Review of splanchnic oximetry in clinical medicine

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Abstract. Global tissue perfusion and oxygenation are important indicators of physiologic function in humans. The monitoring of splanchnic oximetry through the use of near-infrared spectroscopy (NIRS) is an emerging method used to assess tissue oxygenation status. Splanchnic tissue oxygenation (SrSO$_2$) is thought to be potentially of high value in critically ill patients because gastrointestinal organs can often be the first to suffer ischemic injury. During conditions of hypovolemia, cardiac dysfunction, or decreased oxygen-carrying capacity, blood flow is diverted toward vital organs, such as the brain and the heart at the expense of the splanchnic circulation. While monitoring SrSO$_2$ has great potential benefit, there are limitations to the technology and techniques. SrSO$_2$ has been found to have a relatively high degree of variability that can potentially make it difficult to interpret. In addition, because splanchnic organs only lie near the skin surface in children and infants, and energy from currently available sensors only penetrates a few centimeters deep, it can be difficult to use clinically in a noninvasive manner in adults. Research thus far is showing that splanchnic oximetry holds great promise in the ability to monitor patient oxygenation status and detect disease states in humans, especially in pediatric populations.

Keywords: splanchnic oximetry; near-infrared spectroscopy; regional tissue oxygenation; gut perfusion.

Paper 160072SSR received Feb. 3, 2016; accepted for publication Apr. 13, 2016; published online May 10, 2016.

1 Introduction

The Information Age is rapidly progressing, with more data becoming available to everyone at an ever-increasing pace. How one interprets available information and how one reacts to it can be a challenge. More data can potentially be very helpful in decisions that are made, but careful analysis and interpretation is required in order to react properly. This same principle holds true today in modern medicine. Physicians are continuously searching for the ability to gain more quantifiable information about the patients they care for, and this is particularly true in hospital settings where clinical status can change rapidly. New techniques are being employed to help determine global tissue perfusion in order to assess physiologic function, and ultimately lead to better outcomes. Monitoring splanchnic oximetry through the use of near-infrared spectroscopy (NIRS) represents one such method.

Tissue ischemia and hypoxia-oxygenation can be major contributing factors to patient morbidity and mortality. Devices utilizing NIRS have the capability to measure the amount of oxygenated hemoglobin (oxy-Hgb) and deoxygenated hemoglobin (deoxy-Hgb) in human organs and determine regional tissue oxygenation (rSO$_2$). These rSO$_2$ values can then be interpreted to provide information about tissue perfusion, oxygenation, and metabolic status both globally and specifically within particular anatomical systems. NIRS can safely and noninvasively be used to continuously or periodically check patient oxygenation status and provides insight into the delicate balance between oxygen supply and demand that the body requires to function normally. These devices can be used in surgical, emergency, and inpatient settings and on a variety of patients requiring close monitoring. There are also multiple anatomical sites where NIRS sensors can be placed. Although placement of sensors on the front of the skull over the brain to measure cerebral tissue oxygenation (CrSO$_2$) has been the site both most studied and used in clinical practice, alternative monitoring locations are becoming increasingly investigated and utilized. The reason for this is that while it is important to maintain proper tissue oxygenation in the brain to prevent neurologic injury, monitoring other organs either singularly or in conjunction and in relation to CrSO$_2$ is proving effective in providing additional information useful to clinicians.

Splanchnic tissue oxygenation (SrSO$_2$) is thought to be potentially of high value in the monitoring of critically ill patients because gastrointestinal organs are often the first to suffer ischemic injury. It has long been recognized that during low cardiac output states, splanchnic vasoconstriction can be an early physiologic response. During conditions of hypovolemia, cardiac dysfunction, and decreased oxygen carrying capacity, blood flow is diverted toward vital organs, such as the brain and the heart at the expense of abdominal organs and peripheral muscle tissue. Classical bedside training of medical students includes teaching that the gut is considered the “canary in the coal mine.” Circulatory compromise in the splanchnic region is frequently the first step on the way to systemic circulatory collapse or multisystem end organ dysfunction that can ultimately lead to mortality. Even when other parameters such as heart rate, blood pressure, and pulse oximetry are within normal limits, splanchnic tissue oxygenation can already be severely affected, thus making SrSO$_2$ a form of early detection. Other modalities have tried to take advantage of this phenomenon, including gastric tonometry and Doppler ultrasound, but none of these techniques have yet proven to be clinically effective, and none are as feasible, operator independent, continuous in...
capability, or helpful in measuring microcirculation of gastrointestinal organs as measuring \( \text{SrSO}_2 \) with NIRS.\textsuperscript{17,18} In addition to overall patient assessment, there are also gastrointestinal organ-specific disease processes that \( \text{SrSO}_2 \) can be used to potentially detect or even diagnose.

