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A nomogram for neurosurgical intervention in children with mild traumatic brain injury and minor subdural hematoma under 3 years

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Infants and toddlers with mild traumatic brain injury (mTBI) and minor subdural hematoma (SDH) were found to have a higher risk of requiring neurosurgical intervention (NI). However, the ability to identify patients with mTBI and minor SDH who require NI remains limited. This study aims to develop a nomogram to predict NI in these patients. A nomogram predicting NI was established using demographic, clinical, radiographic, and laboratory data from patients with mTBI and minor SDH. The least absolute shrinkage and selection operator (LASSO) regression and best subsets regression (BSR) methods were employed to identify variables and select predictive factors. A nomogram was constructed using multivariable logistic regression. The model's performance was evaluated using the area under the receiver operating characteristic curve, calibration curves, the Hosmer–Lemeshow test, and decision curve analysis. Immediate seizures, anemia, and subarachnoid space depth were identified as significant predictive factors by the BSR, leading to the development of a nomogram. The AUC for this nomogram, obtained through bootstrap validation (resampling = 500), was 0.893 (95% CI, 0.844–0.942). The model demonstrated good calibration, and decision curve analysis showed that when the threshold probability ranged from 7 to 83%, using the nomogram to predict NI provided a net benefit. A novel nomogram has been developed to accurately assess the risk of NI in children under 3 years of age with mTBI and minor SDH, potentially aiding in clinical decision-making.

Keywords Mild traumatic brain injury, Subdural hematoma, Prediction model, Nomogram

Abbreviations

mTBI	Mild traumatic brain injury
SDH	Subdural hematoma
CGCS	Child's Glasgow coma scale
PT	Prothrombin time
APTT	Activated partial thromboplastin time
INR	International normalized ratio
TT	Thrombin time
FIB	Fibrinogen
LASSO	Least absolute shrinkage and selection operator
BSR	Best subsets regression
BIC	Bayesian information criterion
RCS	Restricted cubic splines
VIF	Variance inflation factor
AUC	Area under the curve
DCA	Decision curve analysis
ESS	Enlarged subarachnoid space

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Each year, approximately 69 million people worldwide sustain traumatic brain injury (TBI), with over 80% classified as mild TBI (mTBI)[1,2].In children, the estimated incidence of TBI ranges from 47 to 280 per 100,000, with the highest rates occurring in those under 3 years of age[2–5]. Subdural hematoma (SDH) is the most common form of intracranial hemorrhage and one of the highest-risk types for neurosurgical intervention[6]. Over the past decade, there has been a notable increase in the number of patients presenting with mTBI and SDH[7]. Although most children with mTBI and minor SDH do not experience clinical deterioration during conservative observation, infants and toddlers have been found to be at higher risk of requiring neurosurgical intervention[8–11].

However, due to the prevalence and often subtle symptoms, this group is particularly challenging to prioritize for heightened clinical attention. Additionally, families frequently resist repeat head CT scans, citing concerns about potential radiation-induced brain damage. These factors may delay the identification of disease progression, potentially resulting in poor outcomes.

Therefore, accurately identifying infants and toddlers with mTBI and minor SDH who are at risk for neurosurgical intervention could help clinicians increase vigilance and intervene promptly. However, no clear consensus guidelines exist for the neurosurgical management of patients with mTBI complicated by SDH[12]. Additionally, existing predictive models primarily focus on adult patients[13–15]. In this study, a nomogram was developed to predict the need for neurosurgical intervention in children aged ≤ 3 years with mTBI and minor SDH, utilizing demographic, clinical, radiographic, and laboratory data.

Materials and methods

Study design and population

This study retrospectively recruited patients diagnosed with SDH who were admitted to the Children's Hospital of Soochow University between June 2015 and June 2024. All participant data were obtained from their electronic medical records. The inclusion criteria for the study were as follows: (1) traumatic brain injury; (2) minor subdural hematoma (with hematoma volume at admission not meeting surgical indications); and (3) age ≤ 3 years. Patients meeting any of the following exclusion criteria were removed from the study: (1) Child's Glasgow Coma Scale (CGCS) score < 13[16]; (2) open fracture; (3) admission CT indicating brain herniation or diffuse brain edema; and (4) absence of a CT scan within 48 h post-injury or a follow-up CT during conservative observation.

