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NARRATIVE REVIEW

Neurological outcomes in children assessed with cerebral near-infrared spectroscopy: a mini review

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ABSTRACT

Cerebral hypoxemia is associated with several clinical conditions, making the monitoring of brain oxygenation and perfusion essential. Cerebral near-infrared spectroscopy (NIRS) has emerged as a valuable tool for this purpose, particularly in neonatal and pediatric perioperative and intensive care settings. In recent years, the utilization of NIRS has increased significantly; however, existing literature points to uncertainties regarding its clinical advantages and disadvantages. We have conducted a systematic review encompassing various studies, excluding case reports and editorials. Our primary outcomes included moderate to severe persistent cognitive or neurological deficits. NIRS is particularly important for its ability to rapidly detect early hypoxemia, which can help prevent potential ischemic events and adverse outcomes in infants. Despite the variability in studies regarding the use of NIRS, the available data strongly support its integration into both clinical and surgical settings as a valuable medical tool.

KEYWORDS

NIRS; near-infrared spectroscopy; pediatrics; neurodevelopment

INTRODUCTION

Despite advances in anesthesia safety and perioperative care, the detection and prevention of cerebral hypoxemia remain challenging. Although standard perioperative monitoring has reduced the incidence of unrecognized arterial hypoxia, sustained hypotension, particularly prevalent in neonates, persists[1,2]. The absence of universally accepted guidelines defining neonatal systolic hypotension and varying treatment thresholds worldwide underscores the need for standardized approaches to optimize hemodynamic stability[3,4].

De Graaff et al.[5] highlighted that despite the predominant focus on the potential neurotoxicity of general anesthesia (GA) in both the lay press and peer-reviewed literature, pediatric patients undergoing surgery face inherent risks associated with anesthesia-induced cardiovascular depression. Intraoperative hypotension, a common occurrence even in patients categorized as “low risk”, poses particular concerns due to the unique physiology and immaturity of pediatric systems, rendering these patients vulnerable to even minor hemodynamic fluctuations[6-8].

Although anesthetics are known to decrease cerebral blood flow (CBF), a phenomenon well-established in animal models, the literature remains inconclusive regarding cognitive impairment during anesthesia and surgeries in

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humans[9,10]. Conversely, Koch et al.[6] highlighted the significant risk of systemic and regional hypoperfusion in neonates undergoing surgery and intensive care, which can lead to brain tissue changes and cerebral hypoxia, with poor outcomes, even in the absence of heart disease[9].

Cerebral impairment may arise from the complexity of surgical procedures or anesthesia itself, with intrinsic risks of cerebral oxygenation decline during cardiac procedures under cardiac arrest or cardiopulmonary bypass[11]. Studies have linked cerebral impairment to the neurodevelopmental outcomes of preterm children, while others have identified postoperative neurocognitive disorders associated with anesthesia duration[12,13].

Although cerebral oxygenation monitoring is not yet a standard practice during general anesthesia, its clinical adoption is gradually increasing, particularly in cardiac and aortic surgeries, as well as in pediatric and neonatal intensive care settings[14-16]. A variety of techniques are available for monitoring cerebral oxygenation, including jugular venous blood sampling or catheter-based oximetry for assessing cerebral-venous oxygen saturation, oxygen electrodes for measuring tissue oxygen tension, and near-infrared spectroscopy (NIRS) for determining mixed arterio-venous oxygen saturation[17-20]. It is noteworthy that cerebral NIRS offers the advantage of being a non-invasive technique, which theoretically reduces the risk of adverse effects associated with invasive methods.

The primary objective of monitoring cerebral oxygenation is to prevent hypoxemia in brain tissue. Therefore, this mini-review aims to summarize the positive and negative impacts of clinical care incorporating cerebral NIRS monitoring in children undergoing cardiac and noncardiac surgeries. Given that the primary focus of NIRS monitoring is to prevent brain injury, the majority of selected outcomes center around this aspect.

