

ORIGINAL ARTICLE

A nomogram prediction model for sternal incision problems

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Funding information

Training Plan of Clinical Scientific Research Talents in Army Medical University, China, Grant/Award Number: 2018XLC3025

Abstract

Presently, the incidence and mortality rates of sternal incision problems (SIPs) after thoracotomy remain high, and no effective preventive measures are available. The data on 23 182 patients at Xinqiao Hospital, Army Medical University treated with median sternotomy from 1 August 2009 to 31 July 2019 were retrospectively reviewed. A prediction model of SIPs after median thoracotomy was established using R software and then validated using the bootstrap method. Next, the validity and accuracy of the model were tested and evaluated. In total, 15 426 cases met the requirements of the present study, among which 309 cases were diagnosed with SIPs, with an incidence rate of 2%. The body mass index (BMI), intensive care unit (ICU) time, diabetes mellitus, and revision for bleeding were identified as independent risk factors for postoperative SIPs. The nomogram model achieved good discrimination (73.9%) and accuracy (70.2%) in predicting the risk of SIPs after median thoracotomy. Receiver operating characteristic curve analysis showed that the area under curve of the model was 0.705 (95% confidence interval [CI]: 0.746-0.803); the Hosmer-Lemeshow test showed that $\chi^2 = 6.987$ and $P = 0.538$, and the fitting degree of the calibration curve was good. Additionally, the clinical decision curve showed that the net benefit of the model was greater than 0, and the clinical application value was high. The nomogram based on BMI, ICU time, diabetes mellitus, and revision for bleeding can predict the individualised risk of SIPs after median sternotomy, showing good discrimination and accuracy, and has high clinical application value. It also provides significant guidance for screening high-risk populations and developing intervention strategies.

KEYWORDS

median thoracotomy, nomogram, prediction model, sternal incision problems

Key Messages

- in this work, 23 182 patients at Xinqiao Hospital, Army Medical University treated with median sternotomy from 1 August 2009 to 31 July 2019 were retrospectively reviewed, and found that body mass index, intensive care unit time, diabetes mellitus, and revision for bleeding were identified as independent risk factors for sternal incision problems
- the nomogram based on these risk factors can predict the individualised risk of sternal incision problems
- it provides significant guidance for screening high-risk populations and developing intervention strategies

1 | INTRODUCTION

Currently, median sternal incision is the most common approach in cardiac surgery, based on full exposure and easy operation.¹ However, median sternal incision has a risk to progress to incision healing failure,^{2,3} which may prolong the hospital stay and increase clinical costs.^{4,5} Severe problems, such as high temperature, septicemia, and bleeding, can cause sternal opening.⁶ The death rate from median sternal incision problems (SIPs) can be as high as 19% to 29%.⁷ Although many efforts have been made to cure SIPs, such as optimising the operation techniques and applying antibiotics, the incidence of SIPs remains at 0.9% to 20%.⁸ Previous studies have revealed that the risk factors for SIPs can be approximately divided into patient-related factors and intraoperative and post-operative factors.^{9,10} Patient-related factors include sex, age, obesity, smoking, huge body surface area on chest, renal failure, steroid use, diabetes mellitus, and chronic obstructive pulmonary disease (COPD).^{11,12} Among them, obesity, COPD, diabetes mellitus, and renal failure are the most important independent risk factors.¹³

The incidence of SIPs also varies with the operation type and intervention method.¹⁰ Early data have shown that the incidence of coronary artery bypass grafting (CABG) combined with valve replacement (VR) surgery showed the highest risk, followed by CABG alone, and that the lowest risk occurred after VR surgery.¹⁰ Although many of the above studies have attempted to determine the risk factors for SIPs, no consensus is available regarding the important risk factors for SIPs. Therefore, early screening of high-risk groups remains the top priority clinically, particularly in the field of cardiac surgery. Presently, although the Gatti assessment can be used to screen some high-risk SIPs,^{11,12} it mainly applies to evaluating patients after CABG, and it does not involve the prediction model of other common types of cardiac surgery. Additionally, existing studies are based on logistic regression analysis of small sample data; the results lack visualisation

and are not individualised, and the clinical application is limited.

