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ZHAO Mingyan, Professor of Medicine (Grade I) & Chief Physician, Professor, Doctoral Supervisor, Director of the Department of Critical Care Medicine, The First Affiliated Hospital of Harbin Medical University, and Director of the Critical Care Medicine Teaching and Research Department. She is the Vice-Chairman of the Critical Care Medicine Branch of the Chinese Medical Association, Deputy Leader of the Critical Care Nephrology Group of the Critical Care Medicine Branch of the Chinese Medical Association, Member of the Critical Care Medicine Professional Committee of the Chinese Medical Doctor Association, and Vice President of the Critical Care Medicine Professional Committee of the Chinese Medical Women's Association. She specializes in the comprehensive treatment of critical infections, multiple organ dysfunction, and perioperative management of major surgeries, with a strong theoretical foundation and extensive clinical practice. She has published nearly one hundred papers and contributed to more than ten national textbooks and monographs. She has received multiple awards for scientific and technological progress.

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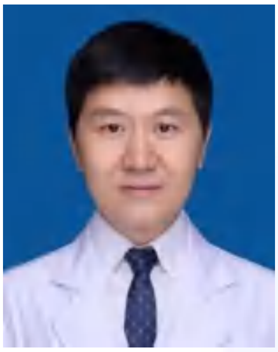

MENG Xianglin, Doctor of Medicine, Postdoctoral Researcher, Chief Physician, Master's Supervisor, Deputy Director of the Department of Critical Care Medicine, The First Affiliated Hospital of Harbin Medical University. He is a Youth Committee Member of the Critical Care Medicine Committee of the Chinese Research Hospital Association, the Vice-Chairman of the Surgical Infection and Critical Care Medicine Committee of the Heilongjiang Medical Association, a Committee Member of the Critical Care Medicine Branch of the Heilongjiang Medical Association, and an Executive Committee Member of the Heilongjiang Provincial Society of Integrated Traditional Chinese and Western Medicine Critical Care Medicine. He has long been engaged in clinical treatment of sepsis, acute respiratory distress syndrome (ARDS), multiple organ dysfunction syndrome, and multiple trauma patients. He has led and participated in several national and provincial research projects, published more than 20 SCI-indexed papers, and won the second prize of the Heilongjiang Provincial Science and Technology Award.

Artificial intelligence prediction models for acute respiratory distress syndrome: progress and challenges

MENG Xianglin*, XIONG Yaxin, HAN Ci, GE Xin, ZHAO Mingyan

**Department of Critical Care Medicine, The First Affiliated Hospital of Harbin Medical University, Harbin, Heilongjiang 150000, China*

Corresponding author: ZHAO Mingyan, E-mail: zhaomingyan@hrbmu.edu.cn

Abstract: Acute respiratory distress syndrome（ARDS）is a highly heterogeneous critical illness with high morbidity and mortality. Early identification and risk assessment are crucial to improving patient prognosis. Current artificial intelligence（AI）technology, especially machine learning（ML）models, have shown significant potential in the early diagnosis, risk stratification and personalized management of ARDS. Compared with traditional scoring systems, AI models perform well in predicting mortality and optimizing clinical decision-making, especially through multimodal data fusion, which can significantly improve the prediction accuracy of the model. However, the lack of interpretability, limited clinical applicability and data privacy of AI models are still the main challenges restricting clinical application. Future research should focus on improving model transparency, optimizing clinical integration and solving ethical issues to promote the further development of AI-enabled ARDS precision medicine.

Keywords: Acute respiratory distress syndrome; Artificial intelligence; Machine learning; Risk prediction; Precision medicine

Fund program: Heilongjiang Provincial Key Research and Development Program（JD22C005）; Binhu Light Senior Medical Expert Team Project（BH202401）

Acute respiratory distress syndrome (ARDS) is one of the most common acute critical conditions in the Intensive Care Unit (ICU), characterized by acute hypoxemic respiratory failure, with high incidence and mortality rates. Despite progress in supportive treatment over the past decade, the mortality rate for ARDS remains around 40%, and early identification and accurate prognostic assessment still face significant challenges [1]. Traditional risk scoring systems, such as the SOFA score, have limited predictive ability and fail to meet clinical needs. The rapid development of artificial intelligence (AI) and machine learning (ML) technologies in recent years has provided new opportunities for early prediction, phenotypic classification, and personalized management of ARDS.

