

Near-Infrared Spectroscopy: Potential Clinical Benefits in Surgery

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Freedom is the oxygen of the soul.

Moshe Dayan

Oxygen is essential to our survival. Nevertheless, as clinicians, we still struggle to assess the adequacy of oxygen delivery to key organ beds.¹ The state of organ perfusion could ideally be assessed by a monitor of tissue oxygenation. An important contribution to the search for such a monitoring method is near-infrared spectroscopy, which can assess tissue oxygen sufficiency. This review will discuss the current state of our knowledge about near-infrared spectroscopy and its potential place in the surgical arena.

EVOLUTION OF OXYGEN TRANSPORT

In our absolute need for oxygen, we are no different from the unicellular organisms from which we evolved.² Single-celled eukaryotes obtain their oxygen through simple diffusion; the rapidity of this process is directly proportional to the differences in partial pressure of the gas and the area of the membrane and is inversely proportional to the distance the gas must travel. Approximately 600 million years ago, single-celled organisms evolved into multicellular forms, the earliest of which were small, segmented, and highly adapted to meet their oxygen needs by simple diffusion. But as body plans became more complex, the time-distance constraints of diffusion had to be overcome, so the cardiovascular system evolved to provide bulk flow to the various tissues of the body (Fig. 1). The body plan of most multicellular organisms can be reduced to a simple scheme with four crucial steps in the chain of oxygen transport: bulk flow from the environment to a highly vascularized surface, whether skin, gills, or lung; diffusion into the blood;

bulk flow to the various tissues of the body; and diffusion into the mitochondrial sink of every cell. This scheme does not defy the laws of physics; oxygen transport ultimately depends on simple diffusion at the level of the lung-blood interface and the blood-tissue interface.

Because oxygen is poorly soluble in water and plasma, most multicellular organisms with a cardiovascular system have evolved a respiratory pigment that serves to bind oxygen for transport in the blood. In invertebrates, the respiratory pigment (usually hemocyanin) circulates freely in solution. In vertebrates, the respiratory pigment (always hemoglobin) is packaged in red blood cells, where it is protected from the oxidative stress of the environment and where oxygen binding may be finely tuned according to allosteric and cooperative interactions. The red blood cells of fish, amphibians, reptiles, and birds are nucleated; the anucleate red blood cell is unique to mammals. There are several possible evolutionary explanations for the loss of the red blood cell nucleus. First, exclusion of the nucleus potentially provides more room in the cell for hemoglobin. Second, an anucleate red cell should weigh less and be more deformable. Finally, perhaps the most compelling explanation is that a red blood cell without a nucleus is a cell without mitochondria and oxidative phosphorylation. So the anucleate red blood cell avoids the conflict of interest that would be associated with being both a consumer and a deliverer of oxygen.

HISTORY OF OXYGEN AND OXIMETRY

The history of oxygen and its measurement are beautifully described in two publications by Astrup and Severinghaus³ and Severinghaus.⁴

Discoverers of oxygen

Air was poorly understood until the late 18th century, when Carl Wilhelm Scheele, a Swedish pharmacist (in 1772), and Joseph Priestley, an English minister and amateur chemist (in 1774), independently discovered oxygen. Both men performed mouse survival experi-

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Abbreviations and Acronyms

CPP	= cerebral perfusion pressure
MODS	= multiorgan dysfunction syndrome
NIRS	= near-infrared spectroscopy
StO ₂	= local tissue oxygen saturation

ments using gas formed by heating red calx of mercury, now referred to as mercuric oxide. Priestley, at one time, lived next to a brewery and became fascinated by the immense quantities of gas that were generated in the brewing vats, where a candle could not burn. He discovered nine gases and elucidated the principles involved in refrigeration, soda water, and oxygen generation by photosynthesis. Scheele identified seven elements and many compounds. It was Lavoisier, perhaps France's greatest chemist, who, in 1779, first coined the term *oxygen* (oxygène); the term is taken from the Greek words for "acid" and "to form," because Lavoisier believed that this element was present in all acids.

The origins of oximetry

The first person to monitor human blood oxygenation was German physiologist Karl von Vierordt in 1874. In the two previous decades, Bunsen and Kirckhoff had invented the spectroscope, and George Gabriel Stokes had discovered that oxygen absorption led to changes in the color of hemoglobin. These innovations enabled von Vierordt to perform experiments demonstrating that the amount of red light transmitted through the hand decreased when the hand was made ischemic. These pioneering studies were essentially ignored until the 1930s, when German physician-scientist Karl Matthes first used variable transmission of red and infrared light through the human ear to assess oxygenation. American researcher Glen Milliken coined the term *oximeter* in 1942. He developed the first small portable ear oximeter, a device that was used for many years in pulmonary and physiology laboratories. Pulse oximetry was described in 1972 by Japanese bioengineer Takuo Aoyagi; the technique was later modified by American anesthesiologist William New for use in anesthesia and critical care. Today, the oximeter is no longer an experimental physiologic laboratory tool; it has evolved to become an integral component of clinical care.