The aim of this review is to describe the basic principles of splanchnic oximetry, demonstrate how \( \text{SrSO}_2 \) has been studied, and examine its use in clinical medicine. Implementation of NIRS into medical practice, and in particular abdominal NIRS, is an emerging area. This paper will show how \( \text{SrSO}_2 \) may provide more than just additional data for physicians and nurses to have to deal with, but rather, truly helpful information that can further fine-tune management of critically ill patients.

### 2 Background on the Use of Oximetry in Clinical Settings

Infrared radiation was discovered at the beginning of the 19th century by Sir William Herschel, who noticed a type of invisible radiation lying in a spectrum lower in energy than that of red light because of its effect upon a thermometer.\textsuperscript{19} More than a 100 years later in the 1940s, Dr. Glenn Millikan invented the first practical pulse oximeter utilizing this NIR light that could be used at the bedside to measure changes in oxygen saturation.\textsuperscript{9}

The big breakthrough in the use of NIRS in medicine to measure not just arterial oxygen saturation, but complete tissue oxygenation, came 30 years later when Dr. Frans Jobsis reported his landmark paper in “Science” demonstrating that organs, such as the brain, can be readily accessible to light energy with minimal interference from overlying tissue, and that NIRS can measure the degree of oxy-Hgb and deoxy-Hgb in such tissue.\textsuperscript{20} Soon after, in 1985, another pioneer in the field of medical NIRS, Dr. Marco Ferrari, published studies showing that NIRS could effectively be used to measure cerebral oxygenation in human adults.\textsuperscript{21} That same year, Dr. Jane Brazy published her work in “Pediatrics,” demonstrating the ability of NIRS to also measure brain oxygenation in the smallest of human patients, preterm infants.\textsuperscript{22}

Since then, there has been a multitude of human research studies conducted and a plethora of case reports demonstrating the clinical utility of NIRS in medical settings. However, to date, there have not been the large randomized control trials required to fully evaluate the impact that monitoring tissue oxygenation has on improving outcomes in either adults or children.\textsuperscript{23} However, because there is little risk involved when monitoring \( \text{rSO}_2 \) with NIRS, it has been determined that class II, level B evidence supports its use as a likely effective and beneficial hemodynamic monitor for the care of patients at risk of critical conditions.\textsuperscript{7} This has led to the growing and now widespread use of NIRS by anesthesiologists, surgeons, and critical care physicians working in a variety of settings. In fact, recent studies have reported routine use of NIRS technology by certain types of specialized critical care units to be between 70% and 90%.\textsuperscript{24,25}

Many tout NIRS technology for its ability to noninvasively provide crucial information on a tissue level that previously could only be obtained with invasive techniques, such as measuring mixed venous oxygen saturation (\( \text{SvO}_2 \)) through the use of inline catheters.\textsuperscript{26} This property of NIRS is especially useful in patients that may not have access to these critical care techniques or in patients where this type of monitoring is not feasible because of patient size, such as in infants and preterm neonates. As more manufacturers begin making NIRS devices and the technology becomes more affordable and accessible, its presence in hospitals will likely only continue to expand.