METHODS

This mini review follows the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement.

Studies were selected according to the following criteria: We included in our analysis all studies utilizing NIRS to evaluate neurological outcomes in children undergoing surgery, regardless of their publication status, type, or publication year. We restricted our inclusion criteria to studies in English, excluding editorial pieces and case reports. We included children of all ages, including neonates, regardless of sex or comorbidities.

Information sources and search strategy

Studies were identified through systematic searches in the Cochrane Central Register of Controlled Trials (CENTRAL), EMBASE, MEDLINE, and Web of Science databases, using the keywords “NIRS,” “near-infrared spectroscopy,” “pediatrics,” “neonatal,” “anesthesia,” linked with the Boolean operator “and.” The search encompassed these databases from their inception onwards. Inclusion criteria for language were limited to English, with no restrictions on the period. Additionally, the reference lists of all relevant studies were also examined.

All studies were uploaded to the Systematic Review Data Repository during the literature search, managed by the Agency for Healthcare Research and Quality in Rockville, USA. Two authors, AJG and PSMMS, independently screened the titles and abstracts of these studies. If either author deemed a study potentially relevant, the full text was obtained and evaluated for eligibility by both authors. In cases where a study was deemed ineligible, the reasons for exclusion were recorded.

Data extraction and management

After incorporating the relevant studies, the authors proceeded with the independent data extraction. In case of any discrepancies, the authors engaged in discussions to reach a consensus, following which a final decision was made. The data extracted from each study encompassed the following aspects:

1. General information: title, author(s), year of publication, and language of publication;
2. Methodology of the study;
3. Sample size, when available, including the number of participants meeting the inclusion criteria.

RESULTS

The literature search identified 171 potentially relevant publications. Following the screening of titles and abstracts and full-text evaluation, 12 studies reporting on 1,332 children met our predefined inclusion and exclusion criteria and were selected for review. Upon thorough examination of the complete text, some studies excluded specific individuals from their analyses, resulting in a total of 1,263 patients included in the review. Details regarding the selection and exclusion of studies are provided in Figure 1. These studies were published between 1998 and 2023.

Among the studies reviewed, six investigations[10,21-25] specifically examined the application of NIRS in cardiovascular procedures, involving a total cohort of 388 individuals, among whom 200 (51.4%) were male.