This study received approval from the Ethics Committee of the Children's Hospital of Soochow University in accordance with the Declaration of Helsinki (2024CS102). The requirement for informed patient consent was waived.

Data collection and definition

The authors collected the following data from the hospital's electronic medical record system: (1) demographic information, including age, sex, weight, and gestational age at birth; (2) trauma history details, such as time from injury to hospital, mechanism of injury, vomiting, immediate seizures, and admission CGCS score; and (3) laboratory results obtained at admission, including prothrombin time (PT), activated partial thromboplastin time (APTT), international normalized ratio (INR), thrombin time (TT), and fibrinogen (FIB). Seizures occurring within 24 h post-injury were recorded as immediate seizures. Anemia was diagnosed based on hemoglobin levels at admission and the patient's age[17].

Head CT images were independently reviewed by two experienced neurosurgeons, and disagreements were settled through joint discussion. The following findings were systematically recorded: skull fractures, intracranial hematomas, subdural effusions, and cerebral contusions. Hematoma volume was calculated using the (ABC)/2 method on 2.5-mm slices of non-contrast brain CT. The depth of the subarachnoid space was measured as the maximum distance from the surface of the gyri to the nearest point on the inner skull cortex[8,18–20]. Subdural crescent-shaped fluid collections with CT attenuation values between those of a hematoma and cerebrospinal fluid were recorded as subdural effusion. The measurement was taken on axial CT scans at the level of the lateral ventricles, with the average of the left and right sides recorded.

Outcome

The neurosurgeon's decision or intent to perform surgery was considered the gold standard. Since families may occasionally refuse neurosurgical intervention, patient communication records were reviewed to identify cases where surgery was recommended by the neurosurgeon but declined by the family. Clinical deterioration, along with repeat head CT showing a significant increase in hematoma volume or deepening of the subarachnoid space, were often considered indications for surgery. All NI decisions in our cohort were reviewed by at least two senior neurosurgeons, with discrepancies resolved through multidisciplinary discussions. The study's outcome was defined as either the execution of a neurosurgical procedure or the neurosurgeon's intent to perform one during the period of conservative observation.

Statistical analysis

Quantitative data following a normal distribution were reported as mean ± standard deviation, while data not adhering to a normal distribution were expressed as median (P25, P75). Categorical variables were presented as frequency and proportion. Independent sample t-tests were used for normally distributed quantitative data, and non-parametric tests were applied to data that did not follow a normal distribution. Chi-square tests were utilized for categorical variables.

To prevent overfitting or underfitting of the model, the least absolute shrinkage and selection operator (LASSO) regression and best subsets regression (BSR) methods were employed for dimension reduction and predictor selection[21–23]. Variable selection for BSR was guided by the Bayesian information criterion (BIC)[24].

Restricted cubic splines (RCS) were used to assess potential nonlinear associations between continuous predictors and outcomes, with nonlinear predictors converted into categorical variables. Collinearity among predictors was evaluated using the variance inflation factor (VIF). A multivariable logistic regression analysis was performed to construct the predictive model and develop a nomogram for neurosurgical intervention. The model's discriminatory ability was assessed by calculating the area under the curve (AUC), and internal validation was conducted using the bootstrapping method (resampling = 500). Model calibration was evaluated with the Hosmer–Lemeshow test, while its clinical utility was assessed through decision curve analysis (DCA).

R software (version 4.2.1; R Foundation for Statistical Computing; https://www.r-project.org/), the R survey package (version 4.1-1), and Free Statistics software (version 1.9.2; Beijing Free Clinical Medical Technology Co., Ltd.) were used for analyses. A two-sided p-value < 0.05 was considered statistically significant.

Results

Baseline characteristics

During the study period, 555 children aged ≤ 3 years with mTBI and minor SDH were admitted to the Children's Hospital of Soochow University, with 133 patients excluded (Fig. 1). Among the remaining participants, 41 (9.72%) underwent neurosurgical intervention. The demographic and clinical characteristics of the study participants are presented in Table 1. The neurosurgical intervention group tended to be younger (9[5,13] vs. 11[6,22]), anemia (24 [58.5%] vs. 51 [13.4%]), and more likely to develop subdural effusions (14 [34.1%] vs. 48 [12.6%]) and (13 [31.7%] vs. 29 [7.6%]). Additionally, they were more likely to have a lower level of PT (12.5 ± 1.5 vs. 12.9 ± 1.2), a higher level of FIB (18.1 ± 3.5 vs. 17.3 ± 2.2), and an enlarged subarachnoid space depth (4.4 [1.5, 5.0] vs. 1 [0, 3.5]).