AI significantly enhances the diagnostic and prognostic evaluation capabilities for ARDS by integrating clinical data, biomarkers, and imaging features. Some studies have utilized dynamic clinical data collected from the ARDSNet FACTT trial to develop a random forest model for mortality prediction, showing high predictive performance (AUC = 0.84) in ARDS prognosis evaluation [2]. Furthermore, AI combined with natural language processing (NLP) and imaging analysis technologies can efficiently process complex clinical information, supporting personalized treatment [3]. These findings demonstrate that AI and ML technologies have significant clinical application potential in the early identification, risk assessment, and personalized management of ARDS. However, despite promising prospects, ML models still require further research to improve their interpretability and clinical applicability. This review summarizes the progress of AI applications in precision medicine for ARDS, analyzes its limitations, and discusses future development directions.

1. AI in Early Detection and Risk Prediction of ARDS

Machine learning (ML) has shown significant advantages in early recognition and risk stratification of ARDS. By analyzing complex, multidimensional clinical data, ML models can accurately identify key prognostic factors. Predictive models based on ML have shown consistency indices of 0.84 and 0.81 in training and external validation datasets, significantly outperforming traditional SOFA scores (AUC = 0.64) [4]. Specific algorithms such as XGBoost achieved an AUC of 0.833 when predicting sepsis-associated ARDS in-hospital mortality [5]. Multimodal data fusion further enhances predictive accuracy. By integrating clinical parameters, imaging features, and biomarkers, models can provide a comprehensive assessment of the patient's condition. Models combining clinical and omics data achieved an AUC of 0.868, with a systematic review showing a summary AUC of 0.91 for multimodal AI models, significantly optimizing early diagnostic capability [6-7]. AI-driven early prediction is of great value in clinical management, enabling timely identification and intervention of high-risk patients, optimizing resource allocation, and improving prognosis. However, the clinical translation of AI models faces challenges: the "black box" nature makes predictions difficult to interpret, which affects clinical trust, and the clinical acceptability and applicability of models need further validation. Future research should focus on improving model interpretability, strengthening clinical validation, and optimizing integration with clinical workflows to promote their broad application in ARDS management.

2. AI in Phenotypic Classification of ARDS

ARDS is a disease with significant clinical heterogeneity, which is the core challenge of precision medicine for ARDS. Phenotypic classification is crucial for guiding treatment strategies. Currently, the phenotypic classification of ARDS patients mainly relies on clinical features, imaging examinations, and biomarkers. AI-driven phenotypic classification through multimodal data provides a new path for personalized treatment. Studies have shown that ML-based phenotypic classification can combine clinical characteristics (such as etiology and physiological parameters), imaging data (such as lung ultrasound), and biomarkers (such as gene expression), identifying subphenotypes with different prognoses and treatment responses. Researchers divided 1,902 patients' lung ultrasound data into seven phenotypes reflecting different pathophysiological states, which represent the typical features of different critical patients [8]. Different subphenotypes respond differently to treatments (such as prone positioning ventilation), and ML-based subphenotypes have revealed significant differences in 28-day mortality in ARDS patients [9]. AI-driven predictive models (such as high-flow nasal oxygen failure risk models) can assist in optimizing treatment decisions [10]. Furthermore, precise phenotypic classification can optimize clinical trial design by selecting homogeneous patient groups to improve research efficiency. AI-enabled phenotypic classification is not only key to understanding the heterogeneity of ARDS but also forms the cornerstone for personalized interventions and improving prognosis.

3. AI-Assisted Prognosis Prediction in ARDS

AI has demonstrated significant advantages in predicting the prognosis of ARDS, with key factors being the precise selection of prognostic indicators and data features. Clinical characteristics (such as age, gender, comorbidities, and blood oxygen saturation) combined with laboratory markers (such as C-reactive protein and white blood cell count) effectively reflect disease severity and inflammation status. Feature selection methods to handle collinearity can prevent overfitting and improve model performance. Deep learning models based on high-quality, diverse datasets have achieved an AUC of 0.833 in predicting ICU patient mortality, and multimodal models integrating clinical, metabolomic, and biochemical data further improved the AUC [5]. AI models excel in identifying high-risk complications (such as acute kidney injury, AUC = 0.865) and specific subtypes (such as low/high inflammation subtypes in pediatric ARDS), providing support for personalized treatment [11-12]. However, the generalizability of models is limited by the diversity of data sources, and the lack of interpretability of complex models may reduce clinical trust; data privacy and ethical issues also restrict the widespread application of these models [13]. Future research should optimize model development processes, enhance interpretability, and establish a data security framework to accelerate AI's translation into clinical practice.

