



Current state of noninvasive, continuous monitoring modalities in pediatric anesthesiology

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Purpose of review

The last decades, anesthesia has become safer, partly due to developments in monitoring. Advanced monitoring of children under anesthesia is challenging, due to lack of evidence, validity and size constraints. Most measured parameters are proxies for end organ function, in which an anesthesiologist is actually interested. Ideally, monitoring should be continuous, noninvasive and accurate. This present review summarizes the current literature on noninvasive monitoring in noncardiac pediatric anesthesia.

Recent findings

For cardiac output (CO) monitoring, bolus thermodilution is still considered the gold standard. New noninvasive techniques based on bioimpedance and pulse contour analysis are promising, but require more refining in accuracy of CO values in children. Near-infrared spectroscopy is most commonly used in cardiac surgery despite there being no consensus on safety margins. Its place in noncardiac anesthesia has yet to be determined. Transcutaneous measurements of blood gases are used mainly in the neonatal intensive care unit, and is finding its way to the pediatric operation theatre. Especially CO₂ measurements are accurate and useful.

Summary

New techniques are available to assess a child's hemodynamic and respiratory status while under anesthesia. These new monitors can be used as complementary tools together with standard monitoring in children, to further improve perioperative safety.

Keywords

bioimpedance, near-infrared spectroscopy, noninvasive monitoring, transcutaneous measurements

INTRODUCTION

Patient safety is the number one issue in anesthesiology. At present, anesthesia is absolutely safe in uncomplicated patients undergoing low-risk procedures, as improvement of monitoring modalities and anesthetics, and the preparation of the perioperative process have led to optimization of care. In general, intraoperative mortality has dramatically decreased in the last decades [1]. This overall safety has led to a change of the paradigm of anesthesia, from survival of the surgery and avoiding direct side effects into concepts based on quality of life and value-based health care. This requires a new view on monitoring to optimize organ preservation by controlling local oxygenation and metabolism.

In perioperative monitoring of pediatric patients, we face specific challenges, which postponed the development of appropriate age and size-related pediatric monitors. First, it is not always possible to get baseline measurements and some equipment is not validated for children or has size limitations. Moreover, there is no consensus on safety margins

of some parameters, while goal directed monitoring in adults has already been established.

Due to rapid hemodynamic and respiratory changes under anesthesia, continuous and noninvasive monitoring would be favorable. Most parameters daily used in anesthesia are only proxies for end organ function. The brain is perhaps the most vulnerable, but also the least monitored organ. Due

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KEY POINTS

- Noninvasive continuous blood pressure measurements are available for children, and show good agreement, however with some underestimation of SBP.
- For noninvasive measurement of CO in children, bioimpedance techniques seem promising, although further refinement in accuracy during anesthesia is needed.
- Near-infrared spectroscopy is at present the best available monitor to measure regional tissue-oxygenation and tissue-perfusion.
- Transcutaneous measurement of carbon dioxide is complementary to blood sampling and capnography.

to the development of encephalopathy in (ex)preterm neonates requiring multiple surgeries, pediatric anesthesiologists are especially interested in brain perfusion [2]. We know that a short anesthetic in healthy children is harmless, but if this is still the case in high-risk neonates and infants undergoing multiple procedures remains unknown [3[■]]. It is unclear what exactly happens within the brain during anesthesia, due to changes in fluid status, cerebral perfusion pressure, CO₂ pressure and unknown local factors.

The current review focuses on recent developments and current evidence on noninvasive monitoring in noncardiac pediatric anesthesia. We will concentrate on cardiac output (CO), near-infrared spectroscopy (NIRS) and transcutaneous blood gas analysis as monitors that may guide our interventions to optimize end organ function of our patients.

HEMODYNAMIC MONITORING

Blood pressure (BP) measured noninvasively with the oscillometry technique (NIBP) has a good correlation with intra-arterial BP (IABP), also in infants and neonates [4]. However, changing the site of measurement from the arm to another location may provide less reliable information. Large deviations are common when NIBP is measured from the leg or forearm in children under anesthesia, compared with arm NIBP. Leg NIBPs are usually lower than arm measurements in children, in contrast to higher leg NIBPs in adults. In children the soft, compliant pediatric arteries produce less augmentation of the signal than stiffer adult arteries. Also a reduced sympathetic tone and a relatively reduced blood volume in the lower limbs of small children may play a role [5[■],6–8].