NEAR-INFRARED SPECTROSCOPY TECHNOLOGY

The physical and mathematic basis for near-infrared spectroscopy (NIRS) is provided by the Beer-Lambert law, which states that a portion of the light transmitted through a solution containing a colored compound is absorbed by the compound, with the result that the intensity of the emerging light is reduced (Fig. 2). Light scatters in tissues; in the microcirculation, it is absorbed differently by oxygenated and deoxygenated hemoglobin (Fig. 3). Our eyes see this difference when bright red oxygenated blood changes to deep bluish and blackish deoxygenated blood. NIRS measures the amount of light returned to the sensor, producing a ratio of oxygenated hemoglobin to total hemoglobin (expressed as a percentage).

Interestingly, because biologic materials are transparent to light in the near-infrared region of the light spectrum, transmission of photons through organs is possible. This characteristic was noted by Jobsis,⁵ who performed pioneering work with NIRS as a noninvasive method of investigating living tissues. He observed that deoxygenated hemoglobin exhibits a weak absorption peak at 760 nm, and oxygenated hemoglobin does not; on the basis of these findings, he was the first to suggest that NIRS might have value as a monitor of oxygen sufficiency. Mancini and colleagues⁶ performed detailed experiments involving human volunteers to validate the functions of the NIRS device. Measuring skeletal muscle changes during forearm exercise. They found that absorption in the near-infrared spectrum (760 to 800 nm) was highly correlated with venous oxygen saturation, was minimally affected by skin blood flow, was altered by changes in limb perfusion, and was related primarily to absorption of light by deoxygenated hemoglobin, not myoglobin.

How accurately does NIRS measure oxygen saturation? In a comparison study, inline measurements were taken in a closed, circulating blood loop with an NIRS device (InSpectra Model 325, Hutchinson Technology), while blood was simultaneously drawn for measurement with a CO-oximeter, the laboratory gold standard for measuring hemoglobin oxygen saturation in circulating blood. The researchers took 384 paired readings at oxygen saturation levels ranging from 5% to 95%. The results obtained by the two methods were very highly positively correlated (r^2 , 0.992),⁷ as shown in Figure 4. But

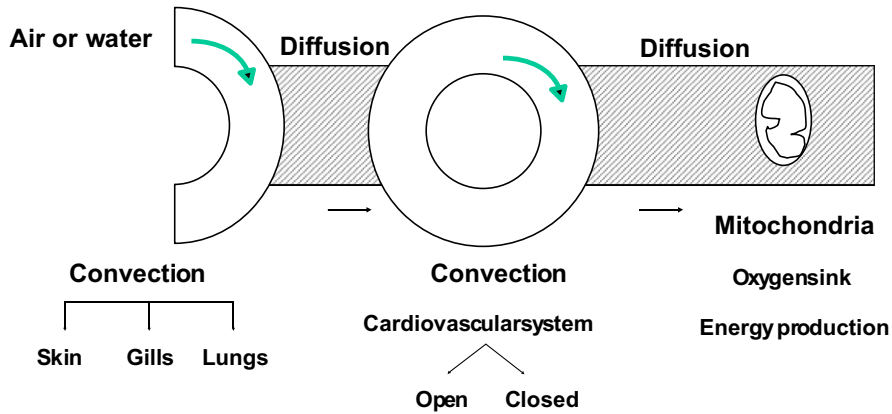


Figure 1. Oxygen transport in multicellular organisms: in multicellular organisms, diffusion of oxygen occurs from the environment (through skin, gills, or lungs) into the circulation for delivery to the tissues, where it can be used by the cell for energy production. (Reprinted from: Hameed SM, Aird WC, Cohn SM. Oxygen delivery. Crit Care Med 2003;31(12 Suppl):S658–667 with permission).

NIRS may be less accurate when used to assess individuals with dark skin pigmentation.⁸

Unlike pulse oximetry, which uses fewer and different wavelengths of light, requires a pulsatile flow, and targets only the small additional arterial blood volume produced at the measurement site during systole,⁹ NIRS assesses primarily the hemoglobin saturation of venous blood, which, along with capillary blood, composes approximately 90% of the blood volume in tissues. Because of these differences, NIRS is believed to reflect the oxygen saturation of hemoglobin in the postextraction compartment of any particular tissue.

In summary, NIRS technology facilitates continuous, noninvasive, and accurate monitoring of tissue oxygen saturation and can interrogate tissues by using light waves transmitted through biologic materials (including skin and bone).

