination. IMPACT/CRASH are more suited to prognostic evaluation.

Keywords: TBI, Trauma, Emergency Medicine, Scoring Systems.

Introduction

TBI is one of the major causes of death, neurologic disabilities, and health care resource consumption. Data on injury severity and prognosis are useful for triage, treatment strategy development, transmission, resource allocation, and research. GCS remains the most widely used clinical measure of altered consciousness, whereas CT scales provide a standardized description of intracranial injuries[1-6].

Marshall's classification defined an early approach to classifying diffuse and focal lesions on CT[7-8]. Rotterdam added new CT prognostic predictors such as TBI subarachnoid or intraventricular bleeding and basal cisterns conditions[3,9]. Helsinki and Stockholm expanded CT characterization and compared it with other classification methods[10]. Comparative analysis showed that effectiveness depended on the endpoint and sample characteristics, not on a single superior CT scale[11-12].

Some other scoring systems serve specific purposes. RTS and TRISS assess trauma patients and predict survival, respectively; FOUR serves as an alternative to the neuro exam when GCS cannot be assessed reliably; and APACHE II describes physiological status in the ICU [13-17]. Multivariate scoring systems, including IMPACT and CRASH, incorporate clinical and radiological predictors to predict long-term prognosis. Meanwhile, BIG provides a model for a few mild-TBI

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subgroups. More advanced AI-based approaches use CT and clinical information [18-24]. In conclusion, this review presents a structured overview of TBI scoring systems. This study focuses on performance comparisons, population-specific validity, reliability, clinical context, barriers to adoption, and future research directions.

2. Methods

2.1 Review Design

In the current review, a structured narrative review approach was used to summarize the historical background, use, validation, predictive accuracy, reliability, and shortcomings of TBI scoring systems. Given the differences among these scoring systems in terms of their purposes, predicting factors, outcomes, and target population, there was no reason to combine statistical results.

2.2 Literature Search Strategy

Literature search was performed using PubMe/MEDLINE, Scopus, Web of Science, and Embase. Literature search period started from the time when the most important CT-based classifications and predictive models were created up until December 2025. The keywords that were used during literature search include: traumatic brain injury, head injury, scoring system, prognostic model, outcome prediction, Rotterdam, Helsinki, classification system, Glasgow Coma Scale, Marshall, Stockholm, TRISS, RTS, FOUR, APACHE II, IMPACT, CRASH, GOS-E, BIG, machine learning, and artificial intelligence.

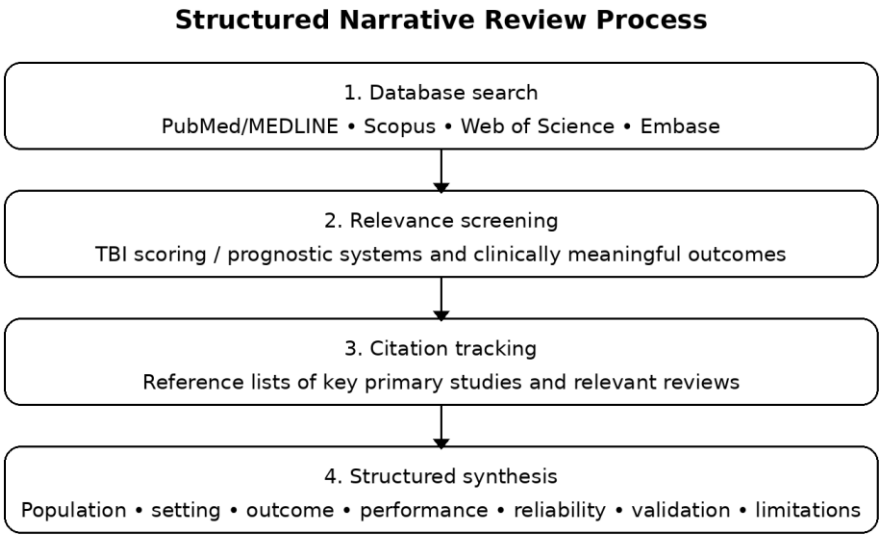


Figure 1. Schematic review process for the structured narrative review.

2.3 Review Process

The review process involved four steps: database search, article relevance selection, citation tracing of key articles, and synthesis of eligible data. Because this manuscript is a structured narrative review, not a systematic review, it reports no PRISMA selection numbers.