Continuous noninvasive BP can be measured with a finger cuff, measuring noninvasive finger arterial pressure (FINAP) by clamping the finger artery to a

constant volume and varying the counter pressure [9,10]. With the Nexfin monitor (Table 1), FINAP is reconstructed into a brachial arterial pulse pressure waveform. In children, the FINAP was reliable, with a good level of agreement for DBP and mean arterial pressure between the Nexfin and IABP. However, underestimation of Nexfin SBP was observed [11,12].

The CNAP monitor (Table 1) provides beat-to-beat noninvasive pressure readings. In pediatric patients, the continuous BP readings were clinically useful. However, there is some variation in accuracy, especially with SBPs. Cuff placement was sometimes problematic, so further development in finger cuffs for children is necessary [14,15].

CARDIAC OUTPUT MEASUREMENTS

CO is the product of cardiac stroke volume (SV) and heart rate (HR). CO is measured by transpulmonary dilution techniques, requiring central venous catheterization [16,17]. Bolus thermodilution is still the most accepted reference method [18]. Less invasive techniques have become available, such as pulse contour cardiac output analysis, arterial pressure curve-based CO measurements, transesophageal Doppler (TED) and partial rebreathing of CO₂. Transthoracic echocardiography or ultrasonic monitors are noninvasive, but noncontinuous measures [16,17,19–21].

Pulse contour analysis (PCA) of IABP waveforms can estimate CO continuously [17]. PCA can be measured noninvasively with devices such as the Nexfin monitor or Mobil-O-Graph (Table 1). Pediatric studies using this method are limited. The PCA-derived CO values of the Mobil-O-Graph were measured in awake adults and children at least 10 years of age, and showed to be comparable with two-dimensional echocardiography CO values; however, the values were not interchangeable [22[■]]. At low CO values, PCA-derived data were higher than data from echocardiography. This type of CO measurement needs further refining in accuracy and precision, before it can be used in pediatric anesthesia.

Another technique of measuring CO continuously is based on the bioimpedance method. Bioimpedance cardiography measures changes in thoracic electrical bioimpedance during the cardiac cycle via electrodes on the skin, from which SV, and subsequently CO can be calculated [23]. Several devices are on the market measuring bioimpedance, electrical velocimetry or bioreactance (Table 1).

Electrical velocimetry relates the maximum rate of change of impedance to peak aortic blood acceleration during the cardiac cycle. The change in orientation of the red blood cells in the aorta, from random during diastole (high-impedance state) to an aligned or parallel orientation during systole