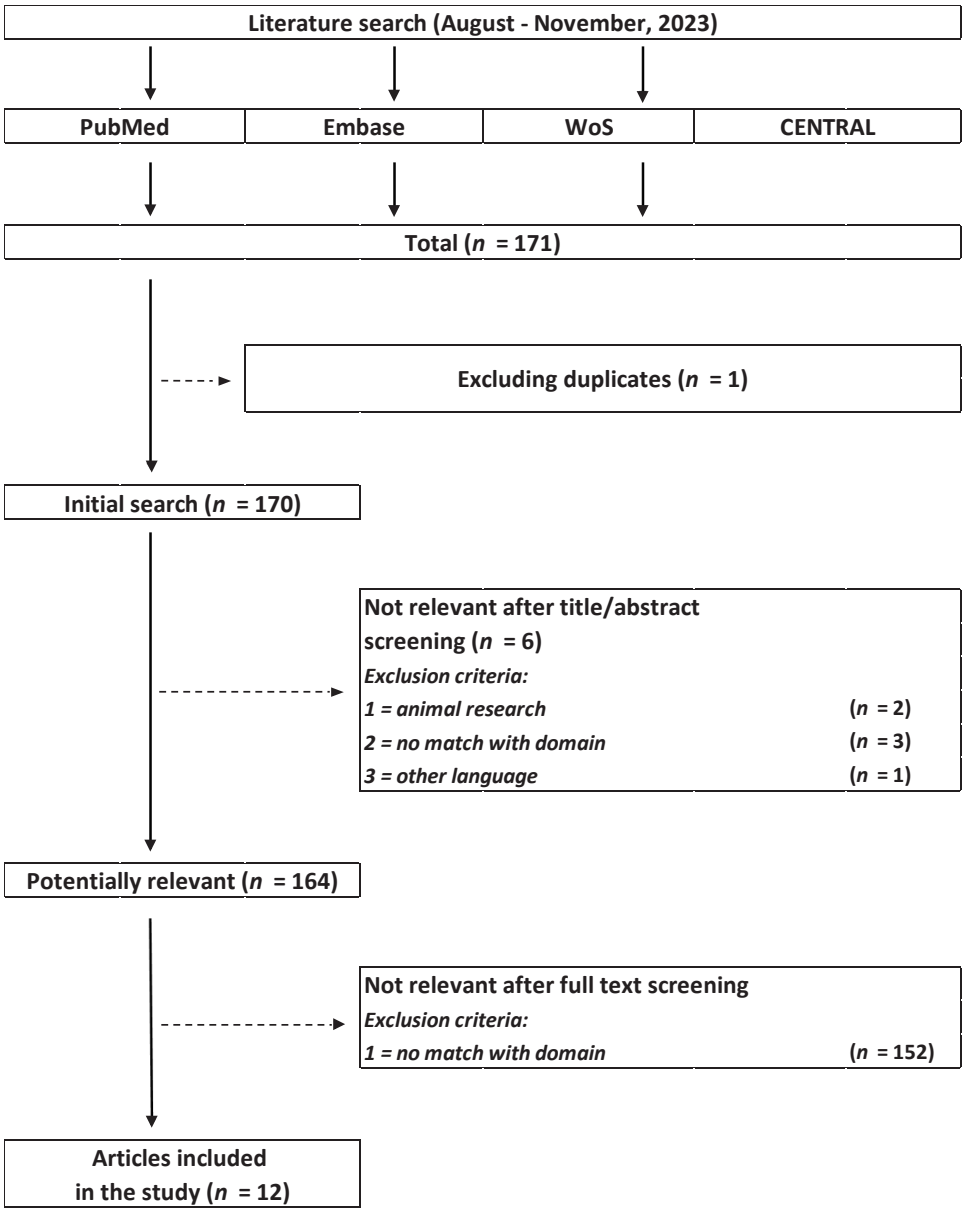

Figure 1. Flow chart illustrating details of the search strategy and the study selection process.

However, gender information was not specified in two studies[24,26], which can lead to bias. The average age of patients undergoing cardiac interventions displayed considerable variability, ranging from 13 days to 1.2 years, with an average weight at the time of surgery recorded at 4.88 kg. Notably, the most prevalent cardiac procedures included arterial switch, ventricular septal defect repair, and Norwood I surgery.

Conversely, the remaining six studies[6,26-30] encompassed procedures excluding those related to cardiac and neurological interventions. They comprised a collective sample size of 875 children, of which 417 were male (60%). The average weight of children during surgical procedures was documented as 4.46 kg. It is noteworthy that one study did not provide information regarding the gender of participants, and two studies solely reported the age of participants without specifying gender.

Except for studies concentrating on major cardiac surgeries, nearly all investigations included in our analysis assessed neurological outcomes in pediatric patients undergoing diverse surgical interventions[12,31-34]. Moreover, certain studies examined the relationship between cerebral autoregulation and blood pressure[22,26,28,35], or structural changes associated with hypoxia or hyperoxia in major surgeries[16,23,24].

The studies conducted in major cardiac surgery primarily assessed the utility of NIRS in monitoring cerebral oxygenation, particularly during critical stages of such procedures[16,29,36]. Additionally, specific investigations aimed to determine whether intraoperative NIRS can detect cerebral hypoxia-ischemia or alterations in cerebral tissue correlated with neurodevelopmental outcomes[10,23,25,29]. Details of all included studies are provided in Table 1.

