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Reflectance spectrophotometry for the assessment of mucosal perfusion in the gastrointestinal tract

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Reflectance spectrophotometry (RS) has been used to measure mucosal perfusion in the gastrointestinal tract for more than two decades. Although early devices were relatively primitive, advances in optical technology have allowed refinement of the instrumentation and a small self-contained apparatus is now available commercially. Using RS, it is possible to measure the average hemoglobin oxygen saturation of blood in the gastrointestinal mucosa. Because the majority of hemoglobin is located in capillary erythrocytes, the measured mucosal oxygen saturation is indicative of tissue capillary oxygenation and declines rapidly in response to both hypoxic and ischemic insults. As such, mucosal oxygenation is significantly different from arterial oxygen saturation, which is measured by standard pulse oximetry and is generally unchanged by local events such as vasoconstriction and arterial or venous occlusion. Work by multiple groups spanning several decades has established the utility of RS as a research tool for studying perfusion in the gastrointestinal tract. Several ongoing studies are exploring possible clinical applications of the technique.

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Physical principles

Light interacts with biologic tissues in a wide variety of processes, including refraction, absorption, and fluorescence. When light encounters a change in the refractive index, such as an interface between air and water, a portion of the light is reflected. The remainder enters the second medium at an angle (refraction). Biologic tissues are filled with structures, such as nuclei, that have a higher index of refraction than the surrounding cytoplasm. As a result, light traveling through tissue undergoes multiple scattering events. By solving Maxwell's equations of electromagnetism, it is possible to calculate the precise scattering behavior of simple model systems, such as a collection of spheres of a certain size, density, and refractive index. Gustav Mie first performed these types of calculations almost a century ago; the theory that bears his name is Mie scattering. Biologic tissue is certainly more complex than a collection of uniform scattering spheres, but Mie scattering offers a crude approximation. Using known properties of cellular structures, such as the refractive index of nuclei, it is possible to estimate nuclear size from the fine periodic variation in scattering at different wavelengths that is predicted by Mie theory [1]. This has been exploited in Barrett's esophagus, where this type of analysis was used to assess dysplasia by analyzing nuclear size [2].

In addition to undergoing scattering, light traveling through biologic tissues is absorbed by multiple molecules. Each type of molecule has a characteristic absorption spectrum; it absorbs light particles (photons) of particular wavelengths more than those of other wavelengths. Most notable of these absorbing molecules are oxygenated and deoxygenated hemoglobin, which have strikingly different absorption spectra (Fig. 1). By virtue of its abundance and strong absorption in the 520- to 600-nm wavelength range, hemoglobin accounts for the majority of absorption in gastrointestinal mucosa and this enables the accurate assessment of hemoglobin oxygenation by reflectance spectrophotometry. In other organs, such as the liver (which contains a substantial concentration of cytochromes that also

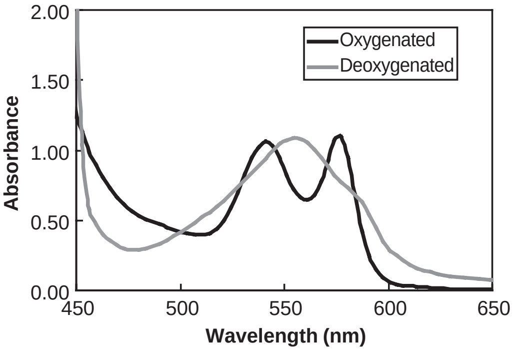

Fig. 1. Absorption spectra of oxygenated and deoxygenated hemoglobin. Published oxyhemoglobin and deoxyhemoglobin spectra can be found in [21,46].

have a strong absorption spectrum in this range), it is more difficult to measure hemoglobin oxygenation because of the competing signal from other molecules. In the gastrointestinal tract, bile and stool are highly absorbent in this wavelength region and can therefore also interfere with measurements if the mucosal surface is coated with them.

