Received: 3 May 2019 | Revised: 10 August 2019 | Accepted: 19 August 2019

DOI: 10.1111/pan.13726

SPECIAL INTEREST ARTICLE

Pediatric Anesthesia WILEY

A practical approach to cerebral near-infrared spectroscopy (NIRS) directed hemodynamic management in noncardiac pediatric anesthesia

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Funding information
This work was funded by departmental resources.

Section Editor: Dean Kurth

Abstract

Safeguarding cerebral function is of major importance during pediatric anesthesia. Premature, ex-premature, and full-term neonates can be vulnerable to physiological changes that occur during anesthesia and surgery. Data from studies performed during pediatric cardiac surgery and in neonatal/pediatric intensive care units have shown the benefits of near-infrared spectroscopy (NIRS) monitoring of regional cerebral oxygenation (c-rSO_2). However, NIRS monitoring is seldom used during noncardiac pediatric anesthesia. Despite compelling evidence that blood pressure does not reflect end-organ perfusion, it is still regarded as the most important determinant of cerebral perfusion and the most relevant hemodynamic management target parameter by most (pediatric) anesthetists. The principle of NIRS monitoring is not self-explanatory and sometimes seems even counterintuitive, which may explain why many anesthesiologists are reserved regarding its use. The first part of this paper is dedicated to a clinical introduction to NIRS monitoring. Despite scientific efforts, it has not yet been possible to define individual lower limit c-rSO_2 values and it is unlikely this will succeed in the near future. Nonetheless, published treatment algorithms usually specify c-rSO_2 values which may be associated with cerebral hypoxia. Our treatment guideline for maintaining sufficient cerebral oxygenation differs fundamentally from all previously published approaches. We define a baseline c-rSO_2 value, registered in the awake child prior to anesthesia induction, as the lowest acceptable limit during anesthesia and surgery. The cerebral rSO_2 is the single target parameter, while blood pressure, heart rate, P_aCO_2, and SaO_2 are major parameters that determine the c-rSO2. Cerebral NIRS monitoring, interpreted together with its continuously available contributing parameters, may help avoid potentially harmful episodes of cerebral desaturation in anesthetized pediatric patients.

KEYWORDS

anesthesia, hemodynamics, hypoxia-ischemia, near-infrared spectroscopy, pediatric

1 | INTRODUCTION

Safeguarding children's brains has always been among the most challenging targets in pediatric anesthesia. Recent research efforts have mainly focused on potential anesthetic drug-induced neurotoxicity and intermediate-and/or long-term neurodevelopmental outcome. Prospective studies published to date have found now no evidence of neurotoxicity in young children, after a single exposure to anesthetic agents.[1-3] On the other hand, recent papers discussing acute severe brain damage associated with general anesthesia, particularly in neonates and infants, are challenging our perception of safety of our current practice of pediatric anesthesia.[4,5]

In a case series, McCann et al delineated the development of postoperative encephalopathy in six infants, where periods of hypotension and/or hypocapnia may have contributed to (prolonged) periods of cerebral hypoperfusion.[6]

Despite research using various methods to determine individual lower limits of blood pressure (BP) in anesthetized infants to prevent them from anesthesia associated acute brain damage,[7-12] there is still no consensus regarding safety margins of BP in anesthetized infants.[13]

Many pediatric anesthetists instinctively link cerebral hypoperfusion with low blood pressure. However, arterial blood pressure (BP) is no more than one of the factors contributing to the maintenance of cerebrovascular autoregulation and is not a surrogate for cerebral perfusion or tissue perfusion in general (see Figure 1). Despite compelling evidence that BP does not reflect end-organ perfusion, it is still regarded as the most important determinant of cerebral perfusion by most (pediatric) anesthetists.