4. AI-Guided Mechanical Ventilation and Fluid Management Strategies

Mechanical ventilation is a key intervention in the treatment of ARDS. However, inappropriate ventilation settings can worsen lung injury, making the optimization of mechanical ventilation settings essential. In recent years, AI technologies, especially reinforcement learning algorithms, have shown significant potential in adjusting ventilation parameters for personalized care. AI models based on physiological data can adjust ventilation parameters (such as tidal volume and positive end-expiratory pressure) in real-time, reducing complications such as barotrauma and shortening ventilation time [14]. Studies have shown that AI models outperform traditional clinical practices in estimating in-hospital mortality and optimizing oxygen saturation, with personalized ventilation settings significantly reducing expected in-hospital mortality.

Fluid management is a crucial task in ARDS management. AI models evaluating fluid load and circulatory status provide effective decision support for clinicians. These models analyze real-time data from patients, including cardiac output, blood pressure, and urine output, to assess fluid status and circulatory function. AI continuously monitors hemodynamic data, dynamically balancing fluid requirements and the risk of overload, thus reducing complications such as pulmonary edema [15]. Clinical trials and real-world data have validated the effectiveness of AI strategies. For example, privileged logistic regression models outperform traditional methods in ARDS subgroup classification and survival prediction, significantly reducing mortality and medical resource consumption [16]. Future studies should further enhance the generalizability and interpretability of models to ensure their safe application in different clinical environments.

5. Diagnosis and Assessment of ARDS Based on Imaging Analysis

AI has significantly improved the diagnostic efficiency and accuracy of ARDS in imaging analysis. Deep learning algorithms based on chest X-rays can automatically identify early pulmonary infiltrates and other pathological features, supporting early diagnosis and patient stratification. These algorithms exhibit high sensitivity and specificity, and are particularly advantageous in resource-limited environments [17]. Recent research has made significant progress in AI-assisted CT imaging segmentation and lesion identification. The introduction of AI has made CT image processing and analysis more efficient and accurate. AI algorithms can rapidly process large volumes of imaging data, automatically detect pulmonary lesions, and perform segmentation, thereby improving the efficiency of clinical doctors during the diagnostic process. AI applications in lung CT have further enhanced diagnostic capabilities. For example, privileged logistic regression models integrate mechanical ventilation variables and imaging features, utilizing a privileged information learning paradigm to identify subtle lesions, optimizing diagnosis and follow-up procedures [18]. Radiomics, as an emerging medical imaging analysis method, extracts numerous quantitative features from medical images and has been widely applied in the diagnosis and prognosis evaluation of various diseases. Specifically, in ARDS management, the combination of radiomic features with clinical data provides multi-dimensional assessment capabilities. By extracting quantitative imaging features (such as texture and shape indices) and integrating clinical information, AI models can comprehensively reveal disease complexity, predict prognosis, and construct accurate risk models [19-20]. This approach supports personalized treatment decisions, enhances patient management efficiency, and future efforts should address data diversity challenges to improve model generalizability.

6. Limitations and Prospects of AI in Precision Medicine for ARDS

The application of AI in ARDS precision medicine holds great potential, covering sub-group classification, early prediction, and personalized management. Multi-modal data integration significantly improves prediction accuracy. However, there are still several challenges: In terms of data dependency, obtaining high-quality, large-scale datasets is difficult, limiting model translation and scalability. The lack of interpretability, due to the "black box" nature of deep learning, reduces clinical trust, necessitating the development of more transparent models. Ethical and technical challenges, such as algorithmic bias, data privacy, and fairness issues, must be addressed through policy frameworks. Future research should focus on developing explainable models, optimizing privacy protection technologies, and standardizing validation processes to promote the safe integration of AI into ARDS management. Furthermore, the use of large-scale cross-regional datasets will further enhance the generalizability of models and accelerate the progress of precision medicine.

7. Conclusion

AI applications in ARDS precision medicine provide powerful tools for early diagnosis, risk prediction, and personalized treatment. Machine learning models integrate multi-modal data, significantly outperforming traditional methods, and laying the foundation for optimizing clinical decision-making and improving patient outcomes. However, issues related to model interpretability, clinical applicability, and data privacy remain to be addressed. In the future, through technological optimization, ethical regulations, and clinical integration, AI is expected to play a greater role in ARDS management and drive the comprehensive development of precision medicine.

