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术中脑氧饱和度监测预测脊柱手术患者术后谵妄的有效性：系统评价与Meta分析

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摘 要

目的：系统评价术中脑氧饱和度监测预测脊柱手术患者术后谵妄的有效性，明确其临床价值与研究争议，为围术期脑功能保护提供参考。方法：检索相关中英文数据库，对术中脑氧饱和度与脊柱手术术后谵妄的关联性研究、监测技术、危险因素、病理生理机制等进行系统梳理，分析现有证据的一致性与局限性，并总结Meta分析的关键要点。结果：术中脑氧饱和度可实时反映脑氧供需平衡，理论上对术后谵妄具有预测潜力，但脊柱手术领域高质量直接证据不足，rSO_2阈值、监测方案、谵妄评估标准不统一，研究结论存在争议。现有证据尚不足以支持其作为独立预测指标。结论：术中脑氧饱和度监测可用于脊柱手术患者脑低氧事件识别与风险分层，但单独用于预测术后谵妄的效能有限。推荐采用多模态脑功能监测，未来需开展大样本、标准化研究以明确其预测价值。

关键词

脑氧饱和度，脊柱手术，术后谵妄，近红外光谱，围术期监测，系统评价

Efficacy of Intraoperative Cerebral Oxygen Saturation Monitoring in Predicting Postoperative Delirium in Patients Undergoing Spine Surgery: A Systematic Review and Meta-Analysis

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Abstract

Objective: To systematically evaluate the efficacy of intraoperative cerebral oxygen saturation monitoring in predicting postoperative delirium (POD) in patients undergoing spine surgery, clarify its clinical value and research controversies, and provide a reference for perioperative cerebral function protection. Methods: Relevant Chinese and English databases were retrieved to systematically sort out the correlation studies, monitoring techniques, risk factors and pathophysiological mechanisms between intraoperative cerebral oxygen saturation and POD after spine surgery, analyze the consistency and limitations of existing evidence, and summarize the key points of meta-analysis. Results: Intraoperative cerebral oxygen saturation can reflect the balance of cerebral oxygen supply and demand in real time, and theoretically has predictive potential for POD. However, there is a lack of high-quality direct evidence in the field of spine surgery, the rSO_2 threshold, monitoring protocol and delirium assessment criteria are not unified, and research conclusions are controversial. Existing evidence is insufficient to support it as an independent predictor. Conclusion: Intraoperative cerebral oxygen saturation monitoring can be used for the identification of cerebral hypoxia events and risk stratification in spine surgery patients, but its efficacy in predicting POD alone is limited. Multimodal cerebral function monitoring is recommended, and large-sample and standardized studies are needed in the future to clarify its predictive value.

Keywords

Cerebral Oxygen Saturation, Spine Surgery, Postoperative Delirium, Near-Infrared Spectroscopy, Perioperative Monitoring, Systematic Review

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1. 引言

术后谵妄(POD)是脊柱手术围术期常见并发症，高龄、认知障碍、脑血管疾病等均为公认危险因素[1]。POD 可显著延长住院时间、增加医疗费用并导致长期认知功能下降[2]。研究显示，手术时间是 POD 与静默性脑梗死关联的显著中介因素[3]。术中脑氧饱和度(rSO_2)监测可早期识别脑低氧事件，理论上有助于预测并降低 POD 发生风险[4] [5]。心脏手术领域已有多项研究证实 rSO_2 与术后脑功能预后相关[6]，但针对脊柱手术患者，rSO_2 监测预测 POD 的直接证据仍较缺乏。术中低血压曾被视为 POD 危险因素，但多项非心脏手术研究提示，术中 MAP < 65 mmHg 与 POD 无显著独立关联[7]，因此本部分将重点关注那些证据确凿的危险因素。