Near-infrared spectroscopy (NIRS) is a non-invasive technology that provides real-time information regarding tissue oxygenation. A growing body of evidence emerging from pediatric cardiac anesthesia papers suggests that NIRS detected cerebral desaturation is linked to bad neurological outcome.[14,15] When interpreted together with standard monitoring parameters, cerebral NIRS provides the anesthetist with early warning signs of impaired tissue perfusion, ventilation, and oxygenation, allowing one to draw conclusions as to the cause [16] and subsequently enabling immediate interventions to prevent the child from potentially life-threatening complications or at least to reduce their severity.[17]

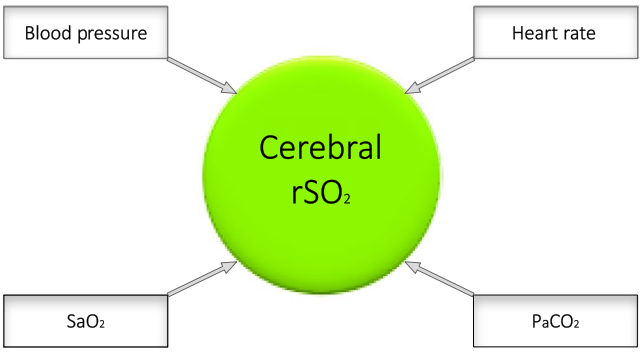

FIGURE 1 Standard continuous anesthesia monitoring parameters contributing to cerebral regional oxygen saturation (c-rSO_2) [Colour figure can be viewed at wileyonlinelibrary.com]

While it has become a standard of care in many pediatric cardiac centers and neonatology units, NIRS monitoring is not yet widely applied in children undergoing noncardiac surgical procedures. The majority of papers delineating the use of NIRS monitoring during major noncardiac pediatric surgery have been published in surgical journals. In these pediatric surgical studies, NIRS was often used as a monitoring tool to address possible safety issues of new surgical techniques, such as thoracoscopic repair of congenital diaphragmatic hernia or esophageal atresia.[18-20]

The aim of this article is threefold: Firstly, we give a practical introduction to near-infrared spectroscopy (NIRS) in pediatric patients. Secondly, we present our approach to managing hemodynamics and maintaining adequate cerebral perfusion/tissue oxygenation, using regional cerebral tissue oxygenation (c-rSO_2) measured by NIRS as the central target parameter. Finally, we shall share with you our thoughts about the future of NIRS monitoring in pediatric anesthesia.

2 | A PRACTICAL INTRODUCTION TO NEAR-INFRARED SPECTROSCOPY (NIRS)

2.1 | The technical background of near-infrared spectroscopy (NIRS)

NIRS technology applies light wavelengths within the 650-1100 nm range, the so-called "optical window" for measuring tissue oxygenation. As opposed to ultraviolet, infrared, and visible light, near-infrared (NIR light) is not strongly absorbed by water, proteins or hemoglobin and scatters less, making it capable of providing information from the inner body after analysis of its spectrum.[21]

Within the NIR spectrum, photons can penetrate tissue several centimeters and even penetrate bone, the latter being a prerequisite for transcranial NIRS monitoring.[22] NIRS monitoring provides real-time information regarding the difference between tissue oxyhemoglobin and deoxyhemoglobin, reflecting tissue oxygen uptake, and consumption.[23]

The basic principle of the currently commercially available medical NIRS devices is the application of a sensor which emits 2-5 different wavelengths of light within the NIR spectrum into tissue. The emitted photons are partly absorbed by optical pigments, among them hemoglobin. Depending on the degree of oxygenation, the resultant NIR spectrum changes and reflected photons are returned to the tissue surface after reflection, where superficial NIR radiation detectors are integrated into the NIRS sensor. Device manufacturers claim that specific algorithms remove the effect of superficial tissue, referred to as extracerebral contamination. However, Kato et al[24] and Davie and Grocott[25] reported significant extracranial contamination in adults by several commercially available NIRS devices. Kurth et al[26] found that extracranial contamination is unlikely in neonates, infants, and young children.

According to Ghosh et al,[27] mitochondrial cytochrome c oxidase (CCO), being responsible for >95% of oxygen metabolism, might be a more important chromophore than oxyhemoglobin and deoxyhemoglobin, and probably less prone to extracerebral contamination. Unfortunately, currently commercially available NIRS monitors have not yet integrated CCO in their algorithms.

