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脑氧饱和度监测与术后苏醒延迟的相关性研究进展

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摘 要

术后苏醒延迟(Delayed Postoperative Awakening)是全身麻醉或手术后患者未能在预期时间内恢复意识或清醒状态的临床问题，其危害包括神经功能损伤风险增加、术后加速康复(ERAS)受阻、医疗资源负担加重、长期神经认知影响及继发性并发症。术中局部脑氧饱和度(regional cerebral oxygen saturation, rSO_2)监测技术基于近红外光谱(NIRS)，通过无创、实时评估脑氧供需平衡，可早期预警脑灌注不足和缺氧事件，为预测和干预术后苏醒延迟提供关键依据。本文系统综述了rSO_2监测技术的原理、与苏醒延迟的相关性、其在心脏手术、腹腔镜手术及特殊人群(如老年、儿科、肥胖患者)中的应用价值，并探讨其局限性(如个体差异干扰、局部缺血分辨能力不足)及未来发展方向(多模态监测整合、动态阈值优化)。现有证据表明，rSO_2监测结合定量脑电图(QEEG)等多参数分析，有望优化围手术期管理策略，改善患者预后。

关键词

术后苏醒延迟，局部脑氧饱和度(rSO_2)，近红外光谱(NIRS)，围手术期管理，脑氧供需平衡，多模态监测

Research Progress on the Correlation between Cerebral Oxygen Saturation Monitoring and Delayed Postoperative Awakening

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Abstract

Delayed Postoperative Awakening is a clinical issue where patients fail to regain consciousness or achieve a state of alertness within the expected time frame after general anesthesia or surgery. Its adverse effects include increased risk of neurological damage, disruption of Enhanced Recovery After Surgery (ERAS) protocols, increased burden on medical resources, long-term neurocognitive impacts, and secondary complications. Intraoperative monitoring of regional cerebral oxygen saturation (rSO_2), based on Near-Infrared Spectroscopy (NIRS), provides non-invasive, real-time assessment of the cerebral oxygen supply-demand balance. It can serve as an early warning for cerebral hypoperfusion and hypoxic events, offering crucial evidence for predicting and intervening in delayed postoperative awakening. This article systematically reviews the principles of rSO_2 monitoring technology, its correlation with delayed awakening, and its application value in cardiac surgery, laparoscopic surgery, and specific patient populations(such as elderly, pediatric, and obese patients). It also discusses its limitations (such as interference from individual differences and insufficient ability to distinguish local ischemia) and future development directions (integration of multimodal monitoring and optimization of dynamic thresholds). Current evidence suggests that combining rSO_2 monitoring with multi-parameter analyses, such as quantitative electroencephalography (QEEG), holds promise for optimizing perioperative management strategies and improving patient outcomes.

Keywords

Delayed Postoperative Awakening, Regional Cerebral Oxygen Saturation (rSO_2), Near-Infrared Spectroscopy (NIRS), Perioperative Management, Cerebral Oxygen Supply-Demand Balance, Multimodal Monitoring

1. 引言

延迟是指患者术后未能在预期时间内(通常为 2 小时内)恢复意识，其危害包括：神经功能损伤风险增加、阻碍术后加速康复、加重医疗资源负担、潜在长期神经认知影响以及继发性并发症风险[1] [2]。研究表明，通过术中脑功能监测(如 QEEG)结合早期干预(优化镇静策略、缩短麻醉药代谢时间)，可有效减少苏醒延迟及相关危害。因此在围手术期早期诊断并预防苏醒延迟的发生对提高患者的康复情况和生存质量至关重要[3]。局部脑氧饱和度(regional cerebral oxygen saturation, rSO_2)监测可以反映局部脑血流及氧供需平衡情况，有利于围手术期脑缺血缺氧的早期诊断和治疗，以保护脑功能，改善苏醒延迟[4]。本综述旨在探讨术中局部脑氧饱和度监测在预测患者苏醒延迟方面的应用。

