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Development and validation of a predictive model for postoperative hepatic dysfunction in Stanford type A aortic dissection

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To investigate the risk factors for postoperative hepatic dysfunction (HD) in patients undergoing acute Stanford type A aortic dissection (ATAAD) surgery and to develop an individualized prediction model. We retrospectively analyzed cardiac surgery patients with ATAAD treated at our hospital from January 2020 to March 2024, dividing them into 7:3 training and validation cohorts and grouping them into HD and non-HD categories based on postoperative liver function. Least absolute shrinkage and selection operator (LASSO) and multivariate logistic regression were used to identify independent predictive factors for postoperative HD, which formed the basis of a nomogram prediction model. We assessed model accuracy, calibration and clinical utility using C-statistics, calibration plots and decision curve analysis (DCA) curves. Internal validation with 1000 Bootstrap resamples was performed to reduce overfitting bias. LASSO and multivariate logistic regression identified key risk factors for HD in ATAAD patients, including chronic kidney disease, preoperative creatinine, international normalized ratio (INR), red blood cell (RBC) transfusion volume, peak intraoperative lactate, aortic cross-clamping time greater than 99 min, and reoperation. Based on these factors, a nomogram prediction model was successfully developed. The Hosmer–Leme show test yielded a p value of 0.952, indicating a good model fit. The area under the curve (AUC) values in the training and validation cohorts were 0.856 (95% CI 0.777–0.936) and 0.958 (95% CI 0.915–1) respectively, indicating good discriminatory power. The calibration curve shows that the bias corrected line is close to the ideal line. The DCA curve indicates that the use of the nomogram provides greater net clinical benefit. The AUC values before and after Bootstrap validation were 0.860 (95% Cl 0.795–0.924) and 0.858 (95% Cl 0.795–0.924), respectively, reflecting stable model performance and minimal risk of overfitting. The internally validated prognostic nomogram demonstrates excellent discriminative power, calibration, and clinical utility for predicting the risk of HD in patients who have undergone ATAAD surgery. This allows for an individualized evaluation and the optimization of clinical outcomes.

Keywords Stanford type A aortic dissection, Hepatic dysfunction, Predictive model

Acute Stanford type A aortic dissection (ATAAD) is a severe cardiovascular disease, with a mortality rate of up to 50% within 3 days and exceeding 70% within 1 week^{1,2}. Currently, surgical intervention is considered the gold standard for treating this disease³. Although surgical techniques and medical care have advanced, the postoperative mortality and complication rates for ATAAD continue to be elevated due to a complex interplay of factors such as extracorporeal circulation, involvement of the dissection, ischemia–reperfusion injury, inflammatory responses, transfusions, and medications^{4–6}.

Hepatic dysfunction (HD) is a common postoperative complication among patients with ATAAD, characterized by a postoperative serum transaminase (Aspartate Aminotransferase/Alanine Aminotransferase, AST/ALT) elevation exceeding 10 times the upper limit of normal^{7–9}. The reported incidence of HD varies widely in the literature, ranging from 8.7 to 22.9%^{7,10,11}. In ATAAD patients, postoperative HD increases the incidence of adverse events and mortality^{7,12,13}. Currently, aside from pharmacotherapy, there are no specific treatments available to prevent or cure postoperative HD in ATAAD patients¹⁴. Moreover, predicting hepatic dysfunction is complicated by its multifactorial nature, often leading to challenges in accurately assessing risk

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using traditional methods. Therefore, early identification of patients at risk for postoperative HD and timely intervention are critical for improving outcomes in ATAAD.

Despite HD being common in ATAAD patients and closely associated with poor postoperative outcomes, studies on postoperative HD in ATAAD patients remain limited. Most existing research is constrained by small sample sizes and produces inconsistent or even contradictory findings^{15–19}. Therefore, we conducted this study to address the gap by identifying independent risk factors for HD in a large cohort of ATAAD patients undergoing surgery. A predictive model for postoperative HD following ATAAD surgery was developed using retrospective analysis. The model, constructed with LASSO, logistic regression, and bootstrap verification, was represented as a nomogram for assessing patient risk. The model's performance was evaluated using receiver operating characteristic (ROC) curves, calibration curves, and decision curve analysis (DCA), showing strong discrimination, good calibration, and clinical utility. This model helps clinicians identify at-risk patients, guide interventions, and improve prognosis while reducing mortality in ATAAD patients (Fig. 1).

