DOI:10.16016/j.2097-0927.202507047

心血管手术患者术后呼吸衰竭的危险因素及预测模型构建

周辅超,刘 祥,鲁开智,邵建良 陆军军医大学(第三军医大学)第一附属医院麻醉科,重庆

［摘要］ **目的** 基于机器学习算法识别心血管手术患者术后呼吸衰竭(postoperative respiratory failure, PORF)的危险因素,并构建特异性的风险预测模型。**方法** 回顾性的纳入INSPIRE数据库2011到2020年间行心血管手术的1 623例患者,进行数据质量分析后,使用多重插补处理缺失数据,并采用Boruta筛选相关特征变量。基于筛选指标构建8种机器学习模型,包括GBM、GLM、XGBoost、KNN、NNET、NB、SVM及RF,以曲线下面积(area under the curve, AUC)、灵敏度、特异性等指标评估模型性能,并基于排列重要性算法识别对PORF有重要影响的变量。**结果** PORF总体发生率为27.05%(439/1 623),PORF组患者院内死亡率显著高于非PORF组(12.98% *vs.* 1.60%,$P<0.001$)。建立的预测模型中,SVM模型效果较好,在测试集中,该模型AUC达到0.705,其灵敏度、特异度、阳性和阴性预测值分别为0.481、0.825、0.504、0.812。根据特征重要性计算,对术后呼吸衰竭预测影响最大的前十个变量为麻醉时长、动脉血二氧化碳分压、钙、淋巴细胞百分比、体外循环时长、术中出血量、年龄、肌酐、天门冬氨基酸氨基转移酶和活化部分凝血活酶时间。**结论** 本研究成功构建了预测心血管手术患者术后呼吸衰竭的模型,该模型可以识别出高危患者及其发生呼吸衰竭的概率,促进数据驱动的临床决策。

［关键词］ 心血管手术;术后呼吸衰竭;机器学习;预测模型
［中图法分类号］ R181.32;R563.806;R654.06 ［文献标志码］ A

Risk factors for postoperative respiratory failure in patients undergoing cardiovascular surgery and construction of a prediction model

ZHOU Fuchao, LIU Xiang, LU Kaizhi, SHAO Jianliang Department of Anesthesiology, First Affiliated Hospital, Army Medical University (Third Military Medical University), Chongqing, China

［**Abstract**］ Objective To identify risk factors for postoperative respiratory failure (PORF) in cardiovascular surgery patients using machine learning algorithms and to construct a specific risk prediction model. Methods A retrospective cohort was conducted on 1 623 patients undergoing cardiovascular surgery between 2011 and 2020 from the INSPIRE database. Following data quality analysis, multiple imputation was employed to handle missing data, and the Boruta algorithm was used for feature selection. Eight machine learning models were constructed based on the selected features, including Gradient Boosting Machine (GBM), Generalized Linear Model (GLM), Extreme Gradient Boosting (XGBoost), K-Nearest Neighbors (KNN), Neural Network (NNET), Naive Bayes (NB), Support Vector Machine (SVM), and Random Forest (RF). Model performance was evaluated using metrics including the area under the curve (AUC), sensitivity, and specificity. Variables significantly influencing PORF were identified using the permutation importance

［通信作者］ 鲁开智,E-mail:lukaizhi2010@163.com;
邵建良,E-mail:654708721@qq.com

2097-0927/Copyright © 2025, 陆军军医大学(第三军医大学)。这篇开放获取文章遵循CC BY许可协议(https://creativecommons.org/licenses/by/4.0/)
引用格式:周辅超,刘祥,鲁开智,等.心血管手术患者术后呼吸衰竭的危险因素及预测模型构建[J].陆军军医大学学报,2025,47(16):1970-1980.DOI:10.16016/j.2097-0927.202507047.
Citation:ZHOU F C, LIU X, LU K Z, *et al*. Risk factors for postoperative respiratory failure in patients undergoing cardiovascular surgery and construction of a prediction model[J]. J Army Med Univ, 2025, 47(16):1970-1980. DOI:10.16016/j.2097-0927.202507047.

algorithm. **Results** The overall incidence of PORF was 27.05% (439/1 623). The in-hospital mortality rate was significantly higher in the PORF group than the non-PORF group (12.98% *vs* 1.60%, $P<0.001$). Among the developed models, the SVM model demonstrated the best performance, achieving an AUC of 0.705 in the testing set, with a sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of 0.481, 0.825, 0.504, and 0.812, respectively. Based on feature importance analysis, the top 10 variables most predictive of PORF were anesthesia duration, arterial partial pressure of carbon dioxide ($PaCO_2$), calcium level, lymphocyte percentage, cardiopulmonary bypass duration, intraoperative blood loss, age, creatinine level, aspartate aminotransferase (AST) level, and activated partial thromboplastin time (aPTT). **Conclusion** A predictieon model for PORF following cardiovascular surgery is successfully developed. This model can identify high-risk patients and estimate their probability of developing respiratory failure, thereby facilitating data-driven clinical decision-making.

[**Key words**] cardiovascular surgery; postoperative respiratory failure; machine learning; prediction model

Corresponding authors: LU Kaizhi, E-mail: lukaizhi2010@163.com; SHAO Jianliang, E-mail: 654708721@qq.com

心血管手术后发生肺部并发症的风险高,而术后呼吸衰竭(Postoperative Respiratory Failure, PORF)是最严重的肺部并发症之一,会导致围术期医疗费用、住院时间以及死亡率的增加[1]。已有报道中,心血管手术PORF的发生率从1.96%到43.7%不等,具体取决于患者相关风险因素、手术类型及其定义[2]。心血管手术中的心脏直视手术常包含胸廓切开术、心肺转流(cardiopulmonary bypass, CPB)、低体温心肌保护等步骤,会导致胸廓顺应性、膈肌和肋间肌功能降低[2-3]。而心脏介入手术器械操作可能直接损伤血管内皮,激活血小板与凝血级联反应[4]。同时,手术应激导致的儿茶酚胺大量释放会引发血流动力学波动,进一步造成远端器官(如肺)的微血栓形成与缺血-再灌注损伤[5]。此外,心血管手术和机械通气还会激活局部和全身炎症反应,从而增加肺部急性损伤的风险[6-8]。

鉴于PORF对心血管手术患者预后的严重影响,需早期识别发生PORF的高危患者,采取针对性的干预措施,改善患者的预后。现已有多种风险评分工具被用于评估心血管手术和非心血管手术后肺部并发症的发生风险,包括术后肺炎、PORF等[9]。然而,这些工具并不是心血管手术特异性的,未能全面纳入心血管手术特有的风险因素,如麻醉时间、体外循环时间、术中出血量等术中关键信息,因此在预测方面存在局限性。此外,针对高风险心血管手术及PORF的标准化预测模型尚且缺乏,无法为临床决策提供足够精准的支持。相比传统统计学以及风险评分,基于机器学习的预测模型能够高效处理和分析海量的临床数据,发现数据中的隐藏模式,从中挖掘出深层次的、非线性的风险因素关联,提供更加精准的风险概率预测,从而提高临床决策的针对性和有效性。

