



# Identification of Optimal Control Compartments for Serial Near-Infrared Spectroscopy Assessment of Lower Extremity Compartmental Perfusion

Keith Jackson II, MD<sup>1</sup>; Ashley Cole, MPH<sup>2</sup>; Benjamin K. Potter, MD<sup>3</sup>; Michael Shuler, MD<sup>2</sup>; Tracy Kinsey, MSPH<sup>4</sup>; and Brett Freedman, MD<sup>5</sup>

*Near-infrared spectroscopy (NIRS) has shown promise in detecting ischemic changes in acute compartment syndrome. The objectives of this study were to 1) assess the correlation in NIRS values between upper and lower extremity control sites for bilateral lower extremity trauma and 2) investigate the effect of skin pigmentation on NIRS values. Forty-four volunteers (14 male, 30 female) were monitored over separate 1-hour sessions. NIRS leads were placed over leg and upper extremity compartments. Colorimeters were used to document skin pigmentation. NIRS values between corresponding contralateral compartments were extremely well correlated ( $r = 0.76-0.90$ ). Upper extremity NIRS values were correlated to leg values in the following order: volar ( $r = 0.65-0.71$ ), dorsal ( $r = 0.36-0.60$ ), and deltoid ( $r = 0.42-0.51$ ). A negative correlation was observed between melanin and NIRS values. Analogous leg compartments are the optimal site of control for each other. The volar forearm may be the best upper extremity control. Skin pigmentation may affect absolute NIRS values. (Journal of Surgical Orthopaedic Advances 22(1):2-9, 2013)*

Key words: acute compartment syndrome, adipose tissue, control sites, near-infrared spectroscopy, skin pigmentation

**T**issue ischemia leading to irreversible necrosis is the pathologic end point of untreated acute compartment syndrome (ACS). As hemorrhage and edema secondary to severe injury lead to elevated intracompartmental pressures, perfusion pressure decreases. These changes can

subsequently cause muscle necrosis, neurologic injury, and permanent loss of function if not diagnosed and treated promptly (1-5). Because most injuries sustained in combat involve the extremities (6-8) and are caused by explosive mechanisms (8, 9), the diagnosis and prompt treatment of ACS is of particular interest to deployed providers. In an 18-month retrospective study of evacuees who underwent fasciotomy in Iraq, Afghanistan, or Landstuhl Regional Medical Center (LRMC), Ritenour et al. (4) noted that 77 service members who had a delayed diagnosis of ACS had significantly higher rates of muscle excision, amputation, and mortality. The authors also reported an 18% rate of revision at LRMC for incomplete fasciotomies originally performed in theater (4). Such cases where affected compartments were inadequately decompressed initially were associated with significantly higher rates of muscle excision and patient mortality (4).

Although intracompartmental pressure measurement currently represents the only objective measure for

From <sup>1</sup>Eisenhower Army Medical Center, Fort Gordon, Georgia; <sup>2</sup>J&M Shuler, Athens, Georgia; <sup>3</sup>Department of Orthopaedics, Walter Reed National Military Medical Center, Bethesda, Maryland; <sup>4</sup>Department of Epidemiology, Gillings School of Public Health, University of North Carolina, Chapel Hill, North Carolina; <sup>5</sup>Department of Orthopaedic Surgery, Landstuhl Regional Medical Center, Landstuhl, Kirchensburg, Germany. Address correspondence to: Keith Jackson II, MD, Eisenhower Army Medical Center, 4530 Glastonbury Drive, Fort Gordon, GA 30905; e-mail: lynn.jackson9@gmail.com.

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detecting ACS, this modality is invasive and has poor reliability if not performed correctly (10, 11). Because of these limitations, intracompartmental pressures are not routinely used by many surgeons in assessing for ACS (10, 12, 13). Instead, many physicians rely solely on clinical clues that are nonspecific and/or late to develop, oftentimes after irreversible damage (3, 14, 15). Given the grave risks associated with both a missed compartment syndrome (1, 2, 4, 5) and the morbidity of a prophylactic fasciotomy (5, 16–19), physicians have long sought measures to increase diagnostic certainty of ACS. An ideal test would reliably identify patients with overt or impending ACS, allow continuous noninvasive monitoring over time, and help avoid unnecessary fasciotomies in those with injury regardless of race, associated injury, or mental status.