Currently, NIRS is mostly used to monitor cerebral tissue oxygenation. In a pediatric study, Watzman et al[28] found mean arterial and venous contributions to c-rSO2 of 16 ± 21% and 84 ± 21%, respectively. Manufacturers have integrated algorithms into their monitors which assign 70%-75% of the scanned blood volume to the venous compartment.[29] This does not mean that current NIRS monitors are capable of measuring arteriovenous partitioning. In their 2014 review article, Scott and Hoffman[30] describe NIRS monitoring as a tool providing "non-invasive continuous access to the venous side of regional circulations."

The measurements reported by the current NIRS devices are expressed by the device manufacturers as either regional oxygen saturation rSO_2 or tissue oxygenation index TOI,[31] which are both expressions of the percentage of tissue oxyhemoglobin. Unfortunately, in the scientific literature many other abbreviations can be found, such as StO_2, ScO_2, and $SctO_2$; actually, all of them are expressions of regional tissue oxygenation but this inconsistency in reporting creates more confusion.

2.2 | Parameters contributing to c-rSO_2

Physiological parameters known to contribute to the cerebral oxygen delivery/demand balance need to be considered as relevant when interpreting c-rSO_2. Oxygen delivery to the brain is basically a function of cardiac output, perfusion pressure, oxygenation, and hemoglobin concentration. Oxygen demand is furthermore related to the cerebral metabolic rate (CMR) which is reduced by all currently used anesthetic drugs except ketamine, which causes a rise in CMR.[32]

(Pediatric) anesthetists traditionally rely on standard monitoring parameters like blood pressure, heart rate, pulse oximetry to assess their patient's cardiocirculatory and respiratory status.

Continuous (non-invasive) measurement of cardiac output, though technically possible,[33,34] has not yet become common practice in pediatric anesthesia. A growing body of evidence suggests that arterial blood pressure, though not a good estimate of cerebral perfusion, seems to contribute mostly to changes in c-rSO_2.[35] Heart rate is also important, especially in neonates and young infants.

The arterial carbon dioxide tension ($PaCO_2$) also significantly contributes to cerebral blood flow with hypocarbia resulting in cerebral vasoconstriction and reduced cerebral blood flow and hypercarbia resulting in vasodilation and increased cerebral blood flow. In a pediatric study, de Waal et al could show that increasing the P_aCO_2 from 32 to 40 mm Hg in anesthetized patients resulted in an increase in c-rSO_2 from 61% to 70%.[36]

The arterial oxygen tension (PaO_2) appears to contribute to c-rSO_2 to a lesser degree than P_aCO_2 [37] but should be considered as well, especially during acute hypoxic events.

Anemia becomes relevant for c-rSO_2 when hemoglobin levels are too low to deliver an oxygen-carrying capacity that meets the demands of cerebral oxygen consumption. Under these conditions, transfusion of red blood cells has been shown to result in increased c-rSO_2 values.[38] It should be kept in mind that in a surgical setting, a decrease in c-rSO_2 can be due to low hemoglobin concentrations following acute blood loss even before decreases in blood pressure occur.

Other physiological parameters, such as body temperature and blood glucose level, also contribute to cerebral perfusion. If possible, any parameter measured should be kept within its age-related and/or patient-specific physiologic range.

As opposed to the cardiorespiratory monitoring parameters, we are used to rely on, such as heart rate, blood pressure, oxygen saturation, and carbon dioxide partial pressure, a c-rSO_2 value is not a "stand-alone" parameter; it is more or less the ultimate expression of the interplay between the aforementioned contributing parameters (see Figure 1). The course of a NIRS reading should therefore always be interpreted in the context of the course (and the possible changes) of the factors contributing to it. In a recent editorial, Skowno et al[14] referred to NIRS as a "multidimensional monitor" enabling the interpretation of multiple variables influencing cerebral blood flow.

2.3 | NIRS monitoring in children under chronic hypoxemic conditions

A closer look at NIRS monitoring in children with cyanotic heart disease nicely illustrates the fundamental difference between NIRS and pulse oximetry.[39,40] While the pulse oximeter shows an oxygen saturation of 85%, NIRS-derived c-rSO_2 values are around 70%, equaling the range usually seen in awake healthy children with an oxygen saturation of ±98%. This equality in c-rSO_2 values can easily be explained by the pathophysiology of cyanotic heart disease: In order to compensate for a low arterial oxygen saturation, secondary erythrocytosis develops resulting in significantly elevated hemoglobin levels and an (almost) normal oxygen delivery capacity. The brain extracts the same amount of oxygen as in healthy children, but from more hemoglobin molecules in the same blood volume, resulting in normal venous oxygen saturation and c-rSO_2 values. This principle applies to pediatric cardiac patients with mild chronic hypoxemia (S_aO_2 ± 85%) but probably not to patients under more extreme hypoxemic conditions.