除 rSO_2 外，炎症因子、脑电图参数、眼动特征等亦被用于 POD 预测研究[8]-[10]，但尚未形成统一标准。近红外光谱(NIRS)是 rSO_2 监测的核心技术，可实时、无创反映脑组织氧供需平衡[5]。在脊柱手术中，rSO_2 可有效识别脑低氧事件，且与平均动脉压呈正相关[11] [12]，但亦有研究未发现 rSO_2 与 POD 存在显著关联[13]。综上，rSO_2 预测脊柱手术 POD 的价值仍存在争议，亟需系统评价与 Meta 分析予以明确。

2. 术后谵妄的临床特征与病理生理机制

2.1. 术后谵妄的定义、分型与临床表现

术后谵妄(Postoperative Delirium, POD)是一种急性发作的注意力与认知功能紊乱综合征，通常在术后1~7 d内发生[14] [15]。其核心特征包括意识清晰度下降、注意力涣散、思维紊乱及认知波动，可伴随感知障碍或幻觉、精神运动行为异常(激越或迟滞) [14]。临床常按精神运动活性分为亢进型、抑制型及混合型[16]。谵妄评估依赖标准化工具，如重症监护谵妄筛查量表(ICDSC)、意识模糊评估法(CAM-ICU)等[17]。

2.2. 术后谵妄的病理生理机制

POD病理生理机制涉及多因素交互作用：

1) 脑灌注不足：术中低氧血症($SpO_2 < 90\%$持续>2 min)、低碳酸血症($ETCO_2 \leq 25$ mmHg持续>5 min)与谵妄风险呈剂量依赖性升高[18]。心脏手术中脑灌注不足与BIS降低显著相关，谵妄患者BIS < 45的时间比例更高；但非心脏手术未发现术中MAP < 65 mmHg与谵妄相关[19]。脑低氧事件(rSO_2下降)不仅直接导致脑功能异常，还可能通过激活炎症反应和影响神经递质系统，进一步放大谵妄风险。研究表明，脑低氧可激活小胶质细胞，促进炎症因子(如IL-1β、IL-6、TNF-α)的释放，加剧神经炎症反应；同时，低氧还可导致多巴胺能网络连接异常和GABA能系统失衡，与谵妄的核心症状(注意力障碍、思维紊乱)密切相关。此外，脑低氧可增加血脑屏障通透性，允许外周炎症因子更易进入脑组织，进一步放大炎症反应。而术中不合理氧疗策略亦可能通过加重氧化应激影响脑功能预后。因此，rSO_2下降可能不是POD的独立预测因素，而是通过与炎症反应、神经递质紊乱等机制的交互作用，共同促进POD的发生发展。

2) 炎症反应：术前IL-6升高与POD显著相关[20]，术后IL-10、NGAL升高可独立预测谵妄。补体系统异常、血脑屏障通透性增加亦参与发病[3]。

3) 神经递质紊乱：多巴胺能网络连接异常、GABA能系统失衡与术后认知障碍及谵妄相关[21]。

4) 其他机制：线粒体功能障碍、神经退行性标志物升高、脑能量代谢异常等均可能参与[22]。

2.3. 术后谵妄对患者预后的影响

POD可显著升高30 d死亡率(OR = 2.77)，增加并发症风险、延长住院时间、降低出院后居家比例，并与长期认知下降、医疗成本增加密切相关[23]。术前神经丝轻链、磷酸化tau蛋白等升高可增加谵妄易感性与远期认知损害风险[10] [22]。

3. 术后谵妄的危险因素与诊断标准

3.1. 非手术相关危险因素

高龄是核心危险因素，65~85岁患者POD风险升高(OR = 2.67)，>85岁风险进一步升高(OR = 6.24) [24]。术前认知障碍、ASA分级 > 2级、共病负担高、抑郁症、低BMI、铁蛋白异常等均为独立危险因素[25] [26]。较高教育水平可通过认知储备发挥保护作用[27]。

3.2. 脊柱手术相关特异性危险因素

脊柱手术POD的特有危险因素包括术中输血、高ASA分级、低白蛋白血症。手术时间每延长10 min，风险增加2.3% [28]。术前CRP、IL-6升高与POD相关[29]；术前细菌外膜囊泡谱异常、补体调节因子降低可特异性预测脊柱手术POD [30]。

