

重症超声在脓毒症相关急性肾损伤中的应用进展

闫广艳, 王琼娅*

华中科技大学同济医学院附属武汉金银潭医院重症医学科, 湖北省传染病临床医学研究中心, 中国医学科学院武汉传染病诊治研究中心, 中国科学院武汉病毒研究所&武汉市金银潭医院感染性疾病与健康联合实验室, 湖北 武汉

收稿日期: 2025年12月29日; 录用日期: 2026年1月23日; 发布日期: 2026年2月3日

摘 要

重症超声是运用超声技术, 以患者的诊治问题为导向, 整合多器官信息动态评估, 确定治疗方向及指导精细调整的重要手段, 具有快速、无创、实时、可视化结构与功能监测结合的特点。脓毒症相关急性肾损伤具有高发病率、高死亡率、长期影响等临床特点。重症超声可通过动态监测心、肺、血管、肾脏等影像信息, 发挥早期识别风险分层、可视化的容量评估管理、明确感染源定位、启动肾脏替代治疗时机的精准选择等作用。现详细综述重症超声在脓毒症相关急性肾损伤诊疗中的应用进展及局限性, 旨在为早期干预和精准诊疗提供参考。

关键词

脓毒症, 急性肾损伤, 重症超声, 容量管理, 肾脏替代治疗

Advances in the Application of Critical Care Ultrasound in Sepsis-Associated Acute Kidney Injury

Guangyan Yan, Qiongya Wang*

Department of Critical Care Medicine, Wuhan Jinyintan Hospital, Tongji Medical College, Huazhong University of Science and Technology, Hubei Clinical Research Center for Infectious Diseases, Wuhan Research Center for Communicable Disease Diagnosis and Treatment, Chinese Academy of Medical Sciences, Joint Laboratory of Infectious Diseases and Health, Wuhan Institute of Virology and Wuhan Jinyintan Hospital, Chinese Academy of Sciences, Wuhan Hubei

Received: December 29, 2025; accepted: January 23, 2026; published: February 3, 2026

*通讯作者。

文章引用: 闫广艳, 王琼娅. 重症超声在脓毒症相关急性肾损伤中的应用进展[J]. 临床医学进展, 2026, 16(2): 690-698.
DOI: 10.12677/acm.2026.162440

Abstract

Critical care ultrasound (CCUS) is an important tool that applies ultrasonic technology in a patient-centered and problem-oriented manner. It integrates multi-organ information for dynamic assessment, determines treatment directions, and guides refined adjustments. CCUS is characterized by rapidity, non-invasiveness, real-time capability, and the integration of structural and functional visualization monitoring. Sepsis-associated acute kidney injury (SA-AKI) exhibits clinical features such as high incidence, high mortality, and long-term sequelae. By dynamically monitoring imaging information of the heart, lungs, blood vessels, kidneys, and other organs, CCUS plays key roles in early identification and risk stratification, visualized volume assessment and management, identification of infection sources, and precise selection of the timing for initiating renal replacement therapy (RRT). This article comprehensively reviews the application progress and limitations of CCUS in the diagnosis and treatment of SA-AKI, aiming to provide references for early intervention and precise clinical management.

Keywords

Sepsis, Acute Kidney Injury, Critical Care Ultrasound, Volume Management, Renal Replacement Therapy

Copyright © 2026 by author(s) and Hans Publishers Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

1. 引言

脓毒症是指机体对感染的免疫反应失调导致威胁生命的器官功能障碍, 肾脏是脓毒症常见的损伤器官[1] [2]。国际共识定义脓毒症相关急性肾损伤(sepsis associated-acute kidney injury, SA-AKI)是指脓毒症发病后 7 d 内出现的急性肾损伤, 诊断需同时满足脓毒症-3 (sepsis-3.0)标准和改善全球肾脏病预后组织(KDIGO)的 AKI 标准, 且无其他诱因, 既往无肾脏疾病[3] [4]。研究显示, 脓毒症相关急性肾损伤具有高发病率、高死亡率、长期影响等临床特点。在脓毒症休克患者中, 约 92.8%的患者发生急性肾损伤[5], 病死率高达 50%~70% [5]-[7], 还是发展成为慢性肾脏疾病(CKD)和心血管事件的独立危险因素[3] [8]-[10]。

脓毒症相关急性肾损伤的临床表现多样, 早期识别、准确诊断和精准管理至关重要。重症超声是运用超声技术, 以患者的诊治问题为导向, 整合多器官信息动态评估, 确定治疗方向及指导精细调整的重要手段, 具有快速、无创、实时、可视化结构与功能监测结合的特点[11] [12]。现围绕重症超声在 SA-AKI 患者的临床应用以及局限性等进行综述, 以期对 SA-AKI 患者的诊治提供参考。

本综述系统检索了 PubMed、Embase、Web of Science、中国知网及万方数据库, 结合“脓毒症”“急性肾损伤”“重症超声”“renal Doppler”等中英文主题词与自由词, 纳入聚焦于重症超声在 SA-AKI 诊断、风险分层、容量管理及治疗决策中的临床研究、综述与共识, 旨在筛选该领域代表性证据进行述评。