NEAR-INFRARED SPECTROSCOPY IN SHOCK AND RESUSCITATION

Animal work

My initial interest in NIRS was stimulated by the work of Peter Rhee and colleagues,¹⁰ who studied 23 rabbits (each weighing 2 to 3 kg) with prototype NIRS probes

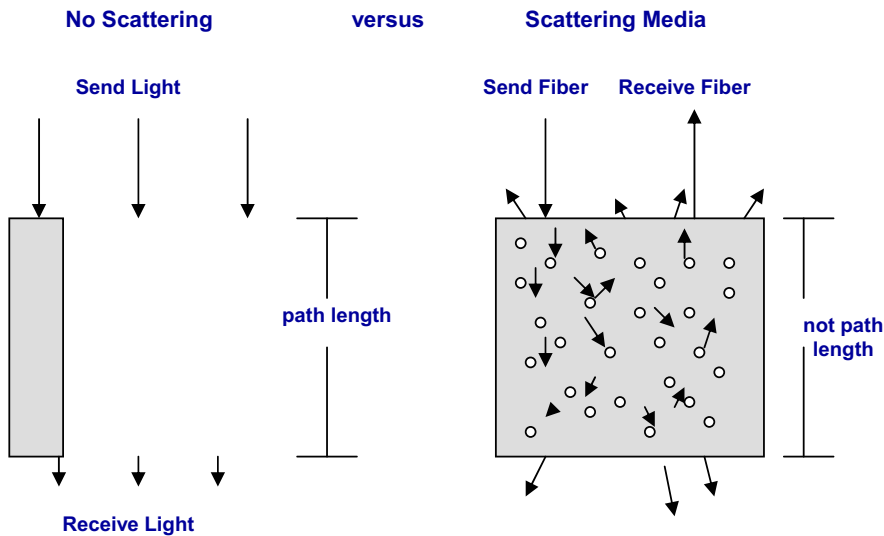


Figure 2. Beer-Lambert Law: a portion of the light transmitted through a solution containing a colored compound is absorbed by the compound, with the result that the intensity of the emerging light is reduced.

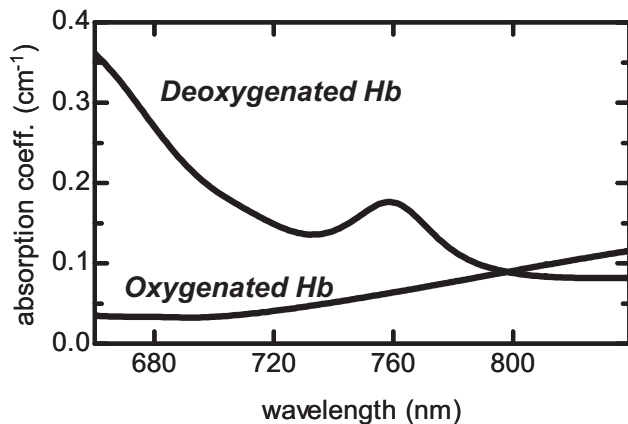


Figure 3. Light absorption of hemoglobin (Hb) related to its state of oxygenation. In the near-infrared range, absorption of light is different in deoxygenated hemoglobin when compared with oxygenated hemoglobin. These differences can be measured and used to differentiate the adequacy of hemoglobin oxygenation in blood.

(Biospectrometer-MB Oximeter, Hutchinson Technology) placed on muscles of the stomach, liver, kidney, and leg. Animals were subjected to hemorrhage until cardiac output decreased to 40% of baseline; output was maintained at this level for 30 minutes, and the animals were then resuscitated until cardiac output returned to baseline and remained there for 1 hour. NIRS was used to interrogate tissues for hemoglobin oxygen saturation during hemorrhagic shock. In this early investigation,

NIRS appeared to detect the changes in cardiac output, but this early NIRS prototype could be calibrated only if the animals were put to death.

My colleagues and I then embarked on a series of animal experiments evaluating a prototype NIRS device (Biospectrometer-MB Oximeter) whose optical probe was placed on the end of a nasogastric tube. We performed NIRS in a porcine liver-injury model using controlled hemorrhage,¹¹ uncontrolled hemorrhage,¹² abdominal compartment syndrome,¹³ and a variety of shock and resuscitation strategies. We found that the NIRS device rapidly detected changes in blood flow that were reflected in systemic perfusion (pulmonary artery-derived SvO_2) or regional perfusion (superior mesenteric artery flow). In similar experiments with pigs, Beilman and colleagues¹⁴ found that oxygen delivery was highly correlated with NIRS-measured hemoglobin oxygen saturation when either leg muscle (r^2 , 0.94) or the stomach wall was evaluated (r^2 , 0.91). In subsequent experiments, our group found that NIRS measurements of muscle tissue reflected both the adequacy of resuscitation and the magnitude of injury (Fig. 5).¹⁵ In addition, when NIRS measurements were used as a sole end point of resuscitation, mortality rates in our LD₅₀ (median lethal dose) model were decreased.