Scattering and absorption are the two optical processes that form the basis for RS. Additional optical processes, such as fluorescence and Raman scattering, also occur but are generally weaker and do not substantially affect the measurements. To perform RS, the tissue of interest is illuminated with white light and the light that returns to the detector from the tissue is analyzed quantitatively. White light is a mixture of wavelengths between approximately 390 nm and 780 nm, and the fraction of light of each wavelength that returns to the detector is measured. As the light travels through the mucosa, it undergoes multiple scattering events, and a fraction of it returns to the detector after being scattered back in the direction of the RS catheter. Along the way, hemoglobin and other molecules absorb a portion of the light. Relatively fewer light photons of frequencies that are strongly absorbed by hemoglobin therefore make it back to the detector, and this is manifested in the wavelength spectrum of light measured by the detector. In typical gastrointestinal mucosa, the average hemoglobin oxygen saturation is approximately 70% (recall that most of the blood is in capillaries) and the measured spectrum is very similar to a weighted average of 70% oxyhemoglobin and 30% deoxyhemoglobin. (see Fig. 2 for an example of a measured spectrum). Additional factors, such as the wavelength dependence of scattering, affect the spectrum. However, these can be minimized by signal processing techniques that allow for a linear or polynomial correction term when fitting the spectra (this is discussed later in the section on device development).

Although it is possible in principle to estimate the total concentration of hemoglobin in the mucosa from the absorption spectrum, there are significant theoretical and practical limitations. The absorption of light by hemoglobin is

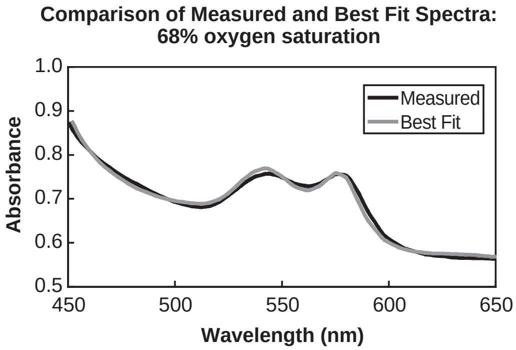

Fig. 2. A representative reflectance spectrophotometry (RS) spectrum measured in the colon is compared with a theoretical spectrum containing 68% oxyhemoglobin and 32% deoxyhemoglobin. The RS and theoretical spectra were obtained as described in [21].

proportional to both the concentration of hemoglobin and the optical path length of the light as it travels through the tissue (Beer's law). Therefore, changes in path length and hemoglobin concentration will both affect the absorption. The path length is highly dependent on the geometry of the probe: the distance between the illumination and detection fibers, the angle the probe makes with the tissue, and other factors [3]. In addition, hemoglobin concentration may differ between the various layers of the gut wall, and a concentration measurement would tend to average the regions traversed by the light. Changes in scattering by the tissue (which may occur in diseases such as ulcers, polyps, and inflammatory bowel disease in which the thickness of various parts of the mucosa may change) may result in changes in optical path length that could therefore be misinterpreted as changes in hemoglobin concentration. In situations where it may be assumed that the optical path length does not change, such as during rapid hemodynamic changes, the change in hemoglobin absorption can be measured and attributed to a change in hemoglobin concentration. The results are typically reported as an index of hemoglobin concentration [4,5]. In highly controlled situations, such as animal experiments involving acute occlusion of mesenteric arteries or veins, it is possible to reproducibly demonstrate a decrease in hemoglobin absorption after arterial occlusion and an increase in hemoglobin absorption after venous occlusion [5,6]. These results are consistent with a decrease in hemoglobin concentration in the mucosa when blood is prevented from entering after arterial occlusion and an increase in hemoglobin concentration when blood is prevented from draining out of the tissue in response to venous occlusion. However, in situations where patients with different gastrointestinal disorders are compared, the assumption that the optical path length is similar may not be valid, and changes in hemoglobin absorption are not necessarily due to changes in hemoglobin concentration.

Rather than viewing the tissue as homogeneous, with uniform scattering characteristics and a uniform hemoglobin concentration, more sophisticated reflection spectrophotometry models have been applied in certain situations. A particular example is the ocular fundus, where there are several well-defined and distinct tissue layers. The ocular fundus has been modeled as a four-layer structure of a defined thickness with various concentrations of hemoglobin, xanthophylls, and melanin [7]. The light entering and exiting each layer is estimated based on reflection and transmission coefficients, and through a series of calculations, it is possible to extract the concentrations of each pigment from the measured spectrum. For the purpose of measuring hemoglobin oxygen saturation in the gastrointestinal mucosa, however, this type of modeling has not been necessary because hemoglobin is the predominant absorber and the average hemoglobin oxygen saturation is a useful measurement of tissue perfusion.