2. SA-AKI 的病理生理学机制

SA-AKI 的发病机制极为复杂, 并非单纯的“肾脏灌注不足”, 而是脓毒症引发的全身性紊乱在肾脏这一脆弱器官的集中体现[3] [13]-[20]。包括血流动力学改变、微循环及内皮功能障碍、炎症反应及免疫失调、细胞代谢重编程、程序性细胞死亡等氧化应激及肾小管细胞损伤等综合性过程。

3. 重症超声脓毒症相关急性肾损伤诊治过程的精准指导作用

3.1. 重症超声指导脓毒症相关急性肾损伤的早期识别和风险分层

早期识别和精准预测是改善患者预后的关键环节。目前 SA-AKI 的诊断主要依赖于尿量的减少和血清肌酐的升高(serum creatinine), 但二者具有易干扰性和滞后性。目前已有基于临床指标和评分的预测模型, 可预测脓毒症相关急性肾损伤发生的风险、合并并发症及死亡的风险, 这些模型利用患者常规临床数据、生命体征和实验室检查结果, 通过统计学或机器学习方法构建, 有的已被开发成小程序供临床医生使用[21]-[26]。近年来也发现一些新型的生物标志物可预测 SA-AKI 的发生[27]-[35], 其中包括金属蛋白酶组织抑制剂、微小 RNA 等损害前阶段生物标志物, 中性粒细胞明胶酶相关脂质运载蛋白等损伤性生物标志物以及胱抑素 C 等功能性生物标志物。但以上方法预测方法在临床应用的可行性方面仍有欠缺, 作用也较为局限。

研究显示, 利用超声动态监测肾动脉阻力指数(RRI)、静脉充盈超声评分(VExUS 评分)在脓毒症相关急性肾损伤的早期预测和风险分层中展现出较好的预测价值[36]-[51]。肾动脉阻力指数(RRI)是通过多普勒超声测量肾内动脉的收缩期和舒张期血流速度计算得出, 是目前研究最广泛、证据相对充分的超声预测指标[36]-[45]。一项针对成人 ICU 脓毒症患者的研究发现, 在诊断 SA-AKI 方面, RRI (入院时测量值 ≥ 0.72) 展现出优异的预测能力, 其受试者工作特征曲线下面积(AUROC)高达 0.905 [39]。另一项研究也证实, RRI 是预测 AKI 发生的最佳参数(AUROC = 0.898) [40]。在儿童脓毒症患者中, RRI 同样显示出良好的诊断准确性, 在 5~12 岁年龄组, RRI 预测第 3 天发生 AKI 的 AUROC 为 0.761 [40]。不同研究提出的预测界值略有差异, 这可能与患者群体、测量时机及 AKI 定义有关[35]-[45]。另有研究显示[42], RRI 预测 SA-AKI 的价值不高, 需要对多普勒超声测得 RRI 的影响因素进一步分析, 才能为预测提供有效的线索。

RRI 并非肾脏特异性指标, 其数值可受心率、脉压差、血管硬化程度及腹内压等因素显著影响, 因此解读时需谨慎[41] [46]。在脓毒症高动力循环状态下, RRI 升高可能更多反映药物性血管收缩或全身血流动力学改变, 而不一定意味着肾灌注真实恶化[39] [40]。因此, 将 RRI 变化与平均动脉压、心输出量、中心静脉压、尿量及血清肌酐等终末灌注指标联合交叉验证, 并在可能时结合早期生物标志物(如 NGAL、CCL14), 以提高脓毒症相关急性肾损伤的判别能力, 从而避免将药物效应误判为肾灌注恶化, 并提升 RRI 在 SA-AKI 诊治中的临床价值[42] [45]。

越来越多研究显示全身性及肾脏局部的静脉充血也是驱动脓毒症相关急性肾损伤发生和恶化的重要独立因素[41]-[52]。静脉充盈超声评分(VExUS 评分)是一项新兴的评估指标, 是通过多普勒超声系统评估中心静脉压力传导至末梢静脉状态的半定量方法, 通常通过扫描下腔静脉、肝静脉、门静脉和肾内静脉的血流频谱, 根据其异常程度进行分级评分。一项研究显示[50]肾静脉血流模式(特别是 PRVF 模式)与患者预后密切相关, 入住 ICU 时 PRVF 的静脉淤血指数(RVSI)对 28 天肾功能预后有一定的预测能力(AUC = 0.626), 联合评估 PRVF 和 IRVF 能显著提高预测效能(AUC = 0.687), VExUS 评估的动态变化比单次测量更具预测价值。

3.2. 重症超声指导容量管理

脓毒症休克患者常伴有复杂的血流动力学紊乱, 血流动力学不稳定或容量过负荷都会对肾脏造成进一步的损伤[2] [6] [8] [45]。综合性的 POCUS 检查(包括容量评估、心脏、肺部、下腔静脉、肾脏)有助于临床医生快速精准的找到干预靶点。