本研究旨在基于机器学习算法,利用已有数据库,探索影响心血管手术患者PORF发生的风险因素,并开发一种预测模型,为临床医生提供及时、个性化的诊疗支持,为优化心血管手术患者的围术期管理,以期改善预后。

1 材料与方法

1.1 数据采集

本研究数据来源于INSPIRE数据库[10]。这是一个公开可用的围手术期医学研究数据集,涵盖了2011年至2020年在韩国某学术机构接受麻醉手术的大约13万例病例,占所有外科手术病例的50%。该数据集涵盖了患者的详细信息,包括年龄、性别、美国麻醉医师协会(american society of anesthesiologists, ASA)分级、诊断、手术程序编码、科室以及麻醉类型。此外,数据集还记录了患者在手术室、普通病房和重症监护病房(intensive care unit, ICU)中的生命体征,以及从入院前6个月到出院后6个月的实验室检查结果。同时,数据集还包含了患者在住院期间的用药情况。并发症相关的信息包括总住院时间、ICU住院时间以及院内死亡情况。数据由作者(认证号:62584102)从https://physionet.org/content/inspire/获取,该数据库遵循开放数据共享原则,无需患者个人知情同意[10]。

本研究拟对行心血管手术患者PORF进行分析,纳入标准:①行心血管手术的患者;②成年患者,年龄>18岁;③术后进入ICU接受治疗。排除术前就存在呼吸衰竭的患者。心血管手术根据ICD-10编码进行

选择,编码如下:02RF0,02110,02CP0,02VP0,021P0,02RJ0,02QJ0,02RG0,02Q50,021K0,02RP0,02QF0,02CN0,02BN0,02SP0,02QA0,02B64,02B60,02100,02CN4,02B6X,02LS3,02QG0,02QM0,02BK0,02RA0,02QN0,02QX0,027H0,02BF0,02YA0,021W0,02LF0,02LP0,02SPX,02B63,02BN4,02HP0,02QP0,02JA0,02YF0,021G0,02BRX,02BW0,02BA0,02J60,021F0,02HA0,02BP0,02NA0,02J64,02UF0,02B50,02Q60,02C60,02QK0,02B04,029N0,02R50,02JA4,027P3,02CW0,02RP4,02JF0,020J3,02RX0。

呼吸衰竭本身被定义为氧气和二氧化碳交换不足,使用较为广泛的标准根据血气分析结果进行诊断,即:当在海平面呼吸空气时,氧气分压(PaO_2)低于60 mmHg和/或二氧化碳分压超过50 mmHg[吸入氧分数(FIO_2)为0.21]。生理条件下,在没有酸中毒或高碳化导致血红蛋白解离曲线移位的情况下,PaO_2为60 mmHg对应的动脉血氧饱和度为90%。在临床环境中,低氧血症的严重程度通过计算PaO_2与FiO_2的比率来定义,PaO_2/FiO_2<300 mmHg时诊断为呼吸衰竭。PORF可以定义为手术后出现的肺部气体交换障碍,是麻醉和手术引起的相关变化的结果。美国医疗保健研究与质量局(agency for healthcare research and quality, AHRQ)将PORF定义为手术后48 h内未能脱离机械通气或术后计划外插管/再插管[11],而欧洲围手术期临床结局(European perioperative clinical outcomes, EPCO)将PORF定义为术后室内空气环境下PaO_2<60 mmHg,或PaO_2/FiO_2比值<300 mmHg,或脉搏血氧仪测得动脉氧合血红蛋白饱和度<90%且需要吸氧治疗。PORF的严重程度可以从术后早期的短暂低氧血症到最具生命危险的急性呼吸窘迫综合征[12]。由于心脏外科患者术后常规进入ICU,因此本研究在判断患者是否存在呼吸衰竭时结合上述3种标准进行评估。

通过INSPIRE数据提取符合纳入排除标准的患者的hadm_id(住院ID)以及op_id(手术ID),纳入患者的术前及手术相关临床指标如下:①一般资料:年龄,性别,体质指数(Body Mass Index, BMI);②手术相关指标:ASA分级,麻醉方式,手术类型(心包手术、大血管手术、冠脉手术、瓣膜手术、其他),麻醉时长,体外循环时长,术中出血量;③术前检验指标(距离手术开始时间最近的一次结果):肌酐,尿素氮,磷,氯,钾,钠,丙氨酸氨基转移酶,天门冬氨酸氨基转移酶,碱性磷酸酶,总胆红素,白蛋白,总蛋白,钙,纤维蛋白原,活化部分凝血活酶时间,凝血酶原时间国际标准化比值,血糖,淋巴细胞百分比,中性粒细胞百分比,血小板,红细胞压积,血红蛋白,白细胞计数,C反应蛋白,乳酸,离子钙,氧饱和度,碳酸氢根,氧分压,二氧化碳分压,pH值,碱剩余;④术前药物使用情况:氨甲环酸、β受体阻滞剂、ACEI类药物;⑤合并症:慢性阻塞性肺病、脑血管疾病、重大心血管疾病(冠心病、主动脉瘤和夹层、缺血性心脏病、心脏瓣膜病、心房颤动)、高血压、糖尿病、凝血功能障碍。

1.2 数据处理以及模型构建、评价

本研究的整个过程包括数据预处理、特征选择、模型拟合和评估。

在数据预处理阶段,首先使用R语言中的tidyverse包针对数据质量进行分析,包括数据缺失情况统计、特征分布检查、异常值检测。针对数据集中的缺失值问题,首先对缺失大于40%的指标予以去除,然后采用了R语言中的MICE(multivariate imputation by chained equations)包进行多重插补[13],以确保数据的完整性和准确性。随后,为了消除不同量纲特征对模型训练的影响,使用base包对连续变量进行了归一化处理和标准化,使得这些特征值被缩放到一个统一的范围内,并将数据集随机分为训练(70%)和测试(30%)两个子数据集,使用训练数据集进行特征选择和模型拟合,在测试数据集进行模型评估开展内部验证。特征选择采用Boruta方法,Boruta是一种基于随机森林的特征选择算法。它通过构建随机森林模型并引入影子特征(shadow features),利用特征重要性来评估每个特征的相关性。Boruta能够有效地识别出对目标变量具有显著影响的特征,同时剔除那些不重要或冗余的特征。这种方法有助于降低模型的复杂度,减少过拟合的风险,并提高模型的解释性[14]。本研究中,Boruta方法通过R软件中Boruta包实现[15]。

选择8种传统的机器学习算法,使用R语言中的caret包进行模型构建,包括梯度增强机(gradient boosting machine, GBM)、广义线性模型(generalized linear model, GLM)、极端梯度增强(extreme gradient boosting, XGBoost)、神经网络(neural network, NNET)、K最邻近(k-nearest neighbors, KNN)、朴素贝叶斯(naive bayes, NB)、支持向量机(support vector machine, SVM)以及随机森林(random forest, RF)。