Feature predictor selection

The optimal combination of variables was selected using the BSR method based on the minimum BIC, achieving the lowest BIC of -65.2 with three final variables (Fig. 2A and B). The selected variables were anemia, immediate seizures, and subarachnoid space depth, which were used to establish Model 1. Additionally, the authors applied LASSO regression to reduce the initial 23 variables to 5 significant predictors with non-zero coefficients (Fig. 2C and D). This process resulted in the creation of Model 2, which included anemia, subarachnoid space depth, immediate seizures, PT, and subdural effusion as the final predictors. None of these variables violated the VIF standards in the models. RCS analysis demonstrated a linear relationship between subarachnoid space depth, PT, and the risk of neurosurgical intervention (Supplementary Fig. 1).

Model development and performance

The models were internally validated using the bootstrap method (resampling = 500). The AUC for Model 1 was 0.893 (95% CI, 0.844–0.942), while Model 2 had an AUC of 0.901 (95% CI, 0.859–0.943) (Fig. 4A). The predictive performance of the two models was compared using DeLong's test, which indicated no statistically significant difference. Consequently, Model 1, which contained fewer variables, was selected for further evaluation. The three predictors were ultimately integrated into the nomogram (Fig. 3).

The calibration curve comparing predicted and observed outcomes confirmed the model's reliability in the validation set (Fig. 4B). Furthermore, the P-value obtained from the Hosmer–Lemeshow test was 0.793, indicating no statistically significant difference, which further supported the model's calibration validity. Based on the nomogram developed in this study, DCA demonstrated that the threshold probability for neurosurgical intervention in children with mTBI and minor SDH ranged between 7 and 83% (Fig. 4C).

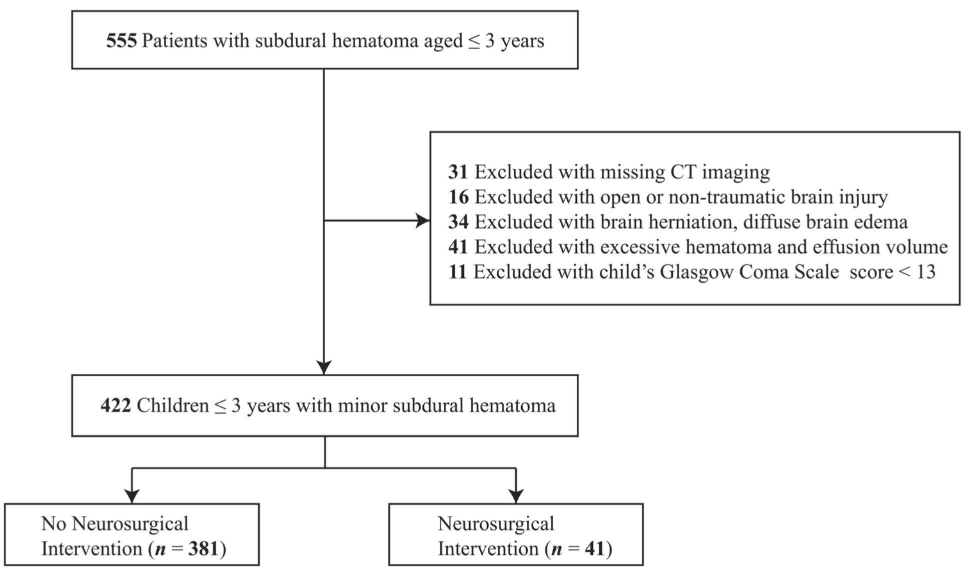

Fig. 1. Flow diagram of study design.

