

Beyond Detection: Prognostic Significance of Early Computed Tomography Findings in More Than 11,000 Patients with Traumatic Brain Injury

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Abstract

Background

Computed tomography (CT) is central to acute traumatic brain injury (TBI) assessment but is often limited to diagnostic rather than prognostic use. High-volume emergency settings require early, objective imaging markers to support disposition decisions.

Methods

We conducted a retrospective cohort study of 11,767 TBI patients who underwent early CT at index presentation. Demographics, injury mechanisms, CT findings, and outcomes were analyzed. The primary outcome was admission or treatment. Chi-square tests, logistic regression, interaction analyses for sex-age and sex-skull fracture, and ROC analysis were performed.

Results

Among the 11,767 patients, 2,219 (18.9%) required admission or treatment, while 9,548 (81.1%) were discharged without intervention. Patients who required admission presented a greater burden of CT abnormalities, including skull fractures, mass effects, and intracranial injury. According to the multivariate analysis, midline shift was the strongest predictor (aOR 12.43), followed by cerebral contusion (10.94), cerebral edema (8.91), and pneumocephalus (6.44). Skull fracture remained independently associated with admission in males (OR 2.81) and females (OR 4.61), with a significant sex interaction. The predicted probability increased from 18.8% to 37.4% in males and 15.6% to 42.5% in females. The age-by-sex interaction was not significant. Model discrimination was modest (AUC 0.6902).

Conclusions

Early CT findings were strongly associated with short-term clinical outcomes in TBI patients. Midline shift, cerebral contusion, cerebral edema, pneumocephalus, and skull fracture were key predictors of admission or treatment. The sex-specific effect of skull fracture suggests improved risk stratification and supports the integration of CT-based parameters into structured triage systems for acute TBI care.

Introduction

If early cranial computed tomography (CT) identifies a traumatic abnormality in only approximately one of every nine patients, but death occurs in fewer than one of every one hundred patients, which early CT findings actually carry prognostic weight rather than merely diagnostic visibility?

This question captures a central difficulty in traumatic brain injury (TBI) research and acute neurotrauma care: the first CT scan is often treated as a binary diagnostic gate, yet the biological meaning of a CT-positive study varies enormously(1–3). A simple example illustrates the problem. Two patients may both be classified as having an “abnormal” early CT after head trauma. One patient may have an isolated nasal bone fracture or scalp hematoma and leave the emergency department after observation; the other may have subdural hemorrhage, traumatic subarachnoid hemorrhage, cerebral edema, midline shift, or early herniation physiology and deterioration despite apparently similar initial triage urgency(4–6). In both cases, CT “detects” injury. The pattern of findings begin to encode prognosis only in the second case. The clinical challenge is therefore not simply whether CT detects trauma but also whether early CT phenotypes can separate low-risk radiological abnormalities from imaging signatures of secondary brain injury, neurological decline, hospitalization, referral, or death(4, 6, 7).

TBI remains among the largest contributors to trauma-related death and disability worldwide(2, 8, 9). Contemporary epidemiological estimates suggest that tens of millions of individuals experience TBI annually, with global estimates ranging from approximately 27 million incident cases in Global Burden of Disease analyses to nearly 69 million cases per year in broader incidence models(2, 8, 10, 11). The burden is particularly relevant in settings where road-traffic injury, delayed presentation, limited neurosurgical access, and heterogeneous emergency observation pathways shape outcomes(2, 8, 12). Although most acute head injuries are clinically mild, TBI consumes disproportionate imaging, emergency, neurosurgical, and rehabilitation resources because a small fraction of patients account for a large share of deaths, urgent interventions, and long-term disability(4, 8). This imbalance makes early risk stratification a systems-level problem: even modest improvements in prognostic discrimination can influence observation policies, transfer decisions, neurosurgical consultation, repeat imaging, and allocation of monitored beds(2, 4).

Noncontrast head CT remains the dominant first-line imaging modality in acute TBI because it is fast, widely available, compatible with unstable patients, and sensitive to clinically actionable hemorrhages, mass effects, skull fractures, and intracranial air(1, 5, 10). However, the same practical advantages that make CT indispensable in emergency care can also reduce its prognostic use to simplified reporting categories. Traditional CT-based prognostic systems, including the Marshall classification and Rotterdam CT score, were developed to translate early imaging abnormalities into structured estimates of outcome risk(6). These systems emphasize pathophysiologically meaningful features such as basal cistern compression, midline shift, epidural mass lesions, traumatic subarachnoid or intraventricular hemorrhage, and mass effects(5, 13). Later, models, including the Helsinki and Stockholm approaches, further highlighted the importance of lesion type, lesion burden, intraventricular hemorrhage, and coronary status(9, 14). Despite these advances, many real-world CT reports contain granular descriptors that are not fully captured by conventional scoring systems, including scalp hematoma, pneumocephalus, facial and calvarial fracture locations, contusions, edema, foreign bodies, encephalomalacia, and mixed hemorrhagic patterns(4, 7, 13, 14).

The prognostic value of individual CT findings is biologically plausible but clinically uneven. A midline shift reflects an asymmetric mass effect and intracranial compartment displacement; cerebral edema and cisternal effacement suggest impaired intracranial compliance(6, 15); traumatic subarachnoid and intraventricular hemorrhage may indicate diffuse injury severity and blood distribution into CSF spaces(6, 13, 16, 17); subdural hemorrhage often reflects higher-energy acceleration–deceleration injury and bridging vein disruption; and epidural hemorrhage may be surgically urgent yet prognostically distinct because timely evacuation can be associated with favorable recovery(6, 16, 18). Conversely, an isolated extracranial hematoma or limited facial fracture may increase the probability of imaging abnormalities without necessarily increasing the probability of death(4, 6, 16, 17). This heterogeneity means that CT findings should not be evaluated only as detection endpoints. They should be tested as prognostic variables, both individually and as structured combinations, against clinically meaningful outcomes(4, 6, 7).

Large-scale real-world datasets are especially valuable for this purpose. Many prior CT prognostication studies have been performed in selected cohorts of moderate-to-severe TBI patients, intensive-care patients, neurosurgical populations, or trial datasets. These designs improve internal consistency but may underrepresent the broader emergency population in which most CT decisions occur(11, 15). In contrast, a large emergency CT cohort can reveal the full base-rate problem: rare high-risk events embedded within a much larger population of patients with negative scans, minor findings, or short observation stays(6, 15–17). In the present cohort of 11,772 patients who underwent early CT evaluation after traumatic brain injury, 8,081 patients were male and 3,686 were female, with a median age of 32 years. Preliminary data revealed that 1,333 patients had at least one traumatic CT finding, while death was recorded in 102 patients. The most frequent coded CT abnormalities were scalp hematoma, nasal fracture, traumatic subarachnoid hemorrhage, contusion, subdural hemorrhage, epidural hemorrhage, pneumocephalus, midline shift, cerebral edema, and intraventricular hemorrhage. These distributions create a statistically demanding but clinically important setting: the model must distinguish common low-risk abnormalities from uncommon high-risk radiological phenotypes(4, 6, 7, 15).

This study was therefore designed to move beyond the binary distinction between normal and abnormal CT findings and to evaluate the prognostic significance of individual early CT abnormalities in a large real-world cohort of patients with traumatic brain injury. Specifically, we aimed to identify which radiological features were independently associated with the need for admission or treatment and to determine whether the prognostic implications of CT findings differed across clinically relevant patient subgroups. By examining more than 11,000 patients, this study seeks to bridge the gap between descriptive radiological reporting and clinically meaningful risk stratification, thereby supporting more individualized decision-making in acute TBI care.

Materials and Methods

Study Design and Setting

This study was designed as a retrospective observational prognostic cohort study evaluating the clinical significance of early computed tomography (CT) findings among patients presenting with traumatic brain injury (TBI). The study was conducted at Trauma Center / Imam Khomeini Hospital, a high-volume emergency and trauma referral center in Urmia, Iran. Consecutive trauma-related emergency department visits were reviewed over a 12-month period, from March 20, 2024, to March 20, 2025, corresponding to 1403/01/01 to 1403/12/30 in the Persian calendar.