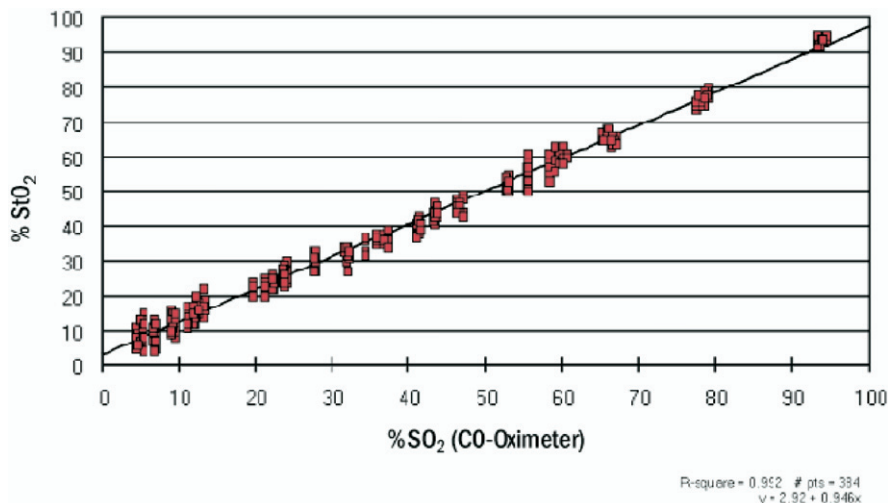


Figure 4. Correlation of near-infrared spectroscopy (NIRS)-measured hemoglobin oxygen saturation in blood with CO-oximeter data. In a closed, circulating blood loop, 384 paired readings at hemoglobin oxygen saturation levels ranging from 5% to 95% obtained with an NIRS device, were highly correlated with CO-oximeter measurements (r^2 , 0.992). (From: Myers DE, Anderson LD, Seifert RP, et al. Noninvasive method for measuring local hemoglobin oxygen saturation in tissue using wide gap second derivative near-infrared spectroscopy. *J Biomed Opt* 2005;10: 034017 with permission). StO_2 , local tissue oxygen saturation.

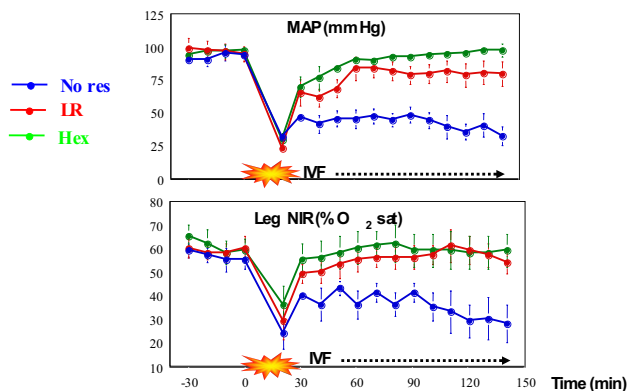


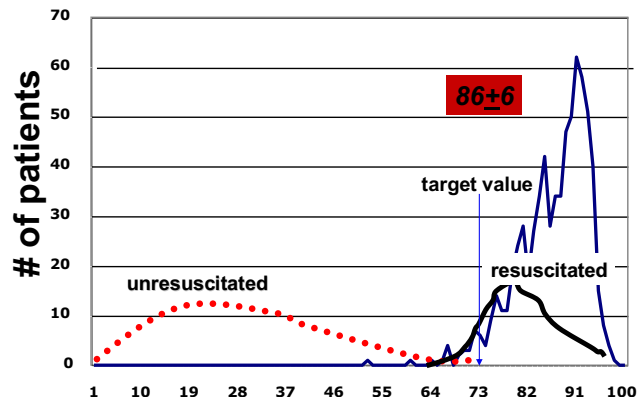
Figure 5. Mean arterial pressure (MAP) data compared with leg near-infrared spectroscopy (NIRS) data in a porcine shock model. Animals underwent hemorrhage followed by resuscitation with no fluid (No res), lactated Ringer's (LR), or Hextend (Hex) (Hospira) solutions. NIRS-measured muscle tissue oxygen saturation was similar in magnitude and duration to blood pressure changes found during hemorrhage and resuscitation. (From: Crookes BA, Cohn SM, Burton EA, et al. Noninvasive muscle oxygenation to guide fluid resuscitation after traumatic shock. *Surgery* 2004;135:662–670, with permission.)

Chaisson and colleagues¹⁶ studied the use of a closed-loop resuscitation method in a sheep aortotomy model of uncontrolled hemorrhage. Tissue oxygen saturation was monitored with the Somanetics INVOS 4100 device placed on the flank muscle. Interestingly, when muscle NIRS measurements rather than cardiac output were used as the target end point of resuscitation, only half of the resuscitation volume was required for full restoration of perfusion.