Near-infrared spectroscopy (NIRS) is a relatively new technology that has shown early promise in detecting ACS (20, 21). NIRS devices function through emission of light in the near-infrared range (600–1000 nm). As the light travels through tissue, it is differentially absorbed by oxygenated and deoxygenated hemoglobin in the microcirculation. In a series of clinical investigations examining NIRS values in injured and noninjured legs, Shuler and associates (20, 21) documented the ability to detect an increased tissue oxygenation in uncomplicated lower extremity trauma (i.e., a hyperperfused postinjury state) and the hypoxic state associated with ACS. Although these observational studies demonstrated the ability to detect changes in tissue oxygenation relative to the corresponding compartment in traumatic injuries at a single point in time, to date the most reliable site of internal control for comparison values during longitudinal monitoring of compartment oxygenation has not been established. Additionally, in each of these prior studies no potential sites of control in the upper extremity were explored for use in cases of bilateral lower extremity trauma, and the effects that skin pigmentation and body hair may have on NIRS values were not quantified (20, 21). Finally, a limitation of prior studies has been the use of short-term, isolated NIRS measurements, limiting the value of this modality as a compartment monitoring technique, because ACS is a process that occurs over time and therefore requires sequential or continuous evaluation.

The purpose of this study was to establish the optimal control compartment under continuous compartment monitoring over a 1-hour period in a cohort of healthy volunteers. Furthermore, we sought to clarify the effects that body hair and objectively quantified skin pigmentation have on NIRS measurements of compartmental perfusion.

## Methods

After receiving Institutional Review Board approval, this prospective study was performed on consented, uninjured adult (ages 18–65) volunteers recruited from a U.S. military clinic setting. Skin pigmentation readings were obtained 3 cm below the antecubital fossa on the volar forearm and the midportion of the posterior calf using Dermaspectrometer (Cyberderm, Broomall, PA) and SmartProbe 400 (IMS, Inc, Portland, ME) colorimeters. The Dermaspectrometer is a narrow-band spectrometer that measures the amount of hemoglobin and melanin contained within the dermal layer by detecting the intensity of reflected light from red and green wavelengths. These measured concentrations of hemoglobin and melanin are expressed linearly from 0 to 100 as the erythema (E) and melanin (M) indices. The IMS SmartProbe measures color by quantifying the reflectance of light through three wavelength filters. The resulting measures are: light/dark ( $L^*$ ), red/green ( $a^*$ ), and blue/yellow ( $b^*$ ) of the skin. With the use of these three measures, any color can be graphically plotted in three-dimensional space. Thickness of subcutaneous fat was measured at the junction of the proximal and middle third of the posterior calf using Bodymetrix BX 2000 (Intelmetrix, Inc, Livermore, CA) system. The BX2000 is a portable ultrasound system used to measure the depth of fat underneath the probe (22).

NIRS measurements were obtained using the INVOS cerebral oximeter (Somanetics Corp, Troy, MI). This system has the capability to automatically obtain and transfer tissue oxygenation data directly to a VitalSync (Somanetics, Corp., Troy, MI) data collection device. NIRS leads were applied over each of the four compartments of the lower extremities at the junction of the proximal and middle thirds of the leg in a manner previously described (20). The anterior compartment sensor (A) was placed 2 cm lateral (approximately the width of one sensor) to the tibial crest, the lateral compartment sensor (L) was placed directly over the fibula, the deep posterior sensor (D) was placed just medial to the subcutaneous surface of the tibia, and the superficial posterior (S) sensor was placed 2 cm posterior to the deep posterior sensor. Additional leads were placed on the volar and dorsal forearm, 2 cm distal to the antecubital fossa, and the midportion of the deltoid, 2 cm distal to the lateral aspect of the acromion. Indelible ink marker was used to trace the outline of the sensors, to ensure exact replacement between testing sequences. Soft tissue oxygenation measures were then recorded on the Vital Sync continually every 30 seconds for 1 hour using the INVOS monitor. Briefly, the INVOS system consists of a monitor, two preamplifiers, four reusable cables, and four disposable sensors. Within each sensor, light signals at

wavelengths of 730 and 810 nm are emitted. The emitted light travels through the underlying soft tissues where it is differentially absorbed by oxygenated and deoxygenated hemoglobin. Unabsorbed light then reflects to the surface where it is measured by two photodetectors placed within the sensor 30 and 40 mm from the light source. Values from the closer photodetector are subtracted from distal readings to isolate the microcirculatory saturation 2 to 3 cm below the sensor (23). Using an algorithm derived from the Beer-Lambert Law (24), subtracted photosensor readings are converted to oxygenation values (%) and displayed on the system's monitor.