Table 1. Devices for noninvasive hemodynamic measurements

Measurement of	Device name (manufacturer)	Technology	Use in pediatric patients (literature)	Method
Cardiac output	Mobil-O-Graph (I.E.M. GmbH, Stolberg, Germany)	PCA	Zocalo <i>et al.</i> [22 [■]] Only investigated in children of 10 years and older	Oscillometric cuff placed around the arm, measures peripheral BP, determines central BP waveform and quantifies several parameters including CO
Cardiac output	ICON (Cardiotronic/Osypka Medical, Inc, La Jolla, California, USA)	Thoracic bioimpedance/ Electrical cardiometry	King <i>et al.</i> [28] Coté <i>et al.</i> [24] Observational studies in children 1 day to 19 years old	In neonates and small infants: 4 EKG electrodes placed on the left leg, left chest, left neck and forehead or cheek. Older patients: 2 EKG electrodes on the left chest and 2 on the left side of the neck
Cardiac output	Aesculon (Osypka Medical GmbH, Berlin, Germany)	Thoracic bioimpedance/ Electrical velocimetry	Absolute CO values in children not reliable (Tomaske <i>et al.</i> [25])	2 EKG electrodes on the left chest and 2 on the left side of the neck
Cardiac output	NICOM (Cheetah Medical, Wilmington, Delaware, USA)	Transthoracic bioimpedance	Not feasible in children <10 kg (Dubost <i>et al.</i> [31]; Sun <i>et al.</i> [30])	A current injecting device (high frequency, 75 kHz alternating current) and 4 dual sensing electrodes, placed on the thorax
Cardiac output	IQ, model 101 (Noninvasive Medical Technologies LLC, Auburn Hills, Michigan, USA)	Thoracic bioimpedance	Martin <i>et al.</i> [13]	Prewired hydrogen electrodes on the skin, and 3 EKG electrodes on the precordium and each shoulder. A 100 kHz, 4 mA alternating current is passed through the thorax by the outer pairs of electrodes and the voltage is sensed by the inner pairs
Cardiac output	USCOM (USCOM Ltd, Sydney, New South Wales, Australia)	Doppler ultrasound, transthoracic	Intermittent measurement. Reliable measurement in children, when operated by trained user (Dhanani <i>et al.</i> [21]; Cattermole <i>et al.</i> [20])	Transducer/probe placed on the chest in suprasternal position
Cardiac output	NICO (Novamatrix Medical Systems Inc, Wallingford, Connecticut, USA)	Partial rebreathing of CO ₂ , determines CO via the Fick principle	Less accurate in patients ventilated with <300 ml tidal volume (Levy <i>et al.</i> [19])	Via an ETT without leak
Continuous BP	Nexfin HD monitor (BMEYE, Amsterdam, the Netherlands)	FINAP; finger volume clamp method	Accurate for continuous measurement of MAP in children, but sometimes difficult placement of finger cuff in small children (Lemson <i>et al.</i> [12]; Garnier <i>et al.</i> [11])	Finger cuff with infrared photoplethysmography. Built-in physiological calibration method (Physiocal; BMEYE) to check and adjust the set point of the clamped artery every 80 heartbeats. Also measures CO with PCA
Continuous BP	CNAP monitor 500 (CNSystems Medizintechnik, Graz, Austria)	CNAP values represent the arterial pressure at the brachial artery	Studies in children ≥20 kg. Sometimes difficult placement of finger cuff (Tobias <i>et al.</i> [15]; Kako <i>et al.</i> [14])	Cuff around 2 adjacent fingers on the same side as an arm cuff; calibration with upper-arm oscillometric measurements

BP, blood pressure; CO, cardiac output; ETT, endotracheal tube; FINAP, finger arterial pressure; MAP, mean arterial pressure; PCA, pulse contour analysis.

(low-impedance state), causes changes in electrical conductivity and electrical impedance [24]. In pediatric patients studies showed agreement, but not consistently [25–27]. Observational studies with the ICON monitor in 402 children, ranging from preterm neonates to teenagers, showed that continuous cardiovascular parameter assessment was feasible during anesthesia for patients of all sizes and that it provided useful, real-time information regarding adverse hemodynamic changes and the response to interventions [24,28].

Bioreactance is the analysis of the variation in the frequency spectra of a delivered oscillating current that occurs when the current traverses the thoracic cavity. It is less susceptible to interference than bioimpedance [17,29]. NICOM CO values showed a good correlation and agreement with echocardiography during anesthesia in pediatric patients with normal heart anatomy, but no agreement in pediatric patients with a cardiac defect [30]. In children undergoing major abdominal surgery, the NICOM showed poor correlation between confidence interval values obtained by bioreactance and TED [31].

A meta-analysis of CO monitoring devices in adults found that no noninvasive device or technology was interchangeable with bolus thermodilution; the percentage of error was 42% for bioimpedance and 45% for noninvasive PCA, where a maximum of 30% percentage of error is considered acceptable [32]. Still, the noninvasive CO monitors could be interesting bedside monitors, as the percentage of error was similar to that of minimally invasive CO monitors, such as FloTrac (Edward Lifesciences Corp., Irvine, California, USA).

NEAR-INFRARED SPECTROSCOPY

Almost 30 years after the introduction of the first commercially available NIRS monitor the value of NIRS and its applicability in pediatric anesthesia are still a matter of debate.

NIRS is still misunderstood while a short introduction to its technical background would help to use it in the best interest of patients at risk of inadequate tissue oxygenation [33,34,35]. NIRS provides blood flow independent real time information regarding regional tissue oxygenation ($r\text{-SO}_2$), and the oxygen uptake/consumption balance. It should not be confused with pulse oximetry.

