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Application of regional cerebral oxygen saturation monitoring for predicting postoperative delirium

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Abstract: Postoperative delirium (POD) is a common postoperative complication that not only affects patients' cognitive functions, but may also increase the incidence of other complications, prolong hospital stays, and increase medical costs. Currently, there is no clear prevention or treatment method , but the incidence of POD can be reduced by avoiding inducing factors. Near-infrared spectroscopy (NIRS) technology-based monitoring of regional cerebral oxygen saturation ($rScO_2$) is a non-invasive method that can reflect changes in the balance of cerebral oxygen supply and demand in real-time and is closely related to the development and progression of POD. This article reviews the progress in the application of $rScO_2$ monitoring in the prediction of POD, including the potential underlying mechanisms of $rScO_2$ reduction related to postoperative delirium, the association between $rScO_2$ and POD, and the potential value of interventions based on $rScO_2$ monitoring in reducing the incidence of POD. This article aims to provide a reference for clinical POD prevention and treatment and to offer new ideas and methods for further research on the relationship between $rScO_2$ and POD.

Keywords: Postoperative delirium; Cerebral oxygen saturation monitoring; Near-infrared spectroscopy; Regional cerebral oxygen saturation; Electroencephalogram; Oxidative stress; Inflammatory response

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Postoperative delirium (POD) is an acute and transient brain dysfunction that occurs after surgery. It typically develops within 7 days postoperatively, characterized by inattention, fluctuations in consciousness level, and acute cognitive impairment. Symptoms of POD may range from reduced responses to hypervigilance and severe agitation, accompanied by psychiatric manifestations such as delusions, hallucinations, and emotion changes [1-2]. Additionally, POD not only impairs long-term cognitive function but also increases the incidence of other complications, prolongs hospital stays, elevates medical costs, raises 30-day readmission rates, and even correlates with higher mortality, exerting a detrimental impact on patient prognosis [3]. Relevant clinical guidelines and expert consensus statements emphasize the importance of POD prevention. Currently, there is no effective treatment for POD. Avoiding perioperative risk factors associated with POD can reduce its incidence, mitigate symptom severity, and improve postoperative recovery outcomes [4-5]. In perioperative management, various techniques are employed for early detection of cerebral ischemia and hypoxia. Regional cerebral oxygen saturation ($rScO_2$) monitoring provides real-time insights into cerebral oxygen supply-demand balance and changes in cerebral blood flow, making it clinically valuable for timely identification and management of perioperative brain injury. Previous studies indicate that cerebral ischemia and decreased cerebral oxygen saturation are potential mechanisms underlying postoperative cognitive changes [6]. Reduced cerebral oxygen saturation is a risk factor for POD, with proposed mechanisms including oxidative stress injury to neurons and neuroinflammatory responses. This review summarizes the progress of $rScO_2$ monitoring in POD prediction, aiming to inform clinical POD prevention and treatment strategies, and offer novel perspectives for further research on the application of $rScO_2$ monitoring in POD prediction.

1 Monitoring Technologies of Cerebral Oxygen Saturation

Cerebral oxygen monitoring technologies include intracranial pressure (ICP) monitoring, cerebral perfusion pressure (CPP) monitoring, jugular bulb oxygen saturation monitoring, brain tissue oxygen partial pressure ($PbtO_2$) monitoring, and near-infrared spectroscopy (NIRS) monitoring. ICP and CPP are traditional methods for brain injury monitoring, but they cannot fully reflect cerebral blood flow and insufficient cerebral oxygen supply. The measurement of jugular bulb oxygen saturation is an indirect method for assessing the supply and demand of oxygen throughout the brain, but it is an invasive approach with insufficient sensitivity to focal cerebral ischemia. Brain tissue oxygen partial pressure, monitored via microelectrodes, can reflect local brain tissue oxygenation and has advantages of easy operation and high data reliability. However, it is also an invasive measurement, and its data are affected by body temperature, probe position (depth), and calibration time [7].

In 1977, Jöbsis [8] first used the tissue permeability of near-infrared light to non-invasively capture information from deep tissues such as the brain. NIRS technology applies the modified Lambert-Beer law and light scattering theory to assess $rScO_2$ by measuring the absorption characteristics of different spectra, and its baseline in healthy adults is usually between 50% and 75% [9]. Real-time monitoring of $rScO_2$ is crucial for preventing subclinical hypoxia and reducing long-term hypoxic complications, and it has become a key indicator in clinical surgical anesthesia. NIRS technology, with its non-invasiveness, real-time performance, and ease of operation, has rapidly become popular in fields such as cardiothoracic surgery, neurosurgery, and intensive care. $rScO_2$ is affected by multiple factors: under normal cerebral blood flow autoregulation, fluctuations in mean arterial pressure (MAP) do not significantly change $rScO_2$, while outside the range of cerebral blood flow autoregulation, such as in cardiac surgery or certain pathological states, the impact of MAP on $rScO_2$ is significantly enhanced [10]. Different anesthesia methods have a significant impact on $rScO_2$ [11]. Additionally, physiological and pathological conditions like changes in arterial partial pressure of carbon dioxide ($PaCO_2$), arterial partial pressure of oxygen (PaO_2), body temperature, pH, and base excess (BE), as well as surgical position, may also indirectly affect $rScO_2$ [12].