For the 12 male patients with leg hair (two males presented with shaved legs), the area where the leads had been applied was shaved at the end of the monitoring period, the sensors were reapplied, and the tissue oxygenation values were obtained for an additional 15 minutes, to evaluate the intrasubject variability in measurements as a result of shaving. After an interval of at least 24 hours, all subjects returned for repeat monitoring. The sensors were placed in the same locations and the monitoring sequence was repeated.

### Statistical Analysis

Within-patient NIRS values over the 1-hour monitoring period were characterized using summary descriptive statistics and graphical methods. The monitoring period on test day 1 before shaving was used for descriptive statistics unless stated otherwise. For bivariate comparisons, a single representative value ("summary NIRS value") was generated based on the average of a 5-minute monitoring period; once NIRS sensors of all compartments were attached and consistently recording values, a 5-minute stabilization period was discarded, and the following 5-minute period was selected and averaged. Because all patients were uninjured, summary statistics and comparisons between legs were performed by designating the right or left (randomly selected) leg as the "test" leg and the other as the contralateral "control" leg. Pearson product moment correlation coefficients and Spearman correlation coefficients were used, as appropriate to the sample distribution, to describe the relationships between NIRS values of the lower and upper extremities, as well as NIRS' relationship with colorimeter values. The intraclass correlation coefficient (ICC) was used to evaluate the reliability of NIRS values between test 1 and test 2.

### Results

Forty-five participants were enrolled between February 3, 2011, and December 11, 2011. Results from one subject were not available for statistical analysis because her

NIRS values did not store correctly on the Vital Sync. This left a total of 44 enrolled patients (14 males, 30 females) who completed the testing protocol with complete data fully available for statistical analysis. The mean age of these 44 participants was 39.9 years (range, 22–65). Among the 44 participants, 36 (81.8%) were white, three (6.8%) were Asian, three were black (6.8%), and two (4.5%) were Hispanic. All participants had < 2 cm subcutaneous fat thickness at the posterior calf (mean 8 mm, range, 4–18 mm); 34 of the 44 (77%) had fat thickness ≤10 mm. Patients were monitored for an average of 62.8 minutes during test 1, and contributed 122 values, on average. All subjects enrolled in the study tolerated NIRS monitoring without discomfort or significant side effects. Three subjects had self-limited areas of mild erythema directly under some of the sensors (no more than two sensor reactions per patient), which was otherwise asymptomatic and completely resolved without treatment within 24 to 72 hours. No significant adverse events were encountered in the course of this study.