The primary objective was to determine whether early noncontrast cranial CT abnormalities are associated with clinically meaningful outcomes, including hospital admission status, duration of emergency department observation, discharge disposition, and in-hospital mortality. The study was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology recommendations for cohort studies and was structured to support reproducible prognostic modeling.

Data Sources and Cohort Assembly

Data were obtained from two linked institutional sources: the emergency department trauma registry and the radiology information system. The emergency dataset included demographic variables, mechanism of injury, admission type, emergency department arrival and exit times, discharge time, disposition, and clinical outcome. The radiology dataset included free-text radiology reports for CT examinations, including noncontrast spiral brain CT reports and, when applicable, accompanying extracranial CT descriptions.

The source dataset contained 11,772 patient-level emergency encounters in the curated analytic sheet. Five records had missing values across core coded variables and were excluded from complete-case prognostic analyses, leaving 11,767 patients in the final analytic cohort. The second radiology-report source sheet contained 22,650 CT report records, which were used for verification and extraction of imaging features where linkages were available.

Eligible records included patients who presented after trauma and underwent early CT evaluation during the index emergency encounter. Patients were included regardless of age, sex, mechanism of injury, or initial disposition, provided that the emergency records contained sufficient coded information for outcome classification. Records with missing sex, age category, mechanism of injury, admission status, outcome, or observation time data were excluded from complete-case modeling. Repeat imaging reports without corresponding eligible emergency encounters were not analyzed as independent patient observations.

Exposure Definition: Early CT Findings

The main exposures were predefined early CT findings recorded as binary variables. Imaging variables were extracted from radiology reports and coded as present or absent. The following intracranial hemorrhagic findings were evaluated: subdural hematoma, epidural hematoma, intraparenchymal

hemorrhage, subarachnoid hemorrhage, intraventricular hemorrhage, and scalp or extracranial hematoma. Additional traumatic and structural findings included contusion, cerebral edema, midline shift, herniation, pneumocephalus, encephalomalacia, foreign body, and skull or facial fractures.

Fracture-related variables included nasal, parietal, frontal, temporal, sphenoid, occipital, maxillary, orbital, zygomatic, and ethmoid fractures. Incidental or chronic findings, including retention cysts and arachnoid cysts, were retained as covariates but were not considered primary traumatic CT predictors unless otherwise specified in sensitivity analyses.

Each CT finding was coded as 1 when it was explicitly reported as present and 0 when it was absent or not described as present. The analytic dataset included the following early CT abnormalities: SDH, EDH, IPH, SAH, hematoma, nasal fracture, parietal fracture, frontal fracture, temporal fracture, sphenoid fracture, occipital fracture, maxillary fracture, orbital fracture, zygomatic fracture, ethmoid fracture, retention cyst, arachnoid cyst, foreign body, herniation, midline shift, encephalomalacia, contusion, edema, pneumocephalus, and IVH.

For descriptive purposes, an “any acute CT abnormality” composite variable was defined as the presence of at least one acute traumatic intracranial, craniofacial, or skull-related CT finding. Chronic or incidental variables were analyzed separately to avoid inflating the apparent burden of acute traumatic pathology.

Covariates

The baseline covariates included age, sex, mechanism of injury, and admission category. Sex was coded as male or female. In the analytic cohort, 8,081 patients were male, representing 68.7%, and 3,686 were female, representing 31.3%.

Age was available both as a continuous raw variable and as a coded categorical variable. The raw age distribution had a median of 32 years, an interquartile range of 19–47 years, a mean of 34.4 years, a standard deviation of 20.3 years, and a range of 1–125 years. For regression modeling, age was analyzed primarily as a continuous variable via restricted cubic splines if the linearity assumption was not satisfied. Categorical age groups were retained for descriptive reporting and sensitivity analyses.

The mechanism of injury was coded into eight mutually exclusive categories on the basis of emergency documentation. These included driver-related motor vehicle trauma, passenger-related motor vehicle trauma, pedestrian injury, motorcycle or bicycle-related injury, assault, falls, blunt-object impact, and other/unspecified trauma mechanisms. Falls represented the largest mechanism group, accounting for 2,921 patients, or 24.8% of the analytic cohort, followed by passenger-related traffic injuries in 2,413 patients, or 20.5%.

The admission type was coded as emergency department observation or inpatient admission. In the analytic cohort, 9,994 patients, or 84.9%, were managed under observation, whereas 1,773 patients, or 15.1%, were admitted as inpatients.

Outcomes

The primary outcome was clinically adverse disposition, defined a priori as death, inpatient admission, referral/transfer, or prolonged emergency observation depending on the specific model. Because disposition outcomes can represent different levels of clinical severity, several complementary outcome definitions were used.

The first outcome was inpatient admission, which compared patients admitted to the hospital with those managed under emergency department observation. The second outcome was the final emergency department or hospital outcome, which was coded as discharge, discharge against medical advice, death, referral, or elopement. In the analytic cohort, 9,556 patients, or 81.2%, were discharged; 1,840, or 15.6%, were left against medical advice; 102, or 0.9%, died; 14, or 0.1%, were referred; and 255, or 2.2%, were elevated.

The third outcome was observation duration, recorded as a coded time variable ranging from 1 to 24. The median observation-time code was 6, and the mean was 5.76. For the main analysis, observation duration was analyzed as an ordinal or continuous operational severity marker, depending on model assumptions. A prolonged-observation endpoint was additionally defined using clinically meaningful thresholds, including an observation duration greater than the cohort median.

Mortality was analyzed as a separate high-specificity endpoint because its low frequency requires a more conservative modeling strategy. For mortality models, predictor selection was restricted to clinically plausible CT features and prespecified covariates to avoid unstable estimates.

Data Cleaning and Quality Control

Data cleaning was performed before statistical analysis. Duplicate or nonpatient header rows were removed. The coded variables were checked against their corresponding Persian-language source fields to verify consistency. Sex codes were cross-checked against the original sex field; admission codes were cross-checked against the admission-type field; and outcome codes were cross-checked against disposition text. Five records with missing values for the core coded variables were excluded from the complete-case analyses.

Radiology reports were reviewed for standard terminology and mapped into binary CT features. The synonymous descriptions were harmonized before coding. For example, hemorrhagic lesions, skull fractures, facial fractures, midline shift, cerebral edema, contusion, herniation, pneumocephalus, and intraventricular extension were treated as separate CT domains. Ambiguous radiology statements were not coded as positive unless the abnormality was explicitly stated. Negative or normal CT descriptions were coded as the absence of the corresponding finding.

A data dictionary was generated before modeling to preserve coding consistency. All predictor definitions were finalized before outcome modeling to reduce analytic drift. Internal frequency checks

were performed for each binary imaging variable, and implausible values outside the expected binary range were queried and corrected where possible.

Statistical Analysis

Descriptive statistics were used to summarize patient characteristics, injury mechanisms, clinical disposition, observation time, and radiological findings. Categorical variables are presented as frequencies and percentages and were compared via Pearson's chi-square test.

To identify factors associated with the need for admission or treatment, univariable logistic regression analyses were initially performed. Variables demonstrating potential associations with the outcome, together with clinically relevant covariates, were subsequently entered into a multivariable logistic regression model. A backward elimination procedure based on likelihood-ratio testing was applied to obtain the final parsimonious model. Adjusted odds ratios and corresponding 95% confidence intervals are reported.

Potential interaction effects between sex and age group, as well as between sex and skull fracture status, were evaluated by including multiplicative interaction terms in the multivariable model. Adjusted predictive margins and marginal effects were estimated and graphically displayed to facilitate interpretation of significant interaction effects.

Model discrimination was assessed via receiver operating characteristic curve analysis, and the area under the receiver operating characteristic curve (AUC) was calculated to quantify the model's ability to distinguish between patients who required admission or treatment and those who did not. Statistical significance was defined as a two-sided p-value less than 0.05. All analyses were performed via Stata version 18 (StataCorp, College Station, TX, USA).

Handling of Missing Data

Missingness was quantified for all candidate predictors and outcomes. Because missingness in core coded variables was minimal, affecting 5 of 11,772 records, the primary analysis used complete-case analysis. For variables with greater missing values, if identified during the final data audit, multiple imputation by chained equations would be considered under a missing-at-random assumption. The imputation models included all the variables used in the analytic model, the outcome indicators, and the auxiliary variables associated with missing data. Sensitivity analyses compare complete-case and imputed estimates.