2 Potential Mechanisms of the Correlation Between Reduced Cerebral Oxygen Saturation and POD

The connection between decreased cerebral oxygen saturation and POD remains unclear. Currently, two widely recognized potential mechanisms in the academic community are oxidative stress and neuroinflammation.

2.1 Oxidative Stress Theory

Oxidative stress refers to a pathological state caused by an imbalance between oxygen supply and demand within cells. During surgery, reduced cerebral oxygen saturation may directly indicate insufficient cerebral perfusion. When brain tissue is damaged by ischemia, hypoxia, or ischemia-reperfusion, the production of reactive oxygen species, reactive nitrogen species, and lipid free radicals may exceed the body’s scavenging capacity, or the scavenging mechanism itself may be impaired. This leads to oxidative damage to neuronal cells, which further triggers excitotoxicity, apoptosis, and local inflammation, ultimately inducing POD [13]. In this pathological process, decreased cerebral oxygen saturation may play a crucial role in the onset of POD.

2.2 Neuroinflammation Theory

The neuroinflammation theory suggests that stress from surgery and anesthesia (including hypoperfusion) can stimulate peripheral neuroendocrine responses, thereby causing neuroinflammation. During this process, the hypothalamic-pituitary-adrenal axis is activated, inducing the production of glucocorticoids. Glucocorticoids have extensive peripheral and central effects, including exacerbating neuroinflammation and ischemic injury [14]. Meanwhile, peripheral inflammation caused by surgery and anesthesia leads to high-level secretion of matrix metalloproteinase 9, which not only degrades tight junctions but also causes pericyte pathology and upregulates endocytosis, resulting in increased blood-brain barrier permeability. This allows peripheral inflammation to migrate to the central nervous system, promoting neuroinflammation and synaptic dysfunction, and inducing POD-like behaviors [15]. Inflammatory responses can also lead to cerebral endothelial cell dysfunction and atherosclerosis, which not only reduce cerebral blood flow but also impair neuronal metabolic function and oxygen consumption. In this hypothesis, decreased cerebral oxygen saturation indicates intraoperative cerebral hypoperfusion, this may act as an initial trigger for neuroinflammation, while also serving as a prominent manifestation of reduced cerebral blood flow caused by neuroinflammation. This bidirectional interaction highlights the importance of cerebral oxygen saturation monitoring during the perioperative period, as it can not only warn of potential neuroinflammation risks but also reflect the impact of inflammation on cerebral blood flow.

Currently, the molecular and cellular mechanisms of POD have not been fully elucidated, and there is a lack of stronger evidence to clarify the potential role of cerebral oxygenation in the pathogenesis of POD.

3 Correlation Between Perioperative $rScO_2$ and POD

3.1 Correlation Between Preoperative $rScO_2$ and POD

There is a significant correlation between preoperative $rScO_2$ and POD, and low preoperative rScO2 may increase the risk of POD. Morimoto *et al.* [16] conducted a prospective cohort study involving 23 elderly patients undergoing elective abdominal surgery, monitoring rScO2 perioperatively and assessing POD. The results showed that the baseline rScO2 in the delirium group was significantly lower than that in the non-delirium group. These findings suggest that preoperative low $rScO_2$ may be an important risk factor for POD in elderly patients undergoing abdominal surgery. Collin et al. [17] observed 90 adult patients undergoing liver resection surgery and found that patients with POD had lower baseline left-sided cerebral $rScO_2$ compared to those without POD, indicating that baseline rScO2 is also associated with POD in adult patients undergoing liver resection. Susano *et al.* [18] had similar findings: each one-point decrease in preoperative rScO2 increased the risk of POD by 8%. In a randomized controlled study of elderly cardiac surgery patients by Lei et al. [19], Among patients with baseline $rScO_2 \leq 50\%$, 71% developed postoperative respiratory failure (POD), whereas only 18% of patients with baseline $rScO_2 > 50\%$ experienced POD, indicating that lower baseline $rScO_2$ correlates with a higher incidence of POD. Multiple studies have shown that preoperative low rScO2 can serve as an independent predictor of POD in cardiac surgery patients, increasing the risk by 7-fold and reflecting insufficient cerebral perfusion reserve [20-21]. He *et al.* [14]'s systematic review also concluded that preoperative low rScO2 is associated with increased POD risk.In pediatric patients, preoperative rScO2 levels also significantly affect POD occurrence. Liu *et al.* [22]'s study included 167 children aged 1-16 undergoing surgery, showed that the POD group had significantly lower $rScO_2$ indicators across multiple dimensions compared to the non-POD group, and these indicators exhibited good sensitivity and specificity in assessing POD risk. However, some studies have raised different views on the relationship between preoperative baseline $rScO_2$ and POD. Clemmesen *et al.* [23] monitored 40 elderly patients aged ≥65 undergoing hip fracture surgery using NIRS before and throughout the operation, finding that preoperative $rScO_2$ <55% lasting ≥2 minutes was significantly associated with 30-day mortality, but no significant association existed between preoperative baseline $rScO_2$ and POD. Eertmans *et al.* [24]'s study also found no statistically significant difference in preoperative $rScO_2$ between POD and non-POD patients.