2. rSO_2 监测技术

rSO_2 (局部脑氧饱和度)监测技术是一种基于近红外光谱(Near-Infrared Spectroscopy, NIRS)的无创脑

氧合监测方法，广泛应用于围手术期管理、重症监护和脑功能评估。具有实时性和连续性，在指导和优化围手术期管理方面发挥重要作用。原理如下：NIRS 的频谱为 650 mm~1100 mm，可以穿透皮肤、颅骨、结缔组织和大脑；测量过程中，将自黏性发射器或传感器贴片贴在额头皮肤上，以非侵入性的方式测量距离 NIRS 发射光源一定距离处的光衰减，基于 NIRS 在氧合血红蛋白和还原血红蛋白之间的光谱差异，利用 Beer-Lambert 定律计算出 rSO_2 [5]。rSO_2 监测通过近红外光谱技术实时评估脑氧供需平衡，在围手术期和重症监护中具有重要价值。其核心优势在于无创性和动态反馈能力，目前 NIRS 是唯一的床边无创脑血氧饱和度监测技术，符合未来医疗卫生领域的发展趋势，具有巨大的潜力和广阔的应用前景。

3. 术后苏醒延迟概述

术后苏醒延迟(Delayed Postoperative Awakening)是指患者在全身麻醉或镇静后，超过预期时间仍未恢复意识或达到足够清醒状态的现象。其发生机制复杂，涉及多种生理、药理学及病理因素，可能对患者预后产生显著影响。目前广泛认为与术前状态、手术与麻醉因素、术后并发症有关[6]。其神经生理机制复杂，有研究认为麻醉药物可能通过抑制小脑－丘脑－皮层环路的功能连接延迟苏醒[7]，动物实验表明激活该通路可加速意识恢复，睡眠－觉醒相关核团(如蓝斑核、下丘脑)的功能抑制可能与苏醒延迟相关，部分麻醉药(如丙泊酚)可模拟自然睡眠的神经活动模式[8]。术后苏醒延迟与脑网络动态变化也密切相关。术中 QEEG 监测显示，低频振荡(delta 波)活动增强和高频振荡(gamma 波)抑制与苏醒延迟相关，提示皮层－皮层下信息整合障碍[9]，术后早期(2 小时内)脑功能连接密度下降可能预示神经认知恢复延迟，尤其在老年患者中更显著[10]。临床上通过采用 Richmond 躁动－镇静量表(RASS)连续评估，结合 EEG 频谱分析，可早期识别苏醒延迟趋势，针对高危患者(如 ASA III 级、术前失眠)，强化术后 2 小时神经功能监测可降低并发症发生率[11]。研究表明术后苏醒延迟会导致神经功能损伤风险增加、阻碍术后加速康复、加重医疗资源负担、潜在长期神经认知影响以及继发性并发症风险，因此，围手术期加强对患者的监测和评估，及时识别和预防术后苏醒延迟至关重要。

4. rSO_2 监测技术与术后苏醒延迟的相关性

1) 心脏手术：现有研究主要集中于心搏骤停或特定手术模型(如心肺复苏)，在心搏骤停复苏模型中，rSO_2 水平与早期神经功能恢复显著相关。早期干预(如 AHUP-CPR)可显著提高 rSO_2 值，并改善 24 小时生存率和神经功能缺损评分(NDS)，从而可能缩短术后苏醒时间。这表明 rSO_2 监测可能通过评估脑氧合状态，间接反映术后神经功能恢复的潜力，进而影响苏醒延迟[12]心搏骤停期间，rSO_2 (或类似参数如 $crrSO_2$)可作为自主循环恢复(ROSC)的实时无创预测指标。术中或术后若发生低脑氧事件，rSO_2 监测可能帮助早期识别脑灌注不足，避免因缺氧导致的苏醒延迟或神经系统并发症[13]。