Materials and methods

Patient selection

A total of 273 patients diagnosed with ATAAD and undergoing surgical treatment at the First Affiliated Hospital of China Medical University between January 2020 and March 2024 were included in a retrospective analysis of clinical data. This study was conducted in accordance with the Declaration of Helsinki and received approval from the Institutional Review Board of the First Affiliated Hospital of China Medical University. Prior to their inclusion in the study, informed consent was obtained from all patients.

Inclusion criteria: (1) No gender restrictions (age \geq 18 years); (2) Patients diagnosed with ATAAD through echocardiography and/or computed tomography angiography, who underwent surgical treatment; (3) Time from onset to surgery not exceeding 1 week; (4) Complete preoperative clinical data, including age, gender, underlying diseases, and biochemical indicators. The exclusion criteria and patient selection process are shown in Fig. 2.

Clinical data collection and definition

A retrospective analysis was conducted to gather and summarize the clinical information of the selected patients, utilizing the database and Hospital Information System. The data encompasses (1) Basic characteristics: age, sex, body mass index (BMI), body surface area (BSA), history of smoking, and alcohol consumption. (2) Medical history. (3) Preoperative assessments: blood tests (e.g., hemoglobin, leukocytes), liver function tests (e.g., ALT: alanine aminotransferase, ALP: alkaline phosphatase, INR: international normalized ratio, GGT: gamma-glutamyl transferase), and coagulation tests (e.g., D-dimer, INR). (4) Surgical-related details: selection



Conclusion: The developed and internally validated prognostic nomogram demonstrated good discrimination, calibration, and clinical utility in predicting the risk of postoperative HD in patients undergoing ATAAD surgery.

Fig. 1. The workflow of the combined model construction.

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Fig. 2. Inclusion and exclusion criteria, experimental flowchart.

of surgical method, cardiopulmonary bypass (CPB) duration, aortic cross-clamping time, and deep hypothermic circulatory arrest time, among others. (5) Postoperative Complications and 30-day mortality rate.

HD is defined as a postoperative elevation of serum transaminases (AST/ALT) exceeding 10 times the upper limit of normal.

Statistical analysis

Following the collection of clinical data, statistical analysis and visualisation were conducted utilising R version 4.3.3. The analysis process utilised various R packages, including readxl, dplyr, glmnet, rms, caret, pROC, rmda, and regplot. Summary statistics, including counts, percentages, ratios, and interquartile range (IQR), were utilized based on the data type in question. The continuous variables with a normal distribution are presented as mean ± standard deviation (SD), while those with a non-normal distribution are expressed as median and IQR. Categorical variables are summarized as frequencies and percentages. For continuous variables, either an independent sample t-test or a Mann-Whitney U test was applied. Categorical variables were expressed as frequencies and percentages, and group comparisons were conducted using chi-square tests or Fisher's exact tests. The patients were randomly assigned to the training and validation groups in a 7:3 ratio and subsequently classified into two groups based on the incidence of postoperative hepatic dysfunction: a group with HD and a group without hepatic dysfunction (non-HD). Least absolute shrinkage and selection operator (LASSO) regression and multivariate logistic regression were employed to ascertain the independent predictors of postoperative HD in Stanford type A aortic dissection patients, and collinearity was evaluated using the variance inflation factor (VIF). A personalized HD nomogram prediction model was constructed and its predictive capability, calibration, and clinical utility were evaluated using c-statistics, calibration plots, and decision curve analysis (DCA) curves. To mitigate the potential for overfitting, internal validation was performed using 1000 bootstrap resamples.

Results

General information

In the cohort of 273 patients, the mean age was 51.11 ± 12.35 years (range 19–84), and the median BMI was 26.20 (IQR 23.40–29.40) kg/m², with 49.5% reporting a smoking history. Hypertension was present in 78.4% of patients, 5.5% had diabetes, and 11.0% had chronic kidney disease. It is worth noting that 33.3% of patients had dissections involving the celiac trunk (see in Table 1).