Conflict of interest None

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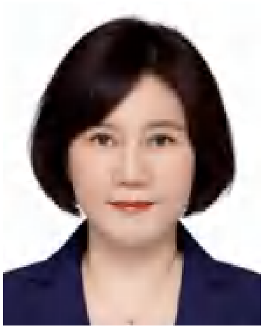
·学术前沿·

急性呼吸窘迫综合征人工智能预测模型:进展与挑战

孟祥林[1]，　熊雅欣[1]，　韩慈[1]，　葛新[2]，　赵鸣雁[1]
1. 哈尔滨医科大学附属第一医院重症医学科，黑龙江 哈尔滨 150000；
2. 无锡市第九人民医院重症医学科，江苏 无锡 214062



赵鸣雁，一级主任医师，教授，博士研究生导师，哈尔滨医科大学附属第一医院重症医学科主任，重症医学教研室主任。现任中华医学会重症医学分会副主任委员，中华医学会重症医学分会重症肾脏学组副组长，中国医师协会重症医学专业委员会委员，中国女医师协会重症医学专业委员会副会长。在重症感染、多脏器功能障碍的综合治疗及大手术围术期管理等方面拥有深厚的理论基础和丰富的临床实践。发表论文近百篇，参编国家规划教材及著作十余部，多次获得科技进步奖项。

孟祥林，医学博士，博士后，主任医师，硕士研究生导师，哈尔滨医科大学附属第一医院重症医学科副主任。现任中国研究型医院学会危重医学专业委员会青年委员，黑龙江省医学会外科感染与危重症医学专业委员会副主任委员，黑龙江省医学会重症医学分会委员，黑龙江省中西医结合重症医学学会常务委员。长期从事脓毒症、急性呼吸窘迫综合征、多脏器功能障碍综合征与多发性创伤患者的临床救治。主持和参与国家级与厅局级科研基金多项，发表SCI收录论文20余篇，获得黑龙江省科学技术奖二等奖。

摘要： 急性呼吸窘迫综合征（acute respiratory distress syndrome，ARDS）是一种高度异质性的临床综合征，具有较高的发病率和病死率，早期识别与风险评估对改善患者预后至关重要。当前人工智能（artificial intelligence，AI）技术，特别是机器学习（machine learning，ML）模型，在ARDS的早期诊断、风险分层及个性化管理中展现出显著的潜力。相较于传统评分系统，AI模型在预测死亡率和优化临床决策方面具有巨大潜力，尤其是通过多模态数据融合能够显著提升模型的预测精度。然而，AI模型在可解释性不足、临床适用性有限以及数据隐私等方面的问题仍是限制其临床应用的主要挑战。未来研究应聚焦于提升模型透明度、优化临床整合并解决伦理问题，以推动AI赋能的ARDS精准医疗的进一步发展。

关键词： 急性呼吸窘迫综合征；人工智能；机器学习；风险预测；精准医疗
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Artificial intelligence prediction models for acute respiratory distress syndrome: progress and challenges

MENG Xianglin*, XIONG Yaxin, HAN Ci, GE Xin, ZHAO Mingyan
**Department of Critical Care Medicine, The First Affiliated Hospital of Harbin Medical University, Harbin, Heilongjiang 150000, China*
Corresponding author: ZHAO Mingyan, E-mail: zhaomingyan@hrbmu.edu.cn

Abstract: Acute respiratory distress syndrome (ARDS) is a highly heterogeneous critical illness with high morbidity

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通信作者： 赵鸣雁，E-mail：zhaomingyan@hrbmu.edu.cn
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and mortality. Early identification and risk assessment are crucial to improving patient prognosis. Current artificial intelligence (AI) technology, especially machine learning (ML) models, have shown significant potential in the early diagnosis, risk stratification and personalized management of ARDS. Compared with traditional scoring systems, AI models perform well in predicting mortality and optimizing clinical decision-making, especially through multimodal data fusion, which can significantly improve the prediction accuracy of the models. However, the lack of interpretability, limited clinical applicability and data privacy of AI models are still the main challenges restricting clinical application. Future research should focus on improving model transparency, optimizing clinical integration and solving ethical issues to promote the further development of AI-enabled ARDS precision medicine.