Table 1. Overview of studies evaluating the effect of clinical care guided by cerebral NIRS monitoring during pediatric surgeries

Year	First author	Title	Study Design	Objectives	No. of participants	Primary outcome	Conclusion
1998	Daubeney et al.[22]	Cerebral oxygenation during pediatric cardiac surgery: identification of vulnerable periods using near infrared spectroscopy.	Observational study	The authors have measured regional cerebral oxygenation in children undergoing cardiac surgery using near infrared spectroscopy to ascertain such vulnerable periods.	18	During bypass, circulatory arrest and reperfusion, regional cerebral oxygenation presents a variable outcome.	Observations suggest that the pre- and early post-bypass periods are vulnerable periods for provision of adequate cerebral oxygenation. Near infrared spectroscopy is a promising tool for monitoring O2 supply/demand relationships especially during circulatory arrest.
2010	Ricci et al.[23]	Cerebral NIRS as a marker of superior vena cava oxygen saturation in neonates with congenital heart disease.	Retrospective observational study	To investigate the correlation between cerebral near-infrared spectroscopy (NIRS) (rSO2c) and superior vena cava venous oxygen saturation (ScvO2) in newborn patients with congenital heart disease (CHD).	100	The preoperative period, rSO2c levels overestimated ScvO2; in the first 18 postoperative hours, rSO2c underestimated ScvO2; after that period, they showed very similar trends. Hypocapnia caused rSO2c to underestimate ScvO2; in normocapnic patients, rSO2c–ScvO2 average differences were close to zero; in hypercapnic neonates, rSO2c tended to overestimate ScvO2.	rSO2c in newborn patients with cyanotic and acyanotic CHD provides a continuous noninvasive information with a fair correlation with ScvO2%: some predictable variables (i.e., time from surgery, carbon dioxide, and venous saturation levels), should guide the operators to adjust rSO2c values in terms of ScvO2. Serial measures of ScvO2 seem recommended to tailor rSO2c information on actual venous saturation percentage.
2012	Kreeger et al.[10]	Evaluation of Pediatric Near-Infrared Cerebral Oximeter for Cardiac Disease.	Observational study	Near-infrared spectroscopy can be utilized at the bedside to detect cerebral hypoxia-ischemia.	86	There were no significant differences in subject characteristics between phases.	NIRS accurately measured the absolute value of cerebral saturation in children over a wide range of oxygenation and subject characteristics, offering advantages in assessment of cerebral hypoxia-ischemia in congenital heart disease.

NIRS, Near-Infrared Spectroscopy; rSO2c, Regional Cerebral Oxygen Saturation; ScvO2, Central Venous Oxygen Saturation; CHD, Congenital Heart Disease; EEG, Electroencephalography; SEF90, Spectral Edge Frequency 90; BSR, Burst Suppression Ratio; RBR, Raw Burst Rate; ApEn, Approximate Entropy; TCD, Transcranial Doppler; CBFV, Cerebral Blood Flow Velocity; MAP, Mean Arterial Pressure; CMRO2, Cerebral Metabolic Rate of Oxygen; BP, Blood Pressure; HR, Heart Rate.GA, General Anesthesia.

Table 1. Continued...