Based on the above background, we used large-sample clinical data on SIPs, analysed the risk factors for SIPs, and built a nomogram prediction model. We aimed to establish an efficient and accurate visualisation model of SIPs that enables clinical workers to identify high-risk patients in the early stage to provide timely and efficient intervention.

2 | PATIENTS AND METHODS

2.1 | Patient data

The data that support the findings of this study are available from the corresponding author upon reasonable request. In total, 23 182 patients were admitted to the Second Affiliated Hospital of the Army Medical University because of cardiac surgical diseases and had undergone median sternotomy from 1 August 2009 to 31 July 2019. The inclusion criteria of all cases were as follows: (1) median sternotomy and (2) at least 8 days of follow-up after sternotomy. The exclusion criteria were as follows: (1) aged younger than 18 years; (2) death within 8 days after surgery; (3) absence of medical records or obvious errors in the medical records; (4) emergency thoracotomy cases caused by infective endocarditis or heart injury; and (5) immunodeficiency or HIV antibody positivity.

2.2 | Screening of risk factors

According to a previous literature review, we collected basic information and primary disease and complication data for all the cases after median sternotomy. The basic information included sex, age, body mass index (BMI), operation time, duration of intensive care unit (ICU) time, and reasons for operation. The operation types

included VR, defect repair of congenital heart disease, CABG, aortic surgery, tumour surgery, and different combined operations. The concurrent diseases included diabetes, hypertension, hyperlipidaemia, myocardial infarction, renal failure, angina pectoris, revision for bleeding, COPD, pulmonary hypertension, cerebrovascular disease, atrial fibrillation, cardiomyopathy, heart failure, hypoproteinaemia, peripheral vascular disease, and other factors. The final outcome was the status of the SIP—that is, sternal incision with non-healing or delayed healing. According to the final outcome of the cases, independent variables with significant differences between the patients without and with SIPs were

screened out and further included in multifactor logistic regression. Next, independent risk factors with statistical significance were screened out. In this study, $P < 0.050$ was considered statistically significant.

2.3 | Construction, verification, and evaluation of the prediction model

The software used in the construction, validation, and evaluation of the prediction model included SPSS (IBM Corp., Armonk, New York) and R (R Foundation, Vienna, Austria). Before multifactor logistic regression

TABLE 1 Patient and disease characteristics

	Overall (n = 15 426)	Patients without sternal incision problems (n = 15 117)	Patients with sternal incision problems (n = 309)
Age (y), median (IQR)	48 (41-56)	48 (41-56)	51 (45-61)
Female sex, n (%)	9613 (62.3)	9421 (62.3)	192 (62.1)
BMI (kg/m ²), median (IQR)	22.4 (20.2-24.7)	22.3 (20.2-24.6)	23.7 (21.8-26.3)
BMI ≥28, n (%)	908 (5.9)	866 (5.7)	42 (13.6)
Season, n (%)			
Spring	5068 (32.9)	4962 (32.8)	106 (34.3)
Summer	3449 (22.4)	3370 (22.3)	79 (25.6)
Autumn	3415 (22.1)	3345 (22.1)	70 (22.7)
Winter	3494 (22.7)	3440 (22.8)	54 (17.5)
ICU time (d), median (IQR)	1 (1-2)	1 (1-2)	2 (1-3)
Operation time (min)	210.0 (175.0-260.0)	210.0 (175.0-260.0)	240.0 (185.0-310.0)
Revision for bleeding, n (%)	135 (0.9)	119 (0.8)	16 (5.2)
Cardiogenic shock, n (%)	22 (0.1)	20 (0.1)	2 (0.7)
Diabetes mellitus, n (%)	636 (4.1)	598 (4.0)	38 (12.3)
Hypertension, n (%)	1639 (10.6)	1572 (10.4)	67 (21.7)
Hyperlipidaemia, n (%)	418 (2.7)	400 (2.6)	18 (5.8)
Hypoproteinaemia, n (%)	150 (1.0)	142 (0.9)	8 (2.6)
COPD, n (%)	132 (0.9)	129 (0.9)	3 (1.0)
Pulmonary arterial hypertension, n (%)	5419 (35.1)	5233 (35.2)	97 (31.4)
Renal failure, n (%)	353 (2.3)	337 (2.2)	16 (5.2)
Hepatic failure, n (%)	374 (2.4)	365 (2.4)	9 (2.9)
Respiratory tract infection, n (%)	704 (4.6)	680 (4.5)	24 (7.8)
Cerebrovascular disease, n (%)	789 (5.1)	771 (5.1)	18 (5.8)
Peripheral vascular disease, n (%)	8 (0.1)	7 (0.0)	1 (0.3)
Atrial fibrillation, n (%)	1823 (11.8)	1786 (11.8)	37 (12.0)
Myocardial infarction, n (%)	241 (1.6)	229 (1.5)	12 (3.9)
NYHA class ≥3, n (%)	9686 (62.8)	9484 (62.7)	202 (65.4)
Angina, n (%)	937 (6.1)	891 (5.9)	46 (14.9)