3.3. 诊断标准与评估工具

CAM、CAM ICU、4AT是临床最常用的谵妄评估工具[31]。采用标准化工具时，脊柱手术POD发

生率约 10.6% [32]。脑电图指标、血液生物标志物等尚处于研究阶段，未纳入常规诊断[33]。

4. 脑氧饱和度监测技术基础

4.1. NIRS 监测 rSO_2 的基本原理

近红外光谱(NIRS, 700~1000 nm)基于比尔朗伯定律，通过检测氧合与脱氧血红蛋白信号，计算脑组织氧饱和度(rSO_2)，可实时、无创监测脑氧供需平衡。NIRS 信号易受头皮血流、颅骨厚度、脑外组织干扰，难以完全区分脑内与外周氧合状态[34]。

4.2. rSO_2 监测的临床意义

rSO_2 可早期识别脑低灌注与缺氧事件。颈动脉内膜剥脱术中，rSO_2 下降与术后认知功能下降相关；蛛网膜下腔出血患者中，脑低氧事件与不良预后及死亡率升高相关。基于 rSO_2 的脑血管反应性指标可预测创伤性脑损伤预后。但大型 RCT 显示，以 rSO_2 指导管理并未显著降低心脏手术术后主要并发症[35]。

4.3. 监测设备与一致性问题

临床常用 NIRS 设备包括 INVOS、ForeSight Elite 等，因算法、探头间距不同，测量值存在系统偏差。设备间一致性有限，对孤立脑缺氧识别能力不足。柔性可穿戴 fNIRS 具备便携优势，但手术场景可靠性仍需验证[36]。

4.4. 俯卧位对脊柱手术 rSO_2 监测的影响

脊柱手术常采用俯卧位，这种体位对脑血流动力学和 rSO_2 监测具有特殊影响。俯卧位可导致脑静脉回流受阻，增加颅内压，进而影响脑灌注和 rSO_2 测量准确性。研究表明，俯卧位下脑组织氧合状态与仰卧位存在显著差异，特别是对 rSO_2 监测的探头位置敏感性增加。NIRS 监测的 rSO_2 值受头皮血流、颅骨厚度和脑外组织干扰，而俯卧位下头皮血流分布不均，可能导致 rSO_2 测量值低估或高估。有研究指出，在俯卧位脊柱手术中，rSO_2 的下降与脑静脉淤血相关，而非单纯的脑灌注不足，这可能导致对脑低氧事件的误判。此外，俯卧位下患者头部位置的微小变化(如颈部屈曲或伸展)可显著影响 rSO_2 监测值，增加了监测的复杂性和不确定性。目前，针对俯卧位脊柱手术中 rSO_2 监测特异性研究极少，导致现有 rSO_2 阈值可能不适用于俯卧位场景，这可能是脊柱手术领域 rSO_2 与 POD 关联性研究结果不一致的重要原因之一。

5. 脑氧饱和度与术后谵妄关联性研究进展

5.1. 心脏及其他手术中的证据

心脏手术中，脑自动调节受损、MAP 超出调节范围与 POD 相关[37]。术前神经丝轻链升高可独立预测谵妄[38]。弥散光学断层扫描(DOT)发现谵妄患者前额叶氧合与功能连接下降[39]。但部分非心脏手术未发现 rSO_2 与术后认知及谵妄相关[7]。

5.2. 脊柱手术中的直接证据

脊柱手术中，rSO_2 与 POD 的高质量直接证据较少。研究提示脑网络连接异常、炎症反应与谵妄相关，但未直接评估 rSO_2 [30]。现有证据未证实 rSO_2 与脊柱手术 POD 存在特异性关联。多数研究关注麻醉方式、炎症、神经损伤标志物、EEG 参数等，未纳入 rSO_2 分析。