2.4 Eligibility Criteria

Articles were deemed relevant if they assessed any clinical, imaging, physiological, trauma, multimodal, or computational scoring or prognostic model in patients with TBI and provided relevant clinical outcomes such as mortality, neurological prognosis, functional outcome, imaging worsening, ICU admission, and need for neurosurgical procedure. Validation, comparative, cohort, prospective, and prognostic studies were included. Excluded were case series, editorial articles, or those that did not provide relevant clinical outcomes. Studies involving pediatric or special populations were included only if they provided information on population-specific validity.

2.5 Data Extraction and Comparative Framework

The following characteristics of each scoring model was taken into consideration: (1) patient population; (2) predictor variables; (3) clinical setting; (4) primary endpoint; (5) discrimination or diagnostic accuracy if available; (6) calibration/validation; (7) interobserver reliability; and (8) practical constraints. Scoring systems can be classified as bedside assessments, CT classifications, trauma scores, ICU scores, multimodal prediction models, clinical outcomes, or new computational models.

2.6 Reporting of Predictive Performance

Predictive performance measures are presented based on results from each individual validation study, not by pooling results from inherently different models. Values for AUC/c-statistics should therefore be understood within the context of the particular study population and outcome of interest. The reason is that discrimination and calibration may differ depending on case mix, age, TBI severity, time period, and healthcare setting.

3. Established TBI Scoring Systems

3.1 Glasgow Coma Scale (GCS)

The GCS assesses eye opening, verbal response, and motor response and is still the gold standard in the first neurological examination[1]. The main strengths of the GCS include speed, experience, minimal resource consumption, and wide usage worldwide. The test is especially helpful in prehospital and emergency care. GCS does not evaluate the structure of the brain directly and is hard to interpret in cases of patients being intubated, sedated, under intoxication, with aphasia, or generally unable to answer verbally. Variability between observers is an important issue too, especially when not all components of the test are fully recorded. GCS must therefore be considered a basic clinical test, not a prognostic one.

3.2 Marshall CT Classification

The Marshall Classification is an established, standardized CT-based classification of TBI[7-8]. It assesses the basal cisterns, midline shift, diffuse injury patterns, and mass lesions. Marshall Classification remains well known in clinical practice and is valuable for facilitating communication and providing the first level of anatomical stratification. The key drawbacks of Marshall Classification are its categorical nature and exclusion of certain features, such as traumatic subarachnoid and intraventricular hemorrhage [25].

3.3 Rotterdam CT Score

The Rotterdam CT score was introduced as an enhancement to prognostic stratification through the inclusion of basal cistern state, midline shift, subarachnoid/ventricular hemorrhage, trauma, and mass lesion features such as epidural [9,26-28]. It has been extensively studied in relation to the prediction of both death and poor outcomes. In a 2023 retrospective study of five CT scoring models, a large area under the ROC curve estimate was seen for in-hospital mortality, but there were no statistical differences between the scoring systems [11]. The major drawbacks include dependency on the use of CT scans, exclusion of important clinical parameters like age and GCS, and population variance.

3.4 Helsinki and Stockholm CT Scores

The Helsinki and Stockholm systems were developed to capture additional radiological characteristics that may improve prognostic discrimination beyond Marshall and Rotterdam [10]. A comparative study of 171 blunt TBI patients reported a kappa of 0.657 between Helsinki and Stockholm classifications and found Rotterdam to have the highest sensitivity for death (90.1%). In contrast, Helsinki had the highest sensitivity for six-month outcome (89.8%) [12]. These findings illustrate that apparent differences between scores depend on the selected endpoint. More recent comparative evidence should therefore be interpreted as complementary rather than as evidence that one system is universally superior.

3.5 Trauma and Injury Severity Score (TRISS)

TRISS uses the Revised Trauma Score, Injury Severity Score, age, and mechanism of injury to predict survival [13]. This system has been very instrumental in trauma-system comparisons and outcomes. However, it was designed to work on general trauma patients, not just TBI patients. The accuracy of this tool is likely affected by patients' pediatric age, injury type, the evolving nature of trauma patients, and the availability of needed anatomical and physiological data [29-34].

3.6 FOUR Score

FOUR score measures the eye, motor, brainstem reflexes, and breathing responses [14]. In intubated patients, the FOUR score is particularly useful because it does not require a verbal response. Research on the application of the FOUR score in TBI and neurocritical care populations suggests that the prognosis it provides is similar to that of the GCS [35-39].

3.7 APACHE II

APACHE II includes physiological, age, and chronic health status factors and is widely used in intensive care units [40-41]. For TBI patients, APACHE II measures physiological load, which a specific brain-function score may not capture. The drawback of APACHE II is that it is not specifically designed for TBI; thus, its predictive value may be impacted by extracranial illness or ICU admission criteria.