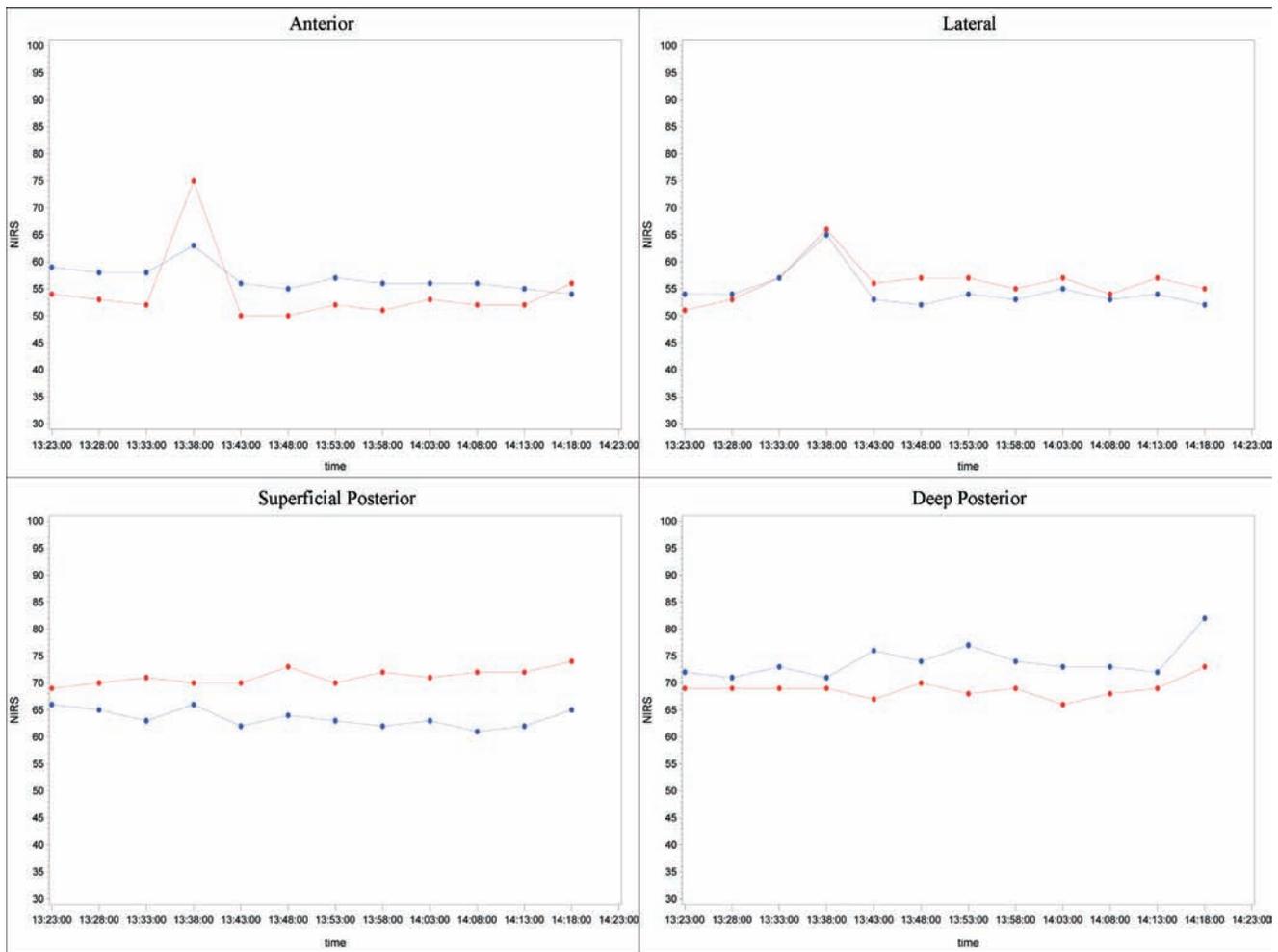
Moderate within-patient, within-compartment variability was observed in intracompartmental NIRS values over the monitoring period. The interquartile range of values over the 1-hour period for each compartment averaged between 2.6 to 3.5 percentage points, with the least fluctuation observed in the deep posterior compartment (Table 1). The range of values contained between the 10th and 90th percentiles over the 1-hour period was 6.9, 5.5, 5.3, and 5.2 percentage points (anterior, lateral, superficial posterior, and deep posterior compartments, respectively). Although NIRS value fluctuations were notable within each compartment over time, fluctuations were typically reflected in the corresponding compartment of the contralateral extremity (Fig. 1).

Between patients, the mean summary NIRS values for the anterior, lateral, superficial posterior, and deep posterior compartments of the test leg were 74.1%, 75.6%, 79.7%, and 82.9%, and 74.0%, 76.5%, 79.9%, and 83.3%,

**TABLE 1** Within-patient summary statistics for each compartment of a randomly selected lower extremity, over 1 hour of NIRS monitoring

Variable Compartment	No. Mean	Before SD	After Min	Gain Max	<i>p</i> Value IQR
<b>Anterior</b>	72.2	2.9	65.5	80.9	3.5
min-max	48.2–91.7	1.2–6.3	41–85	55–95	1.0–7.0
<b>Lateral</b>	75.4	2.3	70.2	81.3	2.9
min-max	49.5–93.5	0.5–5.2	45–87	54–95	0.0–8.5
<b>Sup post</b>	78.9	2.2	73.9	84.1	2.6
min-max	55.4–94.7	0.8–6.3	53–92	60–95	0.0–8.0
<b>Deep post</b>	81.8	2.1	76.6	86.1	2.9
min-max	61.7–95.0	0.1–6.7	53–95	64–95	0.0–13.5

IQR, interquartile range.