构建完成后,通过受试者工作特征(receiver operating characteristic, ROC)曲线、曲线下面积(area

under the curve, AUC)、灵敏度(true positive Rate, TPR)、特异性(true negative rate, TNR)、阳性预测值(positive predictive value, PPV)、阴性预测值(negative predictive value, NPV)、准确性(accuracy, ACC)、F1评分来评价模型的性能。通过决策曲线分析(decision curve analysis, DCA)对模型进行评价,评估模型的临床效益和效用[16]。同时,还利用校准曲线评价模型的校准度。为了研究与PORF相关的重要变量,使用R语言中的h2o包在最终选择的模型上对训练数据集进行了特征重要性排序。

1.3 样本量估计与统计学分析

由于本研究属于二分类问题,适用于采用事件数法则(events per variable, EPV)来估计样本量,我们使用的EPV为20,远高于常被引用的阈值10。估计样本量为56(变量数)×20(EPV值)=1 120例,实际纳入了1 623例患者,大于估计样本量,这显著降低了过拟合的风险[17]。

连续变量用平均值±标准差或中位数及四分位间距表示。分类变量用频率和百分比表示。对于正态分布的连续变量使用t检验进行组间比较,不满足正态分布的连续变量使用Mann-Whitney U检验。分类变量采用卡方检验或Fisher精确检验。所有统计分析均遵循双尾检验的原则,并设定显著性水平为$\alpha=0.05$,即$P<0.05$时认为差异具有统计学意义。本研究所涉及的全部数据分析工作,均在SPSS软件(版本26.0,IBM公司)及R语言环境(版本4.2.2)中完成。

2 结果

2.1 数据基线特征

本研究从INSPIRE数据库纳入了1 623例患者(图1),其中439例出现了PORF,76人出现了院内死亡。PORF组和非呼吸衰竭组的人口特征、实验室结果比较见表1。PORF组患者,男性更多、年龄更大、合并症更多、炎性指标更高、ASA分级更高以及住院死亡率更高等($P<0.05$)。

表1 术后呼吸衰竭组和非呼吸衰竭组的人口特征基线表

Table 1 Baseline demographic data of the postoperative respiratory failure group and the non-postoperative respiratory failure group [$M(P_{25}, P_{75})$, $n(\%)$]

Indicators	Non-postoperative respiratory failure (n=1 184)	Postoperative respiratory failure (n=439)	Z/χ^2	P-value
Age, years	60.00(50.00,70.00)	65.00(55.00,75.00)	-2.928	0.003
Gender			25.816	<0.001
Female	591(49.92%)	157(35.76%)		
Male	593(50.08%)	282(64.24%)		
Body Mass Index/(kg/m^2)	23.42(21.19,25.76)	23.38(20.43,25.91)	-1.242	0.214
ASA			64.513	<0.001
Ⅰ	116(9.96%)	28(6.50%)		
Ⅱ	481(41.29%)	103(23.90%)		
Ⅲ	525(45.06%)	260(60.32%)		
Ⅳ	42(3.61%)	38(8.82%)		
Ⅴ	1(0.09%)	2(0.46%)		
Emergency			1.615	0.204
No	1 047(88.43%)	378(86.10%)		
Yes	137(11.57%)	61(13.90%)		
Anesthesia method			4.859	0.088
Monitoring Anesthesia	10(0.84%)	0(0.00%)		
Nerve Block Anesthesia	3(0.25%)	0(0.00%)		
General Anesthesia	1 171(98.90%)	439(100.00%)		
Surgery type			14.195	0.007
Pericardial Surgery	55(4.65%)	14(3.19%)		
Great Vessel Surgery	17(1.44%)	5(1.14%)		
Coronary Surgery	168(14.19%)	95(21.64%)		
Valve Surgery	736(62.16%)	256(58.31%)		
Other	208(17.57%)	69(15.72%)		

续表1 术后呼吸衰竭组和非呼吸衰竭组的人口特征基线表

Table 1 Baseline demographic data of the postoperative respiratory failure group and the non-postoperative respiratory failure group [$M(P_{25}, P_{75})$, $n(\%)$]

Indicators	Non-postoperative respiratory failure (n=1 184)	Postoperative respiratory failure (n=439)	Z/χ^2	P-value
Surgical Approach			1.033	0.310
Minimally Invasive	32(2.70%)	8(1.82%)		
Open	1 152(97.30%)	431(98.18%)		
Anesthesia Duration, minutes	315.00(220.00,420.00)	425.00(331.25,520.00)	−11.781	<0.001
Cardiopulmonary Bypass Duration, minutes	115.00(0.00,190.00)	185.00(115.00,240.00)	−10.702	<0.001
Surgical Blood Loss/mL	240.56(0.00,698.36)	385.92(0.00,931.39)	−3.057	0.002
Creatinine/(mmol/L)	0.84(0.71,1.05)	0.92(0.77,1.16)	−5.903	<0.001
Blood Urea Nitrogen/(mg/dL)	16.00(12.00,21.00)	17.00(12.00,21.00)	−3.147	0.002
Phosphorus/(mmol/L)	3.60(3.20,3.90)	3.50(2.90,3.90)	−1.504	0.133
Chloride/(mg/dL)	104.00(102.00,106.00)	103.00(100.25,106.00)	−2.743	0.006
Potassium/(mmol/L)	3.60(3.40,4.00)	3.80(3.40,4.00)	−1.856	0.063
Sodium/(mmol/L)	137.00(136.00,139.00)	136.00(135.00,139.00)	−6.599	<0.001
Alanine Aminotransferase/(U/L)	18.00(13.00,27.00)	20.00(13.00,30.00)	−1.922	0.055
Aspartate Aminotransferase/(U/L)	22.00(18.00,28.00)	24.00(19.00,35.00)	−5.385	<0.001
Alkaline Phosphatase/(U/L)	64.00(52.00,80.00)	68.00(55.00,86.00)	−2.667	0.008
Total Bilirubin/(mg/dL)	0.70(0.50,0.80)	0.80(0.50,1.20)	−5.705	<0.001
Albumin/(g/dL)	4.10(3.90,4.30)	4.00(3.60,4.20)	−5.584	<0.001
Total Protein/(g/dL)	6.90(6.50,7.30)	6.90(6.40,7.30)	−2.776	0.006
Calcium/(mg/dL)	9.00(8.60,9.30)	8.80(8.50,9.20)	−4.186	<0.001
Fibrinogen/(mg/dL)	301.00(263.00,357.00)	301.00(263.00,357.00)	−1.170	0.242
Activated Partial Thromboplastin Time, seconds	31.70(29.60,34.70)	33.80(30.10,38.20)	−6.456	<0.001
International Normalized Ratio	1.00(0.95,1.07)	1.03(0.97,1.20)	−6.249	<0.001
Blood Glucose/(mg/dL)	105.00(91.00,132.00)	115.00(96.00,145.00)	−4.633	<0.001
Lymphocyte Percentage	28.70(22.10,37.80)	24.10(18.30,31.30)	−6.262	<0.001
Neutrophil Percentage	58.60(53.10,67.50)	63.20(56.00,71.70)	−5.420	<0.001
Platelet/($\times10^3$/μL)	211.00(166.00,258.00)	189.00(152.00,233.00)	−4.821	<0.001
Hematocrit	35.20(31.00,40.40)	35.20(30.00,39.75)	−1.724	0.085
Hemoglobin/(g/dL)	12.90(11.60,14.20)	12.50(11.00,14.20)	−2.695	0.007
White Blood Cell/($\times10^3$/μL)	6.30(5.20,7.46)	6.30(5.20,7.90)	−2.498	0.012
C-Reactive Protein/(mg/dL)	0.11(0.02,0.31)	0.19(0.06,0.77)	−6.286	<0.001
Lactic Acid/(mmol/L)	0.90(0.60,1.40)	0.90(0.80,1.50)	−1.417	0.156
Ionized Calcium/(mmol/L)	1.10(1.06,1.14)	1.10(1.05,1.14)	−0.437	0.662
Oxygen Saturation	99.00(98.00,100.00)	99.20(98.00,100.00)	−0.904	0.366
Bicarbonate/(mmol/L)	25.40(24.20,27.20)	25.80(23.80,27.80)	−2.260	0.024
Arterial Oxygen Pressure/mmHg	153.00(110.00,209.00)	165.00(110.00,227.80)	−0.790	0.43
Arterial Carbon Dioxide Pressure/mmHg	38.00(35.00,41.40)	40.00(35.00,42.30)	−2.697	0.007
pH	7.42(7.40,7.45)	7.42(7.39,7.46)	−0.178	0.859
Residual Alkali/(mmol/L)	0.40(−1.40,1.30)	0.40(−1.40,2.30)	−0.061	0.061
Chronic obstructive pulmonary disease	24(2.0%)	10(2.3%)	0.098	0.754
Cerebrovascular disease	107(9.04%)	31(7.06%)	1.607	0.205
Major cardiovascular disease	502(42.40%)	255(58.09%)	31.670	<0.001
Hypertension	147(12.42%)	75(17.08%)	5.912	0.015
Diabetes	100(8.45%)	45(10.25%)	1.282	0.258
Coagulation Dysfunction	8(0.68%)	19(4.33%)	26.114	<0.001
In-hospital death	19(1.60%)	57(12.98%)	92.910	<0.001
Preoperative use of tranexamic acid	30(2.53%)	33(7.52%)	21.316	<0.001
Preoperative use of β-blockers	354(29.90%)	145(33.03%)	1.474	0.225
Preoperative use of ACEI drugs	41(3.46%)	29(6.61%)	7.666	0.006