3.8 Revised Trauma Score (RTS)

RTS consists of GCS, systolic BP, and RR and was devised for rapid trauma triage [42-44]. The test is useful in both prehospital and emergency departments because it does not require a CT scan. However, the primary drawback of RTS in TBI is that it gives priority to mortality or physiological triage and not neurological or functional recovery.

4. Comparative Analysis of Major TBI Scoring Systems

This section is showed in Table. 1.

Table 1. Comparative Analysis of Major TBI Scoring Systems

System	Type	Main components	Primary outcomes	Typical setting	Principal limitations
GCS	Clinical	Eye, verbal, motor	Severity; mortality/outcome association	Prehospital/ED/ICU	Interobserver variability; affected by intubation/sedation; no CT information
Marshall	CT classification	Cisterns, midline shift, diffuse injury, mass lesion	Mortality/unfavorable outcome	ED/ICU	Categorical; omits some hemorrhage variables
Rotterdam	CT score	Cisterns, shift, SAH/IVH, mass lesion	Mortality/outcome	ED/ICU	Requires CT; no clinical variables
Helsinki	CT score	Detailed hemorrhage and injury characteristics	Functional outcome/mortality	ICU/research	More complex; validation less extensive than Rotterdam
Stockholm	CT score	Expanded CT biomarkers	Functional outcome/mortality	ICU/research	Interpretation complexity; variable external validation
RTS	Physiological trauma score	GCS, SBP, RR	Mortality/triage	Prehospital/ED	Not TBI-specific; limited long-term outcome prediction
TRISS	Combined trauma model	RTS, ISS, age, mechanism	Survival	Trauma systems	Requires multiple variables; general trauma model
FOUR	Neurological score	Eye, motor, brainstem, respiration	Mortality/neurological outcome	ICU	Training required
APACHE II	ICU severity score	Physiology, age, chronic health	ICU mortality	ICU	Not TBI-specific
IMPACT	Multimodal prognostic model	Age, motor GCS, pupils ± CT/lab	6-month mortality/unfavorable outcome	Research/ICU	Complex; calibration varies
CRASH	Multimodal prognostic model	Age, GCS, pupils ± CT	Mortality/disability	Research/clinical counseling	Calibration varies across populations
BIG	Risk stratification	GCS, CT, neuro exam, anticoagulation/antiplatelets	Radiological deterioration/neurosurgery	Mild TBI/ED	Primarily mild TBI; low specificity for ruling-in intervention
AI/ML models	Computational	Clinical + CT ± other data	Mortality/function	Research/advanced centers	External validation, interpretability, reproducibility

5. Comparative Predictive Performance

The reported performance cannot be taken as an overall ranking, as the predictive models have different endpoints and are being assessed on different populations. The numbers presented below are for illustration purposes only and come from individual validation studies or comparisons; they do not serve as a means for direct comparison. The AUC/c-statistic is specific to the endpoint and population, while sensitivity and specificity are specific to the threshold and outcome used.

Table 2. Comparative Predictive Performance

Model/system	Example reported performance	Outcome/population	Interpretation
Rotterdam CT	AUROC point estimates >0.90 in one 996-patient cohort	In-hospital mortality	Strong discrimination in that cohort; not universally generalizable
Helsinki CT	Sensitivity 89.8% in one comparative cohort	6-month outcome	Useful for longer-term outcome assessment in the studied population
Rotterdam CT	Sensitivity 90.1% in one comparative cohort	Death	Strong short-term mortality sensitivity in that cohort
IMPACT	c-statistics approximately 0.81–0.86 in contemporary TRACK-TBI validation	6-month mortality/unfavorable outcome	Good discrimination, but mortality was overpredicted
CRASH	c-statistics approximately 0.88–0.92 in contemporary TRACK-TBI validation	6-month mortality/unfavorable outcome	Good discrimination, with calibration limitations
AI multimodal model	AUC 0.846 internal and 0.859 external validation in CENTER-TBI/CINTER-TBI study	TBI prognosis	Promising external validation but not yet routine clinical standard
BIG	Pooled sensitivity 1.00 for neurosurgical intervention; 0.98 for radiological deterioration	Mild TBI	High sensitivity for ruling out adverse events but low specificity

6. Emerging Prognostic Models and Advanced Approaches

6.1 IMPACT Models

The IMPACT models have been created in order to predict both mortality and unfavorable outcomes in patients with moderate to severe TBI. The Core model includes age, motor GCS, and pupillary reactivity. The Extended and Lab models include additional CT and laboratory predictors. The IMPACT models have been validated and are especially valuable in case of risk-adjustment, outcome prediction, and comparative analysis [18].