Sensitivity Analyses

Several sensitivity analyses were planned. First, the models were repeated after excluding chronic or incidental CT findings such as retention cysts, arachnoid cysts, and encephalomalacia from the acute imaging predictor set. Second, hemorrhagic CT abnormalities were combined into a single intracranial

hemorrhage composite, including SDH, EDH, IPH, SAH, and IVH. Third, skull and facial fractures were analyzed as grouped fracture-domain variables to reduce sparsity and improve clinical interpretability. Fourth, mortality models were repeated using only high-risk CT findings, including midline shift, herniation, cerebral edema, intraventricular hemorrhage, intraparenchymal hemorrhage, and traumatic hemorrhage composites. Fifth, the models were stratified by the mechanism of injury to determine whether the prognostic value of CT findings differed across road-traffic trauma, falls, assault, and other injury mechanisms.

Subgroup Analyses

Prespecified subgroup analyses were performed by age group, sex, mechanism of injury, and admission category. Age-stratified analyses were used to examine whether CT findings have different prognostic implications among pediatric, adult, and older adult patients. Mechanism-specific analyses were performed for traffic-related trauma, falls, assault, and blunt-object injury. Interaction terms between major CT findings and age or mechanism of injury were tested where clinically justified.

Ethical Considerations

The study protocol was reviewed and approved by the ethics committee of Urmia University of Medical Sciences under approval number IR.UMSU.HIMAM.REC.1403.132. Because of the retrospective design, use of routinely collected clinical data, and deidentification of patient-level records before analysis, the requirement for written informed consent was waived by the ethics committee. All analyses were conducted in accordance with the Declaration of Helsinki and applicable local data-protection regulations.

Results

Study Population and Clinical Outcome

A total of 11,767 patients with traumatic brain injury who underwent early computed tomography were included in the analysis. Overall, 2,219 patients (18.9%) required admission or treatment, whereas 9,548 patients (81.1%) were discharged without further intervention. Most patients were male (68.7%), and the predominant age group was 19–64 years (67.8%), followed by patients aged 2–18 years (22.3%) and those aged 65 years or older (9.4%). Falls were the most common mechanism of injury overall (24.8%), followed by passenger-related traffic accidents (20.5%), assault-related injuries (15.2%), and driver-related traffic accidents (13.7%) (Table 1).

Table 1

Baseline demographic, injury-related, and computed tomography characteristics according to need for admission or treatment.

	Needs Admission or Treatment (Secondary Outcome)			
	No	Yes	Total	Test
Population	9,548 (81.1%)	2,219 (18.9%)	11,767 (100.0%)	
Patient Sex				
Male	6,483 (67.9%)	1,598 (72.0%)	8,081 (68.7%)	< 0.001
Female	3,065 (32.1%)	621 (28.0%)	3,686 (31.3%)	
Age Group				
< 1 year	41 (0.4%)	12 (0.5%)	53 (0.5%)	< 0.001
2–18 years	2,238 (23.4%)	391 (17.6%)	2,629 (22.3%)	
19–64 years	6,509 (68.2%)	1,474 (66.4%)	7,983 (67.8%)	
65 + years	760 (8.0%)	342 (15.4%)	1,102 (9.4%)	
Mechanism of Injury				
Accident (Driver)	1,322 (13.8%)	288 (13.0%)	1,610 (13.7%)	< 0.001
Accident (Passenger)	2,036 (21.3%)	377 (17.0%)	2,413 (20.5%)	
Accident (Pedestrian)	719 (7.5%)	285 (12.8%)	1,004 (8.5%)	
Accident (Motorcycle/Bicycle)	483 (5.1%)	212 (9.6%)	695 (5.9%)	
Conflict/Assault	1,610 (16.9%)	182 (8.2%)	1,792 (15.2%)	
Fall	2,275 (23.8%)	646 (29.1%)	2,921 (24.8%)	
Struck by heavy object	532 (5.6%)	41 (1.8%)	573 (4.9%)	
Other	571 (6.0%)	188 (8.5%)	759 (6.5%)	
SDH				
No	9,548 (100.0%)	2,115 (95.3%)	11,663 (99.1%)	< 0.001
Yes	0 (0.0%)	104 (4.7%)	104 (0.9%)	
EDH				
No	9,548 (100.0%)	2,137 (96.3%)	11,685 (99.3%)	< 0.001
Yes	0 (0.0%)	82 (3.7%)	82 (0.7%)	
IPH				

	Needs Admission or Treatment (Secondary Outcome)			
	No	Yes	Total	Test
No	9,548 (100.0%)	2,203 (99.3%)	11,751 (99.9%)	< 0.001
Yes	0 (0.0%)	16 (0.7%)	16 (0.1%)	
SAH				
No	9,548 (100.0%)	2,113 (95.2%)	11,661 (99.1%)	< 0.001
Yes	0 (0.0%)	106 (4.8%)	106 (0.9%)	
Contusion				
No	9,535 (99.9%)	2,123 (95.7%)	11,658 (99.1%)	< 0.001
Yes	13 (0.1%)	96 (4.3%)	109 (0.9%)	
Edema				
No	9,537 (99.9%)	2,157 (97.2%)	11,694 (99.4%)	< 0.001
Yes	11 (0.1%)	62 (2.8%)	73 (0.6%)	
Skull Fracture				
No	9,201 (96.4%)	1,903 (85.8%)	11,104 (94.4%)	< 0.001
Yes	347 (3.6%)	316 (14.2%)	663 (5.6%)	
Mass Effect				
No	9,495 (99.4%)	2,126 (95.8%)	11,621 (98.8%)	< 0.001
Yes	53 (0.6%)	93 (4.2%)	146 (1.2%)	
Pneumocephalus				
No	9,533 (99.8%)	2,155 (97.1%)	11,688 (99.3%)	< 0.001
Yes	15 (0.2%)	64 (2.9%)	79 (0.7%)	
Midline Shift	0.001 (0.029)	0.032 (0.176)	0.007 (0.082)	

Patients who required admission or treatment differed significantly from those discharged without further intervention with respect to demographic characteristics, injury mechanism, and early CT findings. The admission/treatment group included a greater proportion of males than the discharge group did (72.0% vs. 67.9%; $p < 0.001$). Older adults were also overrepresented among patients requiring admission or treatment; individuals aged 65 years or older accounted for 15.4% of the admission/treatment group compared with 8.0% of those discharged without further intervention ($p < 0.001$).

Injury Mechanisms Associated with Admission or Treatment

The distribution of injury mechanisms differed significantly between the outcome groups ($p < 0.001$). Falls were the most common mechanism among patients requiring admission or treatment, accounting for 29.1% of the cases. Pedestrian-related traffic injuries and motorcycle/bicycle accidents represented 12.8% and 9.6% of the admissions/treatment cases, respectively. In contrast, assault-related injuries were less common among patients requiring admission or treatment than among those discharged without further intervention (8.2% vs. 16.9%), suggesting that mechanism-specific risk varied substantially across injury contexts.

Early CT Findings According to Clinical Outcome

Radiological abnormalities were consistently more common among patients who required admission or treatment. Skull fractures were identified in 14.2% of patients in the admission/treatment group compared with 3.6% of patients discharged without further intervention. Signs of mass effect or herniation were also more common among patients requiring admission or treatment than among those discharged without further management (4.2% vs. 0.6%). Across the evaluated CT findings, abnormal radiological findings were significantly more prevalent among patients requiring admission or treatment, supporting the prognostic relevance of early CT beyond diagnostic detection alone.

Sex-Based Differences in Mechanism and Radiological Presentation

Substantial sex-related differences were observed in both the injury mechanism and CT findings (Table 2). Male patients were more frequently injured in driver-related traffic accidents (17.2% vs. 5.9%), motorcycle or bicycle crashes (8.3% vs. 0.8%), and assault-related events (18.1% vs. 9.0%). In contrast, female patients were more commonly injured as passengers in traffic accidents (34.4% vs. 14.2%) and had a greater proportion of fall-related injuries (30.3% vs. 22.3%) ($p < 0.001$).