For the preoperative clinical indicators, the median left ventricular ejection fraction (LVEF) was recorded at 60.00 (IQR 58.00–63.00)%, while the median left ventricular end-diastolic diameter (LVEDD) was 48.00

Variables	Overall (n=273)	Non-HD (n=227)	HD (n=46)	<i>p</i> value
Age (year)	51.11 ± 12.35	50.50 ± 12.37	54.11 ± 11.95	0.071
Gender, male (%)	208 (76.2)	170 (74.9)	38 (82.6)	0.352
BMI (kg/m ²)	26.20 [23.40, 29.40]	26.10 [23.39, 29.40]	27.45 [23.55, 30.90]	0.196
BSA (m ²)	1.88 [1.73, 2.09]	1.88 [1.72, 2.07]	1.95 [1.77, 2.18]	0.161
Smoking history (%)	135 (49.5)	112 (49.3)	23 (50.0)	1.000
Alcohol consumption (%)	50 (18.3)	40 (17.6)	10 (21.7)	0.653
Hypertension (%)	214 (78.4)	178 (78.4)	36 (78.3)	1.000
Hyperlipidemia (%)	110 (40.3)	86 (37.9)	24 (52.2)	0.102
Diabetes mellitus (%)	15 (5.5)	13 (5.7)	2 (4.3)	0.984
COPD (%)	5 (1.8)	5 (2.2)	0 (0.0)	0.68
CKD (%)	30 (11.0)	19 (8.4)	11 (23.9)	0.005
Marfan syndrome (%)	8 (2.9)	8 (3.5)	0 (0.0)	0.416
Aortic disease history (%)	20 (7.3)	19 (8.4)	1 (2.2)	0.246
Valvular disease history (%)	43 (15.8)	37 (16.3)	6 (13.0)	0.741
Cardiac surgery history (%)	9 (3.3)	6 (2.6)	3 (6.5)	0.373
Aortic surgery history (%)	11 (4.0)	10 (4.4)	1 (2.2)	0.771
Other vascular disease history (%)	69 (25.3)	53 (23.3)	16 (34.8)	0.150
Pericardial effusion (%)	71 (26.0)	52 (22.9)	19 (41.3)	0.016
Time from onset to surgery (days)	3.00 [2.00, 4.00]	3.00 [2.00, 4.00]	2.00 [2.00, 3.00]	0.025
Dissection involving celiac trunk (%)	91 (33.3)	73 (32.2)	18 (39.1)	0.457

Table 1. Baseline clinical characteristics of included patients. BMI body mass index, BSA body surface area,COPD chronic obstructive pulmonary disease, CKD chronic kidney disease.

Variables	Overall (n=273)	Non-HD (n=277)	HD (n=46)	<i>p</i> value
LVEF (%)	60.00 [58.00, 63.00]	60.00 [58.00, 63.00]	59.00 [55.00, 62.00]	0.023
LVEDD (mm)	48.00 [46.00, 52.00]	49.00 [46.00, 52.00]	48.00 [46.00, 52.00]	0.938
LV hypertrophy (%)	155 (56.8)	129 (56.8)	26 (56.5)	1.000
BNP (pg/mL)	61.00 [28.00, 152.00]	56.00 [24.00, 142.50]	100.50 [40.75, 211.50]	0.025
Hemoglobin (g/dL)	138.00 [126.00, 148.00]	139.00 [127.00, 148.00]	133.00 [123.50, 150.75]	0.295
WBC (×10 ⁹ /L)	12.51 [10.02, 15.37]	12.21 [10.00, 14.96]	13.99 [10.31, 16.11]	0.040
Monocytes (×10 ⁹ /L)	0.72 [0.53, 1.01]	0.68 [0.49, 0.98]	0.90 [0.65, 1.12]	0.007
NE (×10 ⁹ /L)	10.73 [8.15, 13.42]	10.51 [8.07, 13.00]	11.60 [8.92, 14.07]	0.059
NE ratio (%)	85.70 [78.20, 89.60]	85.30 [77.10, 89.85]	86.55 [82.32, 88.85]	0.700
Platelets (×109/L)	179.00 [145.00, 220.00]	184.00 [151.00, 220.50]	154.50 [112.25, 208.25]	0.006
Preoperative creatinine (µmol/L)	81.00 [63.00, 110.00]	78.00 [59.00, 102.50]	104.00 [83.50, 175.50]	< 0.001
Albumin (g/L)	40.80 [38.00, 44.30]	41.20 [38.20, 44.40]	39.05 [36.67, 42.15]	0.019
ALT (U/L)	32.00 [23.00, 45.00]	31.00 [22.00, 42.00]	38.50 [27.00, 83.50]	0.005
ALP (U/L)	72.00 [59.00, 87.00]	72.00 [59.00, 87.00]	70.50 [59.00, 80.50]	0.402
GGT (U/L)	33.00 [21.00, 58.00]	32.00 [20.50, 58.00]	37.00 [22.50, 67.75]	0.338
Conjugated bilirubin (µmol/L)	4.00 [2.60, 5.80]	3.60 [2.50, 5.40]	5.85 [3.32, 9.28]	0.001
Total bilirubin (µmol/L)	16.00 [11.80, 23.50]	15.40 [11.40, 23.30]	20.15 [14.55, 29.08]	0.019
Prothrombin (seconds)	13.90 [13.30, 14.60]	13.80 [13.20, 14.45]	14.15 [13.53, 15.95]	0.002
D-dimer (mg/L)	11.00 [3.03, 20.00]	9.51 [2.70, 20.00]	17.41 [7.53, 20.00]	0.019
INR	1.06 [1.01, 1.13]	1.05 [1.00, 1.12]	1.13 [1.04, 1.28]	< 0.001
Fibrinogen (g/L)	2.77 [2.10, 3.93]	2.86 [2.20, 3.98]	2.41 [1.87, 3.38]	0.073