**FIGURE 1** Complete (q 30 seconds) data of four compartments of the right (red) and left (blue) legs of one subject.

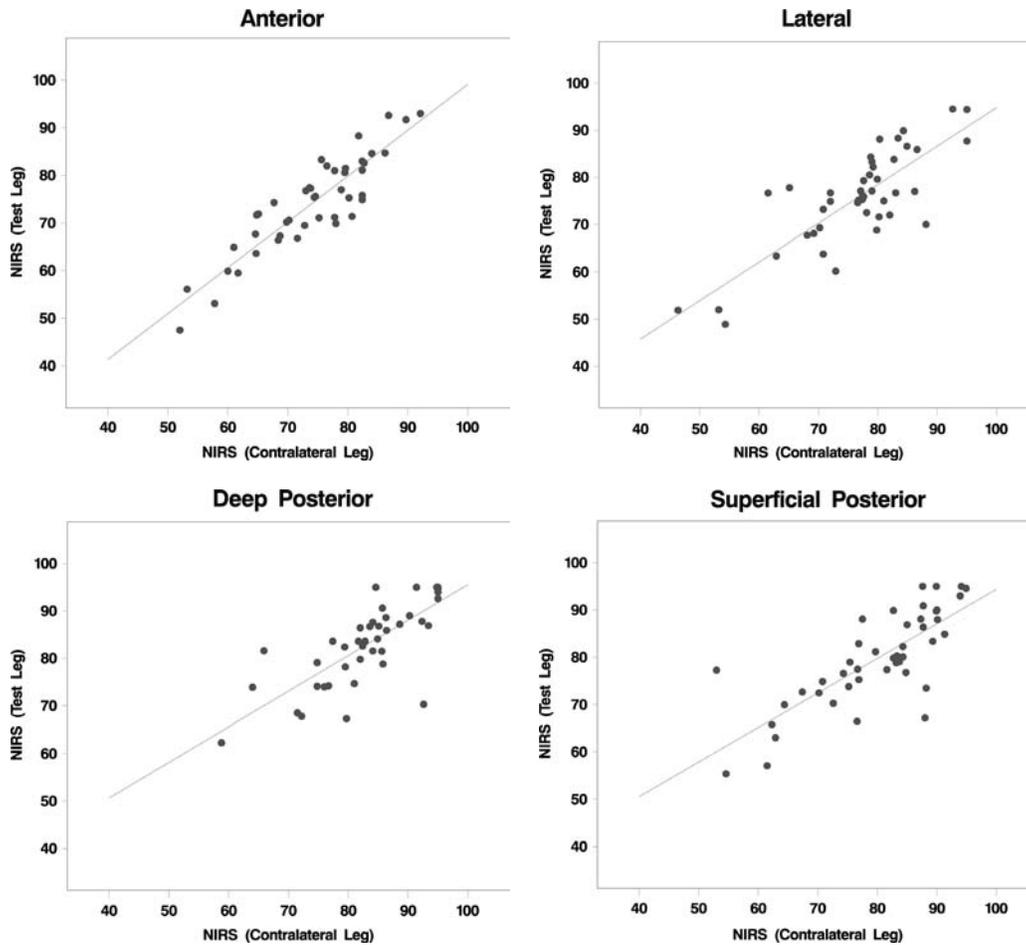
respectively, for analogous compartments of the contralateral leg. The summary NIRS values of analogous compartments of contralateral legs were highly correlated (Pearson correlations:  $r = 0.90, 0.81, 0.78,$  and  $0.76,$  respectively;  $p < .0001$  for all compartments; Fig. 2). Mean differences between corresponding compartments for each compartment were  $0.1\%, -0.9\%, -0.2\%, 0.4\%$  (test minus contralateral leg; anterior, lateral, superficial posterior, and deep posterior compartments, respectively).

In the upper extremity, mean summary values for the volar, dorsal, and deltoid compartments were  $78.2\%, 69.2\%,$  and  $82.0\%,$  respectively. Of the three compartments tested in the upper extremity, NIRS values of the volar forearm were most highly correlated with compartments of the lower extremity (Pearson correlations:  $r = 0.71, 0.65, 0.65,$  and  $0.65;$  anterior, lateral, superficial posterior, and deep posterior compartments, respectively; Fig. 3); however, values of the dorsal and deltoid compartments also demonstrated significant positive correlations with the lower extremity (dorsal:  $r = 0.60, 0.55, 0.5,$

and  $0.36;$  deltoid:  $r = 0.51, 0.50, 0.45,$  and  $0.42$  for Pearson correlations with the anterior, lateral, superficial, and deep posterior compartments, respectively;  $p < .05$  for all compartments). None of the compartments of the upper extremity demonstrated a relationship comparable to the corresponding compartment of the contralateral lower extremity. NIRS values of the leg compartments demonstrated excellent reliability across the 2 days of monitoring ( $ICC \geq 0.70$  for all compartments, Table 2).