Table 2
Sex-based differences in demographic characteristics, injury mechanisms, and computed tomography findings.

	Patient Sex			Test
	Male	Female	Total	
Population	8,081 (68.7%)	3,686 (31.3%)	11,767 (100.0%)	
Age Group				
< 1 year	30 (0.4%)	23 (0.6%)	53 (0.5%)	< 0.001
2–18 years	1,859 (23.0%)	770 (20.9%)	2,629 (22.3%)	
19–64 years	5,591 (69.2%)	2,392 (64.9%)	7,983 (67.8%)	
65 + years	601 (7.4%)	501 (13.6%)	1,102 (9.4%)	
Mechanism of Injury				
Accident (Driver)	1,391 (17.2%)	219 (5.9%)	1,610 (13.7%)	< 0.001
Accident (Passenger)	1,144 (14.2%)	1,269 (34.4%)	2,413 (20.5%)	
Accident (Pedestrian)	682 (8.4%)	322 (8.7%)	1,004 (8.5%)	
Accident (Motorcycle/Bicycle)	667 (8.3%)	28 (0.8%)	695 (5.9%)	
Conflict/Assault	1,459 (18.1%)	333 (9.0%)	1,792 (15.2%)	
Fall	1,805 (22.3%)	1,116 (30.3%)	2,921 (24.8%)	
Struck by heavy object	407 (5.0%)	166 (4.5%)	573 (4.9%)	
Other	526 (6.5%)	233 (6.3%)	759 (6.5%)	
SDH				
No	7,995 (98.9%)	3,668 (99.5%)	11,663 (99.1%)	0.002
Yes	86 (1.1%)	18 (0.5%)	104 (0.9%)	
EDH				
No	8,013 (99.2%)	3,672 (99.6%)	11,685 (99.3%)	0.005
Yes	68 (0.8%)	14 (0.4%)	82 (0.7%)	
IPH				
No	8,066 (99.8%)	3,685 (100.0%)	11,751 (99.9%)	0.030
Yes	15 (0.2%)	1 (0.0%)	16 (0.1%)	
SAH				

	Patient Sex			Test
	Male	Female	Total	
No	7,999 (99.0%)	3,662 (99.3%)	11,661 (99.1%)	0.053
Yes	82 (1.0%)	24 (0.7%)	106 (0.9%)	
Contusion				
No	7,994 (98.9%)	3,664 (99.4%)	11,658 (99.1%)	0.012
Yes	87 (1.1%)	22 (0.6%)	109 (0.9%)	
Edema				
No	8,029 (99.4%)	3,665 (99.4%)	11,694 (99.4%)	0.636
Yes	52 (0.6%)	21 (0.6%)	73 (0.6%)	
Skull Fracture				
No	7,556 (93.5%)	3,548 (96.3%)	11,104 (94.4%)	< 0.001
Yes	525 (6.5%)	138 (3.7%)	663 (5.6%)	
Mass Effect				
No	7,964 (98.6%)	3,657 (99.2%)	11,621 (98.8%)	0.003
Yes	117 (1.4%)	29 (0.8%)	146 (1.2%)	
Pneumocephalus				
No	8,013 (99.2%)	3,675 (99.7%)	11,688 (99.3%)	< 0.001
Yes	68 (0.8%)	11 (0.3%)	79 (0.7%)	
Midline Shift	0.008 (0.090)	0.004 (0.059)	0.007 (0.082)	0.004

The age distribution also differed significantly by sex ($p < 0.001$). Compared with female patients, adults aged 19–64 years represented a greater proportion of male patients (69.2% vs. 64.9%), whereas older adults aged 65 years or above accounted for a greater proportion of female patients than male patients (13.6% vs. 7.4%).

Several CT abnormalities were more common among male patients. Skull fractures were observed in 6.5% of the males and 3.7% of the females ($p < 0.001$). Signs of mass effect or herniation were also more common in males than in females (1.4% vs. 0.8%; $p = 0.003$). Other intracranial abnormalities were generally more prevalent among males, although their absolute frequencies were low.

Age-Based Differences in Mechanism and CT Findings

Marked age-related differences were observed in the injury mechanisms and radiological findings (Table 3). Falls were the predominant mechanism among infants younger than 1 year and older adults aged 65 years or above, accounting for 73.6% and 51.5% of injuries in these groups, respectively. Driver-related traffic accidents were most common among adults aged 19–64 years (19.1%), whereas pedestrian injuries were proportionally more common among older adults (15.3%) than among younger adults. Assault-related injuries were concentrated primarily among adults aged 19–64 years (19.5%) ($p < 0.001$).

Table 3
Age-related differences in injury mechanisms and computed tomography findings.

	Age Group					Test
	< 1 year	2–18 years	19–64 years	65 + years	Total	
Population	53 (0.5%)	2,629 (22.3%)	7,983 (67.8%)	1,102 (9.4%)	11,767 (100.0%)	
Patient Sex						
Male	30 (56.6%)	1,859 (70.7%)	5,591 (70.0%)	601 (54.5%)	8,081 (68.7%)	< 0.001
Female	23 (43.4%)	770 (29.3%)	2,392 (30.0%)	501 (45.5%)	3,686 (31.3%)	
Mechanism of Injury						
Accident (Driver)	0 (0.0%)	17 (0.6%)	1,521 (19.1%)	72 (6.5%)	1,610 (13.7%)	< 0.001
Accident (Passenger)	7 (13.2%)	621 (23.6%)	1,662 (20.8%)	123 (11.2%)	2,413 (20.5%)	
Accident (Pedestrian)	1 (1.9%)	286 (10.9%)	548 (6.9%)	169 (15.3%)	1,004 (8.5%)	
Accident (Motorcycle/Bicycle)	0 (0.0%)	239 (9.1%)	442 (5.5%)	14 (1.3%)	695 (5.9%)	
Conflict/Assault	0 (0.0%)	184 (7.0%)	1,558 (19.5%)	50 (4.5%)	1,792 (15.2%)	
Fall	39 (73.6%)	847 (32.2%)	1,467 (18.4%)	568 (51.5%)	2,921 (24.8%)	
Struck by heavy object	6 (11.3%)	212 (8.1%)	321 (4.0%)	34 (3.1%)	573 (4.9%)	
Other	0 (0.0%)	223 (8.5%)	464 (5.8%)	72 (6.5%)	759 (6.5%)	
SDH						
No	49 (92.5%)	2,615 (99.5%)	7,935 (99.4%)	1,064 (96.6%)	11,663 (99.1%)	< 0.001
Yes	4 (7.5%)	14 (0.5%)	48 (0.6%)	38 (3.4%)	104 (0.9%)	
EDH						
No	53 (100.0%)	2,602 (99.0%)	7,933 (99.4%)	1,097 (99.5%)	11,685 (99.3%)	0.110
Yes	0 (0.0%)	27 (1.0%)	50 (0.6%)	5 (0.5%)	82 (0.7%)	

	Age Group					Test
	< 1 year	2–18 years	19–64 years	65 + years	Total	
IPH						
No	53 (100.0%)	2,626 (99.9%)	7,972 (99.9%)	1,100 (99.8%)	11,751 (99.9%)	0.953
Yes	0 (0.0%)	3 (0.1%)	11 (0.1%)	2 (0.2%)	16 (0.1%)	
SAH						
No	49 (92.5%)	2,622 (99.7%)	7,916 (99.2%)	1,074 (97.5%)	11,661 (99.1%)	< 0.001
Yes	4 (7.5%)	7 (0.3%)	67 (0.8%)	28 (2.5%)	106 (0.9%)	
Contusion						
No	53 (100.0%)	2,618 (99.6%)	7,905 (99.0%)	1,082 (98.2%)	11,658 (99.1%)	< 0.001
Yes	0 (0.0%)	11 (0.4%)	78 (1.0%)	20 (1.8%)	109 (0.9%)	
Edema						
No	52 (98.1%)	2,614 (99.4%)	7,938 (99.4%)	1,090 (98.9%)	11,694 (99.4%)	0.120
Yes	1 (1.9%)	15 (0.6%)	45 (0.6%)	12 (1.1%)	73 (0.6%)	
Skull Fracture						
No	44 (83.0%)	2,504 (95.2%)	7,523 (94.2%)	1,033 (93.7%)	11,104 (94.4%)	< 0.001
Yes	9 (17.0%)	125 (4.8%)	460 (5.8%)	69 (6.3%)	663 (5.6%)	
Mass Effect/ Herniation Signs						
No	52 (98.1%)	2,613 (99.4%)	7,898 (98.9%)	1,058 (96.0%)	11,621 (98.8%)	< 0.001
Yes	1 (1.9%)	16 (0.6%)	85 (1.1%)	44 (4.0%)	146 (1.2%)	
Pneumocephalus						
No	53 (100.0%)	2,600 (98.9%)	7,940 (99.5%)	1,095 (99.4%)	11,688 (99.3%)	0.020
Yes	0 (0.0%)	29 (1.1%)	43 (0.5%)	7 (0.6%)	79 (0.7%)	
Midline Shift	0.000 (0.000)	0.006 (0.075)	0.005 (0.073)	0.019 (0.137)	0.007 (0.082)	< 0.001