5.3. rSO_2 阈值与剂量反应关系

脊柱手术领域 rSO_2 异常阈值及剂量反应关系仍为空白[29]。其他手术提示，低氧、低碳酸血症与谵

安呈剂量依赖[18]；但术中 MAP 与 POD 的研究结论不一致[28]。尚无研究明确 rSO_2 阈值、累积暴露时间与谵妄的量化关系。

6. 脑氧监测预测 POD 的 Meta 分析要点

6.1. 研究概况

直接针对脊柱手术 rSO_2 预测 POD 的系统评价与 Meta 分析仍较缺乏[29]。现有证据多来自心脏手术或观察性研究，结论不一。基于术中 EEG 的深度学习模型可高效预测 POD，但未涉及 rSO_2。

6.2. 纳入研究特征与质量评价

需提取研究设计、人群、手术类型、监测设备、rSO_2 阈值、谵妄评估方法、结局指标等。采用 NOS、Cochrane 偏倚风险工具评价质量，重点关注对象选择、暴露测量、盲法、混杂控制、随访完整性。

6.3. 结局指标与异质性来源

主要指标：rSO_2 参数与 POD 的 OR/RR 及 95% CI；次要指标：敏感度、特异度、AUROC 等。异质性来源：1) rSO_2 阈值、监测设备、探头位置不统一；2) 手术类型、患者基线差异；3) 谵妄诊断工具、评估时点不同；4) 麻醉、血压管理、混杂控制不一致；5) 研究设计与质量差异。

7. 目前研究争议与不足

7.1. rSO_2 临界值尚未统一

各研究采用 rSO_2 绝对值、相对下降幅度及持续时间标准不一，缺乏可推广的预警阈值，限制临床应用。

7.2. 监测方案与干预时机影响效能

设备算法、监测部位、干预策略不规范，可显著影响预测结果。联合麻醉可降低 POD 风险，但可能增加低血压事件[40]；术中血压管理与谵妄的关系仍存争议。不同血管活性药物对脑灌注及谵妄发生的影响存在显著差异。

7.3. 混杂因素控制不足

多数证据来自心脏手术，外推至脊柱手术存在偏倚。炎症、血脑屏障、神经代谢、脑网络等机制未被整合入 rSO_2 预测模型。麻醉方式、镇静药物、低血压定义与统计方法差异，均影响结果可靠性。

8. 临床应用建议与展望

8.1. 术中 rSO_2 监测规范化建议

rSO_2 可用于脊柱手术脑低氧事件识别与 POD 风险分层。建议：麻醉诱导后测定基线、全程监测；结合血流动力学管理；避免低氧与低碳酸血症；联合术前铁蛋白等指标评估；联合麻醉需权衡低血压风险。

8.2. 多模态脑功能监测策略

单一 rSO_2 预测效能有限，推荐联合：术中 EEG (α/β 功率、θ 连接)、功能磁共振网络连接、弥散光学断层扫描、血脑屏障功能评估等，构建多模态预测模型。

8.3. 未来研究方向

1) 开展脊柱手术大样本前瞻性研究，确定 rSO_2 预警阈值；

2) 统一监测方案、设备校准、阈值定义与干预流程；

3) 控制基线脑功能、炎症、神经损伤标志物等混杂因素；

4) 构建 AI 多模态动态预警模型；

5) 开展基于 rSO_2 指导的围术期管理干预研究。

9. 总结与展望

现有证据尚不足以支持 rSO_2 作为脊柱手术 POD 的独立可靠预测工具。其效能受限于特异性证据不足、监测与阈值不统一、混杂因素干扰。特别是脊柱手术俯卧位对 rSO_2 监测的干扰尚未得到充分认识，且 rSO_2 与炎症、神经递质等机制的交互作用未被整合，导致研究结论难以形成统一共识。未来应开展大样本、标准化、多模态联合研究，结合 AI 动态预测，并针对脊柱手术特点优化干预策略，以提升 POD 早期识别与防治水平。

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