Studies of other types of oxygen monitors have also demonstrated that tissue oxygen monitoring reflects the magnitude and duration of shock. Tonometric measurements of subcutaneous oxygen tension during hemorrhage and resuscitation have been shown to be a function of blood flow.¹⁷ A number of investigators have accomplished percutaneous monitoring of tissue oxygen tension with fiberoptic sensors and have shown that oxygen tension measured in muscle or visceral organs mimics perfusion changes in a variety of different animal shock models.^{18–20}

Clinical work

Cairns and coworkers²¹ found a strong association between diminished NIRS measurements (using an early Hutchinson Technology prototype) of hemoglobin oxygen saturation and oxidized cytochrome aa3 in trauma patients during 12 hours of shock resuscitation, and the



Thenar NIR

Figure 6. Near-infrared spectroscopy (NIRS) data from normal volunteers. In 707 subjects, the range of thenar muscle oxygen saturation values was noted. A target value, two standard deviations below the mean, was postulated as a reasonable goal for resuscitation. (From: Crookes BA, Cohn SM, Bloch S, et al. Can near-infrared spectroscopy identify the severity of shock in trauma patients? *J Trauma* 2005;58:806–816, with permission.)

subsequent development of organ dysfunction. McKinley and colleagues²² closely monitored eight severely injured trauma patients during resuscitation for 24 hours after admission. Deltoid muscle NIRS readings (Biospectrometer-MB Oximeter) were correlated with systemic oxygen delivery during the entire monitoring period (r , 0.95).

The results of these studies indicated that NIRS technology might have promise in assessing shock and resuscitation, but little information was available about the normal distribution of hemoglobin oxygen saturation in healthy tissues. A better understanding of the distribution of values in healthy persons was essential if we were to determine threshold criteria for diagnosing hypoperfusion. To resolve this issue, we measured the normal range of thenar muscle local tissue oxygenation (StO_2) in human volunteers. Readings were taken by using an InSpectra device with a nonsterile polyethylene cover (Optoshield, Hutchinson Technology) on intact skin. An analysis of the data collected from 707 ambulatory volunteers showed a mean thenar StO_2 of $87\% \pm 6\%$.²³ A frequency distribution of thenar StO_2 measurements is shown in Figure 6.

We then performed a prospective, nonrandomized, observational study to determine the relationship between the severity of traumatic shock and StO_2 measurements. Thenar muscle NIRS measurements were made while patients were in the resuscitation area of a Level I

Table 1. Outcomes Results in Trauma Patients Related to First Hour Measurements of Local Tissue Oxygen Saturation, Systolic Blood Pressure, or Base Deficit

	Min StO ₂	Maximum base deficit	Minimum systolic blood pressure
Patients with bad/good outcomes, n	96/284	82/210	96/282
Cutoff	75	6	90
Sensitivity, % (95% CI)	84 (78, 90)	77 (69, 84)	79 (72, 86)
Specificity, % (95% CI)	39 (34, 44)	32 (27, 38)	32 (27, 36)
PPV, % (95% CI)	32 (27, 37)	31 (25, 36)	28 (24, 33)
NPV, % (95% CI)	88 (83, 93)	78 (71, 85)	82 (76, 88)
AUC	0.70	0.65	0.62
Bad outcomes			
Mean ± SD (95% CI)	54 ± 24 (49, 58)	11 ± 6 (10, 13)	78 ± 23 (74, 83)
Good outcomes			
Mean ± SD (95% CI)	68 ± 17 (66, 70)	8 ± 5 (8, 9)	87 ± 21 (84, 89)

AUC, area under the receiver operating characteristic curve; NPV, negative predictive value; PPV, positive predictive value; StO₂, local tissue oxygen saturation. (From: Cohn SM, Nathans AB, Moore FA, et al. Tissue oxygen saturation predicts the development of organ dysfunction during traumatic shock resuscitation. *J Trauma* 2007;62:44–54, with permission.)

trauma center. Traumatologists blinded to the NIRS measurements were asked to place patients into one of four groups based on the severity of shock: no shock (n = 98), mild shock (n = 19), moderate shock (n = 14), and severe shock (n = 14). The lowest thenar StO₂ measurement was 83% ± 10% for the no shock and the mild shock groups, 80% ± 12% for the moderate shock group, and 45% ± 26% for the severe shock group. The thenar StO₂ measurements of the severe shock group were considerably different from those of each of the other shock groups (all p < 0.05). We concluded that NIRS could continuously and noninvasively monitor tissue oxygen saturation in muscle and was probably an indicator of the severity of shock.

Ikossi and colleagues²⁴ monitored 28 well-resuscitated critically ill patients simultaneously with an intramuscular Licox oxygen probe (CC1.G2 Oxygen Catheter Micro Probe, Integra NeuroSciences) and a transcutaneous NIRS probe (InSpectra Model 325) placed in the deltoid region approximately 10 hours after hospital admission. Early low values obtained by either device appeared to predict the risk of infectious complications or multi-organ dysfunction syndrome (MODS).