Radiological patterns also differed significantly across age groups. Skull fractures were most common among infants younger than 1 year (17.0%), followed by older adults (6.3%) and adults aged 19–64 years (5.8%) ($p < 0.001$). Signs of mass effect or herniation were more common among older adults (4.0%) than among infants younger than 1 year (1.9%), patients aged 2–18 years (0.6%), and adults aged 19–64 years (1.1%) ($p < 0.001$). Overall, positive CT findings suggestive of clinically meaningful intracranial injury were more common at the extremes of age, indicating a nonuniform relationship between age and radiological severity.

Multivariable Predictors of Admission or Treatment

In the multivariable logistic regression, several injury mechanisms and CT findings remained independently associated with the need for admission or treatment after adjustment (Table 4). Compared with driver-related traffic accidents, pedestrian injuries were associated with nearly twofold greater odds of admission or treatment (adjusted OR, 1.93; 95% CI, 1.57–2.36). Motorcycle/bicycle accidents showed a similarly strong association (adjusted OR, 2.22; 95% CI, 1.78–2.76). Falls were also independently associated with increased odds of admission or treatment (adjusted OR, 1.36; 95% CI, 1.15–1.62), as were other injury mechanisms (adjusted OR, 1.55; 95% CI, 1.23–1.94).

Table 4

Multivariable logistic regression analysis of factors associated with need for admission or treatment.

Needs Admission Treatment	Odds ratio	Std. err.	z	P> z	[95% conf. interval]	
Mechanism						
Accident (Driver)	1 (base)					
Accident (Passenger)	1.038379	.096669	0.40	0.686	.865192	1.246234
Accident (Pedestrian)	1.926934	.1985647	6.37	0.000	1.574538	2.358199
Accident (Motorcycle/Bicycle)	2.218094	.2469657	7.16	0.000	1.783224	2.759014
Conflict/Assault	.5507353	.0575906	-5.70	0.000	.4486756	.6760103
Fall	1.363774	.1183239	3.58	0.000	1.15051	1.616569
Struck by heavy object	.4345574	.0780178	-4.64	0.000	.3056522	.6178267
Other	1.545898	.1772475	3.80	0.000	1.234766	1.935426
Sex						
Male	1 (base)					
Female	.8177399	.5793946	-0.28	0.776	.2039445	3.278826
Age						
< 1 year	1 (base)					
2–18 years	.6690516	.3138693	-0.86	0.392	.2667713	1.677954
19–64 years	1.023368	.4771553	0.05	0.960	.4103465	2.552189
65 + years	1.382172	.6544803	0.68	0.494	.5463926	3.496387
Sex#Age						
Female#2–18 years	.8618207	.6204698	-0.21	0.836	.2101805	3.533796
Female#19–64 years	.9081975	.6459569	-0.14	0.892	.2253004	3.660992
Female#65 + years	1.515546	1.092952	0.58	0.564	.3687363	6.229056
Contusion						
No	1 (base)					
Yes	10.94469	3.496999	7.49	0.000	5.851017	20.47273
Edema						
No	1 (base)					
Yes	8.912008	3.349272	5.82	0.000	4.266588	18.61531

Needs Admission Treatment	Odds ratio	Std. err.	z	P> z	[95% conf. interval]	
Sex#Skull Fracture						
Male#Yes	2.813401	.2960574	9.83	0.000	2.289068	3.457837
Female#Yes	4.612425	.8971822	7.86	0.000	3.150348	6.753052
Mass Effect						
No	1 (base)					
Yes	1.230294	.36252	0.70	0.482	.6905461	2.191921
Pneumocephalus						
No	1 (base)					
Yes	6.435665	2.02661	5.91	0.000	3.471743	11.92997
Midline Shift	12.43359	6.208096	5.05	0.000	4.672951	33.08276
_cons	.1878649	.0884636	-3.55	0.000	.074649	.472789

Conversely, assault-related injuries were associated with lower adjusted odds of admission or treatment than driver-related traffic accidents were (adjusted OR, 0.55; 95% CI, 0.45–0.68). Injuries caused by heavy objects were also associated with lower adjusted odds of admission or treatment (adjusted OR, 0.43; 95% CI, 0.31–0.62).

Among the CT findings, midline shift demonstrated the strongest independent association with admission or treatment (adjusted OR, 12.43; 95% CI, 4.67–33.08). Cerebral contusion was also strongly associated with outcome (adjusted OR, 10.94; 95% CI, 5.85–20.47), followed by cerebral edema (adjusted OR, 8.91; 95% CI, 4.27–18.62) and pneumocephalus (adjusted OR, 6.44; 95% CI, 3.47–11.93). Skull fracture was independently associated with admission or treatment in both males and females, although the magnitude of the association differed by sex. Among males, skull fracture was associated with an adjusted OR of 2.81 (95% CI, 2.29–3.46), whereas among females, the corresponding adjusted OR was 4.61 (95% CI, 3.15–6.75). The mass effect was retained in the final model but was not independently associated with admission or treatment after adjustment (adjusted OR, 1.23; 95% CI, 0.69–2.19).

After adjustment for the injury mechanism and radiological findings, neither sex nor age group was significantly independently associated with admission or treatment. Likewise, the interaction between age group and sex was not statistically significant in the final model.

Interaction Between Sex and Skull Fracture

The interaction between sex and skull fracture status was clinically and statistically informative. Adjusted predictive margins revealed that among patients without skull fracture, the predicted probability

of requiring admission or treatment was slightly greater in males than in females (approximately 18.8% versus 15.6%, respectively). However, the presence of skull fracture substantially increased the predicted probability of admission or treatment in both sexes. This increase was more pronounced among females, in whom the predicted probability rose to approximately 42.5%, than among males, at 37.4% (Fig. 1). These findings indicate that the incidence of skull fracture is greater among female patients than among male patients.

Interaction Between Age Group and Sex

The adjusted predicted probabilities across age groups showed broadly similar age-related patterns in males and females (Fig. 2). In both sexes, the predicted probability of admission or treatment was lowest among patients aged 2–18 years and increased with advancing age. The highest predicted probabilities were observed among patients aged 65 years or older, reaching approximately 25.0% in males and 29.5% in females. Although older female patients had a numerically greater predicted probability than older male patients did, the age–by–sex interaction was not statistically significant, suggesting that the age–related gradient in admission/treatment risk was generally comparable between sexes.

Model Discrimination

The final multivariable logistic regression model demonstrated modest discrimination for identifying patients who required admission or treatment. Receiver operating characteristic analysis yielded an area under the curve of 0.690, indicating that the model provided predictive information beyond chance but had moderate overall discriminatory performance (Fig. 3). The ROC curve remained above the reference line of no discrimination across the evaluated range of thresholds, supporting the prognostic contribution of the combined clinical, mechanistic, and radiological variables.

Discussion

Principal Findings

In this large cohort of 11,767 patients with traumatic brain injury who underwent early computed tomography (CT), we found that early radiological findings were not merely diagnostic markers of intracranial injury but also clinically meaningful prognostic indicators associated with the subsequent need for admission or treatment(3, 14, 19). Nearly one in five patients required admission or active management, emphasizing that the practical clinical question after early CT is not limited to whether an abnormality is present, but whether the abnormality changes downstream care(6, 10, 20).