In this context, it seems sensible to mention that pulse oximeters, undisputed core elements of our standard monitoring, already begin to overrate S_aO_2 under mild hypoxemic conditions (S_aO_2 < 90%). This error further increases with increasing hypoxemia.[41] Nonetheless, most of us erroneously accept the values of the pulse oximeter, no matter how low they are.

2.4 | NIRS—common misconceptions

NIRS monitoring is still widely misunderstood because it is often mistakenly compared to pulse oximetry. Pulse oximetry is dependent on pulsatile blood flow, designed to measure the fraction of oxygenated arterial blood. NIRS monitoring does not depend on pulsatile blood flow and provides information about the tissue oxyhemoglobin/deoxyhemoglobin ratio. To make a clear distinction from pulse oximetry, NIRS can probably best be described as a nonpulsatile venous oximeter. When interpreted together with pulse oximetry, NIRS monitoring provides information regarding tissue oxygen delivery and consumption.

High c-rSO_2 values can be misleading under certain conditions. In our own institution, we commonly see exceptional high c-rSO_2 values (±90%) in ventilated ICU patients sedated with midazolam, especially in neonates and young infants. After discontinuation of midazolam and subsequently decreasing midazolam blood concentrations, c-rSO_2 values usually decline to ±70% within several hours, due to an increase in cerebral metabolism. This observation emphasizes the importance of an initial baseline value, preferably under awake conditions, without any sedative drug effect.

2.5 | Improper use of medical NIRS devices—More than just kidneys and vegetables

A recent provocatively humorous paper by Kahn et al,[42] published in the Christmas issue of the European Journal of Anaesthesiology, comparing NIRS in vegetables and humans is certainly one of the most extreme examples of improper use of medical NIRS technology. Though certainly not meant to be regarded as serious research by the authors, this paper carries the risk of perpetuating foolish misunderstandings of how medical NIRS devices work. However, it is easy to explain why vegetables can have NIRS measurements comparable to humans: Many sorts of vegetables contain chromophores with optical properties comparable to hemoglobin.[43] A medical NIRS device, when attached to these vegetables, receives information via its sensor which, according to the device algorithm, is interpreted as derived from hemoglobin, resulting in a "normal" NIRS value. It is also worth noting that designated NIRS technology has a long history in food safety evaluation and control.[44]

Wallin and Lönnqvist recently eloquently elaborated the risk of unintentional improper use of medical NIRS devices[45]: Currently, commercially available NIRS monitors have their algorithms programmed to exclude the most superficially reflected photons, because they represent bone or cartilage tissue rather than brain tissue. Using NIRS sensors designed for brain monitoring for monitoring somatic tissue oxygenation (where there is no superficial bone layer) may result in invalid NIRS values. Fortunately, NIRS devices with specific somatic measurement algorithms have recently become available for routine clinical use.

The distance between the light source and the light detecting optode of a NIRS sensor is another potential source of error that many users are unaware of. Dix et al found significant differences in c-rSO_2 values in preterm neonates measured with different NIRS sensors.[46] Kleiser et al investigated the impact of the source-detector separation (SDS) of several commercially available NIRS sensors on their performance[47,48] and reported different tissue oxygenation values measured by different device-sensor combinations in the same neonatal head phantom. According to Wallin and Lönnqvist, currently available neonatal cerebral NIRS sensors should not be used in neonates <2.5 kg, because due to the small size of the head of these tiny infants it would be likely that the resulting c-rSO_2 values would represent white matter or lateral ventricle oxygenation rather than a cortical trace.[45]

2.6 | The ongoing search for c-rSO_2 normal values and lower limits of safety

According to a recent meta-analysis published by Chan et al, normal awake c-rSO_2 baseline value in adults range from 51% to 81.8%, with a pooled mean of 66.4%.[49] c-rSO_2 reference ranges have also been described for term and preterm and small for gestational age neonates, with means between ±65% and ±70%.[50,51] Unfortunately, we are not aware of published awake c-rSO_2 baseline data applicable to older infants or children. Many pediatric anesthetists consider a c-rSO_2 value of approximately 25% less than the actual arterial oxygen saturation as normal. This heuristic approach, almost entirely based on (personal) experience, ultimately resulted in some kind of common sense.