### 3 Basis for the Use of Near-Infrared Spectroscopy in Medicine

Monitoring tissue oxygenation in patients with NIRS is based on three principles: (1) biological tissue is relatively transparent to NIR light,\textsuperscript{27} (2) oxy-Hgb and deoxy-Hgb are the primary chromophores that significantly absorb light in the NIRM spectrum,\textsuperscript{28} and (3) oxy-Hgb and deoxy-Hgb have specific absorption properties that make them distinguishable\textsuperscript{29} (see Fig. 1). By utilizing these principles, and then applying a form of the Beer–Lambert Law, amounts of oxy-Hgb and deoxy-Hgb can be determined.\textsuperscript{11} NIRS probes transmit light ~2 cm beneath the skin surface.\textsuperscript{30} The two main types of NIRS devices used clinically either are saturation monitors [i.e., INVOS 5100 (Covidien, Mansfield, Massachusetts)] or concentration monitors [i.e., NIRO 500 (Hamamatsu Photonics, Shizuoka, Japan)].\textsuperscript{31} While the saturation monitor type is most commonly used, similar \( \text{rSO}_2 \) values are obtained when the devices have been compared.\textsuperscript{32,33} and most believe that commercial NIRS devices are highly correlated.\textsuperscript{10} NIRS can also determine some information about other chromophores, including cytochrome aa3. However, this review focuses only on its ability to measure the difference between Hgb in an oxygenated state and a deoxygenated state, reported as \( \text{rSO}_2 \).\textsuperscript{15}

Clinicians think of \( \text{rSO}_2 \) as representing the balance of oxygen that is delivered minus what is extracted at the tissue level because blood in the microcirculation that NIRS measures is heavily venous weighted.\textsuperscript{36} A majority of the circulation being monitored by NIRS comes from venules (70%), while arterioles (20%), and capillaries (10%) make up the remaining components.\textsuperscript{37} Thus, \( \text{rSO}_2 \) can act as a proxy for \( \text{SvO}_2 \) and provide a good indication of oxygen balance.\textsuperscript{25}

Measuring \( \text{rSO}_2 \) can be complimentary to monitoring pulse oxygen saturation (\( \text{SpO}_2 \)). Fractional tissue oxygen extraction is a measurement of the amount of oxygen extracted by tissue. It is calculated with the following formula: \[
\text{Fractional tissue oxygen extraction} = \left( \frac{[\text{SpO}_2 - \text{rSO}_2]}{\text{SpO}_2} \right) \times 100%
\]

![Fig. 1 Absorption properties of chromophores in the NIR energy spectrum.](image-url)
4 Anatomical Sites Monitored with Near-Infrared Spectroscopy

There are multiple anatomical sites that NIRS sensors can be placed in humans to measure rSO₂. NIRS devices have the capability to monitor and display multiple rSO₂ values simultaneously (see Fig. 2). The location that has been vastly more studied and utilized since the inception of clinically capable NIRS is the forehead. The brain is not only a most crucial organ but also it lacks fuel stores and, therefore, requires a continuous supply of oxygen and glucose. Continuous cerebral blood flow, cerebral oxygen tension and delivery, and mitochondrial activity are critically important to maintain normal brain function and tissue viability. Any change of condition leading to hypoxemia can quickly lead to brain damage, and it is why monitoring CrSO₂ during times of critical illness or during surgical procedures can be important.

While the brain was the site first studied, not long after, NIRS began to be utilized to research muscle metabolism. Many muscle systems are located just underneath the skin. NIRS can be used to understand muscle oxygenation during normal health at rest, during various degrees of exercise, and during pathologic states. It has been utilized by sports medicine physicians, but also by critical care physicians. This is because blood flow can be diverted away from peripheral muscle tissue during times of decreased oxygen delivery, as in the case of anemia or shock.

Of perhaps more significance to physicians caring for patients in the hospital setting is another site where NIRS has been utilized, over the flank measuring renal tissue oxygenation (RrSO₂). The kidneys receive ~20% of cardiac output and play a major role in regulating blood pressure and global tissue perfusion. The thinner the patient, the more easily accessible the kidneys are to the skin surface, and much utilization of RrSO₂ values has been performed in pediatric populations.

