



老年患者外周静脉留置针中重度并发症风险预测模型构建

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【摘要】目的 构建并验证老年患者外周静脉留置针(peripheral venous catheter, PVC)中重度并发症的风险预测模型,为临床精准防控提供依据。**方法** 采用前瞻性队列研究,收集2023年11月—2024年9月期间收治的750例接受PVC治疗的老年患者的临床资料。按7:3将患者分层随机分为训练集($n=526$)与测试集($n=224$)。通过单因素与多因素logistic回归分析筛选PVC中重度并发症的独立影响因素,分别构建二元logistic回归(binary logistic regression, BLR)、支持向量机(support vector machine, SVM)、随机森林(random forest, RF)、朴素贝叶斯(naive Bayes, NB)四种预测模型。采用受试者工作特征曲线下面积(area under the curve, AUC)结合DeLong检验评估模型区分度,使用校准曲线评估校准度,并利用决策曲线分析(decision curve analysis, DCA)评价其临床净获益,同时通过沙普利可加性模型解释算法(Shapley additive explanations, SHAP)可视化分析阐释模型的特征重要性。**结果** 多因素logistic回归分析确定自理能力[轻度依赖:比值比(odds ratio, OR)=1.361, 95%置信区间(confidence interval, CI): 1.031 ~ 1.802;中度依赖: OR=1.992, 95%CI: 1.291 ~ 3.061;重度依赖: OR=3.060, 95%CI: 1.700 ~ 5.512]、渗液(OR=8.998, 95%CI: 4.286 ~ 18.887)、临床科室[胃肠外科: OR=28.396, 95%CI: 7.537 ~ 106.990;胰腺外科: OR=5.258, 95%CI: 1.177 ~ 23.499;胰腺炎中心: OR=5.974, 95%CI: 1.287 ~ 27.725]、患者小学及以下文化程度(OR=2.525, 95%CI: 1.158 ~ 5.506)、饮酒(OR=1.970, 95%CI: 1.011 ~ 3.838)、敷料卷边(OR=1.458, 95%CI: 1.150 ~ 1.848)及合并症数量(OR=0.893, 95%CI: 0.821 ~ 0.972)为老年患者PVC中重度并发症的独立危险因素,16G ~ 22G导管为独立保护因素($P<0.05$)。测试集验证显示,RF模型AUC最高(0.891, 95%CI: 0.840 ~ 0.942),经DeLong检验,其区分度与BLR(0.808, 95%CI: 0.738 ~ 0.879)和SVM(0.842, 95%CI: 0.774 ~ 0.909)模型相比,差异有统计学意义($P<0.05$);SHAP分析提示渗液、自理能力、不同临床科室为RF模型的核心影响因素;DCA表明RF模型在0 ~ 0.8的阈值概率范围内具有显著的临床净获益。**结论** 本研究成功构建并验证了老年患者PVC中重度并发症的RF预测模型,该模型区分度优异、临床应用价值突出,可有效早期识别高危人群,为临床精准干预提供科学依据。

【关键词】 老年人 导管,留置 并发症 比例危险度模型

Development of a Risk Prediction Model for Moderate-to-Severe Complications Associated With Peripheral Intravenous Catheters in Older Patients

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【Abstract】 Objective To develop and validate a risk prediction model for moderate-to-severe complications associated with peripheral venous catheters (PVC) in older patients, and to provide evidence for precision-based clinical prevention and management. **Methods** In this prospective cohort study, the clinical data of 750 older patients who underwent PVC placement for intravenous therapy between November 2023 and September 2024 were collected. Patients were stratified and randomly assigned to a training set ($n = 526$) and a test set ($n = 224$) at a ratio of 7 : 3. Independent risk factors for moderate-to-severe PVC-related complications were identified by univariate and multivariate logistic regression analyses. A total of 4 predictive models were established—binary logistic regression (BLR), support vector machine (SVM), random forest (RF), and naive Bayes (NB). Model discrimination was assessed using the area under the receiver operating characteristic curve (AUC) and DeLong test. Model calibration was evaluated by calibration curves. Clinical net benefit was determined using decision curve analysis (DCA). Shapley additive explanations (SHAP) were used to visualize and interpret feature importance in the models. **Results** According to multivariate logistic regression