The exact individual lower safety margin of c-rSO_2 values in anesthetized children is yet unknown. Early animal data published by Kurth et al[52] found cerebral hypoxia-ischemia c-rSO_2 thresholds between 33% and 44% for acute brain energy failure and brain metabolic dysfunction. Another animal study performed by Kurth et al[53] showed that brain tissue injury depends on both severity and duration of ischemia. As severity or duration of ischemia increase, the degree of damage increases. In piglets subjected to a c-rSO_2 of 45% from 1 to 8 hours and subsequently recovered, brain injury by histologic and behavioral examination was not evident until 2 hours c-rSO_2 45%; then, the incidence of brain injury increased 15% per hour, such that by 8 hours c-rSO_2 45%, all piglets displayed brain injury.

In neonates after Norwood stage I palliation for hypoplastic left heart syndrome (HLHS) Dent et al[54] found an association between postoperative c-rSO2 values <45% lasting longer than 3 hours and the development of new or worsened cerebral ischemic lesions on MRI scans. More recent research in infants after Norwood stage I palliation for HLHS has shown that in this particular patient population NIRS-derived c-rSO_2 values are insensitive predictors of cerebral venous oxygen saturation values of <30%, which are known to represent the anaerobic threshold.[55] The authors of this study specifically concluded that even c-rSO_2 values >50% are not necessarily reassuring.

Pellicer et al recommended a nonindividualized c-rSO_2 target range between 55% and 58% for extremely premature infants,[56] which was intended to avoid both cerebral hypoxia and hyperoxia.

Stolwijk et al adopted this recommendation in a case series of neonates undergoing thoracoscopic repair of long gap esophageal atresia and added an individual feature to it by trying to avoid fluctuations in c-rSO_2 of more than 20% from baseline.[57]

Until now, a consensus regarding a lower limit of NIRS-derived c-rSO_2 values, serving as an intervention threshold, could not be reached.

2.7 | Limitations of cerebral NIRS monitoring

There are clinical situations in which NIRS values are difficult to interpret. An almost classic scenario is connecting the NIRS monitor intraoperatively at the moment the patient's conditions begin to deteriorate (ie, low blood pressure, low SaO_2, etc). As we do not have validated nonindividualized lower c-rSO_2 safety margins available, in these cases interpretation of NIRS values is problematic, apart from extremes; that is a c-rSO2 value of 30%, usually accompanied by a low SaO2-value is without any doubt an urgent call for action, whereas a c-rSO_2 value of 85% speaks for a sufficient cerebral oxygenation. However, without knowledge of the individual awake baseline c-rSO_2 value it is difficult, if not impossible to draw a meaningful conclusion as to a c-rSO_2 value of for example ±60%.

2.8 | NIRS and patient outcome

Cerebral NIRS monitoring has been used in pediatric cardiac anesthesia for more than two decades. While some centers integrated c-rSO_2 monitoring into their clinical protocols of perioperative hemodynamic management, others decided not to rely on NIRS monitoring. Today, there is little doubt as to the predictive value of NIRS monitoring with regard to early outcome after pediatric cardiac surgery.[15,17]

As opposed to pediatric cardiac patients, few data are available regarding NIRS monitoring and outcome after pediatric noncardiac surgery. Olbrecht et al published an observational multicenter study in 453 infants <6 months receiving anesthesia for noncardiac surgical procedures and found a 43% incidence of mild cerebral desaturation measured by NIRS, whereas the incidences of usually short periods of severe cerebral desaturation were as low as 1.55% for absolute c-rSO_2 values <50% and 0.95% for a 30% decline from baseline.[58] In this study, low mean blood pressure values, though common, were not well associated with low c-rSO_2 values. The authors concluded that severe cerebral deoxygenation is uncommon in noncardiac infant anesthesia. In a recent observational study performed in pediatric noncardiac surgical patients, Gomez-Pesquera et al[59] found that a decrease of intraoperative c-rSO_2 values of less than 20% from awake baseline was associated with negative behavioral changes on postoperative day 7.