Table 2. Preoperative laboratory and examination variables. LVEDD left ventricular end-diastolic diameter,LVEF left ventricular ejection fraction, WBC white blood cell, BNP B-type natriuretic peptide, INRinternational normalized ratio, ALT alanine aminotransferase, ALP alkaline phosphatase, GGT gamma-glutamyl transferase.

(IQR 46.00–52.00) mm. The leukocyte count measured 12.51 (IQR 10.02–15.37) × 10⁹/L, while the preoperative creatinine level was 81.00 (IQR 63.00–110.00) µmol/L. Notably, preoperative creatinine levels in HD patients were noted at 104.00 (IQR 83.50–175.50) µmol/L, which was significantly higher compared to 78.00 (IQR 59.00–102.50) µmol/L in non-HD patients (see in Table 2).

Variables	Overall (n=273)	Non-HD (n=277)	HD (n=46)	<i>p</i> value
David procedure (%)	33 (12.1)	29 (12.8)	4 (8.7)	0.599
Bentall procedure (%)	4 (1.5)	4 (1.8)	0 (0.0)	0.815
Ascending aorta replacement (%)	264 (96.7)	218 (96.0)	46 (100.0)	0.357
Sun's procedure (%)	262 (96.0)	217 (95.6)	45 (97.8)	0.771
Other procedures (%)	11 (4.0)	10 (4.4)	1 (2.2)	0.771
Combined valve surgery (%)	14 (5.1)	12 (5.3)	2 (4.3)	1.000
Combined CABG (%)	50 (18.3)	38 (16.7)	12 (26.1)	0.199
Combined other procedures (%)	34 (12.5)	28 (12.3)	6 (13.0)	1.000
Machine residual blood volume (mL)	1400.00 [1200.00, 1400.00]	1400.00 [1200.00, 1400.00]	1400.00 [1200.00, 1475.00]	0.531
RBC transfusion volume (units)	3.50 [2.00, 7.00]	2.00 [1.00, 5.50]	7.75 [4.00, 15.12]	< 0.001
Plasma transfusion volume (mL)	0.00 [0.00, 400.00]	0.00 [0.00, 400.00]	400.00 [0.00, 950.00]	0.001
Platelet transfusion volume (units)	2.00 [1.00, 3.00]	2.00 [0.00, 3.00]	2.00 [1.25, 4.00]	0.013
Lactate (mmol/L)	9.30 [6.10, 12.80]	8.60 [5.45, 11.30]	13.35 [9.45, 15.00]	< 0.001
Surgery duration (minutes)	411.00 [358.00, 481.00]	411.00 [354.50, 467.00]	410.00 [369.75, 529.75]	0.177
CPB time (minutes)	143.00 [125.00, 172.00]	141.00 [124.00, 170.00]	161.50 [137.75, 185.00]	0.011
Aortic cross-clamp time (minutes)	101.00 [87.00, 123.00]	99.00 [86.00, 119.00]	120.00 [98.75, 141.25]	< 0.001
Machine support time (minutes)	33.00 [26.00, 45.00]	32.00 [26.00, 45.00]	36.00 [28.25, 44.00]	0.305
DHCA time (minutes)	16.00 [14.00, 17.00]	16.00 [14.00, 17.00]	15.00 [14.00, 17.75]	0.906
Low-temperature (°C)	22.92 ± 1.72	22.94 ± 1.77	22.83 ± 1.46	0.691