It is also possible in theory to use time-resolved reflectance to distinguish light coming from superficial layers from that coming from deeper layers [8]. In such a system, one would distinguish between light photons that return earlier to the detector from ones that return later and have therefore had enough time to reach the deeper layers. This type of analysis is especially suitable for measurement of deep structures, such as of a muscle located beneath a layer of skin. These types of studies would typically use more deeply penetrating near-infrared light, rather than visible light. In theory, if one were interested in measuring the muscularis propria or deeper structures during endoscopy, this type of system may be necessary. Using visible light, the recovered signal in standard RS is predominantly due to hemoglobin absorption in the superficial $\sim$ 0.25 mm of tissue [9], and this provides an excellent indication of mucosal perfusion [10].

Device development and evolution

The first RS studies were performed in the early 1950s by Chance and colleagues [11,12] who measured the reflection spectra of intact mitochondria using bulky desktop devices. In the 1970s, the development of flexible optical fibers—in addition to revolutionizing the field of gastrointestinal endoscopy—offered a decisive breakthrough in RS [13,14]. Measurements of intact mucosa could be made using a light source and spectrophotometer located outside the body, with the illuminating beam and reflected beam carried to the tissue via flexible optical fibers passed through the accessory channel of the endoscope [15].

In the 1970s and 1980s, work by a number of groups demonstrated that it was possible to obtain an adequate estimate of hemoglobin oxygen saturation by measuring absorbance at a small number of wavelengths rather than by measuring a full absorption spectrum with a large number of wavelengths [16–19]. This was important historically because sophisticated signal processing equipment was bulky and prohibitively expensive. To measure absorption due to hemoglobin with only two wavelengths, the absorbance at 569 nm (where deoxy- and oxyhemoglobin absorb equally) is compared with the absorbance at 650 nm (where there is essentially no hemoglobin absorption). The difference between these two values gives the total hemoglobin absorption, which by Beer's law is proportional to the concentration of hemoglobin and the optical path length in the tissue. As expected, under experimental conditions where the optical path length is constant, the hemoglobin absorption increases linearly with the hemoglobin concentration [4]. The results are typically reported as an index of mucosal hemoglobin concentration (IHB), which is defined arbitrarily as IHB = 200 [relative absorbance at 569 nm − relative absorbance at 650 nm] [5]. Note that the relative absorbance at a given wavelength is the logarithm of the ratio of the intensity of a reference standard and the measured RS signal; this normalizes the signal to the intensity of the light source at that wavelength. To estimate hemoglobin oxygen saturation using absorbance measurements at three wavelengths, investigators typically chose two wavelengths where there is equal absorption by deoxy- and oxyhemoglobin (569 and 586 nm) and one wavelength where there is substantially more oxyhemoglobin absorption (the 577-nm peak) [5,20]. Most RS studies performed before the last few years therefore used absorption measurements at two to four wavelengths rather than a full spectrum for analysis. Current devices such as the Erlangen EMPHO I and the Spectros

Corporation T-Stat tissue oximeter analyze a full-absorption spectrum, from which values such as hemoglobin saturation are calculated [21,22].

A typical RS configuration consists of a light source, flexible fiberoptic probe, spectrophotometer, and computer. The light source emits broadband (white) light from a filament lamp, light-emitting diode, or arc lamp. The light is transmitted to the tissue using a fiberoptic probe. Several configurations of optical probes are in use: all of them have one or more illumination fibers that transmit the light to the tissue and one or more fibers that transmit the reflection signal to the spectrophotometer. The simplest probe consists of one illumination fiber and one receiving fiber. A second type commonly used consists of a central illumination fiber surrounded by six detection fibers. The fiberoptic assembly is housed in a flexible rubber or plastic tube that fits in the accessory channel of an endoscope. The illuminating light beam exits the probe and illuminates a small spot of tissue, typically 1 to 3 mm in diameter. The measurements can be performed either at a small distance away from the mucosa or by gently touching the mucosa with the probe. If the probe is pressed into the mucosa with anything more than gentle pressure, it is possible to impede blood flow to the tissue and artificially decrease the tissue oxygenation and hemoglobin content [23,24]. The measurements can be performed with the endoscope light off, which poses some challenge as the operator must maintain the probe in the desired position without the benefit of the endoscope light for visualization. Alternatively, the measurements can be performed with the endoscope light on, preferably at a low level to minimize interference with the measurement light signal [25].