In the elderly population, multiple studies suggest preoperative low rScO2 is associated with increased POD risk [14,16,19]. However, there are relatively few studies on other age groups, and existing research is mostly focused on cardiac surgery with insufficient evidence for other surgical types. Future studies should further explore the complex relationship between preoperative rScO2 and POD, including different surgical types, age distributions, determination of baseline $rScO_2$ thresholds, and potential interventions. Meanwhile, the consistency of existing results needs improvement. Thus, future research should adopt more precise and homogeneous measurement techniques and multivariate analysis to verify whether preoperative $rScO_2$ is an independent predictor of POD.

3.2 Correlation Between Intraoperative $rScO_2$ and POD

Intraoperative cerebral desaturation events in patients typically refer to a decrease in rScO2 monitored via NIRS during surgery, indicating reduced cerebral blood flow and potential cerebral hypoxia. Currently, the commonly used thresholds for intraoperative rScO2 monitoring are a drop below 80% of the baseline or an absolute value below 55%. This decrease is potentially closely linked to the development of POD. Xu *et al.* [25] conducted a single-center randomized controlled trial and found that maintaining MAP at the baseline level to 10% above the baseline significantly reduced the incidence of POD on the first postoperative day in elderly patients undergoing hip replacement surgery. Patients in this strategy group had significantly higher intraoperative $rScO_2$ than the other two groups, suggesting that the reduced POD incidence may be related to increased $rScO_2$ during surgery, reflecting better cerebral oxygen supply. Li *et al.* [26]'s retrospective study found that the relative decrease of intraoperative $rScO_2$ from the baseline is a risk factor for POD in elderly orthopedic patients. Nakamura *et al.* [27] discovered that the minimum $rScO_2$ level during cardiovascular surgery is independently associated with POD development. Liu *et al.* [28]'s prospective randomized controlled trial found that the average and minimum $rScO_2$ were negatively correlated with POD risk in elderly lung cancer patients undergoing thoracoscopic surgery, while the area under the curve (AUC) of $rScO_2$ below 90% of the baseline was associated with POD. Roberts *et al.* [29]'s study confirmed this conclusion in adult patients undergoing thoracic surgery: the decrease in rScO2 during one-lung ventilation was significantly associated with delayed early cognitive recovery, increased POD risk, and prolonged hospital stay. Wang *et al.* [30]'s study in patients undergoing selective intracranial aneurysm embolization also supported that reduced rScO2 is a significant positive predictor of POD.

There is inconsistency in research findings regarding which is more important between the absolute value and relative change of $rScO_2$ in predicting POD. Schoen *et al.* [20] found that the AUC of intraoperative $rScO_2$ below 80% of the baseline showed no statistically significant difference between the two groups in coronary artery bypass grafting surgery, but the AUC of $rScO_2$ below an absolute value of 50% was larger in the delirium group. This indicates that the absolute value of intraoperative $rScO_2$ has significant predictive value for POD for patients with normal preoperative $rScO_2$ levels. Lim *et al.* [31]'s retrospective study found that an absolute intraoperative $rScO_2$ value below 50% was significantly associated with increased POD risk, especially in young patients. The study recommended maintaining $rScO_2$ above 50% during off-pump coronary artery bypass grafting, with higher thresholds for patients under 68 years old. However, some studies suggest that the percentage decrease of intraoperative $rScO_2$ relative to the baseline may have a greater impact on POD than its absolute value. Cui *et al.* [32] found that the minimum intraoperative rScO2 was not associated with POD in patients undergoing thoracotomy. When left-sided cerebral rScO2 dropped below 90% of the baseline or right-sided cerebral rScO2 dropped below 85% of the baseline for 15 seconds or longer, it was significantly associated with increased POD risk. Thus, the study proposed that defining $rScO_2$ reduction using thresholds of both left-sided and right-sided $rScO_2$ below 90% of the baseline may be more clinically reasonable.