ASA, American Society of Anesthesiologists

数据质量分析未发现除缺失值外需特殊处理的显著质量问题。34个变量存在缺失值,缺失情况见表2。使用MICE包进行多重插补后,插补后的数据与原始数据之间的分布无统计学差异,见表3(P>0.05)。

2.2 特征筛选结果

经过Boruta分析,选出了31个关键变量作为预测PORF的重要因素,分别是年龄、性别、ASA分级、麻醉时长、体外循环时长、手术出血量、肌酐、尿素氮、钠、天门冬氨酸氨基转移酶、总胆红素、白蛋白、总蛋白、钙、活化部分凝血活酶时间、国际标准化比值、血糖、淋巴细胞百分比、中性粒细胞百分比、红细胞压积、血红蛋白、白细胞计数、C反应蛋白、碳酸氢根、二氧化碳分压、pH值、碱剩余、重大心血管疾病、凝血功能障碍、术前使用氨甲环酸情况和术前使用ACEI类药物情况,具体筛选结果及相应系数见图2。

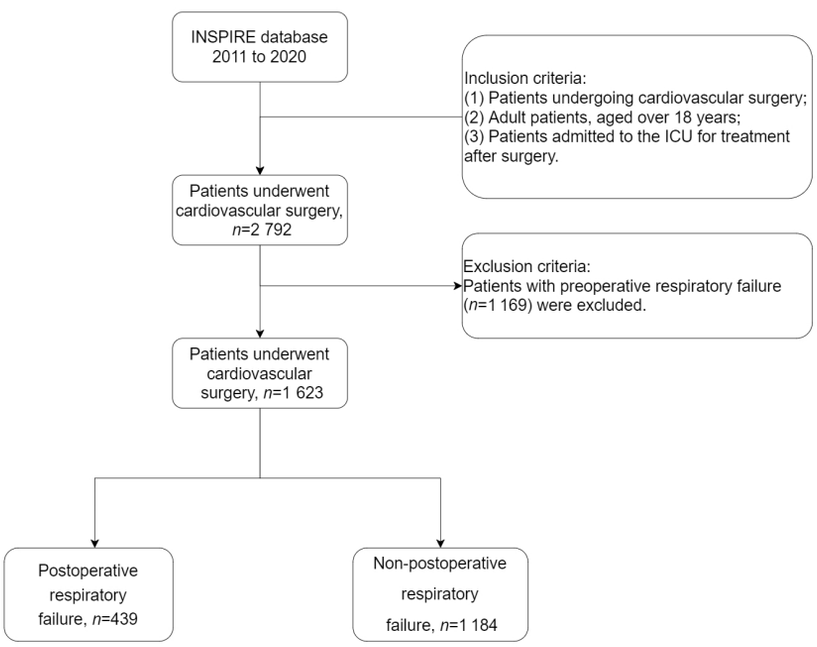


图1 纳入排除流程情况

Figure 1 Flowchart for inclusion and exclusion of the participants

表2 缺失情况表

Table 2 Information about the missing data

Index	Missing number(n)	Missing Percentage	Index	Missing number(n)	Missing Percentage
Body Mass Index	9	0.55%	International Normalized Ratio	36	2.22%
ASA	27	1.66%	Glucose	27	1.66%
Creatinine	24	1.48%	Lymphocytes	205	12.63%
Blood Urea Nitrogen	28	1.73%	Neutrophils	205	12.63%
Phosphorus	41	2.53%	Platelets	30	1.85%
Chloride	20	1.23%	Hematocrit	3	0.18%
Potassium	7	0.43%	Hemoglobin	21	1.29%
Sodium	7	0.43%	White Blood Cells	22	1.36%
Alanine Aminotransferase	35	2.16%	C-Reactive Protein	121	7.46%
Aspartate Aminotransferase	35	2.16%	Lactic Acid	302	18.61%
Alkaline Phosphatase	52	3.20%	Ionized Calcium	281	17.31%
Total Bilirubin	53	3.27%	Oxygen Saturation	90	5.55%
Albumin	51	3.14%	Bicarbonate	90	5.55%
Total Protein	46	2.83%	Arterial Oxygen Pressure	118	7.27%
Calcium	41	2.53%	Arterial Carbon Dioxide Pressure	118	7.27%
Fibrinogen	69	4.25%	pH	118	7.27%
Activated Partial Thromboplastin Time	51	3.14%	Base Excess	415	25.57%

表3 缺失指标插补前后统计表

Table 3 Statistical comparison before and after imputation of missing indicators [$M(P_{25}, P_{75})$, $n(\%)$]