Table 3. Intraoperative surgical variables and associated information. *CABG* coronary artery bypass grafting,

 CPB cardiopulmonary bypass, *DHCA* deep hypothermic circulatory arrest, *RBC* red blood cell.

Variables	Overall (n=273)	Non-HD (n=277)	HD (n=46)	<i>p</i> value
Reoperation (%)	36 (13.2)	16 (7.0)	20 (43.5)	< 0.001
Hypoalbuminemia (%)	81 (29.7)	73 (32.2)	8 (17.4)	0.068
AKI (%)	113 (41.4)	77 (33.9)	36 (78.3)	< 0.001
Postoperative respiratory dysfunction (%)	117 (42.9)	78 (34.4)	39 (84.8)	< 0.001
Mechanical ventilation (hours)	61.40 [23.00, 108.90]	42.00 [21.75, 87.70]	96.95 [65.07, 208.32]	< 0.001
CRRT (%)	58 (21.2)	33 (14.5)	25 (54.3)	< 0.001
Neurological dysfunction (%)	107 (39.2)	70 (30.8)	37 (80.4)	< 0.001
30-Day mortality (%)	42 (15.4)	23 (10.1)	19 (41.3)	< 0.001
DAOH30 (days)	6.00 [0.00, 12.00]	8.00 [0.00, 12.00]	0.00 [0.00, 4.00]	< 0.001
ICU-free (days)	14.00 [9.00, 19.00]	14.00 [10.00, 19.00]	6.50 [0.00, 16.50]	0.001

Table 4. Analysis of postoperative complications and 30-day mortality rate. *AKI* acute kidney injury, *CRRT* continuous renal replacement therapy, *ICU* intensive care unit, *DAOH30* days alive and out of the hospital at day 30 post-surgery.

In terms of surgical-related data, the median duration of cardiopulmonary bypass was recorded at 143.00 (IQR 125.00–172.00) minutes, with an aortic cross-clamp time of 101.00 (IQR 87.00–123.00) minutes, and the peak intraoperative lactate level reaching 9.30 (IQR 6.10–12.80) mmol/L. The median amount of red blood cell transfusion across all patients was 3.50 (IQR 2.00–7.00) units, with HD patients receiving significantly more than non-HD patients (p < 0.001) (see in Table 3).

In our study cohort, a total of 46 patients were diagnosed with HD. Among them, the all-cause mortality rate associated with HD was 41.3% (19 of 46 patients). HD patients had a significantly increased incidence of acute kidney injury (78.3% vs. 33.9%, p < 0.001) and postoperative respiratory failure (84.8% vs. 34.4%, p < 0.001) with prolonged mechanical ventilation time (96.95 h vs. 42.00 h, p < 0.001). The need for postoperative dialysis (54.3% vs. 14.5%, p < 0.001) and the incidence of neurological dysfunction (80.4% vs. 30.8%, p < 0.001) were more frequent in the HD group. The DAOH30 was significantly shorter for HD patients (0.00 days vs. 8.00 days, p < 0.001), while the ICU-free days were also notably reduced in the HD group (6.50 days vs. 14.00 days, p = 0.001). Mortality within 30 days was significantly higher in the HD group than in the non-HD group (41.3% vs. 10.1%, p < 0.001) (see in Table 4).

LASSO regression for screening risk factors

Due to the inclusion of numerous variables, correlations between them, and limited sample sizes for positive outcomes in this study, LASSO regression was used to filter the included variables. The VIF was used to assess collinearity between variables, with those with high VIFs removed to select optimal risk factors for postoperative



Fig. 3. LASSO regression screening results for in-hospital HD risk factors: (**a**) LASSO regression coefficient path plot, (**b**) LASSO regression cross-validation plot.