After interacting with the tissue, the light is collected by the detection fiber(s) on the probe and transmitted to the spectrophotometer. A common type of spectrophotometer uses a diffraction grating to resolve the light into its constituent wavelength components and then measures the light at each wavelength using a charge-coupled device (CCD). The measured signal is sent to a computer for analysis. To measure the hemoglobin oxygen saturation, various signal analysis techniques can be used. A widely used, conceptually straightforward technique uses a mean-square error fitting algorithm that finds the optimum mix of the known reference spectra of oxygenated and deoxygenated hemoglobin that would give a combined absorption spectrum that is most similar to the measured spectrum. For example, in Fig. 2, a measured spectrum is compared with a spectrum that would be expected from a 68% to 32% mix of oxygenated and deoxygenated hemoglobin. Additional accuracy can be obtained by allowing for the addition of a linear or polynomial baseline correction term that in essence corrects for a linear or nonlinear scattering term. It is also possible to extend the algorithm to allow for other absorbing molecules such as cytochromes, but because there is such an overwhelming hemoglobin signal in gastrointestinal mucosa, this is generally not necessary. If the measured signal cannot be well approximated by a mixture of oxygenated and deoxygenated hemoglobin, the computer algorithm can alert the operator that the measurement should be rejected [26]. This could happen because of, for example, a poor signal due to bile or stool in the lumen.

Technical factors

RS provides an accurate measurement of the average hemoglobin oxygen saturation in the superficial portions of the gastrointestinal mucosa. Because most of the blood in the measured region resides in mucosal capillaries, the tissue hemoglobin oxygen saturation measured by RS yields a reliable estimate of the oxygen saturation of hemoglobin in the mucosal capillaries. Conditions that cause inadequate oxygen delivery to the mucosa result in substantial decreases in hemoglobin saturation. These include arterial occlusion, venous occlusion, pharmacologic interventions that cause vasoconstriction, and systemic conditions such as sepsis. In RS, measurements are easily obtained several times per second, allowing real-time monitoring of perfusion. In this respect RS differs from intramucosal pH measurement, which assesses gastric mucosal perfusion by allowing equilibration of carbon dioxide between the mucosa and a saline filled balloon over a period of approximately 60 minutes [9].

RS does not measure blood flow, but rather provides a direct estimate of the adequacy of oxygen delivery for the needs of the mucosa. It is therefore fundamentally different from techniques such as laser Doppler, which estimates mucosal blood flow from the Doppler shift of light reflected off of moving red cells [27]. Some investigators have used RS to estimate mucosal blood flow by noting that in several animal models there are characteristic changes in RS measurements after different types of manipulations [5,6]. Arterial occlusion results in a decreased mucosal oxygen saturation and a decreased mucosal hemoglobin absorption (reported as a decrease in the IHB). Venous outflow blockage, such as by ligation of the portal vein, causes a decrease in mucosal oxygen saturation and an increase in the IHB. Increased blood flow to the mucosa results in a normal or increased mucosal saturation and an increase in the IHB. However, as noted previously, there are theoretical and practical concerns with the interpretation of hemoglobin absorption measurements, and the qualitative estimation of changes in hemoglobin concentration by RS may be inaccurate if measurements in conditions that affect scattering or the optical path length are compared. It is widely accepted that a decrease in tissue hemoglobin oxygen saturation is a direct indicator of inadequate perfusion; the argument that such a decrease is due to decreased flow assumes that the oxygen needs of the tissue have not changed substantially.