We recently completed a multicenter study evaluating how well StO₂ measurements predicted the outcomes of 383 patients with high-risk trauma who were in shock when they arrived at one of seven Level I trauma centers participating in the study. The primary outcomes in this prospective study were MODS (which occurred in 50 of the patients) and death (which occurred in 55 of the patients). StO₂ was measured on arrival and for the next

24 hours; other known predictors of hypoperfusion and clinical outcomes were also measured. Clinicians were blinded to StO₂ measurements. A minimum StO₂ measurement of 75%, a minimum systolic blood pressure of 90 mmHg, and a maximum base deficit of 6 mEq/L were similarly effective in predicting which patients would experience bad outcomes (MODS or death) as demonstrated in Table 1. These measures had a sensitivity of about 80%; specificity was about 32%; positive predictive value was about 30%; and negative predictive value was approximately 80%. We concluded that NIRS measurements of muscle tissue oxygen saturation perform similarly to base deficit levels or systolic blood pressure in detecting poor perfusion and predicting MODS or death after severe torso trauma; the advantage of NIRS is that it allows continuous and noninvasive measurement.²⁵

We can get along on only 20% of our lung capacity, but that dragging sort of existence is a poor substitute for the vitality we enjoy when the twin bellows of our lungs are taking in great drafts of oxygen.

Gene Tunney

NEAR-INFRARED SPECTROSCOPY IN EXTREMITY MONITORING

Compartment syndrome

Diagnosing compartment syndrome can be very difficult after trauma or vascular procedures to the extremity. Delays in diagnosis can lead to catastrophic complications, such as severe tissue loss, which in some patients,

require amputation. Arbabi and coworkers²⁶ and Garr and associates²⁷ placed NIRS (Biospectrometer-MB Oximeter) probes on the leg muscles in a pig model of compartment syndrome. Hypotension and hypoxia had a minimal effect on tissue oxygen measurements, but induction of compartment syndrome caused a dramatic decrease in StO_2 measurements (from $82\% \pm 4\%$ to $16\% \pm 12\%$); after fasciotomy, these measurements improved to near baseline values. Subsequently, we used an NIRS device (Biospectrometer-MB Oximeter) to assess tissue oxygen saturation in the legs of nine patients with an obvious diagnosis of compartment syndrome, as determined by clinical examination and compartment pressures (64 ± 17 mmHg). The tissue oxygen saturation in these limbs was only $56\% \pm 27\%$; after fasciotomy, this measurement improved to $82\% \pm 16\%$ (Fig. 7). We concluded that NIRS may complement clinical examination in diagnosing compartment syndrome.²⁸

Necrotizing fasciitis

Like compartment syndrome, necrotizing soft-tissue infection can be difficult to diagnose in its early stages and can result in profound consequences if the diagnosis is delayed. Investigators in Taipei²⁹ used NIRS (Runman CW2000, NIM, Inc) to diagnose lower-extremity soft-tissue infections. Of the 234 patients assessed, 215 had routine cellulitis and 19 had necrotizing fasciitis (according to the criteria established by the Centers for Disease Control and Prevention). For these 19 patients, NIRS measurements were substantially lower ($52\% \pm 18\%$) than were reference measurements obtained from the contralateral extremity, from the biceps muscle, or from patients with cellulitis (eg, the NIRS measurement of hemoglobin oxygen saturation for the biceps muscle was $86\% \pm 12\%$). The NIRS device had a sensitivity of 100% and a specificity of 97% for predicting necrotizing fasciitis when a threshold value of 70% was used. This appears to be the only report in the English medical literature of a study that has used the NIRS device as a method of diagnosing soft-tissue infection; the results are quite interesting.

Peripheral vascular disease

A logical use for a tissue oxygen monitor would be in assessing peripheral blood flow to predict the outcomes of vascular procedures. This technology might provide valuable assessments of the severity of preoperative hy-