The strongest independent predictors of admission or treatment were CT findings reflecting structural injury severity and intracranial physiological compromise(6, 14, 20). The midline shift demonstrated the greatest association with the outcome, followed by cerebral contusion, cerebral edema,

pneumocephalus, and skull fracture. These findings suggest a biologically coherent hierarchy: abnormalities that imply mass effects, parenchymal injury, impaired intracranial compliance, or communication between intracranial and extracranial compartments carry greater clinical consequences than demographic variables alone(6, 7, 9, 21). The injury mechanism also retained independent prognostic value, with pedestrian injuries, motorcycle/bicycle accidents, falls, and other mechanisms associated with higher odds of requiring admission or treatment than driver-related traffic accidents did(2, 5, 8, 22).

A particularly important finding was the interaction between sex and skull fracture status(12, 18, 23). Although males had a greater overall burden of traumatic mechanisms and radiological abnormalities, the presence of skull fracture was associated with a greater increase in the adjusted probability of admission or treatment among females than among males. In contrast, the interaction between sex and age group was not statistically significant, indicating that age-related increases in clinical risk were broadly similar between sexes after adjustment. This distinction is clinically relevant because it moves the interpretation of sex differences beyond simple baseline comparisons and shows that the prognostic meaning of a specific CT finding may differ across patient subgroups(16, 24, 25).

The final multivariable model achieved an area under the receiver operating characteristic curve of approximately 0.690, indicating moderate discrimination(9, 24, 26). Rather than weakening the importance of the findings, this result highlights a clinically important reality: early CT findings contribute meaningful prognostic information, but disposition and treatment decisions in TBI patients remain multifactorial. Imaging must be interpreted together with clinical examination, neurological status, comorbidities, anticoagulant use, observation capacity, institutional protocols, and social safety factors(1, 5, 27). The value of the present study is therefore not the creation of a standalone replacement for clinical judgment but the clarification of which early CT findings most strongly shift risk within a large real-world population(28–30).

Comparison With Previous Studies

Previous prognostic research on traumatic brain injury has consistently shown that CT abnormalities are associated with adverse outcomes(6, 7, 31, 32). Foundational prognostic models, including those derived from large international datasets, incorporate CT classification systems and individual CT characteristics as important predictors of mortality and unfavorable functional outcomes. Studies such as IMPACT analyses have demonstrated that CT features, including traumatic subarachnoid hemorrhage, epidural hematoma, compressed basal cisterns, and midline shift, improve prognostic accuracy when combined with clinical variables(27, 30). Similarly, later investigations using TRACK-TBI and CENTER-TBI data revealed that individual pathological CT patterns have distinct prognostic implications after mild TBI and may help identify patients who require structured follow-up(7, 13, 19).

Our findings are consistent with these findings, confirming that early CT findings are not equivalent in terms of prognostic value(6, 13, 20). In the present study, midline shift, contusion, cerebral edema, and

pneumocephalus were especially strong predictors of admission or treatment(4, 9, 11, 14). This finding aligns with prior work showing that mass effects, edema, and parenchymal injury are markers of clinically significant brain trauma(6, 7, 16). However, our study differs from many previous reports in terms of its endpoint. Whereas much of the literature has focused on mortality, Glasgow Outcome Scale scores, long-term disability, intensive care admission, or neurosurgical intervention, the present study focused on the immediate and operationally relevant endpoints of admission or treatment. This endpoint is highly meaningful in emergency care because it reflects the point at which radiological findings translate into resource utilization, monitoring decisions, specialist involvement, and active clinical management(1, 3, 24).

Several prior studies have also examined predictors of positive head CT findings or neurosurgical intervention(1, 22, 33). These studies have been valuable in identifying patients who should undergo imaging or urgent procedural care. However, they often address narrower questions: who needs CT, who has intracranial hemorrhage, or who requires surgery. The present study begins at a later and equally important step in the care pathway: once early CT has been performed, which findings predict a need for further management? This makes our study particularly relevant for post-CT triage, disposition planning, and emergency department workflow design(7, 13, 16, 29).

Pediatric head trauma rules such as PECARN, CATCH, and CHALICE have helped reduce unnecessary CT imaging in children by identifying low-risk patients. However, these tools were designed primarily for imaging selection rather than for interpreting the prognostic significance of CT abnormalities after imaging has already occurred. Our study complements, rather than competes with, these decision rules by evaluating a mixed-age population and focusing on the clinical implications of early CT findings. The observed age-related pattern, with a greater risk among older adults and distinctive radiological patterns among infants and elderly patients, reinforces the need for age-aware interpretation of TBI imaging(2, 8, 23, 34).

The present findings also extend previous sex-based TBI research. Previous studies have reported sex differences in injury mechanisms, severity, and outcomes, but the role of sex as an effect modifier of specific CT findings has been less consistently evaluated(12, 18, 23, 33). In our cohort, males were more frequently injured through driver-related traffic accidents, motorcycle/bicycle crashes, and assault, whereas females more commonly experienced passenger-related traffic injuries and falls. Despite the greater crude frequency of several abnormalities among males, the adjusted effect of skull fracture on admission or treatment was stronger in females. This suggests that subgroup-specific prognostic interpretation may reveal clinically relevant patterns that are obscured in traditional main-effect models(12, 18, 23, 33).

Innovation and Added Value of the Present Study

The main innovation of this study is its shift from detection to prognostic translation(7, 13, 16). Most CT-based TBI studies ask whether CT can detect injury or predict long-term neurological outcomes. Our study asks a more immediate systems-level question: which early CT findings actually change the

probability that a patient will require admission or treatment?(6, 7, 16) This distinction is important because emergency departments do not manage CT findings in isolation. They manage risk, bed allocation, observation needs, treatment escalation, and discharge safety(1, 17, 24).

A second innovative feature is the use of a large real-world cohort exceeding 11,000 patients. This sample size allowed the study to evaluate relatively uncommon but clinically important CT findings, including midline shift, cerebral edema, pneumocephalus, and signs of mass effect or herniation(6, 7, 13, 29). Smaller cohorts often lack sufficient power to assess these abnormalities precisely or to examine interaction effects(29, 31). In contrast, the present dataset enabled a more granular analysis of demographic factors, injury mechanisms, and radiological findings within the same modeling framework(17, 24, 29).

A third strength is the evaluation of interaction effects, particularly between sex and skull fracture status. Many clinical prediction studies stop at independent predictors, which can imply that risk factors operate uniformly across all patients(29, 31, 33). Our analysis shows that this assumption may be incomplete. The stronger adjusted association between skull fracture and admission/treatment among females suggests that the prognostic value of the same CT finding may vary by patient subgroup. This creates a more nuanced and clinically intelligent framework for TBI triage(18, 23, 33).

A fourth contribution is the presentation of adjusted predictive margins. Odds ratios are useful for statistical inference, but they are often difficult to translate into bedside decision-making(19, 29). Predictive margins provide a clearer estimate of absolute risk and make interaction effects easier to interpret(20, 31). In this study, the predicted probability of admission or treatment increased from approximately 15.6% to 42.5% among females with skull fractures and from approximately 18.8% to 37.4% among males. This absolute risk framing strengthens the clinical interpretability of the model(21, 29).

Finally, the moderate AUC of the final model is informative. These findings demonstrate that early CT findings provide prognostic value beyond chance and that imaging alone cannot fully explain the need for admission or treatment(9, 22, 24). This finding supports a balanced model of care in which CT findings are integrated into structured clinical pathways rather than used as isolated decision triggers. In practical terms, the study offers a foundation for risk-stratified post-CT management protocols(5, 17, 25, 35).

Clinical Implications

These findings have several direct implications for clinical practice. First, early CT reports in TBI patients should be interpreted not only descriptively but also prognostically(6, 7, 14, 26). Findings such as midline shift, cerebral contusion, cerebral edema, pneumocephalus, and skull fracture should alert clinicians to a substantially increased probability of admission or treatment. Second, skull fracture should not be considered a uniform marker of risk across all patients(4, 11, 13, 14, 27). The stronger association

observed among females suggests that subgroup-specific interpretation may improve disposition decisions(29–31).