Cerebral NIRS monitoring has become a standard monitoring tool in many pediatric cardiac centers and neonatal ICUs. In noncardiac pediatric anesthesia, however, NIRS has not yet become part of the standard monitoring equipment, and the price of the disposables certainly requires careful patient selection.

Despite significant scientific efforts during the last two decades aiming at the definition of normal ranges [36,37] and lower safety margins [38–41] of cerebral $r\text{-SO}_2$ in children, consensus regarding these important targets has not yet been reached. Many pediatric anesthesiologists have adopted common adult patient intervention limits like baseline $r\text{-SO}_2 - 20\%$ or an absolute value less than 55% [35]. Gómez-Pesquera *et al.* [42] recently demonstrated the association of a decrease in cerebral $r\text{-SO}_2$ of less than 20% and negative behavioral changes on postoperative day 7 in noncardiac pediatric patients.

Kamata *et al.* [43] reported a decrease in cerebral $r\text{-SO}_2$ values during laparoscopic surgery in children, not reaching awake baseline levels, while hemodynamic and respiratory parameters remained unchanged. Costerus *et al.* [44] reported decreases in cerebral $r\text{-SO}_2$ ($\leq 10\%$ from baseline) during neonatal thoracoscopic surgery and favorable neurodevelopmental outcome within 24 months despite severe intraoperative acidosis.

Two recent studies conducted in infants found no evidence of an effect of awake caudal [45] and spinal [46] anesthesia on cerebral $r\text{-SO}_2$.

RECENT DEVELOPMENTS IN NEAR-INFRARED SPECTROSCOPY MONITORING

The list of new applications of NIRS monitoring in pediatric anesthesia is continuously growing.

Combined cerebral and peripheral (muscle) NIRS monitoring is a new trend, with some initial evidence of its capability to detect early stage centralization [47].

The calculation of fractional regional tissue oxygen extraction [$\text{FTOE} = (\text{SaO}_2 - r\text{SO}_2)/\text{SaO}_2$] [48], a composite parameter reflecting the regional oxygen delivery/consumption balance is also becoming increasingly used.

Jildenstål *et al.* [49] found an acceptable level of agreement between frontal and occipital recordings of cerebral $r\text{SO}_2$, introducing the possibility to apply NIRS during surgical procedures where the forehead is not available for sensor placement.

Neunhoffer *et al.* [50] found a positive effect of red blood cell transfusion on FTOE and cerebral $r\text{-SO}_2$ in postsurgical infants, suggesting the feasibility of both parameters as transfusion triggers.

Smarius *et al.* [51] observed a significant reduction in cerebral $r\text{-SO}_2$ induced by hyperextension of the neck during positioning for cleft palate repair surgery in children.

Lang *et al.* [52] found initial evidence of additional value of perioperative cerebral NIRS monitoring as a measure of intracranial pressure in symptomatic pediatric hydrocephalus patients.

NEAR-INFRARED SPECTROSCOPY DIRECTED HEMODYNAMIC MANAGEMENT

We recently developed a hemodynamic management algorithm using cerebral $r\text{-SO}_2$ as the single target parameter, using BP, PaCO_2 , HR and SaO_2 as major contributing parameters [34[■]]. A preinduction awake baseline $r\text{-SO}_2$ is defined as the lowest acceptable value during the anesthetic. Our experience from several hundred patients has confirmed the feasibility of this approach.

TRANSCUTANEOUS BLOOD GAS ANALYSIS

The principles of transcutaneous blood gas analysis have already been described in the late fifties by Clark and Stow-Severinghaus [53,54]. Although continuous and noninvasive, it was prone to errors compared with simpler techniques such as pulse oximetry. As the introduction of user-friendly transcutaneous sensors, their use is increasing. Especially, measurement of CO_2 is reliable. This is particularly important due to the increase of video-assisted procedures. Insufflation of CO_2 could lead to an increase in arterial CO_2 , which is a highly vasoactive substance. This is especially the case in neonates, whose brains are very sensitive for changes in CO_2 [55]. However, arterial blood gas analysis, despite the risks of invasive arterial lines, and capnography remain the gold standard. Transcutaneous CO_2 measurement could also be useful during endoscopic airway procedures or in spontaneously breathing children without a definitive airway during procedural sedation. Therefore, further developments on the use of continuous and noninvasive measurements would be favorable.