Large scale pediatric anesthesia studies addressing NIRS and neurodevelopmental outcome are still lacking, both in cardiac and noncardiac patients.

In a 2011 review article, Greisen et al estimated that a trial with sufficient power to detect a 20% reduction of the incidence of brain injury in extreme premature neonates should recruit about 4000 patients.[60] A recent international phase II feasibility randomized clinical trial in 160 extremely preterm infants showed a reduction in cerebral hypoxic events due to a NIRS-guided treatment protocol[56] but failed to detect any effect on the occurrence of early biomarkers of brain injury or EEG burst rates[61] and neurodevelopmental outcome at 2 years of age.[62] In this neonatal ICU trial, only one intervention to normalize c-rSO_2 values was allowed at a time and the patient was re-assessed 30-60 minutes later. Transient anticipated changes in c-rSO_2 values due to routine interventions (ie, endotracheal tube suctioning) were not listed in the treatment protocol. A subsequent trial, aiming to recruit 1600 patients, has been designed by the same consortium to investigate the possible impact of their NIRS protocol on the incidence of death or severe brain injury at 36 weeks.[63]

3 | NIRS-DIRECTED HEMODYNAMIC MANAGEMENT: THE BASELINE-BOTTOMLINE APPROACH

We fully agree with Scott and Hoffman stating that "NIRS opens a window for regional circulation monitoring that can drive organ-specific goal-directed treatments".[30] It is furthermore currently widely accepted that NIRS-derived c-rSO_2 is a reliable non-invasive surrogate parameter of the cerebral oxygen supply/demand balance. Other parameters, among which blood pressure, heart rate, S_aO_2, and P_aCO_2, significantly contribute to cerebral perfusion, but they provide no good estimate of cerebral perfusion. Simultaneous interpretation of NIRS and contributing parameters currently provides us with the most reliable information regarding the cerebral oxygen supply/demand balance.[14,16] As a consequence, our strategy to ensure adequate cerebral perfusion and oxygen delivery uses cerebral rSO_2 as the single target parameter, while BP, heart rate, P_aCO_2, etc are contributors serving rSO_2.

It may appear somewhat counterintuitive to recommend the use of a parameter (c-rSO_2) which comes short of a clearly defined normal range as the central target parameter of hemodynamic management. Worse still, there are also no generally accepted intervention targets for low c-rSO_2 values. Finally, c-rSO_2 values are device specific.[46-48] However, we do not regard these points as a shortcoming, as long as it is possible to obtain an individual c-rSO_2 baseline value, measured under awake conditions. *Awake* is the magic word here: We assume that as long as the child is awake and responsive, cerebral perfusion and oxygenation are both sufficient.

This clearly puts a strong case for handling an individualized c-rSO_2 target for children under anesthesia conditions. The key to our concept is to keep the child's cerebral oxygenation within a range of c-rSO_2 values which we know to be safe, which means higher than awake baseline, instead of allowing the c-rSO_2 to decline until we begin to feel uneasy with the child's condition. Basically, we are aiming at maintenance of an optimal condition rather than treatment of potentially harmful cerebral desaturation. We call this strategy our Baseline-Bottomline approach. Contrary to the treatment guideline

developed by the SafeBooS-C research consortium,[56] we take into account any change of the c-rSO$_2$ under anesthesia conditions with a focus on immediate restoration of normal values.

Our clinical approach to NIRS-directed hemodynamic management is quite straight forward: The child is attached to the NIRS monitor prior to induction of anesthesia to obtain an awake baseline value. This baseline value is considered to reflect adequate cerebral oxygenation. If possible, we measure an awake baseline blood pressure and baseline values of heart rate and pulse oximetry. Unfortunately, it is not always possible to obtain an awake baseline blood pressure.[12] Contrary to this awake blood pressure issue, we cannot remember a single patient where it was not possible to obtain an awake baseline c-rSO$_2$ value. Our experience is that c-rSO$_2$ values usually stabilize within <1 minute. If an infant is upset before induction of anesthesia, we usually see baseline c-rSO$_2$ values slightly lower than in calm infants. A possible explanation for this phenomenon is the increased intrathoracic pressure during crying, resulting in a decreased jugular venous return causing a relative increase of the cerebral venous compartment. Unfortunately, we are unable to comment on baseline c-rSO$_2$ values in asleep infants because application of the NIRS sensor usually wakes them up.