Third, the mechanism of injury remains clinically meaningful after adjustment for radiological findings. Pedestrian trauma, motorcycle/bicycle accidents, and falls may represent mechanisms associated with greater energy transfer, greater vulnerability, or a greater likelihood of occult clinical deterioration(2, 8, 32, 34). These mechanisms should therefore remain part of structured post-CT risk assessment(5, 19).

Fourth, the results support the development of institutional triage pathways in which CT findings, injury mechanisms, age groups, and sex-specific risk patterns are combined into a practical decision-support framework(1, 5, 29). Such a system would not replace clinical judgment but could standardize risk recognition, reduce variability in admission decisions, and improve resource allocation(5, 17, 20, 21).

Strengths

This study has several strengths. The large sample size provides substantial statistical power and improves the precision of estimates for both common and uncommon CT findings. The inclusion of 11,767 patients allows a broad evaluation of TBI across age groups, sex, injury mechanisms, and radiological abnormalities. The use of multivariable logistic regression helps distinguish independent associations from crude group differences, whereas the evaluation of interaction terms provides a more refined understanding of effect modification.

Another strength is the practical relevance of the outcome. Admission or treatment is a clinically actionable endpoint that directly reflects emergency department decision-making and healthcare resource use. Unlike long-term functional outcomes, which may be affected by rehabilitation access, follow-up completeness, and socioeconomic factors, this endpoint captures the immediate consequences of early imaging in acute care.

The study also benefits from transparent reporting of model performance. The ROC analysis revealed moderate discrimination, which appropriately frames the model as informative but not definitive. This honesty strengthens the credibility of the study and avoids overstating the ability of imaging findings alone to predict clinical management.

Limitations

Several limitations should be acknowledged. First, the observational design precludes causal inference. The associations identified in this study should be interpreted as prognostic relationships rather than evidence that specific CT findings directly cause admission or treatment. Second, admission and treatment decisions may be influenced by institutional protocols, clinician judgment, bed availability, comorbidities, anticoagulant status, neurological examination findings, and patient-level social factors that may not be fully captured in the dataset. Third, although the model included demographic variables, injury mechanisms, and CT findings, it did not necessarily incorporate all the clinical variables known to affect TBI prognosis, such as the Glasgow Coma Scale score, pupillary reactivity, hypotension, hypoxia,

anticoagulant use, or detailed comorbidity burden. Fourth, the model demonstrated moderate discrimination, indicating that additional clinical, laboratory, and longitudinal variables are needed to construct a more comprehensive prediction tool.

Finally, the study evaluated the need for admission or treatment rather than long-term neurological recovery. Future studies should assess whether the same early CT findings and interaction patterns also predict delayed deterioration, neurosurgical intervention, functional outcome, and mortality.

Future Directions

Future research should focus on converting these findings into a validated post-CT triage tool. Such a tool should combine early CT findings with neurological examination, medication history, comorbidities, vital signs, and laboratory markers. External validation in other institutions and healthcare systems will be essential to assess generalizability. Prospective studies should also examine whether risk-stratifying pathways on the basis of these findings can reduce unnecessary admissions, improve the detection of patients at risk of deterioration, and optimize neurosurgical consultation.

The sex-specific effect of skull fracture deserves particular attention. Future studies should explore whether this interaction reflects biological differences, differences in injury mechanism, bone structure, age distribution, care thresholds, or residual confounding. Clarifying this mechanism may improve individualized risk stratification in TBI patients.

Conclusion

In this large real-world cohort of patients with traumatic brain injury, early CT findings demonstrated substantial heterogeneity in their prognostic implications. Radiological markers reflecting intracranial mass effect and parenchymal injury, particularly midline shift, cerebral contusion, and cerebral edema, showed the strongest associations with the need for admission or treatment. Notably, skull fracture exhibited a sex-specific prognostic effect, with a greater increase in predicted risk among females than among males. These findings suggest that early CT interpretation in TBI should move beyond a simple normal-versus-abnormal framework toward a more nuanced assessment of individual imaging features and their clinical significance.

Declarations

Data Availability Statement

The original contributions made in this study are included in the article and supplementary material. Please contact the corresponding author if you have any other questions.

Conflict of Interest

The authors declare that the research was performed without any commercial or financial affiliations that might be regarded as potential conflicts of interest.

Supplementary Material

The supplementary material for this article is available alongside the article.

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Author Contribution

HRM: Data curation, methodology, original draft writing, review & editing. BA: Review & editing, methodology, validation, original draft writing. SP: Project administration, resources, formal analysis, methodology, review & editing. BKh: Review & editing, data curation, investigation. AJ: Original draft writing, data curation. MH: Supervision, validation, original draft writing, formal analysis

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Figures

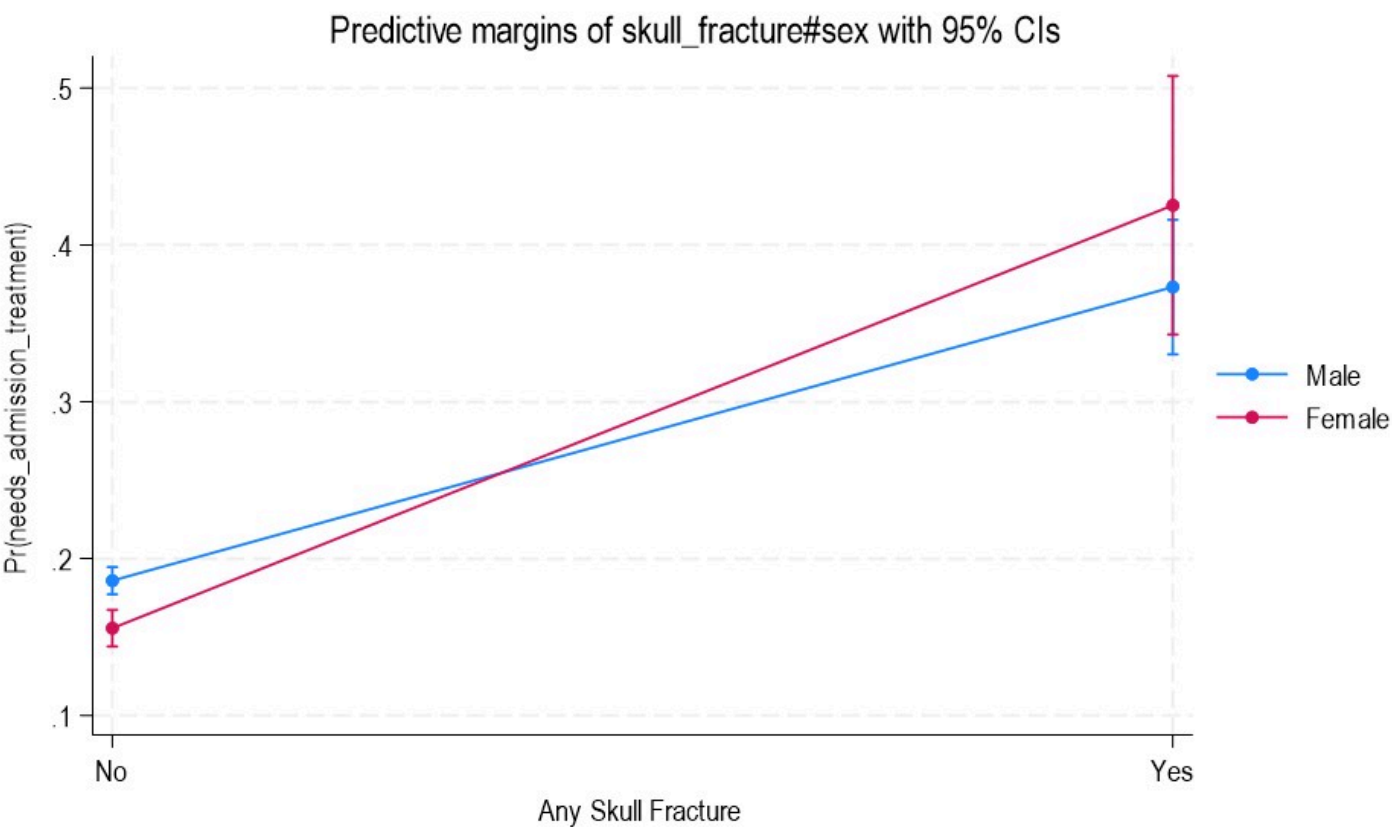


Figure 1

Adjusted predicted probability of admission or treatment according to skull fracture status and sex.