Year	First author	Title	Study Design	Objectives	No. of participants	Primary outcome	Conclusion
2013	Sood et al.[24]	Predictive value of perioperative near-infrared spectroscopy for neurodevelopmental outcomes after cardiac surgery in infancy.	Cross-sectional study	Intraoperative rSO2 measured by NIRS evaluated the predictive value of perioperative NIRS for neurodevelopmental outcomes after infant cardiac surgery.	31	Optimal thresholds for NIRS measures identified through receiver operating characteristic analyses were intraoperative percentage reduction in postoperative cognitive- and gross motor- delay.	Perioperative NIRS monitoring seems to enhance the ability to predict neurodevelopmental outcome.
2015	Hyttel-Sørensen et al.[21]	Cerebral near infrared spectroscopy oximetry in extremely preterm infants: phase II randomized clinical trial.	Clinical trial	To determine the possibility of stabilizing the cerebral oxygenation of extremely preterm infants monitored by cerebral NIRS oximetry.	166	The median burden of hyperoxia was similar between the groups: 1.2 hours in the experimental group compared with 1.1 hours in the control group.	Cerebral oxygenation was stabilized in extremely preterm infants using a dedicated treatment guideline in combination with cerebral NIRS monitoring.
2015	Rhondali et al.[27]	Sevoflurane anesthesia and brain perfusion	Observational study	To assess the impact of sevoflurane and anesthesia-induced hypotension on brain perfusion in children younger than 6 months.	180	TCD and NIRS groups were comparable. CBF velocities (CBFV) or rSO2c reflects a good cerebral perfusion when MAP is above 45 mmHg. When MAP is between 35 and 45 mmHg, CBFV variation reflects a reduction of CBF, but rSO2c increase is the consequence of a still positive balance between CMRO2 and O2 supply. Below 35 mmHg of MAP during anesthesia, CBFV decrease and rSO2c variation from baseline is low.	This study demonstrates that during 1 MAC sevoflurane anesthesia, in a normocapnic child ≤6 months, TCD measurements or rSO2c reflects a good cerebral perfusion when MAP is above 45 mmHg. When MAP is between 35 and 45 mmHg, CBF decreases and rSO2c reflects a still positive balance between CMRO2 and O2 supply. Below 35 mmHg of MAP during anesthesia, CBF decreases and rSO2c variation from baseline is low despite CMRO2 reduction.

NIRS, Near-Infrared Spectroscopy; rSO2c, Regional Cerebral Oxygen Saturation; ScvO2, Central Venous Oxygen Saturation; CHD, Congenital Heart Disease; EEG, Electroencephalography; SEF90, Spectral Edge Frequency 90; BSR, Burst Suppression Ratio; RBR, Raw Burst Rate; ApEn, Approximate Entropy; TCD, Transcranial Doppler; CBFV, Cerebral Blood Flow Velocity; MAP, Mean Arterial Pressure; CMRO2, Cerebral Metabolic Rate of Oxygen; BP, Blood Pressure; HR, Heart Rate.GA, General Anesthesia.

Table 1. Continued...

Year	First author	Title	Study Design	Objectives	No. of participants	Primary outcome	Conclusion
2015	Koch and Hansen[6]	Perioperative use of cerebral and renal near-infrared spectroscopy in neonates: a 24-h observational study.	Observational study	Neonates were monitored with both cerebral and renal NIRS for 24 h after induction of anesthesia and compared with systemic BP, SpO2, HR.	21	NIRS reported hypoxia two to three times more often than SpO2, and SpO2 readings were delayed compared to NIRS.	Near-infrared spectroscopy is an easily applicable technique that appears effective at detecting hypoxic events and postoperative apneas in neonates. The high incidences of regional hypoxia reported by NIRS in this study suggests a need for a more specific regional cerebral and renal monitoring. Despite some practical and economical limitations, NIRS can be a useful adjunct to perinatal perioperative intensive care.
2018	Olbrecht et al.[28]	An International, Multicenter, Observational Study of Cerebral Oxygenation during Infant and Neonatal Anesthesia	Multicenter study	This study aimed to determine the incidence of low cerebral oxygenation and associated factors during general anesthesia in infants.	453	Severe low oxygen saturation measured by pulse oximetry was associated with mild and moderate cerebral desaturation; American Society of Anesthesiology Physical Status III or IV vs I was associated with moderate cerebral desaturation	Mild and moderate low cerebral saturation occurred frequently, whereas severe low cerebral saturation was uncommon. Low mean arterial pressure was common and not linked with low cerebral saturation. Unrecognized severe desaturation lasting 3 min or longer in infants seems unlikely to explain the subsequent development of neurocognitive abnormalities.
2018	Lee et al.[25]	Near-Infrared Spectroscopy and Vascular Occlusion Test for Predicting Clinical Outcome in Pediatric Cardiac Patients: A Prospective Observational Study.	Observational study	Determine the feasibility and utility of vascular occlusion test variables as measured by NIRS in pediatric cardiac patients	121	There was a trend for decreased regional tissue hemoglobin oxygen saturation in younger patients during vascular occlusion.	Vascular occlusion test variables are influenced by age and cardiopulmonary bypass. The minimum regional tissue hemoglobin oxygen saturation less than 51% after sternal closure is associated with worse clinical outcomes in pediatric cardiac patients.