Keywords: Acute respiratory distress syndrome; Artificial intelligence; Machine learning; Risk prediction; Precision medicine

Fund program: Heilongjiang Provincial Key Research and Development Program (JD22C005); Binhu Light Senior Medical Expert Team Project (BH202401)

急性呼吸窘迫综合征(acute respiratory distress syndrome，ARDS)是重症医学科(intensive care unit，ICU)中最为常见的急危重症，以急性低氧性呼吸衰竭为主要表现，具有高发病率与高病死率的特征。尽管支持性治疗在过去十年取得进展，但ARDS的死亡率仍然高达40%左右，其早期识别和精准预后评估仍面临重大挑战[1]。传统风险评分系统(如SOFA评分)因预测能力有限，难以满足临床需求。人工智能(artificial intelligence，AI)和机器学习(machine learning，ML)技术近年来的快速发展为ARDS的早期预测、表型分类及个性化管理提供了新机遇。

AI通过整合临床数据、生物标志物及影像学特征，显著提升了对ARDS的诊断和预后评估能力。有研究利用ARDSNet FACTT试验收集动态临床数据，开发随机森林模型对死亡率进行预测，在ARDS预后评估中展现出较高预测性能[受试者工作特征曲线下面积(AUC)达0.84][2]。此外，AI结合自然语言处理(natural language processing，NLP)和影像分析技术，能够高效处理复杂临床信息，为个性化治疗提供支持[3]。这些研究结果表明，AI和ML技术在ARDS的早期识别、风险评估和个性化管理中具有重要的临床应用潜力。然而，尽管ML模型在ARDS管理中展现出良好的应用前景，但仍需进一步研究以提高模型的可解释性和临床适用性。本文综述AI在ARDS精准医疗中的应用进展，分析其局限性，并展望未来发展方向。

1　AI在ARDS早期检测与风险预测中的应用

ML在ARDS的早期识别和风险分层中展现出显著优势。通过解析复杂的多维临床数据，ML模型能够精准识别关键预后因素。基于ML的预测模型在训练和外部验证数据集中的一致性指数分别达到0.84和0.81，显著优于传统SOFA评分(AUC仅为0.64)[4]。特定算法如XGBoost在预测脓毒症相关ARDS住院死亡率时，AUC高达0.833[5]。多模态数据融合进一步提升了预测精度，通过整合临床参数、影像学特征及生物标志物，模型能够全面评估患者病情。综合临床与组学数据的模型AUC高达0.868，系统评价显示多模态AI模型的汇总AUC为0.91，显著优化了早期诊断能力[6-7]。AI驱动的早期预测对临床管理具有重要价值，可实现高风险患者的及时识别与干预，优化资源分配并改善预后。然而，AI模型的临床转化面临挑战：一是“黑箱”特性导致预测依据难以解释，影响临床信任；二是模型的临床接受度和适用性需进一步验证。未来研究应聚焦于提升模型可解释性、加强临床验证及优化与临床工作流程的整合，以促进其在ARDS管理中的广泛应用。

2　AI在ARDS表型分类中的应用

ARDS是一种临床异质性显著的疾病，其诊治也是ARDS精准医疗的核心挑战。其表型分类对于指导治疗策略至关重要。目前，针对ARDS患者的表型划分主要依赖于临床特征、影像学检查和生物标志物的检测。AI通过多模态数据驱动的表型分类，为个性化治疗提供了新路径。研究表明，基于ML的表型划分可结合临床特征(如病因、生理参数)、影像学数据(如肺部超声)及生物标志物(如基因表达)，识别具有不同预后和治疗反应的亚表型。研究人员利用1 902例患者肺部超声数据划分出七种反映病理生理状态的表型，这些表型可代表不同类型危重病患者的典型特征[8]。不同亚表型患者对治疗(如俯卧位通气)的反应差异显著，利用ML识别的亚表型发现ARDS患者28天死亡率存在明显差异[9]。AI驱动的预测模型(如高流量鼻氧失败风险模型)可辅助优

化治疗方案的选择[10]。此外,精准表型分类可优化临床试验设计,通过筛选同质化患者群体提升研究效率。AI赋能的表型分类不仅是理解ARDS异质性的关键,也是实现个性化干预和改善预后的基石。

3 AI辅助的ARDS临床结局预测

AI在ARDS预后预测中展现出显著优势,关键在于精准选择预后指标和数据特征。临床特征(如年龄、性别、基础疾病、血氧饱和度)结合实验室指标(如C反应蛋白、白细胞计数)能够有效反映疾病严重程度和炎症状态。通过特征选择方法处理共线性,可避免过拟合并提升模型性能。基于高质量、多样化数据集的深度学习模型,在ICU患者死亡率预测中AUC达0.833;多模态模型整合临床、代谢组学和生化数据后,AUC进一步提升[5]。AI模型在识别高风险并发症(如急性肾损伤,AUC达0.865)和特定亚型(如儿科ARDS的低/高炎症亚型)方面表现优异,为个体化治疗提供了支持[11-12]。然而,模型的泛化能力受限于数据来源的多样性,复杂模型的可解释性不足可能降低临床信任;数据隐私和伦理问题也限制了模型的广泛应用[13]。未来需优化模型开发流程、增强可解释性并建立数据安全框架,以加速AI在临床实践中的转化。