Note: Values in parentheses are percentages unless indicated otherwise.

TABLE 2 Univariate and multivariate analyses of predictors for sternal incision problems

Variable	Univariate analysis		Multivariate analysis	
	P value	OR (95% CI)	P value	OR (95% CI)
Age	0.000	1.030 (1.020-1.040)	0.084	1.010 (0.999-1.021)
Female sex	0.947	0.992 (0.787-1.252)		
BMI	0.000	1.138 (1.104-1.173)	0.000	1.114 (1.067-1.162)
Obesity	0.000	2.589 (1.856-3.610)	0.744	0.926 (0.585-1.467)
Season				
Spring	Ref.	Ref.		
Summer	0.536	1.097 (0.817-1.473)		
Autumn	0.895	0.980 (0.722-1.329)		
Winter	0.068	0.735 (0.528-1.023)		
ICU time	0.000	1.085 (1.065-1.105)	0.000	1.057 (1.033-1.082)
Operation time	0.000	1.003 (1.002-1.004)	0.152	1.001 (1.000-1.002)
Revision for bleeding	0.000	6.882 (4.033-11.746)	0.000	5.140 (2.868-9.214)
Cardiogenic shock	0.032	4.918 (1.144-21.131)	0.524	1.666 (0.347-7.998)
Diabetes mellitus	0.000	3.404 (2.401-4.827)	0.004	1.778 (1.201-2.634)
Hypertension	0.000	2.386 (1.811-3.142)	0.978	0.995 (0.709-1.398)
Hyperlipidaemia	0.001	2.276 (1.399-3.701)	0.339	1.285 (0.769-2.148)
Hypoproteinaemia	0.005	2.803 (1.363-5.766)	0.096	1.949 (0.888-4.279)
COPD	0.824	1.139 (0.361-3.598)		
Pulmonary arterial hypertension	0.165	0.842 (0.661-1.073)		
Renal failure	0.001	2.395 (1.431-4.007)	0.684	1.125 (0.639-1.982)
Hepatic failure	0.574	1.212 (0.620-2.372)		
Respiratory tract infection	0.007	1.788 (1.170-2.731)	0.988	1.004 (0.621-1.623)
Cerebrovascular disease	0.567	1.151 (0.711-1.863)		
Peripheral vascular disease	0.069	7.008 (0.860-57.136)		
Thrombotic diseases	0.117	0.741 (0.510-1.077)		
Atrial fibrillation	0.931	1.015 (0.718-1.436)		
Myocardial infarction	0.001	2.627 (1.454-4.747)	0.711	1.128 (0.596-2.136)
NYHA class ≥ 3	0.343	1.121 (0.885-1.421)		
Angina	0.000	2.793 (2.027-3.848)	0.090	1.390 (0.949-2.034)

Note: Values in parentheses are 95% confidence intervals.

analysis, the variance inflation factor and tolerance value of each variable were calculated. If the collinearity diagnosis results showed no linear relationship, multivariate binary logistic regression analysis was performed to screen the independent risk factors. Furthermore, R was used to build the prediction model of the nomogram based on the independent risk factors. Next, three methods to verify and evaluate the model were used. First, receiver operating characteristic (ROC) curves and the concordance statistic (C-statistic) were used to evaluate and validate the predictive performance. Second, 1000 bootstrap validations were performed, the calibration

curve was drawn, the correlation between the calibration curve and the standard curve was verified and evaluated, and the Hosmer-Lemeshow test was conducted to evaluate the fitting degree of the prediction model. Finally, the clinical effectiveness of the model was evaluated by clinical decision curve analysis.