During induction of anesthesia, immediately after loss of consciousness, an increase in c-rSO$_2$ of at least 5%-10%, due to a reduction in cerebral metabolism, is mandatory. If c-rSO$_2$ values drop during induction, the child is either not adequately ventilated and/or blood pressure has dropped significantly due to anesthetic drug effect on the cardiocirculatory system. NIRS values react very fast, usually significantly faster than standard monitoring parameters, serving both as an early warning sign and as an immediate feedback tool for any interventions aiming to improve the cerebral oxygenation. During maintenance of anesthesia, c-rSO$_2$ values are usually slightly lower than during the induction period, but still above awake baseline, likely a result of higher inspired fraction of oxygen during induction compared to the maintenance period. Reduced cerebral metabolism under anesthesia maintenance conditions usually results in c-rSO$_2$ values slightly (±5%-10%) higher than awake baseline. A flowchart (Figure 2) illustrates our concept. A decline in BP is the most common cause of a drop of c-rSO$_2$ values.[35] It is a key feature of our Baseline-Bottomline approach that we do not accept c-rSO$_2$ values lower than or equal to awake baseline. When c-rSO2 values approach awake baseline, we immediately investigate the course of our predefined contributing factors (BP, P_aCO_2, HR, SaO_2). In case of a decrease in BP, we start a continuous infusion of norepinephrine (10 µg/mL), in the first instance at a rate of 0.1 µg/kg/min, administered through a peripheral venous catheter, which in our experience will not result in severe hypertension.

Preoperative fluid deficits should also be compensated, but in our experience a fluid bolus alone is seldom enough to re-establish baseline c-rSO$_2$ values. Additional fluid boli, especially in preterm neonates, come with an increased risk of postoperative fluid overload, which can lead to respiratory compromise.

Having used the Baseline-Bottomline approach in several hundred patients, intraoperative c-rSO2 can be maintained at or above

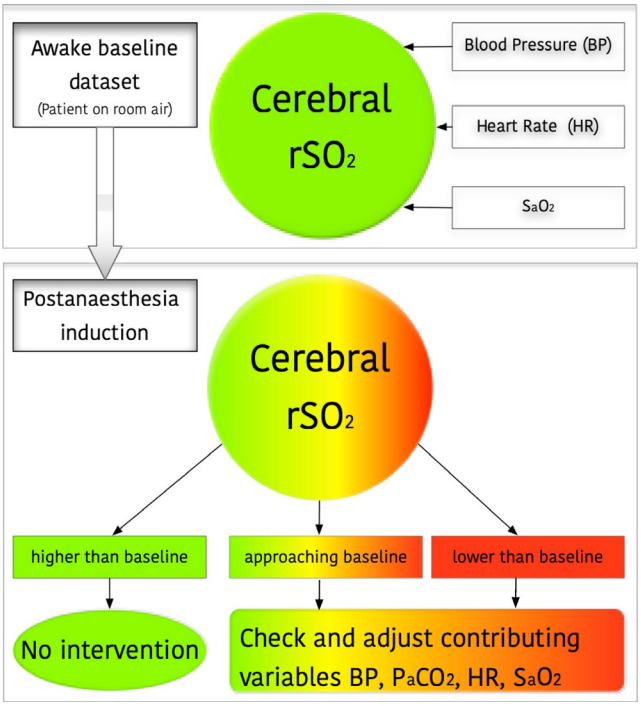

FIGURE 2 NIRS direct hemodynamic management—the "Baseline-Bottomline approach" [Colour figure can be viewed at wileyonlinelibrary.com]

baseline, regardless of circumstances, including epidural analgesia and anesthetic drug effects on vascular tone and/or cardiac output in almost all patients.