**TABLE 2** Mean NIRS values and intraclass correlation coefficients (ICC) for tests 1 and 2, among 44 uninjured subjects

Compartment	Test 1 (Mean)	Test 2* (Mean)	ICC
Anterior	74.1	75.0	0.80
Lateral	75.6	78.1	0.73
Superficial posterior	79.7	81.5	0.81
Deep posterior	82.9	85.1	0.70



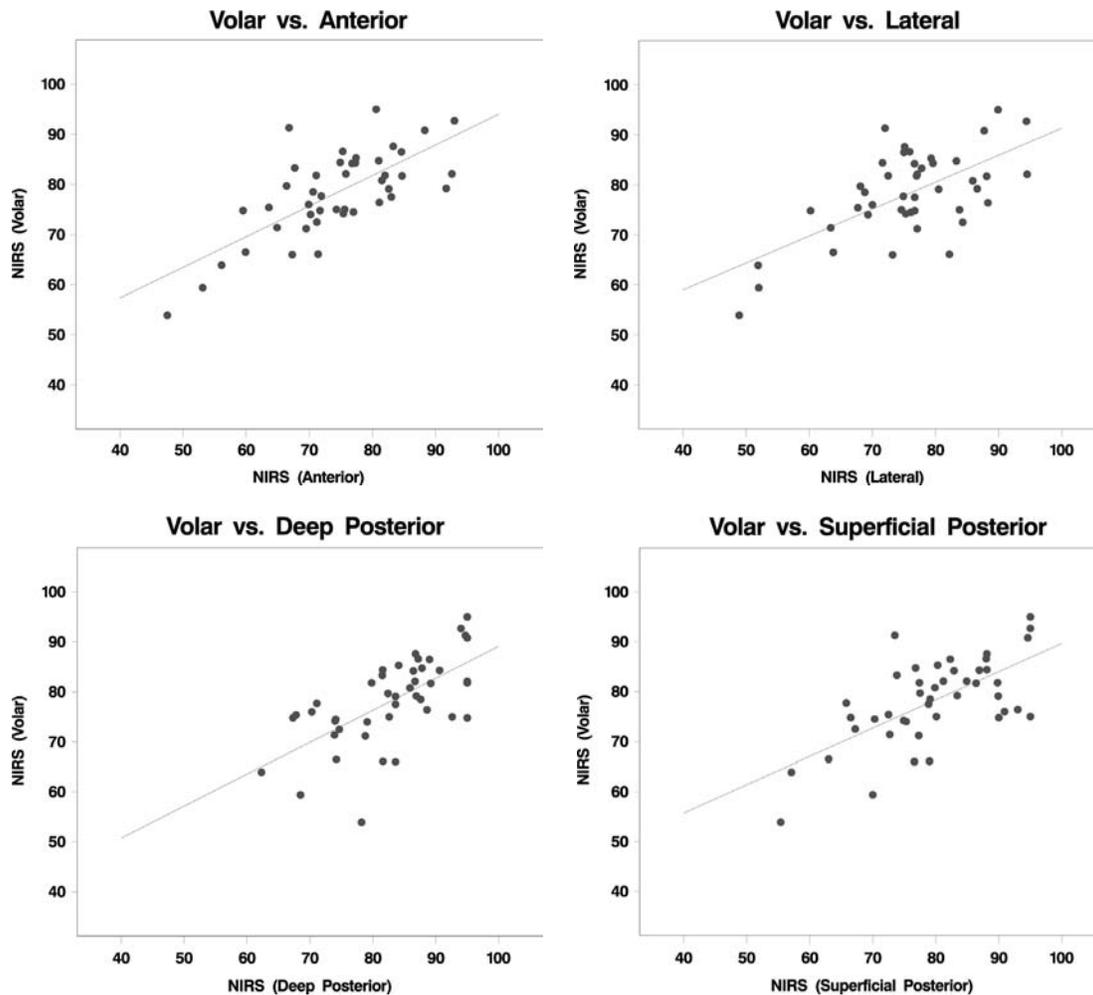
**FIGURE 2** Mean NIRS values and Pearson correlation coefficients for corresponding compartments of contralateral lower extremities, among 44 uninjured subjects. Pearson correlation coefficients: anterior:  $r = 0.90, p < .0001$ ; lateral:  $r = .81, p < .0001$ ; DP:  $r = .78, p < .0001$ ; SP:  $r = .76, p < .0001$ .