2) 在大型腹腔镜手术中，由于气腹压力和体位(如 Trendelenburg 位)的影响，可能导致脑血流灌注不足，rSO_2 降低与术后苏醒延迟显著相关[14]。研究显示，rSO_2 值低于基线 50%时，患者苏醒时间延长风险增加[13]。所以通过持续监测 rSO_2，麻醉团队可动态调整通气参数(如 FiO_2、PEEP)或循环支持措施(如血管活性药物)，以维持脑氧饱和度在安全范围(通常 ＞60%基线值)。例如，一项研究指出，rSO_2 联合 $EtCO_2$ 监测可优化复苏策略，提高自主循环恢复(ROSC)率，间接减少苏醒延迟[14]。rSO_2 监测技术与其他监测技术的联合应用，rSO_2 与 $EtCO_2$、SpO_2 等多模态监测结合，可更全面评估氧代谢状态。例如，腹腔镜术后低氧血症($SpO_2 \leq 85\%$)是苏醒延迟的独立危险因素，而 rSO_2 异常可早于 SpO_2 变化预警脑缺氧风险[15]。在大型腹腔镜外科手术术后呼吸抑制导致的缺氧与气腹压力过大导致的高碳酸血症是苏醒延迟的重要诱因。rSO_2 监测可实时反映脑氧合变化，结合 SpO_2 和 $ETCO_2$ 监测，可能更全面地评估呼吸抑制风险，指导干预时机以缩短苏醒时间[16]。

3) rSO_2 监测技术在特殊人群中的应用。① 心脏手术患者：rSO_2 监测可实时评估脑氧供需平衡，预防术中脑缺氧导致的术后苏醒延迟。研究表明，在心搏骤停猪模型中，早期干预组(通过 rSO_2 监测指导治疗)的 24 小时生存率和神经功能恢复显著优于延迟干预组。对于接受复杂心脏手术的高危患者，维持 $rSO_2 >$ 50%基线值可降低术后认知功能障碍和苏醒延迟风险[14]。② 老年及神经高危患者：老年患者因脑血管自动调节功能减退，更易出现脑氧不足。rSO_2 监测可指导个体化氧疗(如调整 FiO_2)或血流动力学干预(如液体复苏、血管活性药物使用)，从而减少麻醉苏醒延迟[17]。在神经外科手术中，$rSO_2 < 40\%$持续 5 分钟以上与术后谵妄和延迟苏醒显著相关[4]。③ 儿科患者：儿童脑代谢率高且生理储备有限，rSO_2 监测有助于识别隐匿性脑缺氧。例如，在先天性心脏病患儿中，术中 rSO_2 下降幅度与术后机械通气时间延长相关。家庭术后监测中，结合 rSO_2 的客观数据可减少 caregivers 主观评估误差导致的延迟就医[18]。④ 肥胖及 OSA 患者：此类患者术后易发生呼吸抑制和低氧血症。rSO_2 联合 $EtCO_2$ 监测可早期发现通气不足，指导非侵入性通气(如 HFNO)的应用，从而缩短苏醒时间。研究显示，rSO_2 较 SpO_2 更早预警缺氧事件，尤其在肥胖患者中 SpO_2 可能高估实际氧合[19]。⑤ 急诊及创伤手术患者：在失血性休克或创伤性脑损伤患者中，rSO_2 能反映脑灌注不足，指导输血和血压管理。例如，$rSO_2 < 50\%$时通过抬高下肢或血管加压药可改善脑氧合，减少苏醒延迟[20]。

5. rSO_2 监测技术的局限性与突破策略

5.1. 局限性

目前 rSO_2 监测技术存在监测精度与干扰因素的问题，rSO_2 监测易受患者个体差异(如皮肤色素、颅骨厚度)及术中/术后生理状态(如低血压、贫血)的影响，可能导致假阳性或假阴性结果[21]。当前技术对脑氧代谢的局部差异(如不同脑区)分辨能力有限，可能掩盖局部缺血事件。其次术后苏醒延迟的定义缺乏统一标准(如时间阈值或神经功能评估方法)，影响 rSO_2 监测结果的解读。部分研究以 Richmond 躁动–镇静量表(RASS)评分作为苏醒标准，但主观性较强[22]。在临床实践中发现传统方法(如 SpO_2、$EtCO_2$)更关注全身氧合与通气功能，而 rSO_2 侧重脑氧供需平衡，两者数据可能不一致。例如，SpO_2 正常时仍可能因脑灌注不足导致 rSO_2 降低。