Several factors can impact the quality of RS measurements during endoscopy. The presence of bile, stool, and other optically active materials in the lumen will affect the measured spectra; their effect can be minimized by lavaging the area to be measured. The angle of approach of the probe relative to the mucosa, which should ideally be close to 90 degrees, can affect estimates of hemoglobin concentration but generally does not affect oxygen saturation measurements [3]. The endoscope light can also affect the received signal, and because most instruments are typically not calibrated to include the background light from the endoscope, consideration should be given to decreasing the intensity if not turning it off completely. In older systems that only analyzed absorption measurements at two to four light wavelengths, measurements were performed by touching the probe to the mucosa. However, anything firmer than a very gentle touch can decrease the mucosal perfusion by a pressure effect and result in a steady decrease in tissue oxygen saturation and expulsion of blood from the tissue [28]. With newer instruments that analyze a full spectrum and correct for an uneven baseline, reliable measurements can be obtained without touching the mucosa [21] or by advancing the probe blindly until an adequate signal is obtained [29]. This has the added advantage of permitting measurements to be made directly by passing RS catheters embedded in nasogastric or rectal tubes, without the need for an endoscope.

Applications of reflectance spectrophotometry

RS has been used as a tool to investigate the role of mucosal perfusion in the pathophysiology of a variety of disorders, such as peptic ulcer disease, inflammatory bowel disease, and portal hypertensive gastropathy. In other studies, RS has been used to examine the effect of various vasoactive medications, and physiologic interventions such as cardiopulmonary bypass, on mucosal perfusion. The success of RS as a monitor of perfusion in critical care settings has led to optimism regarding a possible role for the technique in monitoring gut perfusion in cardiovascular interventions and sepsis.

Applications of reflectance spectrophotometry in ulcer disease

Several of the earliest applications of RS were in studies of gastric and duodenal ulcers, both in animal models and in patients. In experimental models, maneuvers such as ligation of end arterioles supplying the mucosa results in ulceration [30], and several RS studies have documented a decrease in hemoglobin oxygen saturation after manipulations such as submucosal epinephrine injection, hypotension, and sclerosant injection [5,21,31].

In some of the earliest studies of RS, Kamada and colleagues [23] studied patients with burns and head injuries, who are prone to develop stress ulcers in the stomach. They found that patients with lower hemoglobin absorption (a decreased IHB) tended to develop stress ulcers; hemoglobin oxygen saturation was not measured in these early studies. This study was among the first to suggest that patients with decreased gastric perfusion due to vasoconstriction have a higher risk of stress ulceration. Subsequent studies have confirmed that patients in critical care settings, such as those with septic shock or undergoing cardiopulmonary bypass, often have evidence of poor gastric perfusion as evidenced by substantially decreased hemoglobin oxygen saturation in the gastric mucosa [9,29].

There have been several studies of peptic ulcer physiology using RS [24,28,32,33]. Leung and colleagues [32] demonstrated that duodenal ulcer margins had a normal average hemoglobin oxygen saturation and a higher IHB than nearby normal mucosa. This is the same pattern typically seen in experimental models of increased mucosal blood flow. In a subsequent larger study, performed by the same group of investigators in 97 patients with bleeding duodenal ulcers, the tissue oxygen saturation at the ulcer margin was compared with that of nearby normal mucosa [33]. They found that faster healing ulcers tended to have a higher saturation at the ulcer margin relative to nearby normal mucosa, while slower healing ulcers tended to have a lower saturation at the ulcer margin compared with nearby normal mucosa ($r = -0.35$ in a stepwise multilinear regression model). However, tissue oxygenation was also not one of the statistical associations in a multivariate analysis of ulcer healing time performed in the same study. In addition, there was too much scatter in the data to make RS useful in predicting the healing rate of individual patients, and it appeared that much of the correlation in this study could be attributed to a single patient with a dramatic difference in perfusion and a very prolonged healing time of 16 weeks. The authors therefore concluded that mucosal perfusion was an equivocal factor in ulcer healing rates and needed to be studied in a group that included a larger number of slowly healing ulcers.