TECHNIQUE

Transcutaneous sensors locally heat the skin improving diffusion of oxygen and CO_2 through the skin [56]. This results in a close approximation of arterial values, although accuracy on oxygen measurements is restricted due to limited diffusion capacity and due to increasing skin thickness with age [57[■],58]. It is mostly used on neonatal and pediatric ICUs. However, its use in the pediatric operation theatre is limited and concerns still remain on the accuracy of measured oxygen values and its usability. Membranes of the device must be switched carefully and calibration has to be taken into account afterwards. Furthermore, a short equilibration time of 10 min after skin attachment is necessary, before measurements can be interpreted safely. Nevertheless, due to improvements in sensor application [57[■]], its use perioperatively has increased. During an operation, changes in

hemodynamics or fluid status and anesthetic agents as well as vasoactive medication could have effect on transcutaneous measurements by influencing the microcirculation, so doubts remain about the perioperative validity of measurements.

RECENT FINDINGS

Only few studies have been published on this subject. Nosovitch *et al.* [59] performed the first perioperative study in children in 2002. They concluded that of noninvasive measurements of CO_2 , transcutaneous values were slightly more accurate than end-tidal measurements. Dullenkopf *et al.* [60] compared end-tidal and transcutaneous measurements of CO_2 in 60 children under general anesthesia and found no significant difference in accuracy between the two methods. Karlsson *et al.* [61] concluded on a relatively small group of neonates under general anesthesia that measurements were technically possible but not yet accurate.

Recently, Chandrakantan *et al.* [62[■]] compared end-tidal and transcutaneous CO_2 to venous blood gas values in children under 10 kg and showed that transcutaneous measured CO_2 has good correlation to venous values which are slightly better than standard end-tidal CO_2 . May *et al.* [63[■]] reported similar results comparing single CO_2 values simultaneously obtained during arterial, venous, transcutaneous and end-tidal analysis in 47 children (mean age 13.4 ± 7.8 years old) with cystic fibrosis during anesthesia. Transcutaneous monitoring was more accurate and closer to PaCO_2 than capnography.

DISCUSSION

The ultimate monitor should be easy to set up and should provide the pediatric anesthesiologist of continuous, noninvasive, accurate, reproducible and real-time measurements. Ideally, this would display end organ function.

So far, this monitor has not yet been available.

Some techniques, however, seem very promising. Regarding BP measurements and CO monitoring improvements are being made with regard to availability and accuracy in children. Further development of finger cuffs for smaller children is necessary. Although the bioimpedance technique seems very promising, drawbacks are that in young children the electrodes may be difficult to place, electrocautery induces loss of data, and arrhythmia or pleural effusion may limit its use [24,29,31]. Most importantly, more research needs to be conducted on the accuracy of the absolute CO values of these devices before it can be applied routinely during anesthesia in pediatric patients.

NIRS is not the holy grail, but it is the best currently available to continuously and noninvasively measure regional tissue-oxygenation and tissue-perfusion. Using the r-SO₂ as the single outcome parameter in hemodynamic monitoring requires a paradigm shift in pediatric anesthesia toward tissue oxygenation, away from BP. Additional muscle NIRS monitoring may become the ultimate addition to ensure adequate oxygenation of all tissues.

Transcutaneous measurements are complementary to, and not a replacement of other modalities. It is, however, a great advantage that noninvasively and continuously measurements are now available. But the gold standard for assessment of gas exchange remains blood gas analysis, and for correct tube placement capnography. In the near future more studies are required confirming validity in children under anesthesia and in areas where these measurements can contribute to safety such as laryngeal surgery, video-assisted procedures and procedural sedation.

CONCLUSION

Small steps are being made to improve the monitoring modalities in pediatric anesthesiology as new techniques are available to assess a child's hemodynamic and respiratory status while anesthetized. As perioperative safety is high nowadays, we face the challenge to take these small steps and use these new monitors as complementary tools together with standard monitoring in benefit of the most vulnerable patients.

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Conflicts of interest

There are no conflicts of interest.

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