**TABLE 3** Mean, standard deviation, and Spearman correlation coefficients between NIRS of each compartment of the lower extremity and colorimeter values, taken from the posterior calf of 44 uninjured subjects

	N	Mean (SD)	Spearman Correlation Coefficients			
			Anterior	Lateral	Superficial Posterior	Deep Posterior
Melanin (M)	44	38.9 (12.2)	$r = -0.66$ $p < .0001$	$r = -0.59$ $p < .0001$	$r = -0.54$ $p = .0002$	$r = -0.45$ $p = .002$
Erythema (E)	44	11.2 (3.2)	$r = -0.38$ $p = .01$	$r = -0.30$ $p = .05$	$r = -0.32$ $p = .03$	$r = -0.24$ $p = .12$
Luminance (L*)	26	35.4 (8.5)	$r = 0.61$ $p = .0009$	$r = 0.53$ $p = .006$	$r = 0.69$ $p < .0001$	$r = 0.49$ $p = .01$
a*	26	9.6 (4.6)	$r = -0.17$ $p = .41$	$r = -0.18$ $p = .38$	$r = -0.32$ $p = .11$	$r = -0.10$ $p = .63$
b*	26	10.9 (3.0)	$r = -0.45$ $p = .02$	$r = -0.35$ $p = .08$	$r = -0.41$ $p = .04$	$r = -0.57$ $p = .003$

The average melanin value of this study population was 38.9 (SD = 12.2), while erythema values averaged 11.1 (SD = 3.2; Table 3). Moderate negative correlations were observed between NIRS values and melanin values

(Spearman correlations: anterior:  $r = -0.66, p < .0001$ ; lateral:  $r = -0.59, p < .0001$ , superficial posterior:  $r = -0.54, p = .0002$ ; deep posterior:  $r = -0.45, p = .002$ ; Table 3), whereas correlations observed between NIRS



**FIGURE 3** Mean upper extremity NIRS values and Pearson correlation coefficients for the relationships between NIRS values of upper extremity and lower extremity compartments, among 44 uninjured subjects. Pearson correlation coefficients: volar vs. anterior:  $r = 0.71$ ,  $p < .0001$ ; volar vs. lateral:  $r = 0.65$ ,  $p < .001$ ; volar vs. DP:  $r = 0.65$ ,  $p < .0001$ ; volar vs. SP:  $r = 0.65$ ,  $p < .0001$ .

and erythema values were weak. IMS Smart-Probe L\*, a\*, and b\* values were also available on a subset of participants ( $n = 26$ ) and are also presented in Table 3. Mean L\* (luminance) values were 35.4 (SD = 8.5) and showed moderate positive correlations with NIRS values collected from each compartment (anterior:  $r = 0.61$ ,  $p = .0009$ ; lateral:  $r = 0.53$ ,  $p = .006$ ; superficial posterior:  $r = 0.69$ ,  $p < .0001$ ; deep posterior:  $r = 0.49$ ,  $p = .01$ ; Table 3). Correlations between a\* values, b\* values, and NIRS were not conclusive (Table 3).

No qualitative differences in sensor adhesion were noted in the 12 patients with or without leg hair. Mean differences in summary NIRS values collected pre- and postshave were found to be minimal (pre minus post differences: anterior = 0.73, lateral = -2.54, superficial posterior = 2.52, deep posterior = -1.28). Additionally, ranges of values observed during 5-minute monitoring periods collected pre- and postshave were similar (mean

pre shave range of values: anterior  $r = 7.7$ , lateral = 3.8, superficial posterior = 4.0, deep posterior = 2.4 versus mean postshave range of values: anterior = 7.8, lateral = 6.7, superficial posterior = 3.8, deep posterior = 3.8).

## Discussion

This study found a large amount of variability in NIRS values between individuals and moderate variability of measurements within the same compartment over the hour-long testing interval. However, bivariate comparisons of summary NIRS values revealed high correlations between corresponding compartments. Secondly, skin pigmentation values were associated with NIRS recordings, while the presence or absence (after shaving) of leg hair did not appear to have an effect on NIRS measurements. Fat thickness at the posterior calf was less than 2 cm for all participants and  $\leq 1$  cm for most, in all cases

less than the engineered measurement depth of the device of 2 to 3 cm (22); therefore, we do not expect significant measurement error among this group of participants attributable to fat (22).