As an example, in some institutions, it is now part of routine protocol during cardiac surgeries to monitor RrSO₂. Physicians have found renal oximetry to be helpful in diagnosing low cardiac output conditions that may not be picked up by monitoring CrSO₂ alone, because of the strong autoregulatory mechanisms of the cerebral circulation. In our own experience, we have found RrSO₂ to be easily measured in term infants and able to demonstrate shifts in somatic blood flow that occur during the transition from intrauterine to extraterine life, as hemodynamics changes take place over the first few days after birth.

Splanchnic oximetry is now gaining much increased interest. One of the main reasons is that because of the nature of the splanchnic circulatory system, ischemic injury to abdominal organs, such as the gut or liver, may take place in patients that would appear otherwise stable whether by physical examination or commonly used clinical monitoring tools. The remainder of this article will review the benefits of SrSO₂ monitoring, its limitations, and potential uses in clinical care.

5 Interest in Splanchnic Oximetry

The primary interest of clinicians in measuring SrSO₂ is due to the well-known phenomenon that splanchnic circulation vasoconstriction can occur during any time of metabolic or circulatory stress. This self-preserving mechanism has evolved as an attempt to maintain both coronary artery blood flow and cerebral blood flow at the expense of less vital organs that do not rely on constant oxygen delivery. Therefore, it is felt that SrSO₂ monitoring devices can serve as an early alert system of future complications. If declines in splanchnic oxygenation values occur, this may mean that further circulatory compromise is imminent, despite vital signs that could suggest stability. For example, Price et al. demonstrated in healthy adult humans that simply a 15% reduction in total circulating blood volume resulted in an estimated forty percent reduction in blood volume of the splanchnic circulatory system despite having no discernable effect on heart rate or blood pressure measurements.

This notion is applicable to many different conditions that can affect patients, including, but not limited to, sepsis, hemorrhage, allergic reactions, and anemia. All of these conditions have the same common pathway: they all ultimately lead to a shock-like state, with subsequent decreased perfusion and oxygen delivery. In these cases, it is the abdominal organs that often take the “first hit,” especially in the microcirculation of the gastrointestinal tract. One can, therefore, see that there are many potential applications for monitoring SrSO₂ to track patient condition or progress through different procedures or disease states.

Regional tissue oxygen saturation, including SrSO₂, can be measured as a value by itself or in conjunction with other rSO₂ values (see Fig. 3). Both methods have been shown to demonstrate potential merit. However, even with more established NIRS monitoring modalities, such as CrSO₂, experts still caution about interpreting any absolute values, and most often recommend following trends in patients from their baseline rSO₂ values when making medical decisions. Therefore, it is important to take into context any splanchnic oximetry measurement in and of itself. However, we suggest that if one takes two trends, for example, SrSO₂ and CrSO₂, and compares them with each other in an individual patient, it may be more than just a trend; it could quite possibly tell you “absolutely” about what is happening clinically to that particular patient.

Splanchnic oximetry differs from CrSO₂ or RrSO₂ in that it can be obtained from more than one organ, depending on the
6 Limitations of Splanchnic Oximetry

While monitoring tissue oxygenation status in splanchnic organs has several potential benefits, there are certainly limitations to this technology and these techniques at present. One of the most prominent is that there is a much greater degree of intrapatient signal variability in SrSO2 than with other oximetry values. This was well studied in a neonatal population by Mintzer et al., who found by measuring coefficients of variation for different NIRS values that there can be a multifold increase in the degree of variability seen in SrSO2, as compared with CrSO2 and RrSO2. They discuss how this may result either from real-time changes in blood flow to the splanchnic tissue beds or from momentary alterations in splanchnic organ oxygen consumption. Of particular importance, these researchers concluded that this increased variability in SrSO2 at baseline makes it more difficult to determine when SrSO2 has significantly changed in a monitored patient that would signify some clinical concern. We have seen this in our research and own clinical practice as well.

However, Mintzer et al. describe methods that can be used by clinicians to overcome the SrSO2 variability issue. First, they recommend utilizing relatively short (5 to 15 min) epoch periods as a preferred data averaging interval for SrSO2 measurements when establishing clinical trend monitoring. Second, they recommend that clinicians evaluate SrSO2 over longer periods of time, while using these brief data sampling epochs, than they would with CrSO2 values when making medical decisions based on NIRS monitoring.