Interestingly, Wang *et al.* [33] explored the correlation between the complexity of intraoperative rScO2 (quantified using approximate entropy and sample entropy for rScO2 signals) and POD. It was found that

POD patients had lower intraoperative rScO2 complexity, and the complexity was negatively correlated with age, suggesting it may serve as an early predictive indicator for POD. However, this study was single-center with a small sample size, limiting the generalizability and reliability of its conclusions. In addition, some studies found no correlation between intraoperative $rScO_2$ levels and POD risk [14, 24, 34]. This may be because the etiology and clinical manifestations of POD are complex and cannot be fully explained by a single mechanism. Meanwhile, inconsistent results may be influenced by multiple factors, such as differences in assessment tools and methods, surgical types, intervention thresholds, and NIRS device variations. Overall, there is controversy regarding the importance of the absolute value versus relative change of intraoperative rScO2 in predicting POD. Most studies suggest that maintaining intraoperative rScO2 above a certain threshold may help reduce POD risk, while determining the optimal rScO2 threshold requires further research and individualized assessment considering different application scenarios.

3.3 Correlation Between Postoperative rScO2 and POD

Multiple studies have shown that postoperative $rScO_2$ is significantly associated with the occurrence and severity of POD in cardiac surgery patients [35-36]. Chan *et al.* [37] calculated the tissue oxygenation index using $rScO_2$ and MAP. The results indicated that 0.01 increase in the tissue oxygenation index will rise 5% risk of developing POD, suggesting that impaired cerebrovascular autoregulation in the early postoperative period may be associated with POD after cardiac surgery. Song *et al.* [38]'s study on elderly patients undergoing abdominal surgery supported an independent association between postoperative $rScO_2$ and POD. Liu *et al.* [22]'s findings also revealed that postoperative $rScO_2$ could serve as a predictive factor for POD in pediatric surgical patients. However, He *et al.* [14]'s systematic review failed to identify a significant correlation between postoperative $rScO_2$ and POD, which might be attributed to the insufficient sensitivity of the rScO2 detection threshold used in that study.

Eertmans et al. [24]'s research found that postoperative $rScO_2$ in POD patients decreased significantly, but these differences were only detected after the onset of POD. The sensitivity analysis of this study showed that when $rScO_2$ data collected 8 hours after the first diagnosis of POD were excluded, there was no statistically significant difference in rScO2 between POD and non-POD patients. This implies that the decrease in $rScO_2$ may be a manifestation or consequence of POD, which aligns with the neuroinflammation theory and provides a new perspective for exploring the relationship between $rScO_2$ and POD.

Overall, although current research on the correlation between postoperative rScO2 and POD is not yet sufficient, preliminary literature suggests that a reduction in postoperative rScO2 may be associated with the POD.

4 Potential Value of Perioperative rScO2 Monitoring-Guided Interventions in Reducing POD Incidence

Multiple studies suggest that rScO2 monitoring-guided interventions have potential positive effects in reducing POD incidence. Studies by Wang *et al.* [39] and Yan *et al.* [40] found that rScO2 monitoring-guided goal-directed therapy can decrease POD incidence, lower postoperative levels of inflammatory factors (interleukin-1β, interleukin-6, tumor necrosis factor-α, lactate, and S-100β protein), and improve perioperative safety. A systematic review and meta-analysis by Ding *et al.* [41] further confirmed this finding, showing that interventions combining electroencephalography and $rScO_2$ monitoring significantly reduce the incidence of POD. Zhai *et al.* [42] demonstrated that multimodal monitoring (integrating rScO2 and stroke volume variation) to guide intraoperative management helps maintain cerebral oxygen balance and effective cerebral perfusion, thereby enhancing postoperative recovery quality and reducing the risk of complications (including POD). However, some studies have questioned the efficacy of $rScO_2$ monitoring-based interventions. A systematic review by Semrau *et al.* [34] analyzed multiple interventional studies and found no consistent supportive evidence that such interventions effectively reduce POD incidence, concluding that current evidence for their effectiveness remains insufficient. Overall, perioperative rScO2 monitoring-guided interventions show potential in lowering POD incidence, but existing evidence is not yet conclusive. Their efficacy and mechanisms require further exploration and validation through future research. Additionally, multimodal monitoring, such as rScO2 combined with electroencephalography or stroke volume variation may provide more comprehensive brain function information, helping to improve treatment precision and postoperative recovery quality.

5 Summary

POD is a common postoperative complication that seriously affects patients' prognosis. The decreasing trend of $rScO_2$ during the perioperative period is correlated with the occurrence of POD. Although there are some inconsistencies in research findings, most studies support that maintaining $rScO_2$ above a certain threshold may help reduce the risk of POD. In addition, perioperative $rScO_2$ monitoring has shown potential advantages in reducing POD and improving postoperative recovery, especially when combined with other monitoring methods, such as electroencephalography and stroke volume variation. Future studies need to further clarify the role of $rScO_2$ monitoring in POD prevention, determine the optimal monitoring threshold, and explore how to optimize perioperative management strategies through monitoring to reduce the occurrence of POD.