According to a recent TRACK-TBI validation in 2024, discrimination of the IMPACT model was satisfactory, as the c-statistics for mortality were approximately equal to 0.84, while those for unfavorable outcomes were equal to 0.83. Mortality in IMPACT was overestimated, and there were some differences based on the patient's age and TBI severity, which is why recalibration is necessary in the current population. Thus, IMPACT can be considered a formal prognostic model.

6.2 CRASH Models

The CRASH models were derived from the Corticosteroid Randomization After Significant Head Injury Trial and estimate the risk of mortality and poor outcomes using clinical parameters, including CT models that incorporate imaging data. The combination of IMPACT and CRASH models highlights the value of combining demographic, neurological, pupillary, and imaging features rather than using a single bedside or CT model [18-19]. Additionally, CRASH models showed good discrimination in a recent TRACK-TBI dataset, but calibration varied across outcome groups and patient subgroups [18]. A different validation in 2024 found that CRASH models also had good discrimination for different adverse outcome and mortality endpoints [19]. Thus, the CRASH models can be applied to predict outcomes quantitatively.

6.3 Combined Multimodal Prognostic Models: IMPACT and CRASH

IMPACT and CRASH should be considered complementary multimodal prognostic models rather than bedside scores. Both estimate mortality and neurologic outcomes by combining demographic and neurologic information, and sometimes imaging information too. The main role of these scoring systems is to calculate risk for adjustment, research, and

counseling reasons. Recent work showed that model transportation affects calibration; therefore, local/population-specific calibration is needed before clinical implementation [18-19].

6.4 Glasgow Outcome Scale-Extended (GOS-E)

The GOS-E is an eight-point scale that indicates functional outcome, ranging from death to good recovery. This scale does not predict the initial severity of the condition. Rather, it is an outcome measure tool that helps assess the level of recovery following TBI. GOS-E has been widely used in current TBI studies, and the 2024 Australian TBI Initiative included GOS-E among its core outcome measures for moderate-to-severe TBI [5,20].

6.5 Brain Injury Guidelines (BIG) Score

The Brain Injury Guidelines (BIG) system was devised to categorize selected patients with mild TBI and help guide decisions about observation, repeat imaging, intensive care unit admission, and neurosurgery consultation. A systematic review and meta-analysis of 13 trials involving 9,032 patients conducted in 2024 showed a pooled sensitivity of 1.00 for neurosurgical intervention and 0.98 for radiological deterioration in BIG, but specificity remained poor. This suggests that BIG may help identify patients who do not need intervention, but its utility in selecting patients who do seems limited [21]. Therefore, it should be used within an institutional clinical pathway rather than on its own.

6.6 Artificial Intelligence and Machine-Learning Models

AI-driven models are increasingly incorporating clinical and imaging data, along with other high-dimensional datasets. The 2024 model, which used both clinical data and CT imaging and underwent external validation via CENTER-TBI and CINTER-TBI, achieved an AUC of 0.846 in development and 0.859 in external validation, surpassing the performance of other models that used clinical and conventional CT scoring [22]. A 2025 systematic review of 39 AI-based predictive studies, including 592,323 patients with moderate to severe TBI, uncovered serious limitations in methodology, robustness, and reproducibility, with few studies performing independent external validation [23].

In 2025, a combination of a CT quantitative edema grading scale and machine learning achieved a test-set AUC of 0.944 in 216 patients. Given that this is a retrospective single-study development/validation, this result should be viewed as encouraging but preliminary and should be validated externally [24]. AI is therefore a vital research area; however, technical discrimination is not enough for clinical implementation. Calibration, explainability, dataset shift, fairness, workflow integration, and external multicenter validation are necessary.

7. Special Populations

7.1 Pediatric TBI

Prognostic models derived from adults cannot be applied directly to children because physiological differences, injury mechanisms, developmental status, and outcomes differ. For this reason, age-specific outcome measures and validation groups are required. The 2024 AUS-TBI guidelines include age-specific outcome measures such as GOS-E Peds [20].

7.2 Older Adults

Aging affects both the inherent risk of an event and the model's ability to fit. Recent work shows that model performance depends on patient age of 65 years or more[15]. Hence, age-based validation and recalibration are required. Other factors that influence anticoagulant or antiplatelet therapy, such as comorbidity and pre-injury function, may also play a role.

7.3 Penetrating TBI

Penetrating brain injuries are different from blunt brain injuries and might not be properly reflected in scores that were developed based on data from patients sustaining blunt injuries. TRISS may have limitations given the specific injury mechanism, whereas CT-based scores do not account for the injury's path.