In addition to an increased variability in signal, the literature reports that there also can be more momentary losses of NIRS signal when measuring SrSO2 and longer segments of very low readings as compared to other RsO2 values. This information needs to be taken into account before using NIRS as part of clinical decision-making processes. It emphasizes that SrSO2, at this point, should likely not be used solely, but rather only in context with other physiologic measurements, as well as the probable need to monitor SrSO2 over relatively longer periods of time than with other parameters, such as CrSO2, to make an effective assessment.

Another limitation of splanchnic oximetry is that it can often be hard to determine the exact tissue that one is monitoring with splanchnic NIRS. The intestine is not a fixed organ, and movement can occur. It is also important that the NIRS sensor be placed in a position above where the bladder could interfere with the SrSO2 signal in cases of urinary retention. In addition, abdominal wall thickness can begin to exceed the penetration depth of currently used commercially available NIRS sensors based on patient age, weight, and percentage of body fat. At a certain point, NIRS sensors may not have the capability to actually measure SrSO2. Balaguru et al. found that in most patients, this point occurs around 6 years of age or 30 kg in weight. Essentially, the intestines may be located too deep beneath the surface of the skin in most adult patients for splanchnic oximetry to be of clinical value and is a likely reason why a majority of research and medical usage has been in pediatrics.

There is also concern about the tissue itself that is being monitored. Many speculate that because the intestine is a hollow organ that can be filled with air, fluid, or solids with changing gas fluid surfaces, that SrSO2 values may be too unreliable. Peristalsis occurs and stool that contains biliverdin and bilirubin can move under the NIRS sensor. However, the spectral...
absorption capability of biliverdin and bilirubin is below that which most NIRS devices use.11 The liver is more homogeneous in nature and may not present as many issues in this regard. But that points out another limitation of splanchnic NIRS: that splanchnic oximetry has location specific characteristics. SrSO2 measurements taken over the liver versus those taken over the intestines can correlate but should not be substituted for one another.66

A final concern about splanchnic oximetry is the proprietary algorithms that are used by the various devices.34 To begin with, each manufacturer uses their own, and these slight computational differences may contribute to the interpatient variability that can be seen with SrSO2.5 However, this is also true with pulse oximetry, and this has not been seen as a major problem clinically, as pulse oximetry obtained by any device has now become a standard of care.65,66 Another potential issue with the algorithms used is that they were mostly intended to calculate cerebral oximetry and may not necessarily be ideal to measure tissue oxygenation in other organ systems. Most clinicians are using “universal sensors” that were originally designed for the brain to also monitor abdominal contents.

7 Animal Studies

As with most medical technology, studies examining the utility of splanchnic oximetry were first conducted in animal models. Research mainly has focused on hepatic injury or intestinal injury, both being conditions that represent splanchnic ischemic states.

Using a large pig model, El-Desoky et al.69 measured total hepatic blood flow and SrSO2 directly on the surface of the liver using a laparotomy technique. They demonstrated that SrSO2 measurement correlated well with either hepatic vascular inflow occlusion or reduced inspired oxygen that led to reduced PaO2 levels. This group then went on to demonstrate in a similar model that splanchnic oximetry was superior to hepatic vein oxygen partial pressure measurements in predicting splanchnic ischemia.84 Finally, they demonstrated in a rabbit model that splanchnic oximetry could not only detect hepatic ischemia but could actually help determine the severity of injury to the liver that occurred as a result of under perfusion–reperfusion injury.31

Vanderhaegen et al.72 looked at a rabbit model to demonstrate that SrSO2 measured at the skin surface, as opposed to directly on the liver, could also demonstrate splanchnic ischemia. They occluded the superior mesenteric artery, while monitoring SrSO2 and SpO2 simultaneously. The study results showed that noninvasive NIRS could detect a significant decrease in SrSO2 signifying ischemic injury to the liver and intestines despite peripherally obtained SpO2 remaining stable throughout. Animal models have also demonstrated that shock states due to endotoxin release and subsequent vascular vasodilation that occurs with sepsis can be monitored with SrSO2. Using pigs, Nahum et al.83 induced septic shock with E. coli bacteria and found that decreasing trends in SrSO2 correlate well with the degree of gastrointestinal ischemia monitored by NIRS sensors whether placed on the skin overlaying the liver or directly on the liver.