研究显示可用下腔静脉直径及呼吸变异度、左心室流出道速度时间积分变化率、颈动脉校正血流时

间等超声参数进行容量评估和液体反应性监测,精准指导容量管理[53]-[62]。下腔静脉直径及呼吸变异度(IVC Diameter),通常测量呼气末直径(IVCEE)和吸气末直径(IVCI),下腔静脉塌陷指数(cIVC)(用于自主呼吸患者)、下腔静脉扩张指数(dIVC)(用于机械通气患者)。下腔静脉直径反映静态的容量状态,在自主呼吸的脓毒症休克患者中,下腔静脉直径细小且随呼吸塌陷显著,通常提示血容量不足或相对不足;反之,直径增宽且固定,则提示容量过负荷或右心功能不全[53]-[55]。IVC呼吸变异度反映动态的容量反应性。无论是塌陷还是扩张,其变异幅度越大,通常提示患者对液体治疗有反应的可能性越高,即存在容量反应性[56][57]。自主呼吸的患者的下腔静脉塌陷指数(IVC-CI) > 50%和机械通气的患者下腔静脉扩张指数(IVC-DI) > 18% [55],提示可能从补液中获益。IVC-CI < 20%,且IVC最大直径 > 2.1 cm,通常与容量超负荷和右房压升高(>10 mmHg)相关,提示继续补液风险高。

左心室流出道速度时间积分变化率(Δ LVOT VTI),即在给予一个可逆的容量负荷(如被动抬腿试验)或进行液体负荷试验(如快速输注 500 毫升晶体液)前后,计算左心室流出道速度时间积分变化率。这一变化率直接反映了心脏的 Frank-Starling 机制是否处于功能曲线上升支,即前负荷增加能否有效转化为心输出量的提升,从而判断容量反应性。研究显示,左心室流出道速度时间积分变化率具有高敏感性、特异性和可靠的临界值[57][58]。一项针对脓毒症相关急性循环衰竭患者的观察性研究显示,以液体负荷试验后左心室流出道速度时间积分变化率作为指标,其预测容量反应性的敏感性高达 96%,特异性达到 100%,受试者工作特征曲线下面积(AUC)为 0.992 [58]。一项系统性综述汇总了 199 名成人脓毒症/脓毒性休克患者的数据,发现预测容量反应性的最佳 LVOT VTI 变化率临界值范围在>7%至 16%之间,对应的敏感性为 78%~96%,特异性为 91%~100%,AUC 为 0.84~0.99 [57]。

颈动脉校正血流时间(颈动脉 FTc)是通过颈动脉多普勒超声测量并经过心率校正的收缩期血流时间,反映左心室射血时间,并受到前负荷的显著影响。在评估容量反应性时,临床关注的重点不是静态绝对值,而是其在特定干预(如被动抬腿试验或液体负荷试验)前后的动态变化。用 Δ FTc 预测脓毒症休克患者容量反应性具有较好的灵敏性和特异性[58]-[61]。如果 Δ FTc 在干预后显著增加,表明患者有容量反应性,可以继续密切监测下进行液体复苏。如果 Δ FTc 无显著变化,则提示患者很可能处于心功能曲线的平台期,继续补液不仅无法有效提升心输出量,反而会增加肺水肿和器官水肿的风险。

同时可通过重症超声动态监测肺部超声 B 线评分[62]、静脉超声充盈评分[50][51]等参数指导早期识别肺水肿、体循环淤血等液体过负荷。如肺部超声 B 线数量增多(如每肋间 ≥ 3 条)或出现融合 B 线(“白肺”),或静脉超声充盈评分 ≥ 2 分,可能提示液体过负荷[62][63]。

3.3. 重症超声指导脓毒症相关急性肾损伤患者的心脏状态评估

临床实践中通常综合评估多种心脏参数确定心脏的性能和效率、前向血流及后向淤血情况[63]-[67]。通过评估左心室(LV)大小和运动状态,可对射血分数(EF)进行定性判断,左室收缩力是亢进、正常还是减退[65]。脓毒症早期常表现为高动力状态,而脓毒症相关心肌病则表现为弥漫性室壁运动减弱。同时还可发现心包积液、瓣膜功能障碍及心腔扩大等其他异常。右心室(RV)扩大与室间隔变平是容量超负荷和/或压力超负荷相关,右心室流出道多普勒和经三尖瓣多普勒测量有助于区分毛细血管前性和毛细血管后性肺动脉高压。以上参数综合测量左心室流出道速度时间积分可为临床采取静脉补液、血管加压药或正性肌力药治疗、利尿剂治疗的剂量调整提供精准的决策支持。

3.4. 重症超声指导脓毒症诊断与感染源定位

重症超声可以快速评估肺部(识别肺炎、胸腔积液)、腹部(检查胆囊、胆道、肾脏、腹腔积液)、心脏(识别感染性心内膜炎赘生物)以及深部血管(诊断血栓性静脉炎)等,从而协助早期确定或排除感染灶[68]。

这直接支持了早期目标性抗菌治疗的实施。一项前瞻性研究显示,在符合脓毒症诊断标准的患者中,仅凭初始临床评估来确定感染源的敏感性仅为 48%,特异性为 86%。这意味着超过一半的感染源在初期可能被漏判或误判。采用重症超声辅助诊断后,对感染源识别的敏感性提升了 25%,总体准确率达到 75%。重症超声快速发现感染灶可能的部位,能够在患者就诊后 10 分钟内完成评估,其中诊断肺部感染的敏感度超过 90%,诊断软组织感染和胆囊炎的敏感度接近 80%,诊断憩室炎和阑尾炎的敏感度均为 60%。