7.4 Intubated or Sedated Patients

When the verbal GCS cannot be scored reliably, the FOUR Score serves as an alternative method for assessing neurological function based on brainstem reflexes and respiration. This becomes particularly applicable in ICU settings.

8. Interobserver Reliability and Reproducibility

Reliability in TBI score assessment remains poorly studied. CT categories rely on identifying features such

as cistern compression, midline shift, hemorrhage, and mass effect. Agreement among the Helsinki, Rotterdam, and Stockholm scores was 0.657 between Helsinki and Stockholm, 0.594 between Rotterdam and Stockholm, and 0.407 between Helsinki and Rotterdam for outcome classification [12].

Improvement can be achieved through standards, structured CT reports, education, centralization of evaluations, and decision support systems. These issues are crucial for telemedicine and developing nations. In particular, this applies when there is remote interpretation of images and specialists are inaccessible. Consequently, future research should consider the evaluation of reliability along with discrimination and calibration.

9. Clinical Implementation Barriers

9.1 CT Availability

CT-dependent scores cannot be calculated when imaging is unavailable or substantially delayed. GCS and RTS therefore remain important for early triage in resource-limited environments.

9.2 Electronic Health Record Integration

Automated calculations may lower the risk of arithmetic errors. Including e-health records may allow clinical factors, CT scan reports, and laboratory values to be used in prognostic models without manual re-entry.

9.3 Clinician Training and Adoption

A perfectly validated risk score may still hold little practical value if physicians fail to comprehend its target population, endpoint, and limitations. The training must impress upon physicians that the risk score is supposed to complement rather than replace their clinical judgment.

9.4 Cost-Effectiveness and Resource Allocation

The score's use should consider whether its application produces enough change in clinical practice to be worthwhile. Although BIG might affect resource utilization in some mild TBI treatment pathways, a more complicated multimodal model may suit research purposes now.

10. Future Research Priorities

Future research needs to focus on: (1) prospective multicenter external validation; (2) calibration updates for modern patient cohorts; (3) validation in children, elderly patients, and penetrating TBI; (4) clear interobserver agreement reports; (5) combination with quantitative imaging and biomarkers along with conventional clinical risk factors; (6) transparent AI algorithms with reproducible validation process; and (7) prospective assessment of the clinical value, workflow implications, and cost-effectiveness of AI systems. Regarding the latter, the 2025 systematic review emphasizes the need for better methodology, robustness, and reproducibility [23].

11. Conclusion

TBI scoring systems have progressed from simple bedside scoring to complex CT-based classification and multimodal prediction tools. Based on the findings discussed in this paper, no scoring system is clearly the best choice for all scenarios. GCS and RTS remain relevant and useful tools for quick evaluation before CT is available. Marshall, Rotterdam, Helsinki, and Stockholm are effective complementary classification methods based on anatomical risk stratification after CT. The Glasgow Coma Scale is especially helpful when verbal testing is impossible. APACHE II provides valuable information about the systemic physiology of TBI patients in the ICU setting.

IMPACT and CRASH reliably predict mortality and unfavorable long-term outcomes, although recent validation shows calibration can differ by patient age, injury severity, and treatment setting[15]. GOS-E should be considered a standard outcome measure rather than a severity scale. BIG appears to be useful for selected pathways of mild TBI patients but works better for excluding adverse outcomes than predicting the need for medical interventions [21]. Artificial intelligence models show great promise, especially models using both clinical data and CT images, although they still require further external validation, reproducibility, calibration, and prospective clinical-utility studies [22-24].

Therefore, the best way forward for emergency physicians is a complementary use of the scores in accordance with their intended purpose: initial scoring in the absence of any imaging, stratifying the patients on the basis of computed tomography in the presence of imaging, and the use of multimodal models for calculating long-term prognosis. Future research must aim towards external validation, clinical interpretability, and integration of models with the accessibility of current scoring systems.

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Conflict of Interest Disclosures

All authors were involved in manuscript preparation, review, and editing. The authors declare no financial or non-financial conflicts of interest.

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Authors' Contributions

All authors read and approved the final manuscript. All authors take responsibility for the integrity of the data and the accuracy of the data analysis.

Ethical Statement

This study was approved by the Ethics Committee of Baqiyatallah University of Medical Sciences and the issuance of the Code of Ethics (IR.BMSU.BAQ.RE.1403.046).

Declaration of Generative AI and AI-assisted technologies

None.

Data Availability

No new primary data were generated or analyzed. The review is based on previously published literature and cited sources.

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