Gay et al.74 used a premature piglet model to determine if abdominally positioned NIRS sensors placed over the bowel could predict which animals would develop NEC. They found that SrSO2 readings were significantly lower soon after birth in animals that went on to develop NEC many days later. During the experiments, they also determined that splanchnic oximetry readings also correlated well with apneic episodes that occurred in these preterm piglets. Another group of researchers demonstrated that SrSO2 could also monitor for and diagnose NEC using another piglet model. In their study, Zamora et al.75 found that SrSO2 values consistently <75% predicted NEC with 97% sensitivity and 97% specificity, and that increased SrSO2 variability during initial stages of feeding was also highly predictive of NEC.

One group of researchers examined the utility of placing NIRS sensors directly in the stomach using a nasogastric tube to measure SrO2.76 Bellman et al.77 in this adult pig model demonstrated that a minimally invasive gastric splanchnic oximetry technique was capable of monitoring decreases in SrSO2 that correlated well with increasing degrees of hemorrhagic shock.

8 Pediatric Studies

There have been many fewer human studies examining splanchnic oximetry compared with other NIRS anatomical sites, but those that have been conducted have mostly been done in pediatric patients. As previously mentioned, children are ideally suited to have SrSO2 monitored, as splanchnic organs are more easily accessible to NIRS sensors with an average penetration depth of 2 cm.30 The two commercial NIRS devices primarily available, INVOS 5100 (Covidien) and NIRO 500 (Hamamatsu Photonics), have been used when conducting this splanchnic oximetry research (see Table 1). Studies vary, but most focus on a few populations: children with congenital heart disease (CHD), preterm and term infants, and children with critical illnesses being monitored in an intensive care setting.

8.1 Normal Value Studies

McNeill et al.77 studied baseline SrSO2 values in stable preterm infants during their first weeks of life using infraumbilical sensor placement. They found that baseline SrSO2 values ranged between 32% and 66% and gradually increased with gestational age. They also found that there was a high degree of SrSO2 variability as compared with CiSO2 or RsO2, but that this variability decreased over time. Cortez et al.43 confirmed these results, finding a similar range of normal SrSO2 values in a study examining splanchnic oximetry patterns of preterm infants up to day of life 14. In a study examining healthy full-term infants, Bailey et al.56 reported mean SrSO2 values of 69.9 ± 12.1% on the first day of life and 75.3 ± 12.4% on the second day. This is in line with the preterm normative studies that showed SrSO2 values increasing with gestational age.

These studies demonstrate SrO2 values, but not splanchnic-cerebral oxygenation ratio (SCOR) values that assess splanchnic perfusion and oxygenation in context with subject cerebral oximetry. Bailey et al.78 did report on SCOR values in healthy term babies taking regular feedings, and found normal SCOR to be 0.90 ± 0.16 on the first day of life, which increased to 0.97 ± 0.16 by the second day. This shows how in normal pediatric subjects, splanchnic oximetry values should be similar to cerebral oximetry values in states of standard health.

It is important to note that in all of these studies, there were some subjects who had periods of low SrSO2 values during complete clinical stability. This again emphasizes the point that when using splanchnic oximetry, trend monitoring from baseline values and observing SrSO2 over time is likely required to maximize the diagnostic capabilities of abdominal NIRS.
8.2 Universal Monitoring During Intensive Care

In an early case series demonstrating the utility of splanchnic NIRS, Petros et al. reported that episodes of apnea may have a more significant and long lasting effect on splanchnic circulation than on other organ systems in the body.