3.5. 重症超声指导脓毒症相关急性肾损伤启动肾脏替代治疗的时机

肾脏替代治疗(RRT)联合其他药物治疗已成为脓毒症相关急性肾损伤患者的主要治疗策略[3]。既往启动肾脏替代治疗的时机常被用于急性肾损伤引起的危及生命的并发症(包括严重的高钾血症、代谢性酸中毒、明显的尿毒症等),对于暂无生命危险或紧急并发症的患者启动 RRT 时机存在争议。研究显示肾动脉阻力指数(RRI)、静脉超声充盈评分(VExUS 评分)对指导启动肾脏替代治疗的时机有一定的应用价值[41]-[52][69]-[73]。对于已经发生脓毒症相关肾损伤的患者,在积极的液体复苏、抗感染及血管活性药物支持等治疗下,可动态监测 RRI 的变化。如果尽管进行了充分的保守治疗,RRI 仍居高不下或继续上升,这可能表明肾脏自身调节机制已失效,是启动肾脏替代治疗、清除炎症介质、维持内环境稳定的强指征[68]。动态监测 VExUS 评分,可及时发现临床尚未表现的静脉淤血(如 VExUS 评分高、肾静脉呈单相波)的脓毒症相关急性肾损伤患者,有助于临床做出使用利尿剂或启动肾脏替代治疗的决策[52][71]-[73]。在需要连续肾脏替代治疗(CRRT)的危重 AKI 患者中,一项随机对照试验方案提出使用结合血管、肺和心脏超声的整合评分(BEST 评分)来量化液体过负荷状态并指导超滤,旨在更安全、准确地实现液体平衡[71]。

4. 重症超声在临床中应用的局限性

重症超声可作为指导脓毒症相关急性肾损伤患者诊治的重要工具,有助于实现个体化治疗,但仍存在以下局限性:1) 单一超声技术维度难以全面准确反映疾病的全貌。脓毒症相关肾损伤的病理生理机制极为复杂,常涉及全身炎症反应、血流动力学紊乱、微循环障碍等机制。在脓毒症早期,患者可能同时存在绝对容量不足(前负荷缺乏)和血管张力丧失(分布性休克),此时单用超声评估可能会低估液体复苏的需求。在脓毒症后期或合并心功能不全时,液体正平衡导致的肺水肿和器官淤血,超声评估的静脉淤血征象可能出现较晚,或与临床症状不完全同步[72]。2) 对操作者的技能与经验要求较高。评估时需要规范化的扫描切面、准确的测量以及对细微影像学征象的识别。对于获取图像的正确解读也需要具有一定的重症超声基础及临床诊治经验。不同资历的医师可能得出不一致的评估结果,影响治疗决策的连续性和可靠性。3) 受检者的个体差异。不同患者的个体差异不同,如体型、体位合并机械通气、腹腔高压等因素均会造成重症超声测量评估的误差。在解读参数做出诊疗决策时可能需要更加个体化,缺乏普适性的“金标准”,这在一定程度上限制了重症超声在临床的应用。

5. 结论与展望

目前脓毒症相关急性肾损伤仍是导致 ICU 患者死亡和遗留慢性肾功能不全的重要原因,是 ICU 诊治中的难点。重症超声,可通过动态监测心、肺、血管、肾脏等影像信息,发挥早期识别风险分层、可视化的容量评估管理、明确感染源定位、启动肾脏替代治疗时机的精准选择等作用,具有较大的临床应用潜力。未来,先进的临床预测评分、标准化的操作流程,与生物标志物的多参数整合以及人工智能技术应用,可进一步释放重症超声的潜力,从而有助于改善患者预后。