Variables	Total (*n* = 422)	No Neurosurgical Intervention (*n* = 381)	Neurosurgical Intervention (*n* = 41)	*p*-value
Sex				0.316
Female	155 (36.7)	137 (36)	18 (43.9)	
Male	267 (63.3)	244 (64)	23 (56.1)	
Age (months)	11.0 (6.0, 20.8)	11.0 (6.0, 22.0)	9.0 (5.0, 13.0)	0.05
Weight (kg)	10.5 ± 3.4	10.6 ± 3.3	10.0 ± 3.5	0.27
Time from injury to hospital (hours)	6.0 (3.0, 22.0)	6.0 (3.0, 22.0)	5.0 (3.0, 22.0)	0.481
Mechanism of injury				0.109
Fall	324 (76.8)	295 (77.4)	29 (70.7)	
Motor vehicle accident	82 (19.4)	74 (19.4)	8 (19.5)	
Missing	16 (3.8)	12 (3.1)	4 (9.8)	
Vomiting	238 (56.4)	217 (57)	21 (51.2)	0.482
Immediate seizures	42 (10.0)	29 (7.6)	13 (31.7)	< 0.001
Premature birth	26 (6.2)	21 (5.5)	5 (12.2)	0.16
CGCS score	14.4 ± 0.5	14.4 ± 0.5	14.4 ± 0.5	0.358
Anemia	75 (17.8)	51 (13.4)	24 (58.5)	< 0.001
Epidural hematoma	31 (7.3)	29 (7.6)	2 (4.9)	0.755
Subdural effusion	62 (14.7)	48 (12.6)	14 (34.1)	< 0.001
Subarachnoid hemorrhage	142 (33.6)	125 (32.8)	17 (41.5)	0.265
Cerebral contusion	57 (13.5)	48 (12.6)	9 (22)	0.096
Skull fracture	200 (47.4)	186 (48.8)	14 (34.1)	0.074
Anterior fontanelle closure	146 (34.6)	139 (36.5)	7 (17.1)	0.013
Location of SDH				0.368
Supratentorial	264 (62.6)	236 (61.9)	28 (68.3)	
Occipital	75 (17.8)	71 (18.6)	4 (9.8)	
Temporal	83 (19.7)	74 (19.4)	9 (22)	
PT (s)	12.9 ± 1.2	12.9 ± 1.2	12.5 ± 1.5	0.07
INR	1.1 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	0.704
APTT (s)	33.4 ± 9.4	33.7 ± 9.3	31.2 ± 9.7	0.112
TT (s)	2.2 ± 0.8	2.2 ± 0.8	2.3 ± 1.0	0.847
FIB (g/L)	17.4 ± 2.4	17.3 ± 2.2	18.1 ± 3.5	0.034
Subarachnoid space depth (mm)	1.2 (0, 4.0)	1.0 (0, 3.5)	4.4 (1.5, 5.0)	< 0.001

Table 1. Demographic, clinical, radiographic, and laboratory data of patients. CGCS: child's Glasgow coma scale; SDH: subdural hematoma; PT: prothrombin time; INR: international normalized ratio; APTT: activated partial thromboplastin time; TT: thrombin time; FIB: fibrinogen.

All results indicated that the nomogram prediction model, established using the included predictors, could accurately and consistently assess the probability of neurosurgical intervention in children aged ≤ 3 years with mTBI and minor SDH.

Website of nomogram model

The authors developed a web-based, user-friendly calculator that incorporates only three input variables (available at https://lyc-9876.shinyapps.io/dynnomapp/) to assist clinicians in utilizing the nomogram model more efficiently.

Discussion

Pediatric mTBI has long been a public health concern[25]. Symptoms following mTBI can persist for more than two weeks and, in some cases, may continue for over three months[26]. However, clear consensus guidelines for the neurosurgical treatment of patients with mTBI complicated by SDH are lacking[12]. Additionally, previous predictive models have primarily focused on adults[13–15]. Infants with mTBI exhibit distinct epidemiological characteristics, imaging features, physiological functions, and prognoses compared to adults. Therefore, it is essential to develop a predictive model that innovatively utilizes infant-specific characteristics as observational indicators to guide clinical decision-making.

This study developed and validated a web-based nomogram model to predict the risk of neurosurgical intervention in children under 3 years old with mTBI and minor SDH. The proposed model incorporated three easily obtainable predictive factors: anemia, immediate seizures, and subarachnoid space depth. The model demonstrated good calibration and discrimination. To the authors' knowledge, this is the first nomogram model specifically designed to predict the risk of neurosurgical intervention during conservative observation in this population. The visualized model and web tool may assist healthcare professionals in conducting individualized risk assessments, thereby aiding in clinical decision-making and management.