In our institution, we currently use cerebral NIRS monitoring in noncardiac surgical neonates and other patients assumed to be at high risk of impaired cerebral perfusion during the course of an anesthetic, including the period before surgical incision and the emergence period. While NIRS monitoring in (preterm) neonates has become a standard of care in our institution, we do not yet have a clinical guideline as to the indication for NIRS monitoring in older children. In our hospital, the decision to restrict the use of NIRS monitoring to patients assumed to be at an increased risk of anesthesia associated hypoxic-ischemic neurologic injury is mainly economically driven.

In terms of evidence-based medicine, our Baseline-Bottomline approach is no more than a level III recommendation. It may also be regarded as too conservative. Critics may argue that there are no scientific data supporting our strategy, which is not entirely correct: Olbrecht et al[58] recently reported frequent low (baseline −20%) cerebral desaturations measured by NIRS during infant and neonatal anesthesia, while Gomez-Pesquera[59] found an association of decreases in c-rSO$_2$ values of <20% with negative postoperative behavior changes on postoperative day 7. The logical conclusion of these findings is that even moderate declines in c-rSO$_2$ values may have a negative impact on patient wellbeing and should therefore be avoided.

NIRS monitoring remains a controversial issue, and in the pediatric anesthesia community, there are both NIRS enthusiasts and

sceptics. Even in our own institution, not all pediatric anesthetists rely on NIRS monitoring. Being NIRS enthusiasts, we have to disclose a bias in favor of the use of NIRS monitoring in pediatric patients, while we tried to adequately address the relevant limitations and shortcomings of this technology There is an urgent need for more independent scientific data on NIRS monitoring in anesthetized children. Our research group at Sophia Children's Hospital is currently conducting several clinical studies on NIRS monitoring in neonates and infants.

4 | THE FUTURE: MULTISITE NIRS MONITORING AND COMPOSITE PARAMETERS

Simultaneous application of NIRS probes on the forehead and other regions of the body, usually referred to as multisite NIRS monitoring is becoming increasingly popular, at least in research settings.

Renal rSO_2 values simultaneously recorded with c-rSO_2 may provide relevant additional information regarding renal function.[30] Muscle rSO_2 values also simultaneously recorded with c-rSO_2 have been used as early markers of centralization of the circulation in premature neonates.[64]

Fractional regional tissue oxygen extraction [FTOE = (SaO_2-rSO_2)/SaO_2] is a composite parameter reflecting the balance between oxygen delivery and consumption,[20,65,66] which is becoming increasingly popular in the neonatal ICU setting. Until now, the FTOE needs to be calculated manually. Such a calculation would distract the anesthetist's attention in the short term, which could be an additional risk to the patient. NIRS technology is still being developed by the device manufacturers. Algorithms are updated to diminish the amount of extracerebral contamination and improve the performance of somatic NIRS measurements. Furthermore, integration with standard anesthesia monitoring is slowly emerging and hopefully automated calculations of composite parameters, for example FTOE will soon become available.

Integration of other emerging technologies into the hemodynamic management workflow, such as non-invasive measurement of cardiac output or continuous monitoring of hemoglobin concentration by pulse oximetry may become significant additions to NIRS monitoring.

5 | CONCLUSION

NIRS monitoring can help maintain sufficient tissue perfusion/oxygenation in anesthetized children. Our approach defining baseline awake c-rSO_2 values as the lower limit is fundamentally different from previously reported treatment algorithms defining lower limits of c-rSO_2 values by either percentage reductions compared to baseline or absolute values assumed to be associated with cerebral hypoxemia. Cerebral NIRS monitoring, interpreted together with its continuously available contributing parameters (BP, P_aCO_2, HR, and SaO_2), may help avoid potentially harmful episodes of cerebral desaturation in anesthetized pediatric patients.

CONFLICT OF INTEREST

No conflict of interest declared.

ETHICAL APPROVAL

Not applicable.

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How to cite this article: Weber F, Scoones GP. A practical approach to cerebral near-infrared spectroscopy (NIRS) directed hemodynamic management in noncardiac pediatric anesthesia. *Pediatr Anesth*. 2019;29:993–1001. https://doi.org/10.1111/pan.13726