基金项目

基于多源异构数据的新发突发传染病智能预测预警模型研究(2022YFC2305103); 基于发热伴血小板

减少综合征人群队列的流行病学研究(2023-I2M-C&T-B-127)。

参考文献

- [1] Singer, M., Deutschman, C.S., Seymour, C.W., Shankar-Hari, M., Annane, D., Bauer, M., *et al.* (2016) The Third International Consensus Definitions for Sepsis and Septic Shock (Sepsis-3). *JAMA*, **315**, 801-810. <https://doi.org/10.1001/jama.2016.0287>
- [2] Peerapornratana, S., Manrique-Caballero, C.L., Gómez, H. and Kellum, J.A. (2019) Acute Kidney Injury from Sepsis: Current Concepts, Epidemiology, Pathophysiology, Prevention and Treatment. *Kidney International*, **96**, 1083-1099. <https://doi.org/10.1016/j.kint.2019.05.026>
- [3] Zarbock, A., Nadim, M.K., Pickkers, P., Gomez, H., Bell, S., Joannidis, M., *et al.* (2023) Sepsis-Associated Acute Kidney Injury: Consensus Report of the 28th Acute Disease Quality Initiative Workgroup. *Nature Reviews Nephrology*, **19**, 401-417. <https://doi.org/10.1038/s41581-023-00683-3>
- [4] 刘彩虹, 陈香美, 蔡广研, 等. 《第 28 届急性疾病质量倡议工作组共识报告: 脓毒症相关急性肾损伤》解读[J]. 中华肾脏病杂志, 2024, 40(3): 237-244.
- [5] Patanwala, A.E. and Erstad, B.L. (2025) Epidemiology of Septic Shock Associated Acute Kidney Injury: A National Retrospective Cohort Study. *Critical Care Medicine*, **53**, e1601-e1609. <https://doi.org/10.1097/ccm.0000000000006735>
- [6] Bellomo, R., Kellum, J.A., Ronco, C., Wald, R., Martensson, J., Maiden, M., *et al.* (2017) Acute Kidney Injury in Sepsis. *Intensive Care Medicine*, **43**, 816-828. <https://doi.org/10.1007/s00134-017-4755-7>
- [7] Manrique-Caballero, C.L., Del Rio-Pertuz, G. and Gomez, H. (2021) Sepsis-Associated Acute Kidney Injury. *Critical Care Clinics*, **37**, 279-301. <https://doi.org/10.1016/j.ccc.2020.11.010>
- [8] Kellum, J.A., Romagnani, P., Ashuntantang, G., Ronco, C., Zarbock, A. and Anders, H. (2021) Acute Kidney Injury. *Nature Reviews Disease Primers*, **7**, Article No. 52. <https://doi.org/10.1038/s41572-021-00284-z>
- [9] Wang, N., Li, X., Zhang, J., *et al.* (2024) [Association between Onset Time of Sepsis-Associated Acute Kidney Injury and Clinical Outcome in Patients with Sepsis]. *Chinese Medical Journal*, **104**, 1972-1978.
- [10] White, K.C., Serpa-Neto, A., Hurford, R., Clement, P., Laupland, K.B., See, E., *et al.* (2023) Sepsis-associated Acute Kidney Injury in the Intensive Care Unit: Incidence, Patient Characteristics, Timing, Trajectory, Treatment, and Associated Outcomes. A Multicenter, Observational Study. *Intensive Care Medicine*, **49**, 1079-1089. <https://doi.org/10.1007/s00134-023-07138-0>
- [11] Jury, D. and Shaw, A.D. (2021) Utility of Bedside Ultrasound Derived Hepatic and Renal Parenchymal Flow Patterns to Guide Management of Acute Kidney Injury. *Current Opinion in Critical Care*, **27**, 587-592. <https://doi.org/10.1097/mcc.0000000000000899>
- [12] Ravi, C. and Johnson, D.W. (2021) Optimizing Fluid Resuscitation and Preventing Fluid Overload in Patients with Septic Shock. *Seminars in Respiratory and Critical Care Medicine*, **42**, 698-705. <https://doi.org/10.1055/s-0041-1733898>
- [13] Hato, T. and Dagher, P.C. (2025) Molecular Mechanisms of Sepsis-Associated Acute Kidney Injury. *Journal of the American Society of Nephrology*, **36**, 2259-2268. <https://doi.org/10.1681/asn.0000000809>
- [14] Xu, L. and Sun, P. (2023) [Identification and Management of Sepsis Associated-Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **35**, 221-224.
- [15] 齐鹏, 张颖, 张丽萍. 脓毒症相关急性肾损伤研究进展[J]. 中华医院感染学杂志, 2025, 35(16): 2541-2545.
- [16] Ma, H., Guo, X., Cui, S., Wu, Y., Zhang, Y., Shen, X., *et al.* (2022) Dephosphorylation of Amp-Activated Protein Kinase Exacerbates Ischemia/Reperfusion-Induced Acute Kidney Injury via Mitochondrial Dysfunction. *Kidney International*, **101**, 315-330. <https://doi.org/10.1016/j.kint.2021.10.028>
- [17] Peng, W. and Li, G. (2022) [Research Progress of microRNAs in Sepsis-Associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **34**, 556-560.
- [18] Ergin, B., Kapucu, A., Demirci-Tansel, C. and Ince, C. (2014) The Renal Microcirculation in Sepsis. *Nephrology Dialysis Transplantation*, **30**, 169-177. <https://doi.org/10.1093/ndt/gfu105>
- [19] Hu, Z., Zhang, H., Yang, S., Wu, X., He, D., Cao, K., *et al.* (2019) Emerging Role of Ferroptosis in Acute Kidney Injury. *Oxidative Medicine and Cellular Longevity*, **2019**, Article ID: 8010614. <https://doi.org/10.1155/2019/8010614>
- [20] Li, Z., Wang, Y., Chen, Y., *et al.* (2024) [Research Progress on the Role of Mitochondrial Dynamics Disorder in Sepsis-associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **36**, 1117-1120.
- [21] Li, X., Zhang, J., Wang, N., *et al.* (2024) [Construction of a Predictive Model of Death for Sepsis-Associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **36**, 381-386.
- [22] 李恺, 赵宇亮, 张敏, 等. 脓毒症相关急性肾损伤患者临床特点及 90 天预后影响因素分析[J]. 中华肾病研究电