Indicator	Before imputation	After imputation	Z/χ^2	P-value
BMI/(kg/m^2)	23.42 (21.00,25.78)	23.42 (21.00,25.78)	-0.013	0.991
ASA			0.028	1
Ⅰ	144 (9.02%)	148 (9.12%)		
Ⅱ	584 (36.59%)	593 (36.54%)		
Ⅲ	785 (49.19%)	799 (49.23%)		
Ⅳ	80 (5.01%)	80 (4.93%)		
Ⅴ	3 (0.19%)	3 (0.18%)		
Creatinine/(mg/dL)	0.84 (0.71,1.05)	0.84 (0.71,1.05)	-0.140	0.903
Blood Urea Nitrogen/(mg/dL)	16.00 (12.00,21.00)	16.00 (12.00,21.00)	-0.245	0.832
Phosphorus/(mg/dL)	3.50 (3.20,3.90)	3.50 (3.20,3.90)	-0.125	0.914
Chloride/(mmol/L)	103.00 (101.00,106.00)	103.00 (101.00,106.00)	-0.007	0.995
Potassium/(mmol/L)	3.60 (3.40,4.00)	3.60 (3.40,4.00)	-0.960	0.934
Sodium/(mmol/L)	137.00 (135.00,139.00)	137.00 (135.00,139.00)	-0.048	0.966
Alanine Aminotransferase/(U/L)	18.00 (13.00,30.00)	18.00 (13.00,30.00)	-0.053	0.963
Aspartate Aminotransferase/(U/L)	23.00 (18.00,31.00)	23.00 (18.00,31.00)	-0.108	0.926
Alkaline Phosphatase/(U/L)	64.00 (52.00,80.00)	64.00 (52.00,80.00)	-0.200	0.986
Total Bilirubin/(mg/dL)	0.70 (0.50,1.00)	0.70 (0.50,1.00)	-0.356	0.757
Albumin/(g/dL)	4.10 (3.80,4.30)	4.10 (3.80,4.30)	-0.374	0.745
Total Protein/(g/dL)	6.90 (6.50,7.30)	6.90 (6.50,7.30)	-0.142	0.902
Calcium/(mg/dL)	8.90 (8.60,9.30)	8.90 (8.60,9.30)	-0.254	0.826
Fibrinogen/(mg/dL)	301.00 (263.00,357.00)	301.00 (263.00,357.00)	-0.138	0.905
Activated Partial Thromboplastin Time, seconds	32.30 (29.60,34.70)	31.70 (29.60,34.70)	-0.339	0.768
International Normalized Ratio	1.00 (0.95,1.09)	1.00 (0.95,1.09)	-0.369	0.749
Glucose/(mg/dL)	110.00 (91.00,138.00)	110.00 (91.00,132.00)	-0.184	0.873
Lymphocyte Percentage	28.70 (20.10,34.10)	28.70 (22.10,34.10)	-1.378	0.228
Neutrophil Percentage	61.00 (53.10,67.50)	58.60 (53.10,67.50)	-1.357	0.235
Platelets/(×10^3/μL)	200.00 (166.00,258.00)	211.00 (166.00,258.00)	-0.133	0.908
Hematocrit	35.20 (31.00,40.40)	35.20 (31.00,40.40)	-0.009	0.994
Hemoglobin/(g/dL)	12.90 (11.30,14.20)	12.90 (11.30,14.20)	-0.197	0.864
White Blood Cells/(×10^3/μL)	6.30 (5.20,7.46)	6.30 (5.20,7.46)	-0.041	0.972
C-Reactive Protein/(mg/dL)	0.11 (0.06,0.50)	0.11 (0.06,0.50)	0.500	0.663
Lactate/(mmol/L)	0.90 (0.60,1.40)	0.90 (0.60,1.40)	0.606	0.593
Ionized Calcium/(mmol/L)	1.10 (1.05,1.14)	1.10 (1.06,1.15)	-3.566	0.002
Oxygen Saturation	99.00 (98.00,100.00)	99.00 (98.00,100.00)	-1.403	0.222
Bicarbonate/(mmol/L)	25.80 (23.80,27.20)	25.40 (23.80,27.20)	-0.422	0.714
Arterial Blood Oxygen Pressure/mmHg	165.00 (110.00,227.80)	153.00 (110.00,209.00)	-1.984	0.084
Arterial Blood Carbon Dioxide Pressure/mmHg	38.00 (35.00,41.40)	38.00 (35.00,41.40)	-0.436	0.704
pH	7.42 (7.39,7.46)	7.42 (7.40,7.46)	-0.024	0.983
Base Excess/(mmol/L)	0.40 (-1.40,1.80)	0.40 (-1.40,1.80)	-0.684	0.544

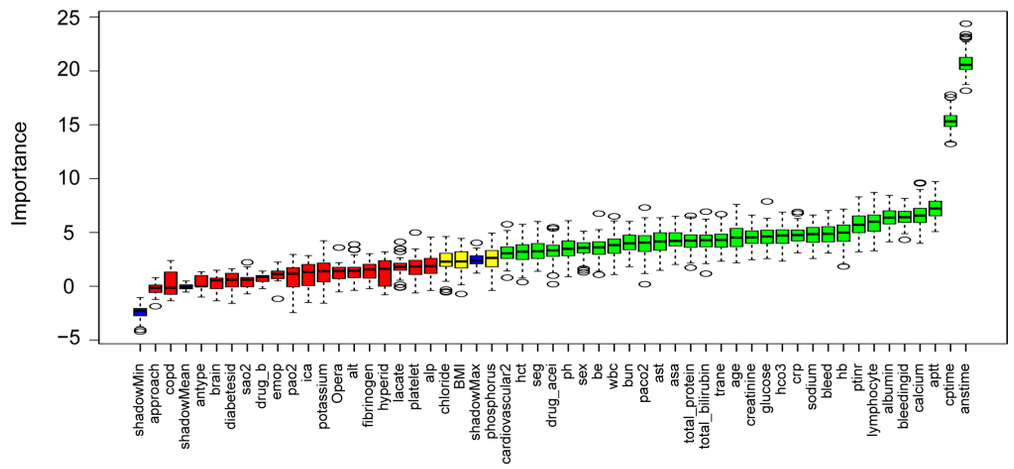
ASA: American society of anesthesiologists

2.3 模型构建表现

基于训练集和特征选择结果,我们成功构建了8种模型,分别是GBM、GLM、XGBoost、KNN、NB、NNET、SVM和RF模型,模型在训练集以及测试集中的表现见表4。在测试集中,GBM、SVM以及RF模型其AUC(曲线下面积)达0.7以上,这一结果显著优于其他模型。校准曲线显示,XGBoost和SVM模型的预测概率与实际发生概率之间的一致性较好。进一步地进行了决策曲线分析(DCA)以评估模型的临床效益和效用,结果表明在不同阈值下,SVM和RF模型的净收益均高于其他模型,见图3。综合所有评估指标,SVM模型效果较好,其灵敏度、特异度、阳性阴性预测值为0.481、0.825、0.504、0.812。