3 | RESULTS

After screening by exclusion criteria, 15 426 patients were included in this study, 5813 male (37.7%) and 9613

FIGURE 1 Nomogram to predict sternal incision problems (SIPs) after median sternotomy. To use this nomogram in individual patients, the information for four (axes 2-5) risk factors should be visualised as a point on the first axis. Next, the sum of these three points out of the total number of points should be plotted on axis 6. Next, a line is drawn downward towards the risk axis (axis 7) to determine the likelihood of an SIP in an individual patient

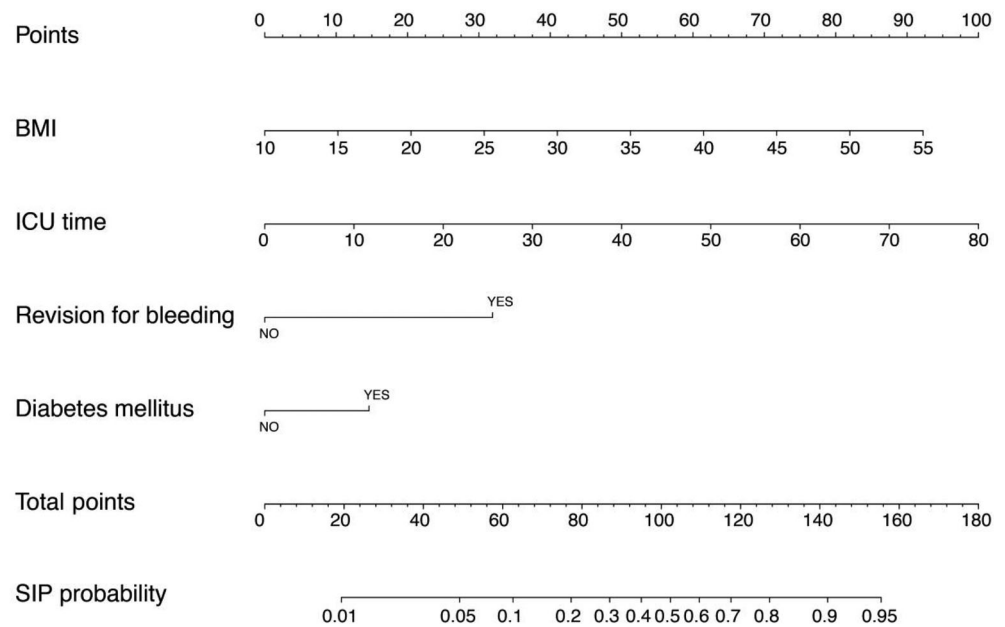
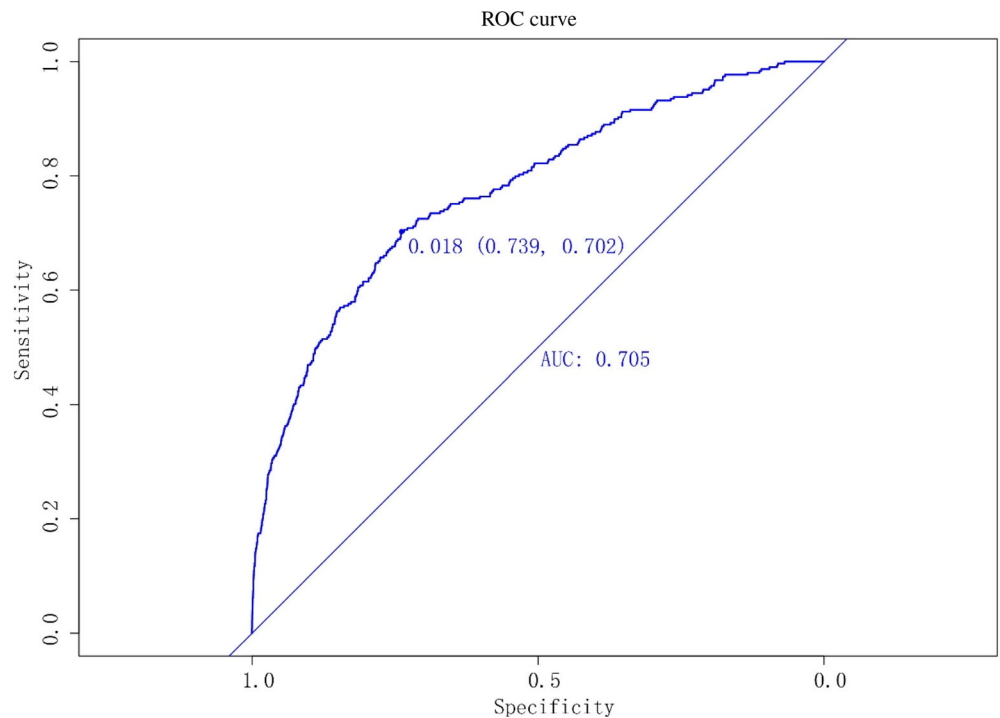