- 子杂志, 2025, 14(5): 248-253.
- [23] Zhang, J., Li, X., Wang, N., *et al.* (2024) [Construction and Validation of a Risk Nomogram for Sepsis-Associated Acute Kidney Injury in Intensive Care Unit]. *Chinese Journal of Critical Care Medicine*, **36**, 801-807.
- [24] Yue, X., Zhang, J., Li, X., *et al.* (2024) [Development and Validation of a Nomogram for Predicting 3-Month Mortality Risk in Patients with Sepsis-Associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **36**, 465-470.
- [25] Yang, L., Zhou, W., Liu, Y., *et al.* (2024) [Impact of Mean Perfusion Pressure on the Risk of Sepsis-Associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **37**, 367-373.
- [26] Zhang, J., Wang, N., Li, X., *et al.* (2023) [Predictive Value of Pulse Infusion Index in the Short-Term Prognosis of Patients with Sepsis-Induced Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **35**, 1195-1199.
- [27] Su, Q., Peng, W., Li, G., *et al.* (2022) [Advances on Machine Learning Applications in Sepsis Associated-Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **34**, 1222-1226.
- [28] Zhang, J., Li, X., Wang, N., *et al.* (2024) [Research Progress on Biomarkers of Sepsis-Associated Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **36**, 1216-1220.
- [29] 邹成林, 方璟, 田孝军, 等. CTRP3 对脓毒症患者并发急性肾损伤的早期预测价值[J]. 国际泌尿系统杂志, 2025, 45(1): 125-129.
- [30] 王炎, 李洁, 刘丹, 等. DKK3 在脓毒症相关急性肾损伤早期诊断的意义[J]. 河北医科大学学报, 2023, 44(11): 1295-1300.
- [31] 向晓红, 钟燕军, 李金秀. 尿 TIMP-2 × IGFBP7 在脓毒症相关性 AKI 中早期诊断价值的 Meta 分析[J]. 中华重症医学电子杂志, 2022, 8(3): 240-247.
- [32] 易雪琳, 欧阳亮, 虞玲. 血清 CysC、UmAlb、Scr 在脓毒症合并急性肾损伤患者中的表达及疾病预测价值[J]. 国际泌尿系统杂志, 2022, 42(1): 72-76.
- [33] 魏薇, 王华, 李婷, 等. miR-21 和 miR-107-5p 对脓毒症所致急性肾损伤患者 28 天生存率影响[J]. 国际遗传学杂志, 2018, 41(4): 266-272.
- [34] Li, N., Tang, T., Gu, M., Fu, Y., Qian, W., Ma, N.N., *et al.* (2025) Single Urinary Extracellular Vesicle Proteomics Identifies Complement Receptor CD35 as a Biomarker for Sepsis-Associated Acute Kidney Injury. *Nature Communications*, **16**, Article No. 6960. <https://doi.org/10.1038/s41467-025-62229-4>
- [35] Tavis, B.S., Morath, C., Rupp, C., Szudarek, R., Uhle, F., Sweeney, T.E., *et al.* (2025) Complementary Role of Transcriptomic Endotyping and Protein-Based Biomarkers for Risk Stratification in Sepsis-Associated Acute Kidney Injury. *Critical Care*, **29**, Article No. 136. <https://doi.org/10.1186/s13054-025-05361-3>
- [36] Das, P.K., Maurya, S.K., Nath, S.S., Kumar, T., Rao, N. and Shrivastava, N. (2023) Furosemide Stress Test and Renal Resistive Index for Prediction of Severity of Acute Kidney Injury in Sepsis. *Cureus*, **15**, e44408. <https://doi.org/10.7759/cureus.44408>
- [37] Fu, Y., He, C., Jia, L., Ge, C., Long, L., Bai, Y., *et al.* (2022) Performance of the Renal Resistive Index and Usual Clinical Indicators in Predicting Persistent Aki. *Renal Failure*, **44**, 2038-2048. <https://doi.org/10.1080/0886022x.2022.2147437>
- [38] Rajangam, M., Nallasamy, K., Bhatia, A., Kumar, V., Kaur, P. and Angurana, S.K. (2024) Renal Resistive Index by Point of Care Ultrasound to Predict Sepsis Associated Acute Kidney Injury in Critically Ill Children. *Pediatric Nephrology*, **39**, 3581-3589. <https://doi.org/10.1007/s00467-024-06392-8>
- [39] Teker, A., Duzenci, D., Teker, N., Senturk, H., Bicakcioglu, M., Dogan, Z., *et al.* (2025) Neutrophil Gelatinase-Related Lipocalin and Renal Resistive Index in the Diagnosis and Prognosis of Sepsis-Associated Acute Kidney Injury: A Cross-Sectional Study from Türkiye. *Nigerian Journal of Clinical Practice*, **28**, 889-896. https://doi.org/10.4103/njcp.njcp_720_24
- [40] Zaitoun, T., Megahed, M., Elghoneimy, H., Emara, D.M., Elsayed, I. and Ahmed, I. (2024) Renal Arterial Resistive Index versus Novel Biomarkers for the Early Prediction of Sepsis-Associated Acute Kidney Injury. *Internal and Emergency Medicine*, **19**, 971-981. <https://doi.org/10.1007/s11739-024-03558-y>
- [41] Zhu, J., Zhou, W., Fu, Y., *et al.* (2021) [Research Progress of Renal Resistive Index in the Evaluation of Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **33**, 1529-1532.
- [42] Fu, Y., Jiang, W., Zhou, W., *et al.* (2020) [Value of the Combination of Renal Resistive Index and Central Venous Pressure to Predict Septic Shock Induced Acute Kidney Injury]. *Chinese Journal of Critical Care Medicine*, **32**, 473-477.
- [43] 王华敏, 刘景, 陈晨, 等. 肾动脉阻力指数对老年脓毒症急性肾损伤患者优化治疗及预后的预测价值[J]. 国际医药卫生导报, 2020, 26(13): 1846-1850.
- [44] Zhou, W., Fu, Y., Jiang, W., *et al.* (2022) [Clinical Value of Renal Artery Resistance Index and Urinary Angiotensinogen in Early Diagnosis of Acute Kidney Injury in Patients with Sepsis]. *Chinese Journal of Critical Care Medicine*, **34**, 1183-

1187.