The results of this study confirm previous findings (20, 21) establishing the analogous compartment in the uninjured leg as the most valid internal control in the setting of unilateral severe leg injury. In cases where bilateral legs are injured, our preliminary findings suggest that the volar forearm is the most promising control site in the upper extremity. However, none of the upper extremity sites were as well correlated as the analogous compartment of the contralateral extremity, and upper extremity NIRS values did not appear to mirror fluctuation seen over a prolonged period as closely as lower extremity controls.

The present study is thus the first to evaluate intracompartamental NIRS values over time in healthy individuals. Not surprisingly, these measures, like most physiologic values, show time-dependent fluctuations and variability. Intracompartamental changes observed over time tended to be mirrored in the analogous compartment of the contralateral extremity. These patterns suggest that the diagnosis of ACS may be more accurately based on deviations between like compartments measured over time than on isolated absolute values. To this end, in a recently published observational study investigating the ability to detect a known compartment syndrome using raw (unadjusted) NIRS values, instead of comparative values between analogous compartments, Bariteau and colleagues concluded that “near-infrared spectrometry would not serve as a reliable diagnostic tool” (25). Although that study was limited by an extremely small sample size ( $n = 7$ ), the findings of the current investigation of uninjured controls are consistent with respect to the use of raw NIRS values. This observed weakness suggests that unadjusted measures, especially isolated readings, are probably not an effective utilization of this technology for diagnosing ACS. The findings of the present study as well as previous work demonstrate that this weakness is overcome by using NIRS-based diagnostic criteria that rely on comparative thresholds between analogous compartments and continuous versus isolated, single point-in-time measurements.

The lack of an observed difference in NIRS values in the presence or absence of leg hair has important implications for the use of NIRS in a clinical setting. The observation that NIRS values were similar when collected with and without hair allows providers to dedicate their resources and efforts to patient care and resuscitation, rather than preparation and shaving of the injured extremity and control sites. Conversely, reliable NIRS values may still be obtained if the extremity had been

shaven preinjury or is to be shaven before an operative procedure or to assist with proper adhesion of the sensor.

Previous reports have noted lower absolute NIRS values individuals with higher skin pigmentation (20, 26). In their 2009 investigation, Shuler et al. (20) observed decreases of 7.4 to 9.9 percentage points, on average, among black individuals. In this study, we observed moderate correlations between NIRS values and two measures that quantify the amount of pigment in the skin, melanin and luminance. This is consistent with previous studies and suggests that skin pigment may have an effect on NIRS values; it is important that control versus test compartment correlations appeared unaffected by these differences. Additionally, this effect may be more substantial with some manufacturers versus other systems that have additional measures to account for skin pigment.

The current investigation is not without limitations. First, this study does not test the stated hypotheses in traumatized patients. Lower extremity fractures, with or without an associated ACS, create a unique physiologic state. Although it is plausible that these physiologic changes would not affect the validity of using the corresponding compartment or the volar forearm as internal controls over time, there are, to date, no longitudinal data to substantiate this supposition. Second, this study does not provide elucidation of the possible role of increased subcutaneous fat, because the participants included in this study had relatively lean lower extremities. Third, the participants of this study were not ethnically diverse. Although the current sample population did demonstrate a negative correlation between NIRS values and melanin content, we do not know if this finding can be extrapolated to all ethnicities. Fortunately, the use of adjusted NIRS values based on an internal control should also control for any differences in skin pigment. Additionally, some other NIRS manufacturers have shown the ability to limit the influences of skin pigments. Ongoing studies are investigating these issues among both soldiers and civilians with severe leg injuries. We are also investigating NIRS on patients in critical condition following major trauma other than lower extremity injury, because we hypothesize that the physiologic response to trauma (regional and systemic) may decrease or eliminate the intracompartamental variability in absolute NIRS values over time that we observed among healthy volunteers in this study. Future investigations should attempt to confirm the findings of the current study in populations with associated major extremity injury or fracture as well as prove the technology’s overall accuracy and clinical utility in identifying the presence of an overt or impending ACS over a prolonged monitoring interval.

## Conclusion

NIRS technology represents a potentially promising advance in the diagnosis of, and monitoring for, ACS in both military and civilian populations. The results of this study suggest that the analogous compartment in the contralateral leg is the ideal control site in cases of unilateral trauma. In cases of bilateral trauma, the volar forearm may provide a useful comparative site, but is not as well correlated with NIRS values as the contralateral lower extremity compartments. The presence or absence of leg hair did not seem to affect NIRS values. Skin pigmentation demonstrated a modest negative correlation with absolute NIRS values; however, the use of an internal control compartment appears to adequately mitigate skin pigment influences on NIRS values.

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