In the immediate postoperative period, Li et al. showed how SrSO\textsubscript{2} can correlate with oxygen levels measured directly from the blood as well as central blood pressure monitoring values. They concluded that SrSO\textsubscript{2} could be helpful during the intensive care required after CHD surgery, but emphasized the importance of trending SrSO\textsubscript{2} in individual patients rather than comparing to a normal range.

Mintzer et al. showed the effects of administering sodium bicarbonate on SrSO\textsubscript{2}. This is a common therapy used during intensive care. A result of their study was that sodium bicarbonate did decrease blood base deficit and increase pH but had no significant effect on splanchnic oxygenation. It, therefore, suggested the potential futility of such intervention.

Recently, Bozzetti et al. looked at SCOR values to monitor subjects who were severely growth restricted at birth. They found that splanchnic oximetry, used in conjunction with cerebral oximetry, could help determine if patients are ready for enteral feedings to begin, or if splanchnic blood flow and perfusion remains impaired. This may be very helpful for surgeons and intensivists if determining in any postoperative patient when feedings may first be attempted.

8.3 Feeding

Dave et al. have reported that SrSO\textsubscript{2} values increase after feedings in stable preterm infants tolerating bolus feedings while CrSO\textsubscript{2} values remain constant. They also examined the SCOR and showed that this too increases after feedings, all accounted for by an increase in intestinal tissue oxygenation. Dani et al. examined preterm infants during their first days of life receiving continuous feeds. These researchers did not find that SrSO\textsubscript{2} correlated with the time needed to achieve full enteral feedings. This perhaps could be because these subjects were receiving continuous feeds rather than bolus feeds. Another group studied the correlation of SrSO\textsubscript{2} with superior mesenteric after velocities in infants before and after feedings.

8.4 Necrotizing Enterocolitis

The first clinical investigators to report that splanchnic oximetry could help detect and diagnose NEC were Fortune et al. In their prospective, observational cohort study, they looked at infants with acute abdomens, who were referred for surgery and infants receiving intensive care only for medical reasons. They monitored SrSO\textsubscript{2} and CrSO\textsubscript{2}, and calculated a SCOR. They found that a SCOR of <0.75 had a sensitivity of 90% and positive predictive value of 75% to diagnose NEC and a negative predictive value of 96% to exclude it. DeWitt et al. prospectively studied infants with CHD, who had single ventricle palliation surgery and were known to be at risk for postoperative NEC. They found that patients who developed NEC had lower mean SrSO\textsubscript{2} values at baseline and more times when SrSO\textsubscript{2} intermittently dropped to very low levels. In addition to CHD, red blood cell transfusion possibly also places infants at risk for NEC. In a study of preterm infants who were either fed or not fed during transfusions, Marin et al. found that those subjects who had fed experienced significantly lower SrSO\textsubscript{2} values for at least 15 h after the transfusion completed. They speculated that this placed them at increased risk for mesenteric ischemia, which could then lead to NEC.

8.5 Transfusion

In regards to blood transfusion, splanchnic oximetry has been investigated in two ways. Researchers have sought to observe what happens to splanchnic blood flow and SrSO\textsubscript{2} as a result of a blood transfusion, and also what is occurring in terms of splanchnic oxygenation and perfusion during anemic states prior to any transfusion. The information could be clinically relevant by determining if splanchnic oximetry has utility in

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**Table 1** NIRS devices used in human splanchnic oximetry studies.

<table>
<thead>
<tr>
<th>Patient population</th>
<th>Study type</th>
<th>Study</th>
<th>Year</th>
<th>NIRS device</th>
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<td>Pediatric</td>
<td>Normal values</td>
<td>McNeill et al.</td>
<td>2011</td>
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<td>Banerjee et al.</td>
<td>2015</td>
<td>NIRO 300&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Bailey et al.</td>
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<td>Adult Resuscitation</td>
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<td>Kalkan et al.</td>
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<td>Abdominal hypertension</td>
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<td>NIU-Pro01&lt;sup&gt;c&lt;/sup&gt;</td>
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<sup>a</sup>Covidien, Mansfield, Massachusetts.
<sup>b</sup>Hamamatsu Photonics, Shizuoka, Japan.
<sup>c</sup>Urodynamix Corporation, Vancouver, British Columbia.
monitoring transfusions for complications, and perhaps more importantly, to see if splanchnic oximetry could be used as a tool to determine red blood cell transfusion need.