analysis, functional status (mild dependence: odds ratio [OR] = 1.361, 95% CI: 1.031-1.802; moderate dependence: OR = 1.992, 95% CI: 1.291-3.061; severe dependence: OR = 3.060, 95% CI: 1.700-5.512), infusion extravasation (OR = 8.998, 95% CI: 4.286-18.887), the clinical department the patient was admitted to (Gastrointestinal Surgery: OR = 28.396, 95% CI: 7.537-106.990; Pancreatic Surgery: OR = 5.258, 95% CI: 1.177-23.499; Pancreatitis Center: OR = 5.974, 95% CI: 1.287-27.725), primary school or less formal education (OR = 2.525, 95% CI: 1.158-5.506), drinking history (OR = 1.970, 95% CI: 1.011-3.838), the edges of the dressing being curled up (OR = 1.458, 95% CI: 1.150-1.848), and the number of comorbidities (OR = 0.893, 95% CI: 0.821-0.972) were identified as independent risk factors for moderate-to-severe PVC-related complications in older patients, while 16G-22G catheters were identified as an independent protective factor ($P < 0.05$). Validation in the test set revealed that the RF model yielded the highest AUC value (0.891, 95% CI: 0.840-0.942). According to the DeLong test, the discrimination performance of the RF model was significantly superior to those of the BLR model (AUC = 0.808, 95% CI: 0.738-0.879) and the SVM model (AUC = 0.842, 95% CI: 0.774-0.909) ($P < 0.05$). SHAP analysis revealed that infusion extravasation, functional status, and the clinical department into which the patient was admitted were the top 3 features of the RF model. DCA showed that the RF model provided significant net clinical benefit within the threshold probability range of 0-0.8. **Conclusion** In this study, an RF prediction model for moderate-to-severe PVC-related complications in older patients was successfully developed and validated. The RF prediction model demonstrates excellent discrimination and high clinical applicability, enabling early identification of high-risk patients and informing precision-based clinical interventions.

[Key words] Older adults Catheters, indwelling Complications Proportional hazards models

随着人口老龄化,住院患者中老年群体占比持续升高^[1],外周静脉留置针(peripheral venous catheter, PVC)是老年住院患者静脉治疗的核心通路,使用率居高不下^[2],受生理机能减退、血管条件不佳及多重慢病共存等因素影响^[3],该群体PVC并发症发生率更高、损伤程度更重,已成为临床静脉治疗安全管理的突出难题。中重度PVC并发症可引发局部肿胀、治疗中断、住院周期延长,显著增加医疗成本并加重护理负荷,亟须精准化风险预警与分级防控策略^[4]。

当前研究多聚焦于PVC并发症危险因素分析与现况调查^[5-6],能够量化并发症严重程度的预测模型仍较为匮乏。机器学习凭借强大的数据挖掘与特征拟合优势,为构建高精度、个体化的并发症严重度预测模型提供了关键技术支撑^[7-8]。基于此,本研究拟构建老年患者PVC中重度并发症风险预测模型,为临床早期识别高危人群、实施精准干预提供循证依据与智能化工具。

1 资料与方法

1.1 研究对象

本研究采用前瞻性队列研究设计,选取2023年11月—2024年9月在我院接受PVC穿刺行静脉治疗的老年住院患者为研究对象。纳入标准:①年龄 ≥ 60 岁;②住院期间行PVC穿刺。排除标准:①因转科、转院、自动出院等非医疗因素提前拔除导管者;②临床病历资料缺失率 $\geq 20\%$ 者。本研究经四川大学华西医院生物医学伦理审查委员会批准(2023年审1940号),批件有效期为一年,且符

合《赫尔辛基宣言》^[9]。

1.2 样本量计算

本研究依据临床预测模型样本量计算公式(events per variable, EPV)^[10],每个预测因子对应10个阳性事件,见式(1)。

$$N = 10 \times \frac{k}{p} \quad (1)$$

其中, p 指总体的阳性发生率, k 为自变量个数。根据文献回顾,老年患者PVC并发症发生率为17.60%~55.60%,本研究中预计纳入37个预测指标,计划纳入665~2102例,最终纳入750例患者。