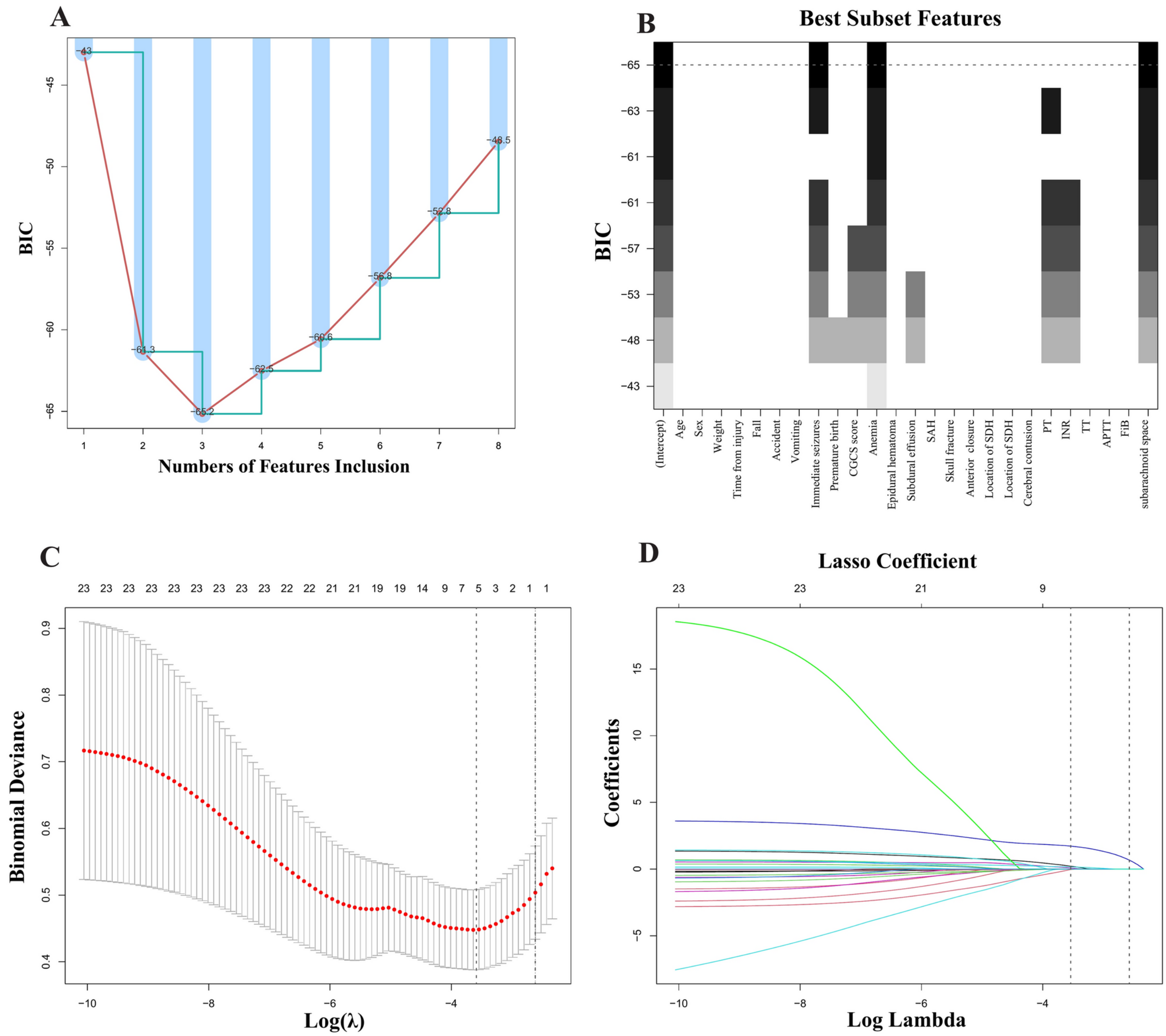

Fig. 2. Predictor selection was performed using LASSO regression analysis with tenfold cross-validation and BSR based on the minimum BIC. (**A**) The BSR method achieved the lowest BIC of -65.2. (**B**) The final number of selected variables was three. (**C**) The tuning parameter (lambda) selection in LASSO regression was based on the minimum criterion (left dashed line) and the 1-SE criterion (right dashed line). (**D**) A coefficient plot was generated for the log(lambda) sequence. In this study, the selection of predictive factors was guided by the minimum criterion (left dashed line), resulting in the identification of five non-zero coefficients. LASSO: least absolute shrinkage and selection operator; SE: standard error; BIC: Bayesian information criterion; BSR: best subsets regression.