5.2. 突破策略

当前 rSO_2 监测的局限性可通过多维度技术革新与临床策略优化加以改善：① 个体化校准与干扰控制：基于双波长 NIRS 与术前影像数据(如颅骨 CT 值)建立个体化光衰减模型，减少皮肤色素与颅骨异质性对信号的干扰。术中联合血红蛋白浓度与动脉血压动态修正基线，区分全身氧合不足与脑氧供需失衡。采用高密度 NIRS (HD-NIRS)传感器阵列覆盖多脑区，结合拓扑算法定位局部缺血灶，实验显示其对前额叶缺血的检测敏感度提升 30% [23]。② 多模态数据融合与智能分析：整合 rSO_2、定量脑电图(α/θ 功率比)及血流动力学参数(脉压变异度 PPV)，利用贝叶斯网络模型降低假阳性报警率(验证研究显示假阳性率 <15%)。③ 联合脑微透析技术监测乳酸/丙酮酸比值(LPR)，明确脑氧代谢异常机制(缺血性缺氧 vs.细胞代谢障碍)，指导精准干预[24]。

6. 未来发展与临床转化

未来研究需重点围绕多模态监测系统的智能化整合与临床转化展开，通过深度融合定量脑电图(QEEG)、脑氧饱和度(rSO_2)及血流动力学参数(如脉压变异度、$EtCO_2$)构建动态预测模型，以提升术后苏醒延迟的早期预警效能[1]。例如，可开发基于深度学习的实时分析平台，利用术中 QEEG 的 α 波抑制指数联合术后 2 小时内 rSO_2 趋势斜率，建立苏醒时间预测算法，其在心脏手术中的初步验证显示曲线下面

积(AUC)达0.89，显著优于单一参数分析。同时，需突破现有阈值设定的局限性，通过机器学习动态解析个体化 rSO_2 基线特征，结合脑氧代谢速率($CMRO_2$)与组织氧摄取率(TOI)生成自适应报警阈值(如“基线-2SD”或趋势偏离预警)，以减少因个体差异或生理波动导致的误报。此外，应拓展 rSO_2 监测在非心脏手术中的循证证据，例如在老年骨科手术中探索 $rSO_2 < 45\%$ 持续10分钟作为干预阈值，并通过多中心随机对照试验验证其对缩短苏醒时间及改善神经认知预后的临床价值。技术创新层面，可研发柔性可穿戴设备集成光子计数近红外光谱(PC-NIRS)与无线脑电监测模块，实现术后转运及病房连续监测，结合闭环反馈系统(如 rSO_2 导向的智能氧疗调控)优化围术期管理流程。最终，需建立涵盖技术验证、成本效益分析与长期随访的国际协作网络，明确 rSO_2 监测在不同术式及人群中的标准化应用路径，推动其从辅助工具向核心决策支持系统的转化[25]。

7. 结论

术后苏醒延迟的机制复杂，涉及麻醉药物代谢、脑网络动态变化及氧供需失衡等多因素。rSO_2 监测技术通过实时评估脑氧合状态，在预测和减少苏醒延迟中展现出独特优势，尤其在心脏手术、腹腔镜手术及高危人群中具有重要临床价值。然而，当前技术仍面临监测精度受个体差异影响、局部缺血分辨能力有限等挑战。未来需通过多模态监测整合(如联合 QEEG、血流动力学参数)、动态阈值优化(基于机器学习)及扩大临床适应症(如普通外科手术)提升其预测效能。此外，统一苏醒延迟的临床定义标准、加强术中干预与术后早期评估的衔接，是进一步改善患者神经功能预后的关键方向。rSO_2 监测技术的应用前景广阔，但其全面推广仍需技术创新与多中心研究支持。

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