Conflict of Interest None

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· 研究进展 ·

局部脑氧饱和度监测预测术后谵妄的应用进展

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摘要： 术后谵妄(POD)是一种常见的手术后并发症，不仅影响患者的认知功能，还可能增加其他并发症的发生率，延长住院时间，并增加医疗费用。目前关于POD尚无明确的防治方法，但可通过避免诱发因素降低其发生率。基于近红外光谱(NIRS)技术的局部脑氧饱和度($rScO_2$)监测作为一种非侵入性手段，能够实时反映大脑氧供需平衡的变化，与POD的发生发展具有密切关系。现对$rScO_2$监测在POD预测中的应用进展进行综述，包括$rScO_2$降低与POD相关的潜在作用机制、$rScO_2$与POD的关联以及基于$rScO_2$监测的干预对降低POD发生率的潜在价值，以期为临床POD防治提供参考，并为深入研究$rScO_2$与POD的关系提供新的思路和方法。

关键词： 术后谵妄；脑氧饱和度监测；近红外光谱；局部脑氧饱和度；脑电图；氧化应激；炎症反应
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Abstract: Postoperative delirium (POD) is a common postoperative complication that not only affects patients' cognitive functions, but may also increase the incidence of other complications, prolong hospital stay, and increase medical costs. Currently, there is no clear prevention or treatment method, but the incidence of POD can be reduced by avoiding inducing factors. Near-infrared spectroscopy (NIRS) technology-based monitoring of regional cerebral oxygen saturation ($rScO_2$) is a non-invasive method that can reflect changes in the balance of cerebral oxygen supply and demand in real-time and is closely related to the development and progression of POD. This article reviews the progress in the application of $rScO_2$ monitoring in the prediction of POD, including the potential underlying mechanisms of $rScO_2$ reduction related to POD, the association between $rScO_2$ and POD, and the potential value of interventions based on $rScO_2$ monitoring in reducing the incidence of POD. This article aims to provide a reference for clinical POD prevention and treatment and to offer new ideas and methods for further research on the relationship between $rScO_2$ and POD.

Keywords: Postoperative delirium; Cerebral oxygen saturation monitoring; Near-infrared spectroscopy; Regional cerebral oxygen saturation; Electroencephalogram; Oxidative stress; Inflammatory response
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术后谵妄(postoperative delirium, POD)是一种在手术后出现的急性、暂时性的大脑功能障碍。它通常在术后7 d内发生，主要特征包括注意力不集中、意识水平变化以及认知功能的急性改变。POD的症状可能包括从反应性降低到过度警觉和严重激动的意识水平变化，以及包括妄想、幻觉和情绪变化在内的精神症状[1-2]。此外，POD不仅影响患者远期的认知功能，还可能导致其他并发症的发生率增加，延长住院时间，增加医疗费用，同时增加30 d内的再入院率，甚至与死亡率的增加相关，对患者的预后产生负面影响[3]。相关临床指南和专家共识声明建议预防POD的发生。目前对于POD尚无有效治疗手段，在围手术期避免可能诱发POD的因素可降低患者POD发生率、减轻病症严重程度、提高术后恢复质量[4-5]。在

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围手术期管理中，多种技术已被应用于早期检测脑缺血和缺氧，局部脑氧饱和度（regional cerebral oxygen saturation，$rScO_2$）监测可以实时反映大脑氧供需平衡变化，反映脑血流量的变化，对于及时识别和管理围手术期脑损伤具有重要的临床意义。既往研究结果表明脑缺血和脑氧饱和度下降是术后认知状态改变的潜在发病机制之一[6]。脑氧饱和度的下降被认为是POD的一个潜在危险因素，其潜在的作用机制可能涉及大脑神经元的氧化应激损伤以及神经炎症反应。本文对$rScO_2$监测在POD预测中的应用进展进行综述，以期为临床POD防治提供参考，并为深入研究$rScO_2$监测在POD预测的应用方面提供新的思路和方法。

1　脑氧饱和度监测技术

脑氧监测技术包括监测颅内压、脑灌注压、颈静脉球氧饱和度、脑组织氧分压和近红外光谱（near-infrared spectroscopy，NIRS）监测技术等。颅内压和脑灌注压是脑损伤监测的传统手段，它们不能全面反映脑血流量和脑供氧不足。颈静脉球氧饱和度通过置入颈静脉导管测量，是评估全脑氧供需的间接方法，但这是一种有创操作，且对局部脑缺血的敏感性不足。脑组织氧分压通过微电极监测，可反映局部脑组织氧合情况，具有操作简便和数据可靠性高的优势，但也是一种有创技术测量，且数据受体温、探针位置（深度）以及校准时间的影响[7]。