2.4 特征重要性

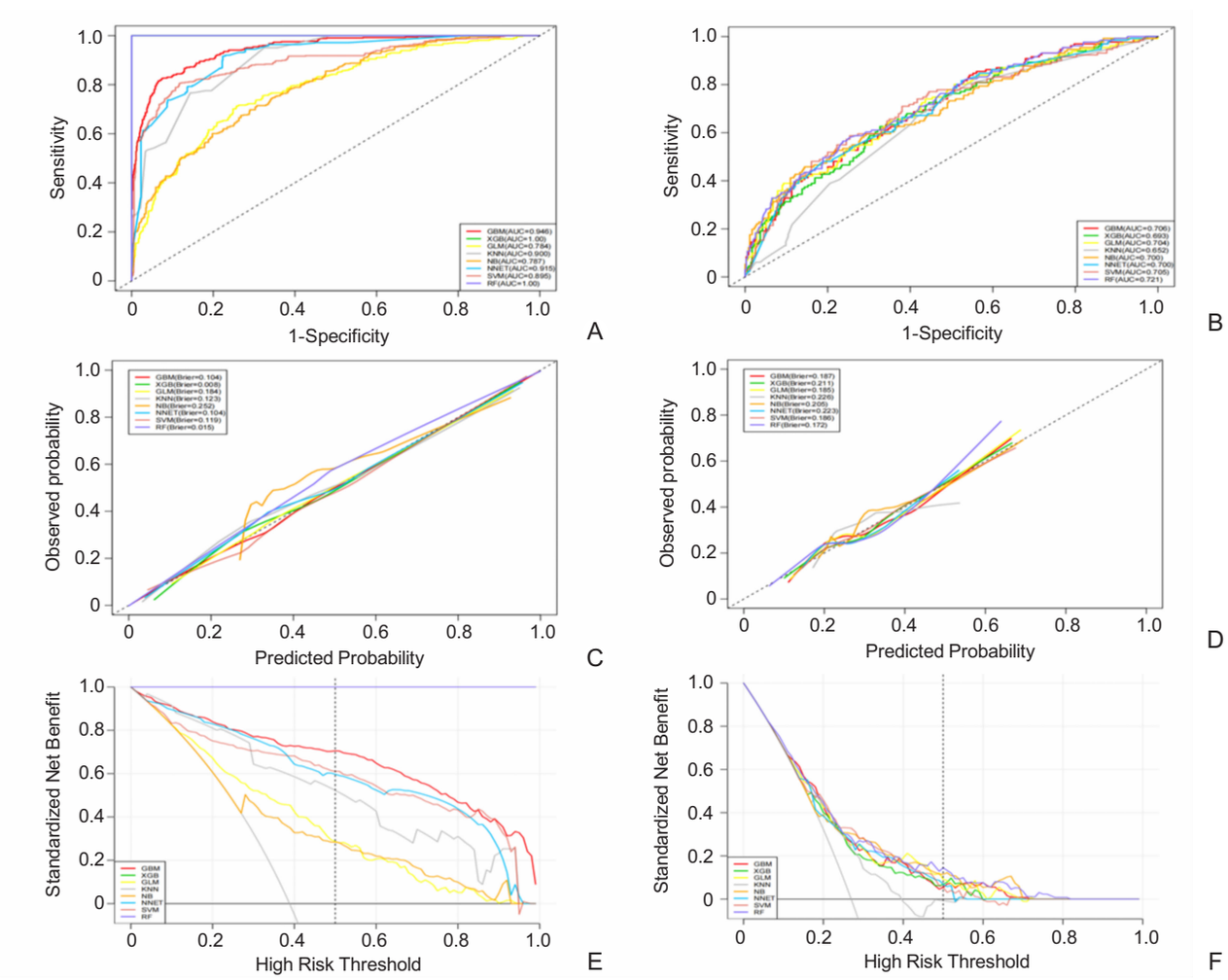
基于排列重要性算法,通过随机打乱单个特征值,观察模型性能下降程度,确定对PORF预测影响最大的前十个变量,为麻醉时长、动脉血二氧化碳分压、钙、淋巴细胞百分比、体外循环时长、术中出血量、年龄、肌酐、天门冬氨基酸氨基转移酶和活化部分凝血活酶时间,它们在模型中的贡献度显著高于其他特征,见图4。



Green indicates importance, yellow indicates temporary importance, blue indicates shadow values, and red indicates unimportance

图2 Boruta特征选择示意图

Figure 2 Feature selection using Boruta



A, B, and C: the ROC curve, calibration curve, and decision curve of the training set respiratory failure prediction model, respectively; D, E, and F: the ROC curve, calibration curve, and decision curve of the test set respiratory failure prediction model, respectively

图3 8种呼吸衰竭预测模型表现

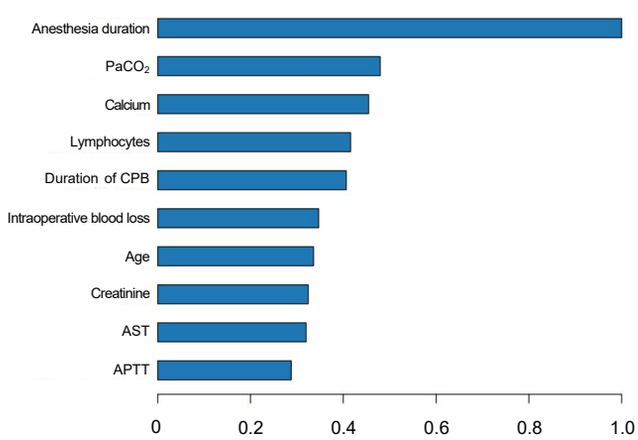
Figure 3 Performance of 8 respiratory failure prediction models

表4 呼吸衰竭风险预测模型结果

Table 4 Comparisons of predictive performance of machine learning models for risk of respiratory failure

Training set									
Models	AUC	ACC	Sensitivity	Specificity	PPV	NPV	F1	Kappa	Brier
GBM	0.946	0.883	0.791	0.942	0.897	0.877	0.840	0.749	0.104
XGBoost	1.000	0.999	0.998	1.000	1.000	0.998	0.999	0.998	0.008
GLM	0.784	0.714	0.435	0.891	0.718	0.713	0.542	0.352	0.184
KNN	0.900	0.809	0.774	0.831	0.744	0.853	0.759	0.601	0.123
NB	0.787	0.712	0.316	0.964	0.847	0.689	0.460	0.316	0.252
NNET	0.915	0.844	0.738	0.911	0.840	0.846	0.785	0.663	0.104
SVM	0.895	0.847	0.711	0.932	0.870	0.836	0.782	0.666	0.119
RF	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.015
Test set									
Models	AUC	ACC	Sensitivity	Specificity	PPV	NPV	F1	Kappa	Brier
GBM	0.706	0.726	0.428	0.837	0.491	0.798	0.457	0.275	0.187
XGBoost	0.693	0.722	0.374	0.851	0.480	0.787	0.421	0.242	0.211
GLM	0.704	0.728	0.420	0.842	0.797	0.797	0.455	0.275	0.185
KNN	0.652	0.679	0.397	0.793	0.403	0.779	0.400	0.181	0.226
NB	0.700	0.757	0.344	0.910	0.584	0.790	0.433	0.291	0.205
NNET	0.700	0.712	0.481	0.797	0.467	0.806	0.474	0.275	0.223
SVM	0.705	0.733	0.481	0.825	0.504	0.812	0.492	0.311	0.186
RF	0.721	0.765	0.260	0.952	0.667	0.777	0.374	0.262	0.172