NIRS, Near-Infrared Spectroscopy; rSO2c, Regional Cerebral Oxygen Saturation; ScvO2, Central Venous Oxygen Saturation; CHD, Congenital Heart Disease; EEG, Electroencephalography; SEF90, Spectral Edge Frequency 90; BSR, Burst Suppression Ratio; RBR, Raw Burst Rate; ApEn, Approximate Entropy; TCD, Transcranial Doppler; CBFV, Cerebral Blood Flow Velocity; MAP, Mean Arterial Pressure; CMRO2, Cerebral Metabolic Rate of Oxygen; BP, Blood Pressure; HR, Heart Rate.GA, General Anesthesia.

Table 1. Continued...

Year	First author	Title	Study Design	Objectives	No. of participants	Primary outcome	Conclusion
2022	De Silvestro et al. [29]	Cerebral desaturation during neonatal congenital heart surgery is associated with perioperative brain structure alterations but not with neurodevelopmental outcome at 1 year.	Cohort study	To compare brain structure changes and neurodevelopmental outcome in patients with severe CHD with and without intraoperative cerebral desaturation.	32	New intracranial lesions occurred predominantly in cerebral desaturation groups, while neurodevelopmental outcome at 1 year was not associated with intraoperative cerebral desaturation.	This study demonstrates the clinical relevance of NIRS monitoring during congenital heart surgery. The occurrence of intraoperative cerebral desaturation is associated with perioperative lateral ventricle volume change and new intracranial lesions.
2022	Karlsson et al.[26]	Randomized controlled trial of low vs high oxygen during neonatal anesthesia: Oxygenation, feasibility, and oxidative stress.	Controlled trial	Evaluation of oxygenation during general anesthesia with a low vs a high fraction of inspired oxygen, in newborn infants undergoing surgery.	35	Analysis of the oxidative stress biomarker urinary F2-Isoprostane revealed no differences between the low and high oxygen group.	The authors concluded that in healthy newborn infants, low oxygen during general anesthesia was feasible, while the prevailing practice of using high levels of inspired oxygen resulted in significant hyperoxia. The trade-off between careful dosing of oxygen and risks of hypo- and hyperoxia in neonatal anesthesia should be further examined.
2023	Iller et al.[30]	Intraoperative monitoring of cerebrovascular autoregulation in infants and toddlers receiving major elective surgery to determine the individually optimal blood pressure - a pilot study.	Clinical trial	Assessment of autoregulatory blood pressure limits in infants and children.	20	Using weight-adjusted blood pressure recommendations or regional cerebral tissue saturation, only a fraction of the phases with inadequate MAP could be identified.	Non invasive cerebral autoregulation monitoring using NIRS-derived hemoglobin volume index in infants, toddlers, and children receiving elective surgery under GA was reliable and provided robust data in this pilot study. Using a cerebral autoregulation-driven approach, individual optimal MAP could be determined intraoperatively. The intensity of blood pressure fluctuations influences the initial measuring time optimal. MAP may differ considerably from recommendations in the literature, and the MAP range within limits of autoregulation in children may be smaller than that in adults.