1977年，Jöbsis[8]首次提出利用近红外光的组织渗透性非侵入性地捕获大脑等组织深处的信息。NIRS技术应用改良的朗伯-比尔定律和光散射理论，通过测量不同光谱的吸收特征来评估$rScO_2$，其在健康成年人中的基线通常在50%~75%[9]。$rScO_2$的实时监测对于预防亚临床缺氧和减少长期缺氧并发症至关重要，已成为临床手术麻醉的关键指标。NIRS技术以其非侵入性、实时性和操作简便性，在心胸外科、神经外科手术以及重症监护等领域迅速普及。$rScO_2$受多种因素影响，在正常脑血流自动调节下，平均动脉压（mean arterial pressure，MAP）的波动不会显著改变$rScO_2$；在脑血流自动调节范围之外，如心脏手术或某些病理状态，MAP对$rScO_2$的影响显著增强[10]。不同麻醉方法对$rScO_2$有显著影响[11]。生理和病理条件，如动脉血二氧化碳分压（arterial partial pressure of carbon dioxide，$PaCO_2$）、动脉血氧分压（arterial partial pressure of oxygen，PaO_2）、体温、pH和碱剩余（base excess，BE）的变化，以及手术体位，都可能间接影响$rScO_2$[12]。

2　脑氧饱和度降低与POD相关的潜在作用机制

脑氧饱和度降低与POD之间的联系尚未明确，目前，学术界普遍认同的两种潜在机制分别是氧化应激和神经炎症。

2.1　*氧化应激学说*　氧化应激是指细胞内氧气供需失衡所引起的一种病理状态。在手术过程中，脑氧饱和度的下降可能是脑灌注不足的直接表现。脑组织缺血、缺氧以及缺血再灌注等损伤时，活性氧、活性氮以及脂类自由基的生成可能超出了机体的清除能力，或者清除机制本身受损，从而引起神经元细胞遭受氧化损伤，进而引发兴奋性毒性、细胞凋亡和局部炎症，诱发POD[13]。在这一病理过程中，脑氧饱和度的下降可能在POD的发病中扮演着至关重要的角色。

2.2　*神经炎症学说*　神经炎症理论指出，手术及麻醉的应激（包括低灌注）能够激发周围神经内分泌反应，进而引起神经炎症。在这一过程中，下丘脑—垂体—肾上腺轴被激活，并诱导糖皮质激素的产生。糖皮质激素具有广泛的外周和中枢效应，包括加重神经炎症和缺血性损伤[14]。同时，手术和麻醉引起的外周炎症导致基质金属蛋白酶9高水平分泌，不仅使紧密连接降解，而且造成周细胞病变，并上调胞吞作用，导致血脑屏障通透性变高，外周炎症向中枢神经系统迁移，促进神经炎症和突触功能障碍，诱发POD样行为[15]。炎症反应可导致脑内皮细胞功能障碍和动脉粥样硬化，这不仅减少了脑血流量，还降低了神经元的代谢功能和耗氧量。在这一假说中，脑氧饱和度的下降预示着术中大脑的低灌注，这可能成为触发神经炎症的初始因素，同时也可作为神经炎症引起脑血流量减少的一个显著表现。这种双向作用突显了脑氧饱和度监测在围手术期的重要性，因为它不仅能够预警潜在的神经炎症风险，还能反映炎症对脑部血流的影响。

目前，POD的分子和细胞机制尚未完全阐明，缺少更为有力的证据以明确脑氧合在POD发病机制中的潜在作用。

3　围手术期$rScO_2$与POD的关联

3.1　*术前（基线）$rScO_2$与POD的关系*　术前$rScO_2$与POD之间存在显著的相关性，术前低$rScO_2$可能增加POD的风险。Morimoto等[16]进行了一项针对23例接受选择性腹部手术老年患者的前瞻性队列研究，围手术期监测$rScO_2$并评估POD。研究结果表明，谵妄组的基线$rScO_2$显著低于未谵妄组。这些发现提示，术前低$rScO_2$可能是腹部手术老年患者POD的一个重要危险因素。Collin等[17]的研究观察了90例接受肝脏切除手术的成年患者，发现发生POD的患者与未发生POD的患者相比具有较低的基线左脑$rScO_2$。这表明在肝脏切除手术的成年患者基线$rScO_2$与POD的发生同样具有相关性。Susano等[18]研究也有类似的发现，术前$rScO_2$每降低一个点，POD风险增加8%。Lei等[19]的一项针对老年心脏手术患者的随机对照研究中，发现基线$rScO_2 \leq 50\%$的患者中有71%出现POD，基线$rScO_2 > 50\%$的患者中有18%出现POD，表明较低的基线$rScO_2$与POD发生率增加有关。多项研究结果表明，术前低$rScO_2$可作为心脏手术患者POD独立预测因子，导致POD风险增加7倍，反映脑灌注储备的不足[20-21]。He等[14]的一项系统综述和荟萃分析的结果也提示术前低$rScO_2$与POD风险增加有关。在儿童患者中，术前$rScO_2$水平对POD的发生同样具有显著影响。Liu等[22]的研究，涉及167例1~16岁接受手术治疗的儿童患者，其研究结果显示，发生POD的患者组在多个$rScO_2$指标方面均显著低于未发生POD的患者组，这些指标在评估POD风险时显示出良好的敏感性和特异性。亦有研究对术前基线$rScO_2$与POD之间关系提出不同观点。Clemmesen等[23]对40例65岁及以上接受髋部骨折手术的老年患者在术前和整个手术期间进行