1.3 资料收集

本研究为前瞻性队列研究,通过系统文献回顾与两轮德尔菲专家函询(11位静脉治疗专家,权威系数 $Cr = 0.85$),构建了包含患者基础资料、实验室指标与风险评估、操作者信息、留置针及治疗特征四个维度的初始预测指标库,并据此制定《住院老年患者外周静脉留置针并发症风险因素收集表》开展数据采集。基础资料与临床特征来源于病历系统;实验室指标与风险评估数据提取自检验记录与评估量表;操作者信息通过上述收集表收集;留置针及治疗相关数据(如型号、部位、留置时间、输液参数、敷料状况、药物性质等)则通过每日床旁观察与记录获取,确保数据的全面性与前瞻性。

1.4 PVC并发症及严重程度

患者自PVC置管当日起至导管拔除全程,由责任护士每日床旁观察记录,持续随访至导管拔除,同步记录随访期间并发症发生与否、发生时间及严重程度。

1.4.1 PVC并发症

根据文献回顾,老年患者PVC并发症主要包含静脉炎、渗出与外渗、堵管、意外脱管等,相关定义参考2024年美国静脉输液护理学会(Infusion Nursing Society, INS)颁布的《输液治疗实践标准》^[11]:①静脉炎:静脉血管的无菌性炎症;②渗出与外渗:非腐蚀性/腐蚀性药液进入静脉管腔以外的周围组织;③堵管:无法回抽血液或血液回流缓慢、无法推注冲管液或阻力大、液体无法输注;④意外脱管:患者或医务人员非故意将PVC导管拔出血管。

1.4.2 严重程度分级

严重度评估矩阵(severity assessment code, SAC)是一种系统化的临床风险评估工具,从“事件对患者健康的影响程度”这一核心维度出发,对不良事件的严重性进行量化分级^[12]。SAC具有较高的评估一致性(k 值0.72~0.86),为本研究建立客观、可操作的并发症严重度分级体系提供了理论依据。本研究中,PVC中重度并发症是指引发明显症状(如疼痛、肿胀),需额外干预(如硫酸镁湿敷、水胶体敷料使用、重置导管或延长住院)^[12]。将总体样本根据PVC并发症的严重程度,划分为中重度并发症组与非中重度并发症组。为确保模型构建与验证的可靠性,在亚组内部,按7:3的比例随机划分训练集与测试集,并保持两组间基线特征的均衡性。训练集用于机器学习模型的开发与参数调优,测试集则用于对模型预测性能进行独立、客观的评估。

1.5 统计学方法

将所有原始数据经Excel整理后,采用SPSS29.0进行统计分析。对于符合正态分布的计量资料,以 $\bar{x} \pm s$ 表示,组间比较采用独立样本 t 检验;非正态分布的计量资料以中位数(四分位距)描述,组间比较采用Mann-Whitney U 检验;计数资料以频数(百分比)表示,组间比较采用 χ^2 检验, $P < 0.05$ 为差异有统计学意义。采用逐步二元logistic回归筛选特征变量,纳入标准 $\alpha_{\text{入}} = 0.05$,剔除标准 $\alpha_{\text{出}} = 0.10$ 。基于R4.4.2平台,分别构建随机森林(random forest, RF)、二元logistic回归(binary logistic regression, BLR)、支持向量机(support vector machine, SVM)、朴素贝叶斯(naive Bayes, NB)四种机器学习模型,以受试者工作特征(receiver operating characteristic, ROC)曲线下面积(area under the curve, AUC)为主要优化指标,采用网格搜索调优关键超参数:RF模型设置决策树数量为500,对每次分裂尝试的特征数在1~10的范围内进行寻优;SVM模型采用径向基核函数,并对惩罚系数与核函数参数进行自动寻优;BLR采用Enter法将经筛选后的特征全