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Variable	Odds Ratio (95% CI)		p-value
CKD	2.61(0.82 - 7.92)	◆−1	0.09
Preoperative creatinine	1.00 (0.99 - 1.00)	•	0.31
INR	13.38(1.05 - 239.29)	↓ → →	0.06
RBC transfusion volume	1.06(1.01 - 1.12)	÷	0.02
Lactate	1.18(1.05 - 1.36)	•	< 0.01
Aortic cross-clamp time (>99)	2.44(1.04 - 10.76)	 •	0.04
Reoperation	4.09 (1.54 - 10.76)	↓ ↓◆──┥	< 0.01
		0 10 20 30	

Fig. 4. Logistic multivariable regression analysis showing the risk variables of HD after ATAAD surgery. *CI* confidence interval, *CKD* chronic kidney disease, *INR* international normalized ratio, *RBC* red blood cell, *ACT* aortic cross-clamp time.

HD. Ten-fold cross-validation was performed to determine the optimal value of Lambda=0.076353 as the solution for the variable selection model, counting the number of variables with non-zero regression coefficients at this stage (Fig. 3). The LASSO regression results showed that the following seven variables were selected and included in the model: history of chronic kidney disease, preoperative creatinine, INR, red blood cell (RBC) transfusion volume, highest intraoperative lactate level, aortic cross-clamp time and reoperation.

Logistic regression

The risk factors identified by LASSO regression were used as independent variables, with the occurrence of HD as the dependent variable in a multivariate logistic regression analysis. The results showed that RBC transfusion volume, peak intraoperative lactate level, aortic cross-clamp time and reoperation were independent risk factors for postoperative HD (p < 0.05) (Fig. 4). Figure 5 shows the ROC curves for various predictive factors in assessing the risk of occurrence of HD.

Nomogram and performance of the model

Based on the risk factors selected from the multivariate logistic regression analysis as predictive factors, and taking into account the dual aspects of statistical significance levels and the clinical utility of LASSO regression, which can help to remove redundant variables and thus improve the generalizability of the model, we included



Fig. 5. Analysis of ROC curves for different predictive indicators on the risk of HD occurrence.



Fig. 6. Dynamic nomogram for predicting HD risk in patients after ATAAD surgery. Preoperative factors: INR, Creatinine, CKD; Intraoperative factors: Lactate levels, RBC transfusion volume, ACT. *CKD* chronic kidney disease, *INR* international normalized ratio, *RBC* red blood cell, *ACT* aortic cross-clamp time.

chronic kidney disease (CKD), INR and preoperative creatinine as predictive factors in the model, in line with comparable research²⁰. We developed a nomogram to predict the risk of HD in patients following ATAAD surgery, shown in Fig. 6. The total score is obtained by adding the individual scores derived from each predictive variable marked vertically on the horizontal axis, which is then used to estimate the likelihood of HD occurring.

Model validation was conducted through the construction of ROC, calibration, and DCA curves to assess the model's discriminatory ability, calibration accuracy, and clinical utility. The ROC curve indicates that the area under the curve (AUC) values were 0.856 (95% CI 0.777–0.936) for the training group and 0.958 (95% CI 0.915–1) for the validation group, both of which demonstrate the model's strong discriminative ability (see in



Fig. 7. ROC curves of the model in the training cohort (a) and validation cohort (b).



Fig. 8. Calibration curves of the predictive model in the training cohort (**a**) and validation cohort (**b**). The diagonal line indicates the perfect prediction of an ideal model.

Fig. 7). The calibration curve comprises three distinct lines (see in Fig. 8): the dotted line denotes the model's performance on the training dataset (Apparent), the red line represents the ideal scenario where predicted probabilities align perfectly with actual occurrences (Ideal), and the blue line displays the calibration results post-resampling (Bias-corrected). The Fig. 8 demonstrates that the model's estimated probabilities are in close alignment with the actual outcomes in both the training and validation groups, indicating a high degree of consistency. As illustrated by the DCA curve (see in Fig. 9), when the predicted probabilities of the nomogram model fall within the range of 0–0.85, the model's clinical net benefit exceeds that of both the "full intervention" and "no intervention" scenarios, thereby confirming the nomogram's favorable clinical utility.