AUC: area under the ROC curve, quantifies the overall performance under the receiver operating characteristic curve (ROC Curve); F1 score: the harmonic mean of precision and recall, assessing the model's comprehensive performance on positive class samples; Kappa: Kappa coefficient, measures the agreement between classification predictions and random chance expectations, accounting for the possibility of agreement occurring by chance; Brier score: a metric assessing the accuracy of probabilistic predictions. Sensitivity: the proportion of actual positive samples correctly identified; Specificity: the proportion of actual negative samples correctly identified; PPV: positive predictive value, the proportion of samples predicted as positive that are actual positives; NPV: negative predictive value, the proportion of samples predicted as negative that are actual negatives



$PaCO_2$: partial pressure of carbon dioxide; CPB: cardiopulmonary bypass; AST: aspartate amino transferase; APTT: activated partial thromboplastin time

图4 特征重要性排序

Figure 4 Ranking of Feature Importance

3 讨论

心血管手术后发生PORF是最严重肺部并发症之一,会增加医疗费用、住院时间及死亡率。本研究通过深入分析INSPIRE数据库数据,构建了多种机器学习模型对PORF进行预测,其中SVM模型在预测性能上表现最优,并基于特征重要性算法识别了PORF的10个重要风险因素。

本研究纳入了人口学特征、实验室检查及合并症等多元信息,以全面评估患者状态。基线分析显示,PORF组与非PORF组患者在年龄、合并症、实验室指标等多方面存在显著差异,为构建预测模型提供了基础。基线分析也发现呼吸衰竭组ASA III-IV级患者比例显著更高,依然凸显出传统模型进行静态评估的重要性。通过Boruta特征筛选方法,我们识别出具有显著预测能力的变量,有效降低了模型过拟合风险。在评估的8种机器学习算法中,支持向量机(SVM)模型展现出最优异的预测性能。其优势体现在:高判别能力,具有较高的AUC值;均衡的临床指标,在特异度、灵敏度、阳性预测值等关键指标上表现优异;良好的校准度与临床实用性,校准曲线表明预测概率与实际风险匹配良好,决策曲线分析证实了其临床净获益;强大的建模能力,SVM具备自动特征学习、强大的非

线性建模能力、良好的泛化性、对噪声的鲁棒性以及良好的可扩展性,非常适合应用于围术期风险预测这类复杂场景。基于排列重要性算法,我们进一步确定了影响PORF预测的十大关键风险因素:麻醉时长、动脉血二氧化碳分压、钙、淋巴细胞百分比、体外循环时长、术中出血量、年龄、肌酐、天门冬氨酸氨基转移酶和活化部分凝血活酶时间。这些发现与既往研究报道的风险因素方向一致[18-19],并涵盖了国际指南强调的部分关键因素,如年龄、ASA分级[20-22]以及术中因素(出血量、体外循环时长)[20,23]。相比EuroSCORE[24]或STS评分[25]等主要依赖术前静态指标(年龄、基础疾病)的传统心血管风险评估工具,本研究创新性地纳入了术中实时监测数据(如麻醉时长、体外循环时长、术中出血量),相比ARISCAT评分[26]等传统呼吸衰竭预测工具,本研究构建的PORF特异性SVM模型达到了0.825的特异度,显示出更优的性能。此外,模型中纳入的炎症与代谢指标(如淋巴细胞百分比等),能够更全面反映手术应激对呼吸功能的直接影响,有助于更深入地揭示炎症状态[27]和代谢紊乱[18]在PORF发生中的潜在作用机制。CPB时长被识别为关键风险因素之一,其影响机制值得深入探讨。研究表明,CPB时间延长是术后并发症的重要独立危险因素,并可能使呼吸衰竭风险增加高达3.2倍[28]。其潜在机制包括:直接心肺损伤,长时间CPB可能导致心肺功能受损,影响术后恢复。系统性炎症反应,CPB本身可触发显著的全身炎症反应[27],炎症因子释放可能直接损伤肺组织,诱发或加重呼吸衰竭。多器官功能受累,CPB时间延长增加术后急性肾损伤、脑损伤等并发症风险[29],这些并发症可间接导致或加重呼吸衰竭。值得注意的是,与CPB时间密切相关的主动脉阻断时间也被多项研究[3,23]证实是PORF的重要危险因素。遗憾的是,本研究数据库未能包含主动脉阻断时间这一变量。

本研究存在一定局限。一是作为单中心数据库研究,缺乏外部验证是主要局限,限制了模型在更广泛人群中的泛化能力,存在潜在的选择偏倚。未来需要在多中心、大样本的独立队列中进行外部验证。二是尽管经过严格筛选,模型可能仍遗漏了某些重要风险因素。例如本研究未能纳入主动脉阻断时间。未来研究应持续探索和纳入更多潜在风险因素以优化模型。三是尽管本研究已经采用了排列重要性等方法进行特征解释,但SVM等复杂机器学习模型的内在“黑箱”特性仍是临床应用的一个考量点。

综上所述,本研究通过深入分析心脏手术患者临床数据,成功构建了预测性能优异的SVM模型,识别了PORF的风险因素。该模型可以实现个性化的风险分层,识别出高危患者及其发生并发症的概率,促进数据驱动的临床决策。

利益冲突 本文所有作者声明不存在利益冲突

参考文献:

[1] NTELIOPOULOS G, NIKOLAKOPOULOU Z, CHOW B H N, *et al*. Lung injury following cardiopulmonary bypass: a clinical update[J]. Expert Rev Cardiovasc Ther, 2022, 20(11): 871-880. DOI: 10.1080/14779072.2022.2149492.

[2] MILLS G H. Respiratory complications of anaesthesia[J]. Anaesthesia, 2018, 73(Suppl 1): 25-33. DOI: 10.1111/anae.14137.

[3] FERNANDEZ-BUSTAMANTE A, FRENDL G, SPRUNG J, *et al*. Postoperative pulmonary complications, early mortality, and hospital stay following noncardiothoracic surgery: a multicenter study by the perioperative research network investigators[J]. JAMA Surg, 2017, 152(2): 157-166. DOI: 10.1001/jamasurg.2016.4065.

[4] PEI J Q, CAI L, WANG F, *et al*. LPA(2) contributes to vascular endothelium homeostasis and cardiac remodeling after myocardial infarction[J]. Circ Res, 2022, 131(5): 388-403. DOI: 10.1161/CIRCRESAHA.122.321036.

[5] JIA P, JI Q, ZOU Z, *et al*. Effect of delayed remote ischemic preconditioning on acute kidney injury and outcomes in patients undergoing cardiac surgery: a randomized clinical trial[J]. Circulation, 2024, 150(17): 1366-1376. DOI: 10.1161/circulationaha.124.071408.

[6] MISKOVIC A, LUMB A B. Postoperative pulmonary complications[J]. Br J Anaesth, 2017, 118(3): 317-334. DOI: 10.1093/bja/aex002.