Applications of reflectance spectrophotometry in inflammatory bowel disease

RS has also been used to investigate the status of the microcirculation in inflammatory bowel disease. Tsujii and colleagues [34] examined 32 patients with active ulcerative colitis and found a mild but statistically significant decrease in mucosal hemoglobin oxygen saturation compared with normal controls and patients with inactive ulcerative colitis. In addition, patients with active colitis had an increased IHB compared with the control groups, suggesting an element of mucosal vascular congestion. In contrast, Su et al [35] studied 13 patients with active colitis, due to ulcerative colitis or Crohn's disease and found that areas with active colitis had slight increases in both hemoglobin oxygen saturation and the IHB. The discrepancies between these two studies could perhaps, as Tsujii and colleagues suggested, be explained by different sedation practices (which could affect blood flow to the gut) or by inadvertent measurement of bloody mucosa (which would give a signal from the hemorrhaged blood on the surface that is oxygenated by the air in the lumen). In any case, the differences in tissue hemoglobin saturation between active disease and controls in both studies were small, and neither study demonstrated dramatic alterations in mucosal oxygenation. No studies have compared the colonic mucosal oxygenation in inflammatory bowel disease with ischemic colitis; this would be particularly interesting clinically because the conditions can be confused in the elderly [36]. Also, there is increasing awareness of the presence of cytomegalovirus infection in severe refractory cases of ulcerative colitis [37], and cytomegalovirus infection is known to be associated with colonic ischemia and vasculitis [38]. With RS it may be possible to assess whether certain cases of refractory inflammatory bowel disease are associated with significant mucosal ischemia.

Applications of reflectance spectrophotometry in portal hypertension

In portal hypertension gastropathy, enteropathy, and colopathy, multiple lines of evidence, including laser Doppler measurements and anatomic studies showing dilated vessels, suggest that there may be increased mucosal blood flow. RS has also been used in the context of portal hypertension to document a pattern suggestive of increased mucosal flow, albeit with somewhat mixed results when animal models and human studies are compared. In an animal model of surgically induced portal hypertension via portacaval shunt creation and inferior vena cava ligation, Leung and colleagues [32] found no significant change in either the tissue hemoglobin oxygen saturation or in the IHB. Interestingly, in this animal model of portal hypertension, mucosal blood flow in the stomach was also not changed as measured by the more traditional hydrogen gas technique. Therefore, although this animal model shares much in common with chronic portal hypertension in humans, as varices are seen in both, it is possible that gastric blood flow is different in the two.

In patients with chronic portal hypertension, RS studies have suggested that mucosal blood flow is increased. Panes and colleagues [39] observed a normal mucosal hemoglobin oxygen saturation in cirrhotic patients with portal hypertension gastropathy. The IHB ratio, which they defined as the IHB divided by the blood hemoglobin concentration, was higher in cirrhotics with portal hypertensive gastropathy than in noncirrhotics. This suggested that at any given level of anemia, the cirrhotics had a higher mucosal blood flow than noncirrhotics. Tezuka and colleagues [40] had generally similar findings in patients with portal hypertensive colopathy: they noted a normal rectal hemoglobin oxygen saturation and an increase in the IHB ratio (which they called the RHB) that correlated with severity of cirrhosis on the Child-Pugh classification. Patients with severe anemia were excluded in that study. As expected, the IHB ratio decreased in two patients after reduction of portal pressure by placement of a transjugular portosystemic stent shunt.

RS has also been used to investigate the effects of various medications given to decrease portal hypertension. Leung and colleagues [41] applied RS in the canine model of portal hypertension where the inferior vena cava was ligated after a surgical portacaval shunt was performed. Under general anesthesia, they demonstrated that vasopressin administration resulted in a substantial reduction in gastric mucosal hemoglobin oxygen saturation, along with a decrease in the IHB. This suggested that vasopressin reduced portal pressure by splanchnic vasoconstriction (as opposed to ischemia resulting from a impaired venous drainage, which would be expected to cause a decrease in the oxygen saturation and an increase in the concentration index). In contrast, intravenous propranolol had no significant effect on the mucosal oxygen saturation or the IHB in this model. In a subsequent study, the same group observed that octreotide infusion also resulted in a decrease in both the mucosal oxygen saturation and the IHB [42]. In a randomized study of patients with portal hypertensive gastropathy, Li et al [43] showed that somatostatin infusion resulted in no significant change in mucosal oxygen saturation and a small decrease in the IHB. This suggested that somatostatin infusion caused a small decrease in mucosal blood flow, which did not compromise tissue oxygenation. Although the subtleties of portal hypertension and the response to various medications, in humans and in animal models, are beyond the scope of this review, these studies demonstrate the general applicability of RS as a tool for studying the local hemodynamic effects of medications.