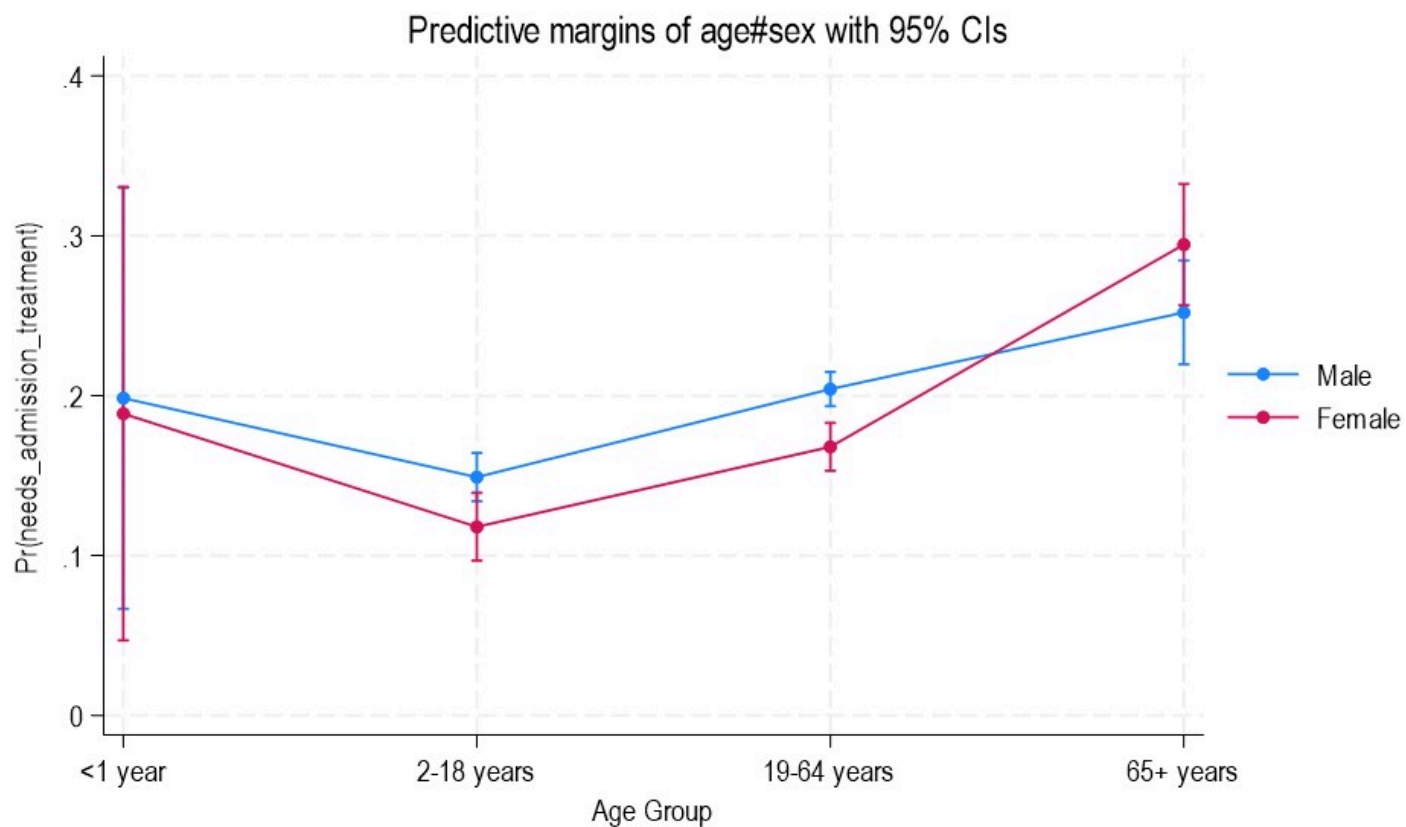


Figure 2

Adjusted predicted probability of admission or treatment across age groups by sex.

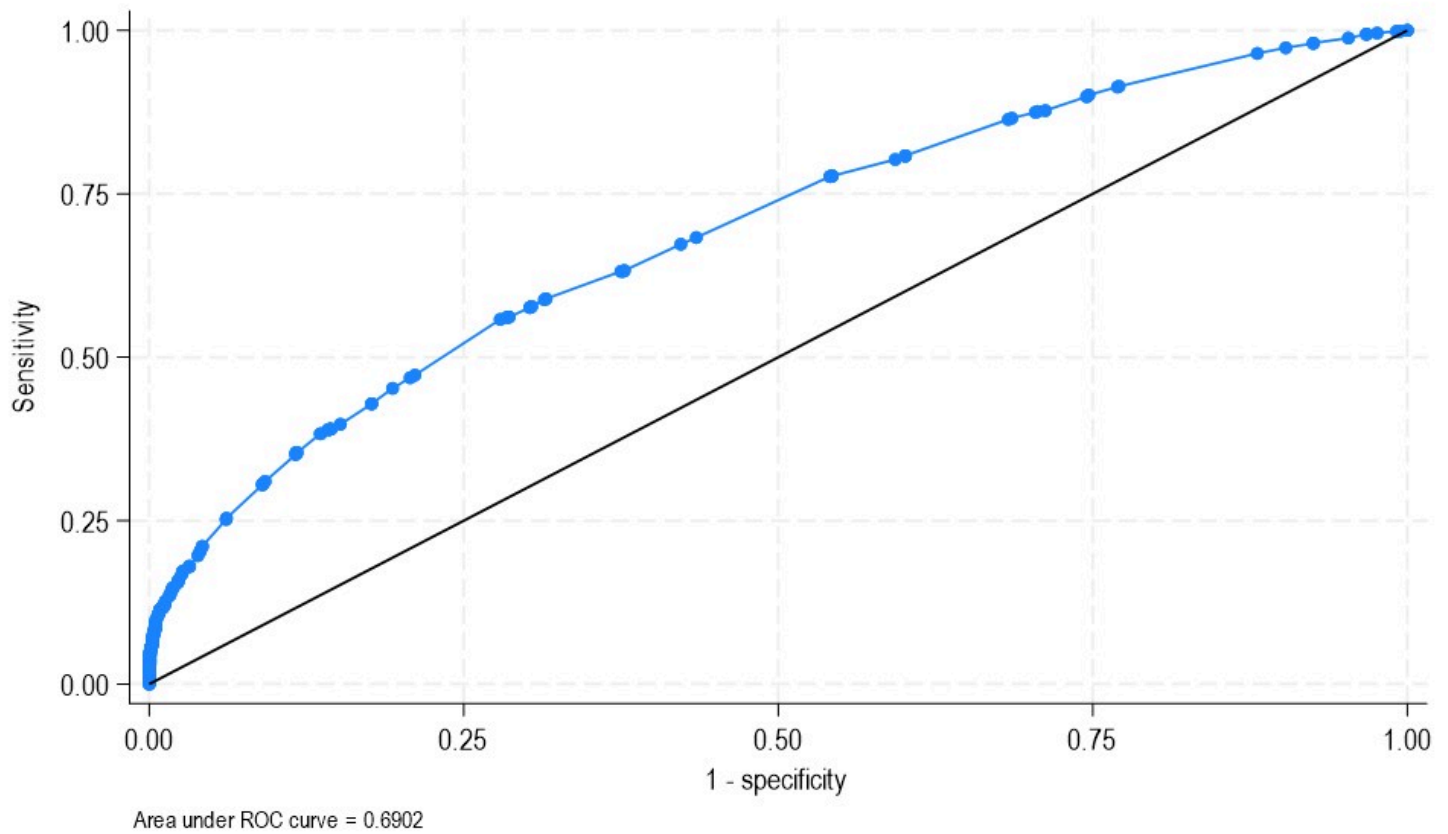


Figure 3

Receiver operating characteristic curve for the final multivariable logistic regression model.

Supplementary Files

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