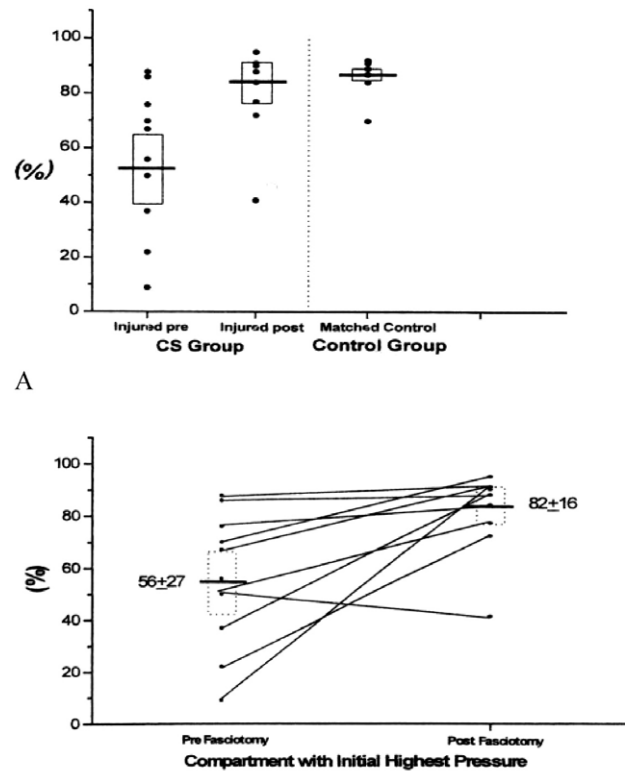


Figure 7. Near-infrared spectroscopy (NIRS) data from patients with compartment syndrome (CS), (A) before and (B) after fasciotomy. Prefasciotomy, patients with compartment syndrome had substantially lower tissue oxygen saturation values than uninjured limbs. After fasciotomy, there was typically a dramatic improvement in muscle oxygenation. (From: Giannotti G, Cohn SM, Brown M, et al. Utility of near-infrared spectroscopy in the diagnosis of lower extremity compartment syndrome. *J Trauma* 2000;46:396–401, with permission.)

poperefusion and the improvements in tissue oxygenation after procedures aimed at restoring blood flow to an ischemic extremity. Svendsen and colleagues³⁰ used NIRS (INVOS 3100, Somanetics) to evaluate lower-extremity muscle oxygenation during urinary tract surgery with the patient in the lithotomy position. On elevation of the leg, perfusion pressures decreased dramatically, with a corresponding reduction in NIRS-measured oxygen saturation of the gastrocnemius muscle (68% to 58% , $p < 0.05$). Eiberg and colleagues³¹ placed an NIRS device (Somanetics IVOS 3100) on the dorsum of the foot of 14 patients undergoing infringuinal bypass. After proximal clamping, tissue oxygenation decreased from baseline by a mean of 61 U (range 6 to 94 U). After bypass grafting, tissue oxygenation levels increased to a mean of 28 U (range 10 to 81 U)

over baseline. These authors concluded that NIRS was appropriate for perioperative monitoring of peripheral vascular procedures.

Comerota and associates³² investigated the ability of NIRS (InSpectra Model 325) to measure tissue oxygenation before and after exercise in patients with claudication and in normal volunteers. Baseline measurements were similar in both groups, but the NIRS-measured oxygen saturation levels of patients with claudication were profoundly lower and required more time for recovery to baseline values. Additional studies will be required to determine whether NIRS should be used routinely in the perioperative assessment of patients with peripheral vascular disease.

Free flaps

Another seemingly ideal function for NIRS technology would be in postoperative evaluation of tenuous microvascular grafts. These free flaps are prone to arterial and venous occlusion because their placement requires tiny vascular anastomoses. Irwin and colleagues³³ suggested that NIRS may play a role in monitoring these flaps. They used the NIRO 500 NIRS device (Hamamatsu Photonics KK) to measure oxygen saturation in the hind limb muscles of 10 rabbits. The device rapidly detected arterial occlusions as drops in tissue oxygen saturation; venous occlusion alone did not result in as great a change. The NIRS device's rapid detection of changes in the vascular perfusion of human muscle is well described.^{34,35} But there are limited data about the clinical use of NIRS to monitor patients undergoing microvascular grafting. Scheufler and coauthors³⁶ used an NIRS device (Multiscan OS 10, NIOS-Medical Technologies) to assess 11 patients undergoing a pedicle tram flap for breast reconstruction. They assessed flap tissue at a depth of 4 mm and found that tissue oxygenation plummeted and NIR-derived hemoglobin values rose dramatically in the immediate postoperative period and normalized late postoperatively. Holzle and colleagues³⁷ found NIR (O2C, Oxygen-to-see, LEA-Medizintechnik GmbH) measuring tissue at a depth of 2 to 4 mm to be a good identifier of impending tissue loss, before clinical indicators. In 61 patients undergoing radial forearm flaps before microsurgical reconstruction of the head and neck, 9 patients (15%) had vascular disturbances detected, and profound decreases in tissue oxygenation along with increases in venous hemoglobin concentration were noted in flaps lost because of venous congestion. Alterations were noted 4

hours before clinical signs of flap compromise. These data suggest a major role for NIR as a monitor of free flaps.

What oxygen is to the lungs, such is hope to the meaning of life.