FIGURE 2 Receiver operating characteristic (ROC) curve of our model to predict sternal incision problems after median sternotomy



female (62.3%) (Table 1). The male-to-female ratio was 0.6:1. Among the included cases, 309 cases exhibited SIPs, accounting for 2% of the total patients. Among all the patients, 9315 had undergone thoracotomy because of heart VR, accounting for 60.4% of the total patients; 175 patients had SIPs, which had an incidence rate of 1.9% (Supplemental Table 1). Twenty-four clinical variables were analysed (Table 1), and the statistically significant variables were selected to apply to univariate binary logistic regression. The statistically significant variables

were further included in multivariate logistic regression, and the variables were finally introduced into the prediction model. Through single factor analysis, we found significant differences (Table 2) among the 15 variables—age, BMI, obesity, ICU time, operation time, revision for bleeding, shock, diabetes, hypertension, hyperlipidaemia, hypoproteinaemia, renal failure, respiratory tract infection, myocardial infarction, and angina. The collinearity diagnosis results for these 15 variables are also shown in Supplemental Table 2. No linear relationship was

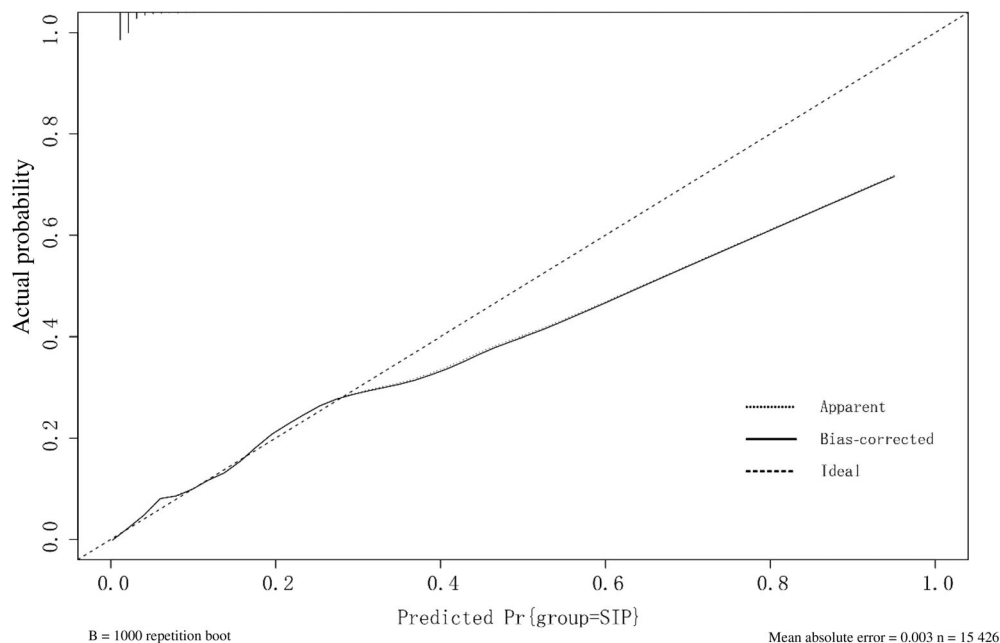


FIGURE 3 Calibration curve to predict sternal incision problems (SIPs) after median sternotomy. The nomogram-predicted probability of the SIP is plotted on the x-axis, and the actual SIP is plotted on the y-axis