部纳入模型;NB模型则采用默认的核密度估计方法进行建模。绘制ROC曲线并计算AUC值及95%置信区间(confidence interval, CI);采用DeLong检验比较模型间AUC差异;采用校准曲线评价模型校准度;通过沙普利可加性模型解释算法(Shapley additive explanations, SHAP)可视化分析各个变量在模型中的贡献度;采用决策曲线分析(decision curve analysis, DCA)评价临床净获益。

2 结果

2.1 训练集和验证集基本资料

本研究共纳入11个科室(外科7个、内科4个)老年患者,以男性为主(54.67%),平均年龄(69.96 ± 7.14)岁,共146名患者发生了PVC中重度并发症,发生率为19.47%。采用分层随机法按7:3比例分为训练集[526例,中重度并发症发生率20.53%(108例)]和测试集[224例,中重度并发症发生率16.96%(38例)]。两组在基础资料、临床及实验室相关指标等方面差异均无统计学意义($P > 0.05$),具备后续研究基础,详见网络资源附件附表1。

2.2 训练集患者PVC中重度并发症的单因素及多因素分析结果

训练集单因素分析显示,营养风险、血栓风险、自理能力、合并症数量、饮酒史、临床科室、PVC导管类型、留置时间、输液方式、敷料卷边、渗液、U型固定、疼痛程度及穿刺部位在中重度并发症组与非中重度并发症组间差异均有统计学意义($P < 0.05$),见网络资源附件附表2。本研究变量赋值:连续型变量保留原值,二分类变量采用0~1赋值,分类变量均构建哑变量并设置参照组(自理能力以完全独立、科室以创伤外科、PVC导管类型以24G、学历以大专及本科为参照),将单因素分析中 $P < 0.05$ 的变量全部纳入初始模型,采用向后逐步回归筛选独立影响因素。多因素logistic回归分析提示(表1),自理能力下降、渗液、胃肠外科、胰腺外科、胰腺炎中心、小学及以下文化程度、饮酒及敷料卷边为老年患者PVC中重度并发症的独立危险因素($P < 0.05$);16G、18G、20G、22G导管是PVC中重度并发症的独立保护因素($P < 0.05$);合并症数量与并发症风险呈独立负相关($P < 0.05$),该结果与临床认知存在差异,可能受混杂因素影响,其临床意义有待进一步探讨。

2.3 建立老年患者PVC中重度并发症四种预测模型及预测效果

本研究基于训练集构建BLR、RF、SVM、NB四种预测模型。测试集ROC曲线分析显示(图1),RF模型AUC最高(0.891, 95%CI: 0.840~0.942)。经DeLong检验,

表 1 训练集患者PVC中重度并发症的多因素logistic逐步回归分析 (n=526)

Table 1 Multivariate stepwise logistic regression analysis of moderate-to-severe complications in patients with PVC in the training set (n = 526)

Factor	β	SE	Wald	P	OR (95% CI)
Functional status (Fully independent)			16.038	0.001	
Mild dependence	0.310	0.140	4.890	0.027	1.361 (1.031-1.802)
Moderate dependence	0.690	0.220	9.862	0.002	1.992 (1.291-3.061)
Severe dependence	1.120	0.300	13.951	< 0.001	3.060 (1.700-5.512)
Infusion extravasation (No)	2.197	0.378	33.720	< 0.001	8.998 (4.286-18.887)
Department (Trauma Surgery)			37.176	< 0.001	
Gastrointestinal Surgery	3.346	0.677	24.446	< 0.001	28.396 (7.537-106.990)
Pancreatic Surgery	1.660	0.764	4.722	0.030	5.258 (1.177-23.499)
Pancreatitis Center	1.787	0.783	5.210	0.022	5.974 (1.287-27.725)
Nutritional risk (No)	0.684	0.356	3.684	0.055	1.981 (0.986-3.983)
PVCs type (24G)			8.695	0.069	
16G	-1.393	0.686	4.123	0.042	0.248 (0.065-0.953)
18G	-2.114	0.944	5.019	0.025	0.121 (0.019-0.768)
20G	-4.881	0.811	36.098	< 0.001	0.008 (0.001-0.048)
22G	-0.377	0.816	5.489	0.019	0.148 (0.030-0.732)
Catheter indwelling time*	-0.329	0.176	3.497	0.061	0.720 (0.510-1.016)
Formal education (Junior-college and bachelor degree)			11.808	0.019	
Primary education or below	0.926	0.398	5.420	0.020	2.525 (1.158-5.506)
Drinking history (No)	0.678	0.340	3.973	0.046	1.970 (1.011-3.838)
Dressing edge curling (No)	0.377	0.121	3.592	0.038	1.458 (1.150-1.848)
Number of comorbidities*	-0.113	0.043	6.914	0.009	0.893 (0.821-0.972)