NIRS监测，发现术前 $rScO_2$ 值低于55%且持续至少2 min的情况与30 d内死亡率显著相关，但术前基线 $rScO_2$ 值与POD之间没有显著关联。Eertmans等[24]的研究结果也未发现术前 $rScO_2$ 在POD和非POD患者之间存在有统计学意义的差异。

在老年患者群体中，多项研究提示术前低 $rScO_2$ 与POD风险增加相关[14,16,19]。然而，针对其他年龄段患者的研究相对较少，且现有研究多集中于心脏手术领域，对于其他类型手术的相关证据尚且不足。未来研究应进一步探讨术前 $rScO_2$ 与POD之间的复杂关系，包括不同手术类型、不同年龄、基线 $rScO_2$ 值阈值的确定以及可能的干预措施。同时，现有研究结果的一致性尚待提高。因此，未来的研究需要采用更精确、同质化的测量技术，并考虑多因素分析方法，以验证术前 $rScO_2$ 作为POD独立预测因子的有效性。

3.2　*术中 $rScO_2$ 与POD的关系*　术中患者脑去氧饱和事件通常指的是在手术过程中，通过NIRS技术监测到的 $rScO_2$ 下降，提示脑血流量减少和潜在的脑缺氧状态。目前术中 $rScO_2$ 监测普遍采用的阈值为低于基线的80%或绝对值低于55%。这种下降与POD的发生具有潜在的密切联系。Xu等[25]的一项单中心随机对照研究发现将MAP维持在基线水平至基线以上10%，能够显著降低老年髋关节置换手术患者术后第1天的POD发生率。采用此策略的患者，术中 $rScO_2$ 显著高于其他两组。该研究提示POD发生率的降低可能与手术期间增加的 $rScO_2$ 有关，这反映了更好的脑氧供应。李茜等[26]的一项回顾性研究发现术中 $rScO_2$ 相对基线的下降是骨科高龄患者发生POD的危险因素。Nakamura等[27]发现在心血管手术中最低 $rScO_2$ 水平与POD的发生独立相关。Liu等[28]的前瞻性随机对照研究发现，在接受胸腔镜手术的肺癌老年患者中，平均 $rScO_2$ 和最低 $rScO_2$ 与POD风险呈负相关关系，而 $rScO_2$ <90%基线的曲线下面积与POD的发生相关。Roberts等[29]的研究发现在胸外科手术的成年患者群体中，这一结论同样适用。研究发现在单肺通气期间的 $rScO_2$ 下降与术后早期认知恢复延迟、POD风险增加和住院时间延长显著相关。Wang等[30]在选择性颅内动脉瘤栓塞手术患者中的研究也支持 $rScO_2$ 降低是POD发生的显著正向预测因子。

关于 $rScO_2$ 的绝对值与相对变化在预测POD方面何者更加重要，研究结果并不一致。Schoen等[20]的研究发现，在冠状动脉搭桥手术中，术中 $rScO_2$ 低于基线80%的曲线下面积在两组间差异无统计学意义，但低于绝对值50%的曲线下面积在谵妄组中较大。这表明，对于术前 $rScO_2$ 水平正常的患者，术中 $rScO_2$ 的绝对值在预测POD方面具有显著预测价值。Lim等[31]的回顾性研究发现术中 $rScO_2$ 绝对值低于50%与POD风险增加显著相关，特别是在年轻患者中。研究建议非体外循环冠状动脉旁路移植手术中 $rScO_2$ 应维持在50%以上，68岁以下患者则应更高。然而有研究认为术中 $rScO_2$ 相对于基线的下降百分比可能比其绝对值更能影响POD的发生。Cui等[32]发现术中最低的 $rScO_2$ 与开胸手术患者POD无关，术中左脑 $rScO_2$ 低于基线90%或右脑 $rScO_2$ 低于基线85%，且这种下降持续15秒或更长时间时，与POD风险的增加显著相关。因此，该研究认为，使用左 $rScO_2$ 和右 $rScO_2$ 均低于90%基线的阈值来定义 $rScO_2$ 降低在临床上可能更为合理。