[7] LI W, LIAO Y, CHEN J, *et al*. Ischemia - Reperfusion injury: a roadmap to precision therapies[J]. Mol Aspects Med, 2025, 104: 101382. DOI: 10.1016/j.mam.2025.101382.

[8] STONE P H, LIBBY P, BODEN W E. Fundamental pathobiology of coronary atherosclerosis and clinical implications for chronic ischemic heart disease management-the plaque hypothesis: a narrative review[J]. JAMA Cardiol, 2023, 8(2): 192-201. DOI: 10.1001/jamacardio.2022.3926.

[9] GUPTA P K, GUPTA H, SUNDARAM A, *et al*. Development and validation of a risk calculator for prediction of cardiac risk after surgery[J]. Circulation, 2011, 124(4): 381-387. DOI: 10.1161/circulationaha.110.015701.

[10] LIM L, LEE H, JUNG C W, *et al*. INSPIRE, a publicly available research dataset for perioperative medicine[J]. Sci Data, 2024, 11(1): 655. DOI: 10.1038/s41597-024-03517-4.

[11] STOCKING J C, UTTER G H, DRAKE C, *et al*. Postoperative respiratory failure: an update on the validity of

the Agency for Healthcare Research and Quality Patient Safety Indicator 11 in an era of clinical documentation improvement programs[J]. Am J Surg, 2020, 220(1): 222-228. DOI: 10.1016/j.amjsurg.2019.11.019.

[12] JAMMER I, WICKBOLDT N, SANDER M, *et al*. Standards for definitions and use of outcome measures for clinical effectiveness research in perioperative medicine: European Perioperative Clinical Outcome (EPCO) definitions: a statement from the ESA-ESICM joint taskforce on perioperative outcome measures[J]. Eur J Anaesthesiol, 2015, 32(2): 88-105. DOI: 10.1097/EJA.0000000000000118.

[13] VAN BUUREN S, GROOTHUIS-OUDSHOORN K. **mice**: multivariate imputation by chained equations in*R*[J]. J Stat Soft, 2011, 45(3): 1-67. DOI: 10.18637/jss.v045.i03

[14] HUANG J Z, LIU W C. Comparison of machine learning models for predicting stroke risk in hypertensive patients: Lasso regression model, random forest model, Boruta algorithm model, and Boruta algorithm combined with Lasso regression model[J]. Medicine, 2025, 104(22): e42690. DOI: 10.1097/MD.0000000000042690.

[15] KURSA M B, RUDNICKI W R. Feature selection with the**Boruta**Package[J]. J Stat Soft, 2010, 36(11): 1-13. DOI: 10.18637/jss.v036.i11

[16] AGYEKUM E A, ZHANG Y Z, FANG Y, *et al*. Ultrasound-based classification of follicular thyroid Cancer using deep convolutional neural networks with transfer learning[J]. Sci Rep, 2025, 15(1): 21708. DOI: 10.1038/s41598-025-05551-7.

[17] STEYERBERG E W, VERGOUWE Y. Towards better clinical prediction models: seven steps for development and an ABCD for validation[J]. Eur Heart J, 2014, 35(29): 1925-1931. DOI: 10.1093/eurheartj/ehu207.

[18] STOCKING J C, DRAKE C, ALDRICH J M, *et al*. Outcomes and risk factors for delayed-onset postoperative respiratory failure: a multi-center case-control study by the University of California Critical Care Research Collaborative (UC(3)RC)[J]. BMC Anesthesiol, 2022, 22(1): 146. DOI: 10.1186/s12871-022-01681-x.

[19] LIVINGSTONE S A, WILDI K S, DALTON H J, *et al*. Coagulation dysfunction in acute respiratory distress syndrome and its potential impact in inflammatory subphenotypes[J]. Front Med, 2021, 8: 723217. DOI: 10.3389/fmed.2021.723217.

[20] CASSELMAN F P A, LANCE M D, AHMED A, *et al*. 2024 EACTS/EACTAIC guidelines on patient blood management in adult cardiac surgery in collaboration with EBCP[J]. J Cardiothorac Vasc Anesth, 2025, 39(8): 1964-2018. DOI: 10.1053/j.jvca.2024.10.006.

[21] DING X C, CHENG D, SUN B, *et al*. Nomogram and risk calculator for severe hypoxemia after heart valve surgery[J]. Front Cardiovasc Med, 2022, 9: 972449. DOI: 10.3389/fcvm.2022.972449.

[22] SMETANA G W, LAWRENCE V A, CORNELL J E. Preoperative pulmonary risk stratification for noncardiothoracic surgery: systematic review for the American College of Physicians[J]. Ann Intern Med, 2006, 144(8): 581-595. DOI: 10.7326/0003-4819-144-8-200604180-00009.

[23] TAKAGAKI M, YAMAGUCHI H, IKEDA N, *et al*. Post-cardiotomy venovenous extracorporeal membrane oxygenation without heparinization[J]. Gen Thorac Cardiovasc Surg, 2019, 67(11): 982-986. DOI: 10.1007/s11748-018-0990-2.

[24] BOUABDALLAOUI N, STEVENS S R, DOENST T, *et al*. Society of thoracic surgeons risk score and EuroSCORE-2 appropriately assess 30-day postoperative mortality in the STICH trial and a contemporary cohort of patients with left ventricular dysfunction undergoing surgical revascularization[J]. Circ Heart Fail, 2018, 11(11): e005531. DOI: 10.1161/CIRCHEARTFAILURE.118.005531.

[25] KUMAR A, SATO K, NARAYANSWAMI J, *et al*. Current society of thoracic surgeons model reclassifies mortality risk in patients undergoing transcatheter aortic valve replacement[J]. Circ Cardiovasc Interv, 2018, 11(9): e006664. DOI: 10.1161/CIRCINTERVENTIONS.118.006664.

[26] MAZO V, SABATÉ S, CANET J, *et al*. Prospective external validation of a predictive score for postoperative pulmonary complications[J]. Anesthesiology, 2014, 121(2): 219-231. DOI: 10.1097/ALN.0000000000000334.

[27] TONER A J, CORCORAN T B, VLASKOVSKY P S, *et al*. Inflammation risk before cardiac surgery and the treatment effect of intraoperative dexamethasone[J]. Anaesth Intensive Care, 2024, 52(1): 28-36. DOI: 10.1177/0310057X231195098.

[28] KESKINIDOU C, VASSILIOU A G, PAPOUTSI E, *et al*. Dysregulated coagulation and fibrinolysis are present in patients admitted to the emergency department with acute hypoxemic respiratory failure: a prospective study[J]. Biomedicines, 2024, 12(5): 1081. DOI: 10.3390/biomedicines12051081.

[29] ZHANG J R, ZHANG H, WANG J, *et al*. The organ-protective effects of nitric oxide in adult patients undergoing cardiac surgery with cardiopulmonary bypass: a systematic review and meta-analysis[J]. BMC Anesthesiol, 2025, 25(1): 335. DOI: 10.1186/s12871-025-03207-7.

(收稿:2025-07-15;修回:2025-08-01)

(编辑 邓强庭)