observed among the 15 variables in single-factor analysis. The 15 variables were further included in multivariate logistic regression analysis, and the enter method was used. BMI, ICU time, diabetes mellitus, and revision for bleeding were independent risk factors (Table 2). To further explore the relationship between different types of surgery and SIPs, the influencing factors of individual surgical methods were analysed with respect to outcome. The disease characteristics of patients with different operation types are shown in Supplemental Tables 3-6. BMI and revision for bleeding were independent risk factors for thoracotomy of VR (Supplemental Figure 1A); revision for bleeding was an independent risk factor for thoracotomy of defect repair of congenital heart disease (Supplemental Figure 1B); sex, hypoproteinaemia and diabetes were independent risk factors for thoracotomy of CABG (Supplemental Figure 1C); and risk factors for VR combined with CABG were analysed. Obesity (BMI ≥ 28) and pulmonary hypertension were independent risk factors (Supplemental Figure 1D). Analysis of the above factors further confirmed that BMI, revision for bleeding, ICU time, and diabetes mellitus could be included in the nomogram as independent risk prediction factors for all operation types. Multivariate logistic regression analysis showed that BMI, ICU time, revision for bleeding, and diabetes mellitus were selected as independent risk factors. R software was used to establish the nomogram (Figure 1). At the same time, the risk factors for each operation type were analysed, and the nomogram was also established (Supplemental Figure 2). According to these factors, the specific

probability value of the incision problem was queried, but the probability value did not clearly indicate the degree of risk. In the next step, we used ROC curves and C-statistics to analyse the threshold value, sensitivity and specificity (Figure 2). The threshold value of the ROC curve was 0.018, its sensitivity and specificity were 0.739 and 0.702, respectively, and the area under the ROC curve—that is, area under curve (AUC) or C-statistics—was 0.705 (95% confidence interval [CI]: 0.746-0.803), indicating that the model had a certain value (Figure 2). When the predicted probability was greater than 0.018, the risk of incision problems was high. The ROC curves of different surgical methods were drawn, and the AUC values of the different models were found to be similar but had certain predictive values (Supplemental Figure 4).

To further verify the validity of the model, R was adopted to establish the calibration curve (Figure 3). The calibration curve of the model showed a relatively acceptable goodness of fit with the standard ideal curve, which is the ideal situation where the probability of occurrence predicted by the corresponding model is completely consistent with the actual probability of occurrence (Figure 3). Additionally, the Hosmer-Lemeshow goodness of fit test showed that $\chi^2 = 6.987$, $P = 0.538$, further indicating that the model has good fitting validity and high prediction value. At the same time, we also established calibration curves of the different surgery types and performed the Hosmer-Lemeshow test on each model. The relative fitting degrees of the VR and CABG models were better (Supplemental Figure 5).

To further evaluate its clinical effectiveness, R was used to draw the clinical decision curve (Supplemental Figure 3). Most areas of the decision curve of the model were greater than 0, indicating certain clinical effectiveness (Supplemental Figure 3). Additionally, from the perspective of prediction models by operation type, each model showed good sound benefit (Supplemental Figure 6). These results demonstrated that all the models had a certain predictive value.

4 | DISCUSSION

Since the early 1950s, the implementation of cardiopulmonary bypass and cardiac surgery has developed rapidly; however, at the same time, the incidence of incision problems after median sternotomy has also shown an upward trend.^{2,3} Because of the special location, the skin and subcutaneous tissue are relatively weak and the sternotomy incision is associated with a large amount of tension, leading to a relatively high risk of complications.^{9,11,12} Generally, complications of sternal incisions or wounds include infection of the sternal incision that can cultivate microorganisms in the traditional sense. For example, infection of a superficial sternal incision involving the skin, subcutaneous tissue, and fascia of the pectoralis major muscle or infection of a deep sternal incision can involve osteomyelitis of the sternum, cystitis, costochondritis, and mediastinitis. Additionally, SIPs include issues with healing of the incision without obvious microorganism infection, such as incision fat liquefaction, suture rejection, and other problems involving non-healing or delayed healing.^{2,3,14}