β : partial regression coefficient; SE: standard error; OR: odds ratio. * Continuous variable.

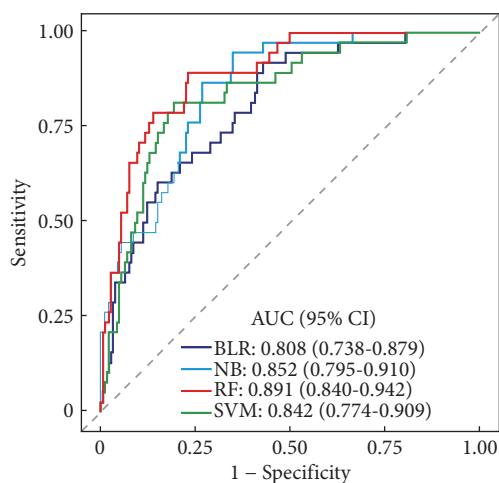


图 1 测试集预测老年患者PVC中重度并发症的ROC曲线图

Fig 1 Receiver operating characteristic curve for predicting moderate-to-severe PVC-related complications in older adults in the validation set

BLR: binary logistic regression; NB: naive Bayes; RF: random forest; SVM: support vector machine; AUC: area under the curve.

RF模型区分度优于BLR模型(0.808, 95%CI: 0.738 ~ 0.879, $P=0.010$)和SVM模型(0.842, 95%CI: 0.774 ~ 0.909, $P=0.044$); NB模型AUC为0.852(95%CI: 0.795 ~ 0.910), 与RF、BLR及SVM模型差异均无统计学意义($P>0.05$)。校准曲线提示RF模型预测概率与实际发生概率拟合度最优, BLR、SVM、NB模型存在一定高估、低估趋势, 见图2。SHAP特征重要性分析显示, 渗液、自理能力、临床科室为RF模型的Top3重要影响因素, 见图3。DCA表明, RF模型在0 ~ 0.8的阈值概率区间内净获益显著高于“全干预”与“无干预”策略, 临床应用价值突出, 见图4。综合区分度、校准度与临床净获益, 最终确定RF模型为老年患者PVC中重度并发症的最优预测模型。

3 讨论

PVC是老年住院患者首选静脉治疗工具, 防控其相关并发症是临床护理重点难题。老年患者血管弹性减

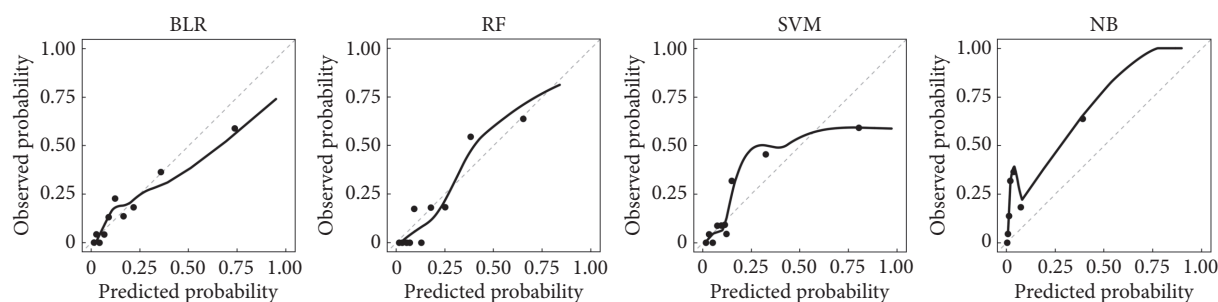


图2 测试集预测老年患者PVC中重度并发症的校准曲线图

Fig 2 Calibration curve for predicting moderate-to-severe PVC-related complications in older adults in the test set

BLR: binary logistic regression; NB: naive Bayes; RF: random forest; SVM: support vector machine.