4 AI指导的机械通气与液体管理策略

在ARDS的治疗中,机械通气是关键的干预措施。然而,不恰当的通气参数设置会导致肺损伤加重,因此,优化机械通气的设置至关重要。近年来,AI技术,尤其是强化学习算法在个性化通气参数调整中的应用,展现出显著的潜力。基于生理数据的AI模型可实时调整通气参数(如潮气量、呼气末正压),降低气压伤等并发症并缩短通气时间[14]。研究表明,AI模型在估计住院死亡率和优化氧饱和度方面的表现优于传统临床实践,显示出个性化通气设置显著降低了预期的住院死亡率。

在ARDS的管理中,液体管理是一项至关重要的任务。利用AI模型评估液体负荷与循环状态,为临床医师提供了有效的决策支持。这些模型能够分析来自患者的实时数据,包括心脏输出量、血压、尿量等,从而评估患者的液体状态和循环功能。AI通过持续监测血流动力学数据,动态平衡液体需求与过负荷风险,减少肺水肿等并发症[15]。临床试验和真实世界数据验证了AI策略的有效性。例如,特权逻辑回归模型在ARDS亚组分类和生存预测中优于传统方法,显著降低死亡率和医疗资源消耗[16]。未来需进一步提升模型的泛化能力和可解释性,确保其在不同临床环境中的安全应用。

5 基于影像分析的ARDS诊断与评估

AI在影像分析中显著提升了ARDS的诊断效率和准确性。基于胸部X线的深度学习算法可自动识别早期肺浸润等病变特征,支持早期诊断和患者分层,敏感性和特异性较高,尤其在资源有限的环境中具有优势[17]。在AI辅助CT影像分割与病灶识别方面,近年来的研究进展显著。AI技术的引入,使得CT影像的处理与分析变得更加高效和准确。AI算法能够快速处理海量的影像数据,自动识别肺部病变,并进行分割,从而提高了临床医生在诊断过程中的效率。肺部CT的AI应用进一步增强了诊断能力,例如特权逻辑回归模型通过整合机械通气变量和影像特征,利用特权信息学习范式识别细微病变,优化诊断和随访流程[18]。

影像组学(radiomics)作为一种新兴的医学影像分析方法,通过从医学影像中提取大量定量特征,已被广泛应用于多种疾病的诊断和预后评估。特别是在ARDS的管理中,影像组学特征与临床数据的结合提供了多维度的评估能力,通过提取定量影像特征(如纹理、形状指标)并结合患者临床信息,AI模型能够全面揭示疾病的复杂性,预测预后并构建精准风险模型[19-20]。这种方法支持个性化治疗决策,提升对患者的管理效率,未来需解决数据多样性挑战以增强模型泛化性。

6 AI在ARDS精准医疗中的局限与展望

AI在ARDS精准医疗中的应用前景广阔,涵盖亚组分类、早期预测以及个性化管理。多模态数据整合显著提升了预测准确性。然而,目前仍面临多重挑战:数据依赖性方面,高质量、大规模数据集获取困难,限制了模型的转化和可扩展性;可解释性不足,深度学习的"黑箱"特性降低临床信任,亟需开发更透明的模型;伦理与技术挑战,包括算法偏见、数据隐私及公平性问题,需通过政策框架解决。未来研究应聚焦于开发可解释模型、优化隐私保护技术及标准化验证流程,以推动AI在ARDS管理中的安全整合。此外,跨区域大规模数据集的应用将进一步提升模型的泛化性,加速精准医疗的进展。

7 结 语

AI在ARDS精准医疗中的应用为早期诊断、风险

预测和个性化治疗提供了强大工具。ML模型整合了多模态数据,显著优于传统方法,为优化临床决策和改善患者预后奠定了基础。然而,模型可解释性、临床适用性及数据隐私问题仍需解决。未来通过技术优化、伦理规范及临床整合,AI有望在ARDS管理中发挥更大作用,推动精准医疗的全面发展。

利益冲突 无

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