Previous studies have shown that, among patients undergoing open-heart surgery, those receiving CABG and combined CABG are more likely to have postoperative incision problems. On the one hand, CABG surgery itself is likely to be an independent risk factor for postoperative incision problems.¹⁰ On the other hand, most elderly patients with CABG have diabetes mellitus and a medical history of poor blood control.¹¹ Furthermore, CABG often requires transplantation of the internal thoracic artery, leading to infection of the deep sternal incision.¹⁵⁻¹⁷ Gattia's study identified six factors—sex, obesity, diabetes, blood glucose control, chronic lung disease, and emergency surgery—as independent risk factors for deep chest incision infection and established a predictive model.^{11,12} An analysis by Meszaros in 2016 revealed that, in patients with CABG, bilateral internal thoracic artery resection, an operation duration of more than 300 minutes, diabetes, obesity, COPD, and sex were independent risk factors for SIPs¹⁰; however, in patients

with VR, revision for bleeding and diabetes were independent risk factors.

In the present study, the incidence of SIPs increased with increasing ICU time. This outcome was related to the patient's basic condition and concurrent diseases. Additionally, many studies have reported that a prolonged hospital stay increases the risk of infection.¹⁸ The extension of the ICU time indicates that the basic condition of the patient is not good. Furthermore, many positive inotropic drugs are used in the ICU, likely leading to an unstable hemodynamic state, reduced incision perfusion, and changes in the local immune response, resulting in the occurrence of SIPs. The prolonged ICU time could also lead to a decline in autoimmunity, which greatly increases the risk of problems.¹⁹ Additionally, positive-pressure ventilation is often used in the ICU, and the pressure exerted by positive-pressure ventilation on the chest wall is different from the physiological negative pressure of normal breathing, causing additional mechanical pressure to the sternal incision and seriously affecting its healing.²⁰

For patients undergoing revision for bleeding, the body is traumatised again when the patient has low immunity. Additionally, because of anaesthesia drug use, body blood loss, and fluid loss, further damage can occur.²¹ Furthermore, the sternal incision tissue will be mechanically damaged again, and the wound will be exposed to air for a long time, increasing the chance of infection.^{22,23} Kristensen et al showed that the complication rate of deep sternal incisions was 11.1% in patients who required a second operation because of bleeding after heart surgery that was three times higher than that in patients who did not require a second operation.²¹

Related retrospective studies have shown that poor glycaemic control of diabetes mellitus is an important risk factor for deep sternal incision infection.^{3,20} Furnary et al found that lowering the blood sugar levels in diabetic patients after cardiac surgery reduces the incidence of SIPs.²⁴ After the operation, blood glucose stress caused an increase in blood glucose and a decrease in insulin sensitivity, resulting in increased blood glucose and failure of effective control and neovascularization, which affect healing of the sternal incision.²⁴ Many studies have shown that postoperative wound healing in diabetic patients is delayed, and postoperative infection occurs easily.²⁵ Therefore, blood glucose must be controlled during the perioperative period in patients with diabetes who require thoracotomy.

Previously, once the problem of sternal incision occurred, the chronic refractory wound patient was transferred to the plastic surgery department for treatment. Presently, after establishing a personalised prediction model, surgeons with extensive experience in wound

diagnosis and treatment can intervene in advance. Once high-risk patients are screened out and the risk level for a hospital stay for cardiac surgery is reached, we will intervene in advance.

ACKNOWLEDGEMENTS

This study was supported by the Training Plan of Clinical Scientific Research Talents in Army Medical University, China, under Grant No. 2018XLC3025.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest.

AUTHOR CONTRIBUTIONS

All the authors were involved in the design of the study. YP and ZX were major contributors in collecting and analysing and interpreting the data. All the authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The present study was approved by the Medical Ethics Committee of Second Affiliated Hospital of Army Medical University, PLA.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: You P, Zhou X, He P, et al. A nomogram prediction model for sternal incision problems. *Int Wound J.* 2022;19(2):253–261. <https://doi.org/10.1111/iwj.13626>