Bootstrap verification

To prevent overfitting of the nomogram, this study conducted internal validation through bootstrap resampling 1000 times (see in Fig. 10). Prior to validation, the findings indicated an AUC of 0.856 (95% CI 0.777–0.936). Following Bootstrap validation, the AUC was 0.854 (95% CI 0.792–0.919). The proximity of the AUC values before and after internal validation corroborates the stability of the model's performance and a reduced risk of overfitting. The narrow confidence interval range observed before and after internal validation also substantiates the model's robust reliability.

Discussion

HD represents a significant postoperative risk for patients with ATAAD, strongly linked to the elevated incidence of other complications and increased postoperative mortality rates²¹. This liver injury is frequently the result of a combination of factors, including systemic hypoperfusion, ischemia–reperfusion injury, and metabolic disturbances^{22,23}. In accordance with the findings of previous studies with a high mortality rate, our study also revealed a postoperative incidence of HD of 16.8% and an all-cause mortality rate of 15.4% among ATAAD patients. These results highlight the critical need for precise, individualized risk assessments and preventive



Fig. 9. DCA curves of the predictive model in the training cohort (**a**) and validation cohort (**b**).



Bootstrap ROC Curve

Fig. 10. Bootstrap ROC curve for the prediction model of HD.

strategies. The traditional liver assessment scores, including the Child–Turcotte–Pugh (Child–Pugh), model for end-stage liver disease (MELD), and acute-on-chronic liver failure scores, lack the requisite specificity for accurately predicting postoperative HD in ATAAD patients^{24,25}. Accordingly, the creation of bespoke predictive models is vital to enable the refinement of outcome-driven clinical interventions for this high-risk population.

The objective of this study was to enhance the prediction of HD by developing a nomogram that incorporates demographic, intraoperative, and laboratory data from ATAAD patients. Although previous research has identified a number of factors, including gender, diabetes, lower CPB temperature, valvular disease, surgery duration, and celiac trunk involvement, as potential contributors to liver function impairment^{12,23,26,27}, our model did not find any significant associations between these factors and the development of postoperative HD in ATAAD patients. Instead, through the use of LASSO regression, seven independent risk factors for HD were identified: CKD, preoperative creatinine levels, INR, RBC transfusion volume, intraoperative lactate levels, aortic cross-clamp time, and reoperation. Of these, peak intraoperative lactate levels, RBC transfusion volume, aortic cross-clamp time, and reoperation were identified as the primary drivers of HD risk.

As posited by Deeb and colleagues, aortic dissection may precipitate stenosis in the celiac and mesenteric arteries, thereby reducing liver blood flow and potentially leading to hepatic impairment or infarction^{17,18,28}. However, as evidenced by our findings, some studies indicate that the extent and location of the dissection do not reliably predict postoperative HD¹⁹. It is notable that celiac artery involvement itself may not emerge as a significant risk factor. Instead, intraoperative aortic cross-clamping time was identified as an independent predict of HD, which aligns with existing literature²⁹. This finding suggests that anatomical involvement alone may not fully reflect the risk of HD. Instead, hepatic ischemia–reperfusion injury caused by intraoperative aortic

clamping may be a key mechanism. Ischemic hepatic tissue is prone to oxidative stress, inflammatory mediator release, and microcirculatory dysfunction, leading to hepatocellular impairment or necrosis³⁰. This underscores the need for further research on the role of hepatic blood supply status and ischemia duration before and during surgery in impacting liver function in ATAAD patients.

Building on previous findings indicating a close relationship between liver and kidney function^{31–33}, our study provides further evidence that renal impairment can significantly impact hepatic outcomes. In ATAAD, dissection involvement of the abdominal aorta and renal arteries may reduce renal blood flow, often leading to acute kidney injury (AKI) and renal failure^{34–36}. Our analysis of ATAAD patients revealed that a history of CKD and elevated preoperative creatinine levels were both risk factors for postoperative HD, consistent with existing research. The underlying pathophysiology may involve systemic inflammation and immune activation. Renal dysfunction can trigger the excessive release of pro-inflammatory cytokines and chemokines, such as TNF- α and IL-6, which may directly impair hepatic microcirculation and promote hepatocellular injury^{37,38}. Conversely, the HD—especially in acute settings—may induce HRS-like AKI through similar inflammatory pathways, resulting in renal tubular injury, acute tubular necrosis, and systemic vasodilatation³⁹. This emphasizes the necessity of monitoring renal function as part of a comprehensive approach to managing hepatic risk in these high-risk patients.