有趣的是，Wang等[33]的研究探讨了术中 $rScO_2$ 的复杂性（使用近似熵和样本熵量化 $rScO_2$ 信号的复杂性）与POD的相关性，发现POD患者术中 $rScO_2$ 复杂性较低，且术中 $rScO_2$ 复杂性与年龄负相关，研究表明其可能可以作为POD早期预测的指标。该研究为单中心、小样本，其结论的普适性和可靠性受到一定的限制。

此外，部分研究在术中 $rScO_2$ 水平与POD风险之间未发现相关性[14,24,34]。这一发现可能因为POD的病因和临床表现复杂，并非单一机制所能完全解释。同时，结果的不一致性可能受到多种因素影响，如评估工具和方法不同，手术类型、干预阈值不一致以及NIRS设备差异等。

综上所述，术中 $rScO_2$ 的绝对值与相对变化在预测POD方面的重要性存在争议，多数研究倾向于维持术中 $rScO_2$ 在一定阈值以上，可能有助于降低POD的风险，而确定最佳的 $rScO_2$ 阈值需要考虑不同应用场景进行进一步研究和个体化评估。

3.3　*术后 $rScO_2$ 与POD的关系*　多项研究显示，心脏手术患者术后 $rScO_2$ 与POD的发生和严重程度显著相关[35-36]。Chan等[37]通过 $rScO_2$ 与MAP计算出组织氧合指数。结果显示，组织氧合指数每增加0.01，发展为POD的风险增加5%。这表明术后早期脑血管自我调节受损可能与心脏手术后的POD有关。Song等[38]针对老年腹部手术患者的研究，支持术后 $rScO_2$ 与POD独立相关。Liu等[22]的研究结果也表明在儿童手术患者中术后 $rScO_2$ 可作为POD的预测因素。但He等[14]的系统综述和meta分析中未发现术后 $rScO_2$ 与POD之间的显著相关性，这可能由于该研究中使用的 $rScO_2$ 检测阈值不够敏感。

Eertmans等[24]的研究结果发现POD患者的术后 $rScO_2$ 明显下降，但这些差异在POD发生后才被检测到。该研究的敏感性分析发现，当POD首次确诊后8 h的 $rScO_2$ 数据被排除时，POD患者和非POD患者 $rScO_2$ 差异无统计学意义，这表明 $rScO_2$ 的下降可能是POD的表现或后果，与神经炎症学说的观点相吻合，为探究 $rScO_2$ 与POD的关系提供了新的思路。

总之，虽然目前关于术后 $rScO_2$ 与POD之间联系的研究尚不充分，但初步文献资料表明，术后 $rScO_2$ 的降低可能与POD的发生具有相关性。

4　基于围手术期 $rScO_2$ 监测的干预降低POD发生率的潜在价值

多项研究提示基于 $rScO_2$ 监测的干预治疗对降低POD发生率具有潜在的积极效果。Wang等[39]和闫龙剑等[40]的研究发现基于 $rScO_2$ 监测的目标导向治疗可以降低POD的发生率以及术后炎症因子白细胞介素1β、白细胞介素6、肿瘤坏死因子α、乳酸和S-100β蛋白水平，提高围手术期的安全性。Ding等[41]的系统评价和meta分析进一步证实了这一发现，研究发现基于脑电图和 $rScO_2$ 监测的干预能显著降低POD的发生率。翟明玉等[42]的研究发现应用包含 $rScO_2$ 和每搏输出量变异度的多模式监测指导术中管理有助于维持脑氧平衡和有效脑灌注，从而提高患者术后恢复质量，降低术后并发症

(包括POD)风险。然而,也有研究对基于$rScO_2$监测的干预措施的效果提出了质疑,Semrau等[34]的系统综述中分析多项干预性研究,发现这些研究并没有提供一致的支持性证据来证明基于$rScO_2$监测的干预手段能够有效降低POD的发生率,认为目前基于$rScO_2$监测的干预在降低POD发生率方面的效果的证据尚不充分。

总体而言,基于围手术期$rScO_2$监测的干预措施显示出了降低POD发生率的潜力,但目前的相关证据尚不足以形成定论,其有效性及作用机制仍需通过未来的研究来深入探索和验证。同时,多模式监测,如$rScO_2$监测联合脑电图、每搏输出量变异度监测,可能提供更全面的脑部功能信息,有助于提高治疗的精确性和患者术后恢复质量。

5 小　结

POD是一种常见的手术后并发症,严重影响患者的预后。$rScO_2$在围手术期的降低趋势与POD的发生具有相关性。虽然研究结果在一致性上存在一定差异,但大多数研究支持维持$rScO_2$在一定阈值以上,可能有助于降低POD的风险。此外,围手术期$rScO_2$监测已显示出在降低POD和改善术后恢复方面的潜在优势,尤其是当与其他监测手段(如脑电图、每搏输出量变异度)联合使用时。未来研究需进一步明确$rScO_2$监测在预防POD中的作用,确定最佳的监测阈值,并探索如何通过监测优化围手术期管理策略以减少POD的发生。

利益冲突　无

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