Previous case series studies reported a potential association between subarachnoid space depth and the development of acute intracranial hypertension in children with mTBI and minor SDH[8–11]. Enlarged subarachnoid space (ESS) is a characteristic feature of benign external hydrocephalus, occurring in approximately 0.4 per 1,000 live births[27]. ESS typically resolves spontaneously before the age of three. However, Lee et al. suggested that children with ESS complicated by traumatic SDH are more likely to experience an “acute” stage[10]. In the study by Kumar et al., 35% (7/20) of children with ESS complicated by SDH required emergency surgical intervention[11]. In this study, subarachnoid space depth was identified as an important predictive factor for the need for neurosurgical intervention during conservative observation in children under 3 years old with mTBI and minor SDH.

Children with mTBI are estimated to experience immediate seizures in 5% to 21% of cases[28], often triggered by ischemia and neuronal hypoxia[29]. Numerous studies have shown that patients with mTBI who develop immediate seizures tend to have longer hospital stays and a higher risk of clinical deterioration[28,30,31]. Similarly, this study indicated that this phenomenon also occurs in children under 3 years old with mTBI and minor SDH. However, whether immediate seizures necessitate surgical intervention remains controversial. On the one hand,

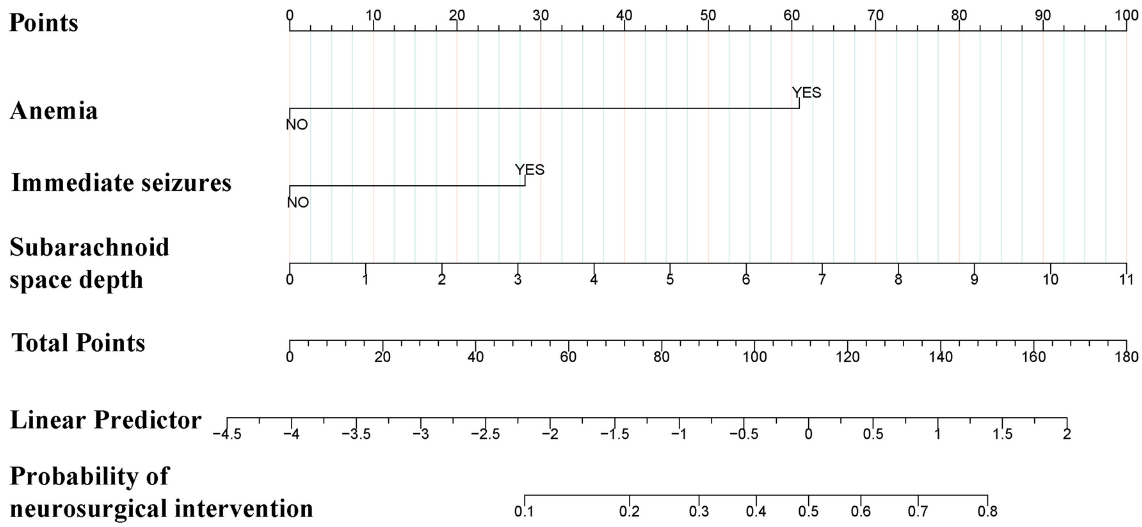

Fig. 3. The nomograms predict the risk of neurosurgical intervention in children aged ≤ 3 years with mTBI and minor SDH.