Lactic acid, a byproduct of glycolysis, is frequently elevated following cardiac surgery and has been demonstrated to be a significant predictor of adverse postoperative outcomes^{40–42}. Hyperlactatemia, a common occurrence in patients who have undergone cardiac surgery, can be attributed to a number of factors, including the flow rate, duration, and temperature of extracorporeal circulation, as well as fluctuations in blood pressure^{40,43}. These conditions contribute to tissue hypoxia and metabolic stress, thereby rendering elevated lactate levels a reliable clinical marker for assessing disease severity and risk of complications. In accordance with the results of our study, we found a significant correlation between elevated intraoperative lactate levels and the occurrence of postoperative HD in ATAAD patients. This highlights the importance of monitoring lactate as a predictive factor for hepatic risk. Moreover, our findings suggest that maintaining stable perfusion and minimizing circulatory disruptions during surgery may be crucial for reducing the risk of liver-related complications in this patient group.

Red blood cells (RBCs) are essential for systemic oxygen delivery, particularly to metabolically active organs such as the liver, which is highly susceptible to hypoxia-induced injury⁴⁴⁻⁴⁶. Patients undergoing ATAAD often necessitating significant RBC transfusions to maintain adequate oxygenation^{19,47}. As intraoperative blood loss is challenging to quantify with precision, the volume of RBC transfusion offers a more reliable indicator of the patient's oxygenation status during surgery. Our findings substantiated that intraoperative RBC transfusion volume is an independent risk factor for postoperative HD. Beyond indicating the severity of bleeding and impaired oxygen delivery, transfusion of stored RBCs may aggravate liver injury through several mechanisms. During storage, depletion of antioxidants such as NADH and glutathione increases hemoglobin susceptibility to oxidative degradation, releasing free iron and heme that induce oxidative stress. Membrane damage leads to microparticle formation, which reduces nitric oxide availability and disrupts hepatic microcirculation⁴⁸. In addition, aged RBCs and their breakdown products activate hepatic macrophages, promoting inflammatory cytokine release. Transfusion also raises systemic iron levels, resulting in hepatic accumulation of non-transferrin-bound iron and iron-mediated cytotoxicity, further impairing liver function^{48,49}. This underscores the significance of transfusion management as a constituent of liver protection strategies in ATAAD patients, assisting in the mitigation of hypoxic damage and the enhancement of postoperative outcomes.

Based on the above findings and confidence in our results, we developed a nomogram that demonstrated superior predictive performance, achieving an AUC above 0.8 in both the training and validation cohorts. This model outperformed traditional liver assessment tools, offering a more precise, individualized risk assessment for ATAAD patients. By identifying key risk factors and leveraging this predictive nomogram, our study supports a more proactive approach to mitigating the impact of HD and improving patient outcomes in ATAAD.

Limitation

This research introduces a nomogram model for predicting the risk of postoperative HD in ATAAD patients based on multivariable analysis for the first time, demonstrating notable clinical value for postoperative management. Nevertheless, this study is not without limitations, including a single-center design, a relatively limited sample size, an internal validation of the predictive model, a markedly smaller number of HD patients compared to non-HD patients (approximately 17% vs. 83%) without the application of data balancing techniques during analysis, and constraints inherent to retrospective analysis, which may affect the external validity of the predictive model. Furthermore, the intricacy of interventions, including reoperation, extracorporeal membrane oxygenation, and intra-aortic balloon pump, makes it challenging to assess their impact on the risk of hepatic dysfunction in this study independently. This highlights the necessity for further investigation. Notwithstanding these limitations, the nomogram model demonstrates robust predictive performance, exhibiting good calibration and clinical utility, and offers enhanced capabilities for individualized risk assessment.

Conclusion

In conclusion, we developed a nomogram prediction model for forecasting HD following surgery for ATAAD based on a retrospective analysis of clinical data. We then performed internal validation, confirming the model's significant clinical utility. This predictive model serves as a tool for individualized forecasting, facilitating early intervention for postoperative HD in ATAAD patients and improving treatment strategies.

Data availability

All data generated or analyzed during this study are included in this published article.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the First Affiliated Hospital of China Medical University, and informed consent was obtained from all participants.

Consent for publication

Written informed consent for publication was obtained from all participants.

Additional information

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