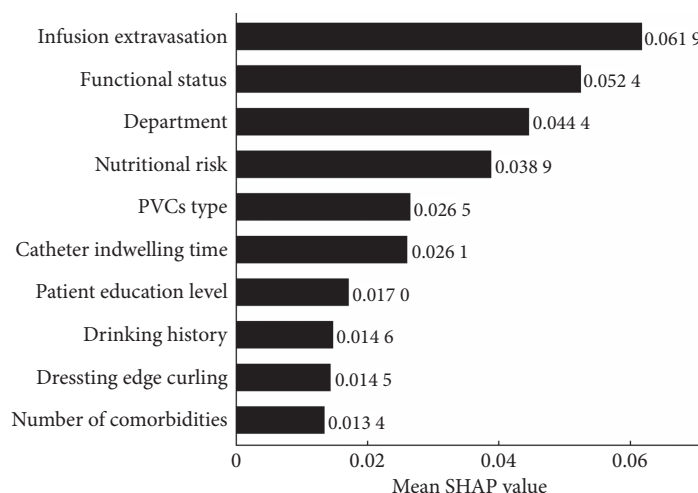


图3 RF模型预测老年患者PVC中重度并发症的SHAP特征重要性图

Fig 3 SHAP feature importance plot for RF predictive model for moderate-to-severe PVC complications in elderly patients

The values beside each bar indicate the mean absolute SHAP value of the corresponding features.

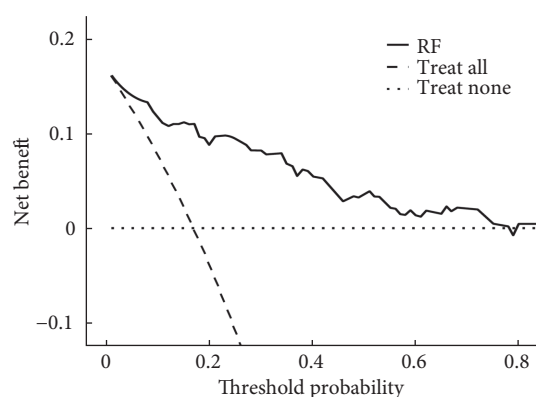


图4 RF模型预测老年患者PVC中重度并发症的决策曲线图

Fig 4 Decision curve analysis for RF predictive model for moderate-to-severe PVC-related complications in older adults

RF: random forest.

退、内皮修复能力下降、皮肤屏障薄弱,叠加高血压、糖尿病等慢性病,机体免疫及代偿能力减退;长期输液带来的机械损伤、化学刺激和血流动力学异常,致使老年人群PVC并发症发病率高于普通成年人。王文歆等^[13]证实老

年患者PVC并发症发生率可达38.6%,且并发症严重程度更高,严重时可诱发血栓、局部组织坏死,伴随患者疼痛、非计划拔管及住院时间延长,加重医疗及护理负担。本研究中老年患者PVC中重度并发症发生率为19.47%,因此构建精准的风险预测模型,对高危患者早期甄别、分层干预及合理调配护理资源意义显著。

本研究通过单因素及多因素logistic回归筛选独立危险因素,涵盖患者基本资料、实验室检查与风险评估、护理操作层面等,从多个维度阐明并发症发生发展机制。本研究结果显示,渗液是作用最强的危险因素,其本质为穿刺道密封失效造成液体渗漏,破坏静脉通路稳定性,是并发症加重的始动因素。自理能力低下同样会升高患病风险:患者肢体活动减少,静脉炎发病概率增加,与Brown等^[14]结论相符;同时该类患者对穿刺部位不适感知迟钝,轻度并发症得不到及时处理继而进展加重^[15],提示临床应将自理能力低下的老年患者判定为高危人群,增加巡视并辅助肢体活动,姜珊等^[16]提出对此类患者每1~2 h开展管路评估,以此降低并发症发生率。临床科