Bailey et al.89 looked at symptomatic anemic preterm infants and examined SrSO2 during and after the transfusion period. They found that SrSO2 increased from 41.3 ± 2.2% before the transfusion to 51.1 ± 2.8% immediately after. SrSO2 began to decline again after the transfusion was completed over the subsequent 12 h, although not to pretransfusion levels. Dani et al.90 likewise found that SrSO2 increased significantly during blood transfusion. Recently, Banerjee et al.,91 examined not only SrSO2 but also mesenteric blood flow utilizing Doppler ultrasound. This group also found an increase in SrSO2 during the transfusion period, but without a significant alteration in blood flow velocity through the splanchnic circulatory tree.

Bailey et al.90 later published another paper demonstrating the possible usefulness of splanchnic oximetry in helping to determine red blood cell transfusion needs. The study included 34 symptomatic preterm infants who were given blood transfusions, and 18 asymptomatic infants with low Hgb levels found on routine weekly laboratory sampling who were not transfused. The researchers found that baseline SCOR values were significantly lower in neonates who improved with transfusion (0.61) when compared to those without improvement (0.75) as well as those asymptomatic subjects with equally low Hgb levels (0.77). They concluded that a baseline SCOR < 0.73 had a 74% sensitivity and 73% specificity, and a positive predictive value of 78% in determining if a patient would improve after transfusion.

9 Adult Studies

There are very few studies with adult subjects examining the use of splanchnic oximetry in clinical medicine. As mentioned previously, this is almost certainly because splanchnic organs are difficult to monitor using current NIRS sensor technology that is only capable of measuring tissue oxygenation ~2 cm beneath the skin surface.92 In most adults, muscle and fat layers beneath the skin are too thick to allow consistent access to splanchnic organs. Despite this, recently, a research group did examine SrSO2 values in adult patients using NIRS sensors placed on the abdomen. Kalkan et al.93 evaluated adults who suffered cardiac arrest outside of the hospital and were brought to the emergency room. These researchers placed two abdominal NIRS sensors, one over the liver and one in the mid-abdomen over the abdomen. They were able to demonstrate strong splanchnic NIRS signals and show the potential for this technique to monitor SrSO2 during laparoscopic surgery.

10 Summary

In summary, while far from proven, this review demonstrates that monitoring splanchnic oximetry holds promise in its ability to judge physiological status and detect disease states in humans, especially in the most vulnerable population, neonates. Although there are yet to be randomized control trials proving the effectiveness of monitoring SrSO2 as part of patient care, this is also true with other tissue oximetry values and other different physiologic parameters that have been incorporated into patient care practices.

Over the last 20 years, there have been hundreds of studies examining the use of NIRS in clinical medicine. However, only a small number of these have examined splanchnic oximetry in conjunction with the more established anatomical sites. Even fewer have focused solely on splanchnic NIRS monitoring. Clearly, there is much more work in this area that needs to take place. With further research and improvements in technology, it seems quite reasonable to think that splanchnic oximetry can become a valuable tool for clinicians caring for patients.

At this time, it is unclear if splanchnic NIRS monitoring will become helpful in all patient populations. However, for smaller children and infants, splanchnic oximetry can likely provide great physiologic insight. This is especially true in children when at risk of shock or who require intensive care. SrSO2 has the capability to become a useful clinical parameter, and not just ever-increasing extra information that clinicians have to filter through when caring for patients.

Of all the somatic tissue oxygenation values that can be monitored using NIRS, splanchnic oxygenation likely has the most clinical potential, but also the most questions that remain regarding how it can become an established part of medical care methodology.

Acknowledgments

Neither author has any conflicts of interests to report. Some of our previous research described in this review had been funded in part by a research grant from Covidien. The oximeters used in our previously described research were funded by a KIDS of NYU research grant.

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