- [45] Jiang, W., Liao, T., Yu, J., Shao, J. and Zheng, R. (2023) Predictability Performance of Urinary C-C Motif Chemokine Ligand 14 and Renal Resistive Index for Persistent Sepsis-Associated Acute Kidney Injury in ICU Patients. *International Urology and Nephrology*, **55**, 1995-2003. <https://doi.org/10.1007/s11255-023-03511-6>
- [46] Mårtensson, J. and Bellomo, R. (2016) Pathophysiology of Septic Acute Kidney Injury. In: Ding, X. and Ronco, C., Eds., *Contributions to Nephrology*, S. Karger AG, 36-46. <https://doi.org/10.1159/000442363>
- [47] Wong, B.T., Chan, M.J., Glassford, N.J., Mårtensson, J., Bion, V., Chai, S.Y., et al. (2015) Mean Arterial Pressure and Mean Perfusion Pressure Deficit in Septic Acute Kidney Injury. *Journal of Critical Care*, **30**, 975-981. <https://doi.org/10.1016/j.jcrc.2015.05.003>
- [48] Legrand, M., Dupuis, C., Simon, C., Gayat, E., Mateo, J., Lukaszewicz, A., et al. (2013) Association between Systemic Hemodynamics and Septic Acute Kidney Injury in Critically Ill Patients: A Retrospective Observational Study. *Critical Care*, **17**, Article No. R278. <https://doi.org/10.1186/cc13133>
- [49] Chen, R., Lian, H., Zhao, H. and Wang, X. (2024) Renal Venous Flow in Different Regions of the Kidney Are Different and Reflecting Different Etiologies of Venous Reflux Disorders in Septic Acute Kidney Injury: A Prospective Cohort Study. *Intensive Care Medicine Experimental*, **12**, Article No. 115. <https://doi.org/10.1186/s40635-024-00700-0>
- [50] Pierre-Grégoire, G. (2025) VExUS Score: Optimizing Its Use in Perioperative and Critical Care Management. *Critical Care*, **29**, Article No. 472. <https://doi.org/10.1186/s13054-025-05687-y>
- [51] 陈工泽, 王艺萍, 张丽, 等. 静脉淤血超声评分与脓毒症患者急性肾损伤的相关性研究[J]. 中华危重症医学杂志(电子版), 2024, 17(6): 465-472.
- [52] 朱宣伟, 王晓波, 梁培培, 谢晓东, 陈蕊, 李冉, 丁振兴, 张泓. VExUS 评分在脓毒症合并急性肾损伤患者中的应用价值[J]. 中华急诊医学杂志, 2024, 33(3): 312-316.
- [53] Kawata, T., Daimon, M., Nakanishi, K., Kimura, K., Sawada, N., Nakao, T., et al. (2022) Factors Influencing Inferior Vena Cava Diameter and Its Respiratory Variation: Simultaneous Comparison with Hemodynamic Data. *Journal of Cardiology*, **79**, 642-647. <https://doi.org/10.1016/j.jcc.2021.11.022>
- [54] Hakim, D., Meilyana, F., Peryoga, S., Arniawati, I., Wijaya, E. and Martiano, M. (2024) Usefulness of Non-Invasive Parameters (Inferior Vena Cava Diameter, Inferior Vena Cava Collapsibility, Inferior Vena Cava-Aortic Ratio) for Hemodynamic Monitoring in Critically Ill Children: A Systematic Review. *Medical Devices: Evidence and Research*, **17**, 123-133. <https://doi.org/10.2147/meder.s454849>
- [55] Kaptein, M.J. and Kaptein, E.M. (2021) Inferior Vena Cava Collapsibility Index: Clinical Validation and Application for Assessment of Relative Intravascular Volume. *Advances in Chronic Kidney Disease*, **28**, 218-226. <https://doi.org/10.1053/j.ackd.2021.02.003>
- [56] Campos, N.B., de Lima, L.B., Ferraz, I.d.S., Nogueira, R.J.N., Brandão, M.B. and de Souza, T.H. (2023) Accuracy of Respiratory Variation in Inferior Vena Cava Diameter to Predict Fluid Responsiveness in Children under Mechanical Ventilation. *Pediatric Cardiology*, **45**, 1326-1333. <https://doi.org/10.1007/s00246-023-03115-y>
- [57] 张安科, 李伟, 王静, 等. 不同体位下腔静脉直径及其变异度的相关性分析[J]. 心血管病学进展, 2024, 45(7): 661-665.
- [58] Yu, H. and Xiu, G. (2023) [Research Progress of Critical Care Ultrasound in Volume Management of Sepsis]. *Chinese Journal of Critical Care Medicine*, **35**, 1106-1110.
- [59] Saji, S.Z., Murga, O., Khurana, S., Hung Phan, B., Khalil, B., Nagra, A.M., et al. (2025) Utilization of Left Ventricular Outflow Tract Velocity Time Integral in the Assessment of Fluid Responsiveness in Adult Patients with Sepsis or Septic Shock—A Systematic Review. *Journal of Ultrasound*, **28**, 823-833. <https://doi.org/10.1007/s40477-025-01072-1>
- [60] Sasidharan, P., Kaeley, N., Sharma, P., Jain, G., Shankar, T., Jayachandran, S., et al. (2025) The Left Ventricular Outflow Tract Velocity Time Integral as a Predictor of Fluid Responsiveness in Patients with Sepsis-Related Acute Circulatory Failure. *Cureus*, **17**, e77353. <https://doi.org/10.7759/cureus.77353>
- [61] Cui, J., Huang, L., Shang, X. and Liu, M. (2025) Evaluating the Role of Critical Care Ultrasonography in Predicting Volume Responsiveness among Septic Shock Patients Undergoing Fluid Resuscitation. *Ultrasound Quarterly*, **41**, e00719. <https://doi.org/10.1097/ruq.0000000000000719>
- [62] Velasco Malagón, S., Acosta-Gutiérrez, E., Nuñez-Ramos, J.A., Salinas, S. and Mora Pabón, G. (2024) Subclinical Congestion Evaluated by Point of Care Ultrasound (POCUS) at Discharge Predicts Readmission in Patients with Acute Heart Failure: Prognostic Cohort Study. *POCUS Journal*, **9**, 125-132. <https://doi.org/10.24908/pocus.v9i2.17709>
- [63] Martínez, A.R., Luordo, D., Rodríguez-Moreno, J., de Pablo Esteban, A. and Torres-Arrese, M. (2025) Point of Care Ultrasound for Monitoring and Resuscitation in Patients with Shock. *Internal and Emergency Medicine*, **20**, 1505-1515. <https://doi.org/10.1007/s11739-025-03898-3>
- [64] Moura de Azevedo, S., Duarte, R., Krowicki, J., Vázquez, D., Pires Ferreira Arroja, S. and Mariz, J. (2024) Heart in Focus: Advancing Pericardial Effusion Diagnosis with Point-of-Care Ultrasound. *Cureus*, **16**, e76681.