NIRS, Near-Infrared Spectroscopy; rSO2c, Regional Cerebral Oxygen Saturation; ScvO2, Central Venous Oxygen Saturation; CHD, Congenital Heart Disease; EEG, Electroencephalography; SEF90, Spectral Edge Frequency 90; BSR, Burst Suppression Ratio; RBR, Raw Burst Rate; ApEn, Approximate Entropy; TCD, Transcranial Doppler; CBFV, Cerebral Blood Flow Velocity; MAP, Mean Arterial Pressure; CMRO2, Cerebral Metabolic Rate of Oxygen; BP, Blood Pressure; HR, Heart Rate.GA, General Anesthesia.

DISCUSSION

The methodologies employed across the reviewed studies were not consistently used. This mini review identified 171 studies indexed with Medical Subject Headings (MeSH) terms in the literature concerning NIRS application in neonatal and pediatric surgeries. However, only 12 studies aligned with the primary focus of assessing the advantages of employing NIRS monitoring during surgical procedures. These studies in question encompassed a wide range of variables and discrepancies, which can introduce confounding factors and complicate data interpretation.

The susceptibility of neonates and young children to perioperative hypoxemia is attributed to a combination of factors, including their heightened oxygen demand and reduced oxygen supply. Additionally, the immature neonatal brain is particularly vulnerable to ischemic and neurotoxic damage during general anesthesia, even at low concentrations of anesthetic agents[4,8]. This vulnerability is compounded by various factors, including a high incidence of cardiovascular and respiratory depression, the immaturity of neonatal organ systems, the complexity of surgical procedures, and the unique physiology of newborns[37-39].

Despite the advancements in evaluating cerebral oxygen saturation (ScO2) using techniques such as Transcranial Doppler (TCD) and electroencephalography (EEG), these methods lack sufficient specificity and exhibit poor sensitivity when applied to the developing brain. Moreover, the absence of a global consensus on the optimal approach to assess CBF further complicates utilizing these techniques in pediatric settings. Alternative modalities have also shown limitations in accurately identifying hypoxia-ischemia (H-I) [2,16]. At the same time, some studies included in this paper were aimed to determine whether intraoperative NIRS can detect cerebral hypoxia-ischemia or alterations in cerebral tissue correlated with neurodevelopmental outcomes, with positive correlations[40,41].

NIRS, a light-based technology pioneered by Jobsis in 1977, offers a non-invasive means of assessing oxyhemoglobin levels in a wide range of tissues[1]. Since its inception, NIRS has undergone significant refinement, rendering it suitable for clinical use owing to its feasibility, non-invasiveness, and ease of use in oxygen saturation assessment[30,35]. It plays a pivotal role in evaluating tissue oxygen status, particularly in the context of neonatal and pediatric surgeries, even when relatively low oxygen concentrations are utilized during GA[32,33,42].

The human brain remains inadequately monitored, leaving room for unforeseen events that may lead to undetected impairments or delayed interventions. Despite remarkable advancements in medical technology over the past three decades, conditions such as H-I continue to pose challenges in early diagnosis, consequently contributing to neurocognitive and behavioral disruptions[34].

Young children undergoing surgical procedures face a heightened risk of perioperative mortality, primarily attributed to the intricacy of the surgery, compromised cerebrovascular autoregulation, the severity of the infant's illness, and their physiological status. Intraoperative hypotension stands out prominently among the critical risk factors impacting both cardiac and neurological outcomes. Mean Blood Pressure (MBP) during surgery has been advocated as a pivotal parameter for ensuring safety in pediatric anesthesia[39,43].

Hypotension occurring during GA in neonates and infants significantly contributes to adverse neurological outcomes. Consequently, continuous monitoring of cerebral perfusion becomes imperative for this patient population. Recent retrospective observational cohort studies, some multicentric in nature, have developed non-invasive blood pressure (NIBP) reference curves tailored to age and sex, with the objective of aiding anesthesiologists during procedures. These reference curves indicate a mean NIBP ranging from 33 mmHg at birth to 67 mmHg at 18 years of age[44,45].