Applications of reflectance spectrophotometry in critical care

RS provides a rapid, quantitative, and reliable measurement of mucosal microvascular oxygen saturation. With newer instruments, such as the Erlangen and Spectros devices, it is also possible to obtain a stable signal without endoscopy by using a probe that is embedded in a nasogastric or rectal tube. Investigators have exploited these capabilities and applied RS to assess mucosal perfusion in situations such as cardiopulmonary bypass, continuous positive airway pressure, and vasoactive medication infusion [9,29,44]. Temmesfeld-Wollbruck and colleagues [9] studied 15 patients in septic shock with RS. They observed a substantially decreased average gastric mucosal hemoglobin oxygen saturation of 51%, compared with 70% in healthy controls. In addition, some of the septic patients, but none of the controls, had saturations below 40% that suggested severely decreased perfusion. Infusion of dopexamine, which had previously been shown to increase gut blood flow in experimental models (via dopaminergic and β-2 adrenergic receptor–mediated vasodilation), increased mucosal saturation in the septic patients by an average of 10%. The investigators noted that the responsiveness to dopexamine was much less apparent by gastric mucosal pH measurements (tonometry). They postulated that several factors, including a long equilibration time of 60 minutes required for the tonometry measurements, and the confounding effects of systemic changes in acid-base status on tonometry measurements, were responsible for the difficulties in interpretation of tonometry data. RS may therefore offer several important advantages over tonometry, including rapid responsiveness to hemodynamic changes and a lack of confounding effects due to acid-base disturbances.

Fournell and colleagues [29] used an RS probe embedded in a nasogastric tube to measure mucosal oxygen saturation in 12 patients undergoing cardiopulmonary bypass during cardiac surgery. They observed a small to moderate decrease in mucosal oxygen saturation from baseline in every patient. The average gastric mucosal oxygen saturation decreased from 65% before bypass to 57% during bypass, with a P value of < 0.01. Also, continuous tracings in several patients demonstrated substantial decreases in mucosal saturation that occurred within seconds of the development of a nodal rhythm in one patient and after heart-lung machine flow was impeded in a second patient (the surgeon needed to lift the heart briefly to control a bleeding vessel, and this maneuver impeded flow to the machine). In a third patient, a low mucosal saturation during ventricular tachycardia normalized within approximately 90 seconds of a successful reversal with pindolol infusion. The investigators also noted that, unlike pulse oximetry, RS continues to provide reliable readings even when patients are pulseless. This recent study convincingly demonstrated the application of RS to continuous monitoring of mucosal perfusion in a critical care situation.

Future directions

RS offers a rapid, simple to measure, and accurate assessment of local perfusion. As such, it has potential applications in critical care monitoring, where it could complement existing technologies such as pulse oximetry by offering an assessment of oxygen delivery to selected tissues such as the buccal, esophageal, gastric, or rectal mucosa. Unlike measures such as gastric tonometry and quantitative urine output, which provide relatively delayed and indirect assessments of gastric and renal perfusion, respectively, tissue hemoglobin saturation responds directly and almost instantaneously to hypoxic and ischemic insults. Multiple trials are currently exploring the application of RS in anesthesia and critical care medicine.

A second area of active investigation of this technology is in vascular interventions, both surgical and radiologic. Colonic ischemia is a relatively common and potentially fatal complication of abdominal endovascular aortic aneurysm repair primarily due to compromise of major arteries such as the inferior mesenteric artery and internal iliacs by the grafts [45]. Current studies are examining the role of rectosigmoid tissue oxygenation monitoring during these types of interventions. By measuring the response of the mucosa to transient occlusion of particular vessels by balloon inflation, it may be possible to better predict whether or not particular stents could be deployed safely. In addition, in those cases where recstoigmoid ischemia occurs, it may be possible to improve outcomes by bypassing blocked vessels immediately rather than responding to the complications of necrotic bowel hours later.

Summary

RS is an optical technology that has been used for over two decades in the measurement of tissue hemoglobin oxygen saturation in the gastrointestinal tract. The technology has evolved substantially throughout this period, and commercial devices are now available for use in clinical trials. Numerous studies have used RS to investigate the importance of mucosal perfusion in disorders such as ulcer disease, portal hypertension, and septic shock. More recently, the technique has been applied to measure changes in perfusion in response to infusion of vasoactive medications and maneuvers such as cardiopulmonary bypass. The results of current trials investigating the application of RS in critical care monitoring and vascular interventions will likely determine whether the technique will evolve from predominantly a research tool to a clinically useful device.

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