- <https://doi.org/10.7759/cureus.76681>
- [65] Batool, A., Chaudhry, S. and Koratala, A. (2023) Transcending Boundaries: Unleashing the Potential of Multi-Organ Point-Of-Care Ultrasound in Acute Kidney Injury. *World Journal of Nephrology*, **12**, 93-103. <https://doi.org/10.5527/wjn.v12.i4.93>
 - [66] Lopez-Candales, A. and Edelman, K. (2011) Shape of the Right Ventricular Outflow Doppler Envelope and Severity of Pulmonary Hypertension. *European Heart Journal—Cardiovascular Imaging*, **13**, 309-316. <https://doi.org/10.1093/ejehocard/jer235>
 - [67] Schnittke, N., Schmidt, J., Lin, A., Resop, D., Neasi, E. and Damewood, S. (2023) Interrater Reliability of Point-Of-Care Cardiopulmonary Ultrasound in Patients with Septic Shock: An Analysis of Agreement between Treating Clinician and Expert Reviewers. *The Journal of Emergency Medicine*, **64**, 328-337. <https://doi.org/10.1016/j.jemermed.2022.12.020>
 - [68] Sweeney, D.A. and Wiley, B.M. (2021) Integrated Multiorgan Bedside Ultrasound for the Diagnosis and Management of Sepsis and Septic Shock. *Seminars in Respiratory and Critical Care Medicine*, **42**, 641-649. <https://doi.org/10.1055/s-0041-1733896>
 - [69] Cortellaro, F., Ferrari, L., Molteni, F., Aseni, P., Velati, M., Guarnieri, L., *et al.* (2016) Accuracy of Point of Care Ultrasound to Identify the Source of Infection in Septic Patients: A Prospective Study. *Internal and Emergency Medicine*, **12**, 371-378. <https://doi.org/10.1007/s11739-016-1470-2>
 - [70] Zheng, F., Wang, Y., Zhou, W., Zhang, J., Lu, M., Pan, N., *et al.* (2024) Continuous Renal Replacement Therapy with Adsorbing Filter Oxiris in the Treatment of Sepsis Associated Acute Kidney Injury: A Single-Center Retrospective Observational Study. *BMC Nephrology*, **25**, Article No. 456. <https://doi.org/10.1186/s12882-024-03897-0>
 - [71] Liu, C., Huang, Y., Tang, X., Wei, W., Jin, L., Zeng, X., *et al.* (2025) Bedside Ultrasound-Guided Ultrafiltration for Acute Kidney Injury Patients Receiving CRRT: Protocol for a Randomised Controlled Trial (the BEST-AKI Study). *BMJ Open*, **15**, e093198. <https://doi.org/10.1136/bmjopen-2024-093198>
 - [72] Cieza Terrones, M., Rodríguez Tudero, C., Nanwani, A.C., Jiménez Mayor, E., Dominguez Davalos, M., De La Flor, J.C., *et al.* (2025) Extreme Fluid Accumulation Syndrome or Compartmental Balance Disorder? A Sepsis-Associated Acute Kidney Injury Case Report and Literature Review. *Journal of Clinical Medicine*, **14**, Article 8310. <https://doi.org/10.3390/jcm14238310>
 - [73] Prager, R., Arntfield, R., Wong, M.Y.S., Ball, I., Lewis, K., Rochweg, B., *et al.* (2024) Venous Congestion in Septic Shock Quantified with Point-of-Care Ultrasound: A Pilot Prospective Multicentre Cohort Study. *Canadian Journal of Anesthesia/Journal canadien d'anesthésie*, **71**, 640-649. <https://doi.org/10.1007/s12630-024-02717-1>