室异质性显著影响中重度并发症的发生风险,本研究发现胃肠外科、胰腺外科及胰腺炎中心患者发生中重度并发症的风险更高,该类患者长期禁食、依赖肠外营养、输液量大、卧床时间久且整体营养状况较差。邹盼盼等^[17]、陈亚美等^[18]提出不同科室用药种类和输液总量存在差异,并发症发生风险各不相同,临床应结合科室特点制定个性化管路管理方案^[19]。患者基本资料方面,小学及以下文化程度、饮酒史为独立危险因素:文化程度属于社会人口学指标,无直接致病作用,低文化程度患者可能对导管维护知识掌握不足,依从性欠佳,易出现敷料污染、导管移位;饮酒会破坏血管舒张-收缩平衡、损伤血管内皮并降低痛觉敏感度,加快血管损伤进展,体现健康素养和生活习惯对静脉治疗安全的重要作用^[10]。护理操作相关因素中,敷料卷边代表管路固定与日常维护不到位,导管反复移位摩擦局部组织,增加损伤和感染概率。尽管目前PVC固定方案已经规范化^[9],但固定失效问题依旧普遍^[20-21],亟须推行标准化固定操作,并尝试皮下固定系统^[22]、组织黏合剂等新技术。16G~22G导管为保护因素($P<0.05$),对比24G细管径导管,该类导管血流阻力更低,导管堵塞及反复穿刺概率下降,减轻血管内皮损伤,该结果与既往研究结果一致^[23-24]。本研究发现合并症数量与中重度并发症发生风险呈负相关,与传统认知相悖^[17],究其原因,合并多种慢性病的老年患者住院期间受到重点监护,医护人员管路管理更加严谨,抑制并发症进一步加重。但该结果受单中心样本、病情分层、变量交互及混杂因素制约,仍需多中心大样本研究验证。

本研究突破传统单一统计模型局限,对比BLR、SVM、RF、NB四种机器学习模型,从区分度、校准度、临床净获益及可解释性综合评判模型效能。RF模型预测性能最优,测试集AUC为0.891(95%CI: 0.840~0.942),DeLong检验表明其AUC显著优于BLR与SVM;校准曲线提示预测概率和实际发病情况吻合度良好;DCA结果显示在0~0.8阈值范围内该模型临床净获益更高。RF作为集成学习算法,能够挖掘变量之间非线性关联和交互效应,抗过拟合能力更强^[24]。SHAP分析结果与logistic回归结果保持一致,渗液量、自理能力、临床科室是核心预测指标,保障模型临床可解释性,为老年患者PVC中重度并发症智能化预警提供可靠方法。

本研究存在一定局限性:其一,单中心前瞻性队列研究存在潜在选择偏倚,模型外推性与泛化能力受限;其二,预测指标体系不完善,未纳入病情严重程度、照护情况等潜在影响因素;其三,敷料卷边、渗液等观察指标依

赖护理人员主观判断,存在信息偏倚;其四,仅纳入文化程度单一社会人口学指标,未细化健康素养、认知功能等变量;其五,合并症数量与并发症的负相关结论需进一步验证;其六,逐步logistic回归特征筛选方法对变量非线性关系识别能力有限^[25]。未来需开展多中心、大样本研究,优化特征筛选方法与指标体系,进一步提升模型的预测效能与临床实用性。

* * *

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Author Contribution Chen Xiao is responsible for conceptualization, data curation, formal analysis, investigation, methodology, and writing--original draft. Guo Yuchen is responsible for data curation, investigation, visualization, and writing--review and editing. Liang Zhimin is responsible for formal analysis, methodology, software, and validation. Li Lingli is responsible for supervision. All authors consented to the submission of the article to the Journal. All authors approved the final version to be published and agreed to take responsibility for all aspects of the work.

利益冲突 所有作者均声明不存在利益冲突

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