As it is well-established and validated, GA is associated with a higher hypotension incidence than other techniques. A recent cross-sectional descriptive analysis reported a hypotension incidence of 29% among adult patients undergoing GA, characterized by a mean arterial pressure <65 mmHg, even in patients considered "low risk"[46,47]. Moreover, a multicenter trial demonstrated a greater likelihood of hypotension in children undergoing GA compared to regional anesthesia (relative risk, 2.8, 95% CI, 1.7-4.4 by intention-to-treat analysis)[45].

Given that anesthetic agents can compromise cerebral autoregulation, even in small doses, stringent blood pressure control during surgeries becomes imperative. This is particularly crucial as cerebral perfusion pressures may directly correlate with arterial blood pressures, potentially exceeding the limits of cerebral autoregulation. This risk is amplified in infants with open fontanels, necessitating the implementation of measures to maintain adequate cerebral perfusion pressure (CPP)[48].

Moreover, Sottas et al.[49] emphasized the absence of a consensus regarding pediatric hypotensive thresholds, highlighting that a systolic decrease of 20% from the preinduction value is commonly utilized as a surrogate marker. They observed a typical mean blood pressure (MBP) decline of 28.6% in newborns aged 0-10 weeks. An observational study revealed a significant positive correlation between a decrease in MBP exceeding 20% and a reduction in NIRS-measured cerebral oxygen

saturation (ΔStcO2 > 20%) among newborns undergoing noncardiac surgeries[47].

Additionally, Rhondali et al.[27] demonstrated a strong correlation between NIRS and TCD measurements of regional cerebral oxygen saturation (rSO2c) in normocapnic children undergoing general anesthesia using sevoflurane. Consistent findings by other researchers support the potential of NIRS as a suitable tool for CBF, filling a critical gap in the absence of a consensus regarding the optimal method for evaluating central blood perfusion. Therefore, NIRS stands out as a noninvasive means to continuously monitor regional cerebral oxygen saturation (crSO2)[50].

Therefore, NIRS is a crucial clinical tool for real-time assessment of infants' oxyhemoglobin levels in vital organs such as the brain and kidneys. It effectively detects acute changes in oxygenation during apnea. It can identify brain hypoxia before alterations in peripheral saturation or EEG are apparent, demonstrating high sensitivity in detecting cerebral circulatory arrest[51-55].

A cohort explored the relationship between NIRS monitoring and changes in brain structure, alongside neurodevelopmental outcomes in patients undergoing complex congenital heart diseases, such as d-transposition of the great arteries[54]. The findings revealed that perioperative relative lateral ventricle volume changes were elevated in patients experiencing intraoperative cerebral desaturation ($p = 0.003$ for 45%rSO2, $p = 0.008$ for 20%BLrSO2). Furthermore, a predominance of new intracranial lesions was observed within this group (6 out of 6 patients for 45%rSO2, 5 out of 6 patients for 20%BLrSO2)[54].

However, several limitations should be acknowledged. First, the heterogeneity among the included studies challenges drawing definitive conclusions. Due to limited longitudinal follow-up data, it remains uncertain whether these children experience delayed long-term neurodevelopmental issues or exhibit improvement over time.

Secondly, the studies' lack of hemoglobin level data is noteworthy, as anemia can significantly impact oxygen-carrying capacity, potentially leading to cerebral tissue hypoxia. Thirdly, many studies utilizing NIRS to investigate the pathophysiology of Hypoxic Ischemic Encephalopathy focus on changes in cerebral perfusion and oxygenation under hypothermia treatment. This may potentially introduce a degree of bias to the findings.

CONCLUSION

NIRS has emerged as a critical tool in contemporary medical practice, particularly in intricate neonatal surgeries such as cardiovascular procedures. Its capability to swiftly identify early hypoxemia plays a pivotal role in preempting potential ischemic events and adverse outcomes in infants. Notwithstanding the discrepancies among studies examining the use of NIRS, the extant evidence is compelling in supporting the integration of NIRS into both clinical and surgical settings as a valuable medical instrument.

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