Emil Brunner

NEAR-INFRARED SPECTROSCOPY MONITORING OF THE BRAIN

Most clinicians still regard the brain as a "black box," and our ability to assess brain function in comatose patients is still limited. NIRS technology may offer a means of monitoring the brain in these patients who have complex conditions. Because light in near-infrared wavelengths can penetrate skull and brain, transcranial monitoring is feasible with the NIRS device. Wyatt and colleagues^{38,39} were among the first to suggest that NIRS technology can be used to measure cerebral blood volume and assess pathophysiologic brain damage in newborn infants. An NIRS device (Somanetics IVOX 3100) has been compared with the LICOX oxygen sensor in assessing comatose critically ill patients with subarachnoid hemorrhage (n = 3) or severe brain injury (n = 9). Reasonable coherence of results was demonstrated when these monitors were placed over the frontal lobe in the area demonstrated by CT to have the greatest degree of pathologic changes.⁴⁰ In another study, the Somanetics IVOS 4100 system was used to assess four patients after severe brain injury. NIRS values > 75% were associated with normal cerebral perfusion pressure in 96% of instances. When NIRS measurements were < 55%, cerebral perfusion pressure was dangerously low 68% of the time.⁴¹

NIRS has been used to evaluate cerebral oxygenation during carotid surgery^{42,43} and during cardiac surgery, both on-bypass⁴⁴⁻⁴⁶ and off pump.⁴⁷ In a study of carotid endarterectomy, Kuroda and colleagues⁴² found that NIRS measurements (OM-100 or OM-110 device, Shimadzu Co) identified severe cerebral hypoxia during clamping of the carotid artery. Despite concerns that the accuracy of intracranial monitoring may be negatively affected by extracranial tissues, the sensitivity and specificity of NIRS in reflecting cerebral tissue oxygenation have been extremely good.⁴³ Recent analyses of data obtained during coronary bypass procedures demonstrated that the NIR device (Hamamatsu Photonics KK) measured notable differences in brain tissue oxygenation during conventional extracorporeal circulation and dur-

ing off-pump surgery.⁴⁸ It is unclear whether the information derived from the NIRS device provides an adequate sample of the brain so that areas of hypoperfusion can be detected. In addition, we require more investigations to determine whether monitoring brain tissue oxygenation is clinically relevant and can translate into therapeutic actions that will improve neurologic outcomes.

NEAR-INFRARED SPECTROSCOPY MONITORING IN NEONATES

The size of premature neonates and their high frequency of associated critical illnesses make monitoring particularly important. Schulz and colleagues⁴⁹ used NIRS technology for transcutaneous measurement of liver oxygenation. They assessed 100 critically ill neonates with a 40-mm Hamamatsu (Photonics) probe placed over the upper abdomen (liver). NIRS values were correlated with mixed venous oxygen saturation levels (r^2 , 0.72). The correlation was even higher when the central venous pressure monitor was located in the right atrium and the patient had neither shunts nor sepsis (r^2 , 0.88). The possibility of transcutaneous measurement of oxygen saturation in the tissue of abdominal organs is quite futuristic and fascinating. But a monitor is helpful only if it leads to clinically relevant changes in management. A recent large multicenter trial assessed the use of fetal pulse oximetry during the obstetric delivery of the infants of 5,341 women.⁵⁰ Availability of oximetry data did not affect the rates of cesarean delivery or the outcomes of the infants.

NEAR-INFRARED SPECTROSCOPY MONITORING IN HEART FAILURE

The ability of NIRS measurements of thigh muscle oxygenation to distinguish patients with congestive heart failure from normal volunteers during exercise was demonstrated nearly 20 years ago.⁵¹ Recently, Soller and colleagues⁵² performed an elegant study in which 18 patients undergoing coronary artery bypass grafting were monitored with an NIRS device placed on the hypothenar eminence and with a reference fiberoptic oxygen probe placed into the abductor digiti minimi muscle. NIRS measurement of hemoglobin oxygen saturation was compared with invasive oxygen tension; both were recorded during the perioperative and intraoperative periods and were reasonably well correlated (r^2 , 0.66). The authors concluded that NIRS muscle monitoring was sensitive to changes in tissue perfusion during cardiopulmonary bypass surgery.

Again, additional clinical work is needed to assess the clinical impact of NIRS in cardiac patients.

Money is like Oxygen. . .

– *Not enough is NOT compatible with life.*

– *But too much is toxic,*

not to you, but to your children. . .

Stanley Rosenbaum, MD

In summary, published studies have demonstrated the benefits of near-infrared spectroscopy in monitoring patients with various conditions, such as shock and resuscitation or extremity disorders (compartment syndrome, necrotizing fasciitis, peripheral vascular disease, and microsurgical grafts). Other reports have described innovative uses of NIRS for monitoring neonates and patients with brain injury or cardiac failure. Future applications for NIRS will depend on the results of additional clinical experience and on the therapeutic value derived from our gaining a better understanding of the state of tissue oxygenation. From my perspective, the outlook for near-infrared spectroscopy is “rosy.”

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