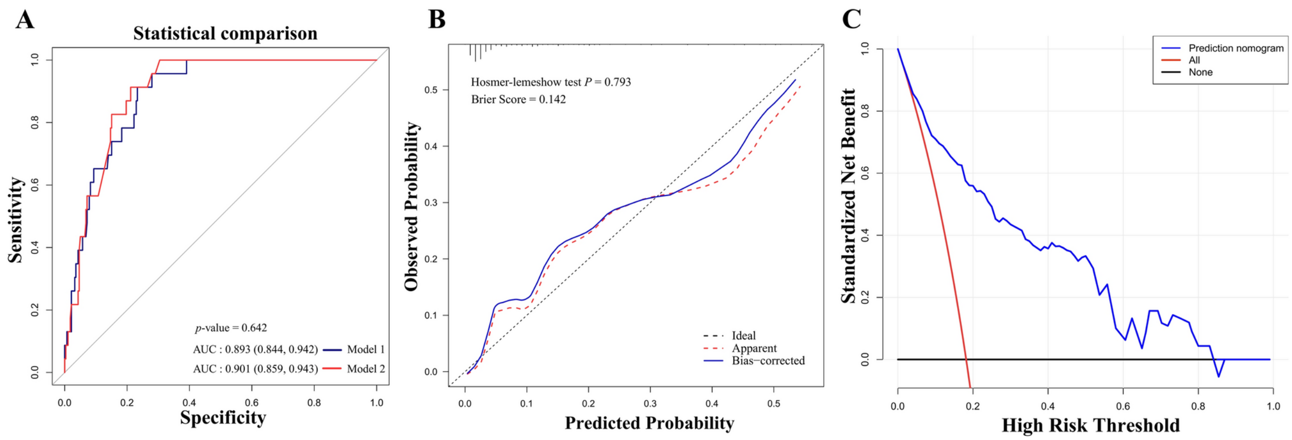

Fig. 4. Performance of the nomogram model: (**A**) ROC curve for the risk of neurosurgical intervention in children aged ≤ 3 years with mTBI and minor SDH. (**B**) Calibration curve for Model 1. (**C**) Decision curve analysis for Model 1. ROC: receiver operating characteristic; AUC: area under the curve.

some studies suggest that immediate seizures indicate a higher risk of intracranial hypertension or brain tissue injury, potentially warranting urgent surgical intervention to reduce mortality and improve prognosis[32]. On the other hand, other studies argue that immediate seizures are not always an independent predictor for surgery, and the effectiveness of surgical intervention may vary depending on the individual patient's condition[33,34].

In 2019, the World Health Organization estimated that 40% of children aged 6 to 59 months worldwide suffer from anemia[17]. Previous studies have indicated that anemia can significantly reduce venous oxygen saturation in patients with traumatic brain injury[35]. Furthermore, Hidenobu et al. reported a negative correlation between hemoglobin levels and the progression of traumatic intracranial hematomas[36]. These findings align with our results, underscoring the need for increased clinical attention for these patients.

The limitations of this study should be acknowledged. First, our single-center retrospective design and relatively small sample size may limit the generalizability of our findings. Although internal validation using bootstrap resampling (n = 500) demonstrated robust performance, external validation is necessary before clinical implementation. Additionally, continuous monitoring of certain parameter changes was not feasible. Second, although our model incorporates objective predictive factors, the outcome variable inherently reflects the subjective decisions of neurosurgeons at our institution. Variations in surgical thresholds across centers, influenced by local protocols, resource availability, and clinician experience, may limit the generalizability of our nomogram. Future studies should validate this tool in settings with standardized decision-making criteria. Finally, as children under the age of three often have difficulty remaining still during CT examinations, the imaging data are frequently skewed, making it challenging to measure the midline shift accurately. Consequently, this variable was not included in the model and should be further explored in future studies. Despite these limitations, this study represents the first effort to develop a nomogram for predicting the risk of neurosurgical intervention in children under 3 years of age with mTBI and minor SDH.

Conclusion

Our predictive model demonstrates the potential for estimating the risk of neurosurgical intervention in children under 3 years of age with mTBI and minor SDH. However, further studies are needed to validate its effectiveness and assess its broader applicability.

Data availability

The data are available from the corresponding author upon reasonable request.

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Author contributions
Yuchen Liu and Houxin Fu conducted data collection, statistical analysis, visualization, and original draft writing. All authors contributed to the data curation, conceptualization, and supervision. All authors have approved the submitted version and agreed both to be personally accountable for the author's contributions and to ensure that questions related to the accuracy or integrity of any part of the work.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics approval and consent to participate
The study was approved by the Research Ethics Committee of the Children's Hospital of Soochow University (2024CS102). Due to the retrospective nature of this study, the need for informed consent was waived by the Research Ethics Committee of the Children's Hospital of Soochow University.

Consent for publication
Not applicable.

Additional information
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