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Correlation Between Muscle Oxygenation and Compartment Pressures in Acute Compartment Syndrome of the Leg

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Investigation performed at Grady Memorial Hospital, Atlanta, and Emory University, Atlanta, Georgia

Background: Near-infrared spectroscopy estimates soft-tissue oxygenation approximately 2 to 3 cm below the skin. The purpose of the present study was to evaluate muscle oxygenation in the setting of an acute compartment syndrome of the leg and to determine if near-infrared spectroscopy is capable of detecting perfusion deficits.

Methods: Fourteen patients with unilateral lower extremity trauma were enrolled after the diagnosis of an acute compartment syndrome was made clinically and confirmed with intracompartmental pressure measurements. Lower extremity muscle compartments were evaluated with near-infrared spectroscopy, and near-infrared spectroscopy values of the uninjured, contralateral leg of each patient were used as internal reference values. The compartment perfusion gradient was calculated as the diastolic blood pressure minus the intracompartmental pressure.

Results: Intracompartmental pressures ranged from 21 to 176 mm Hg (mean, 79 mm Hg) and exceeded 30 mm Hg in all compartments but two (both in the same patient). Thirty-eight compartments had a perfusion gradient of $\leq 10$ mm Hg (indicating ischemia). Among ischemic compartments, near-infrared spectroscopy values in the anterior, lateral, deep posterior, and superficial posterior compartments of the injured limbs were decreased by an average 10.1%, 10.1%, 9.4%, and 16.3% in comparison with the corresponding compartments of the uninjured leg. Differences in near-infrared spectroscopy values (the near-infrared spectroscopy value for the injured leg minus the near-infrared spectroscopy value for the uninjured leg) were positively correlated with compartment perfusion gradient within each compartment ($r = 0.82, 0.65, 0.67, \text{ and } 0.62, \text{ for the anterior, lateral, deep posterior, and superficial posterior compartments, respectively; } p < 0.05 \text{ for all}$).

Conclusions: Normalized near-infrared spectroscopy values decrease significantly with decreasing lower limb perfusion pressures. Near-infrared spectroscopy may be capable of differentiating between injured patients with and without an acute compartment syndrome.

Level of Evidence: Diagnostic Level IV. See Instructions to Authors for a complete description of levels of evidence.

The diagnosis of an acute compartment syndrome is based on clinical suspicion and is confirmed with physical examination and intracompartmental pressure measurements. Intracompartmental pressure measurements, the only objective diagnostic tool available to clinicians, are invasive, and values can vary greatly if measurements are not performed correctly.

Tissue ischemia results from hypoperfusion due to the loss of the pressure gradient between arterial pressure and the intracompartmental pressure. Historically, on the basis of laboratory experimentation in the late 1960s followed by clinical confirmation, Whitesides et al. identified the pressure perfusion gradient at which ischemia is imminent and prophylactic fasciotomy should be done as $<20$ mm Hg below diastolic blood pressure. Later, a pressure of 30 mm Hg was suggested as an absolute threshold for the diagnosis of compartment syndrome and was popularized and used for numerous years. However, further research confirmed the importance...
of the pressure gradient between blood pressure and the intracompartmental pressure as a cause of tissue ischemia.\textsuperscript{1,3,14-16}

Tissue injury is based on ischemia caused by hypoperfusion or deoxygenation. The measurement of tissue oxygenation has been suggested as a possible noninvasive, continual, and responsive means for physicians to evaluate a suspected compartment syndrome.\textsuperscript{7-21} Near-infrared spectroscopy utilizes differential light absorption properties to solve for the concentrations of oxygenated and deoxygenated hemoglobin through the use of the Beer-Lambert law.\textsuperscript{22-25} Light in the near-infrared range (600 to 1000 nm) is capable of penetrating through skin, soft tissue, and bone. The majority of light absorption is based on the relative concentrations of oxygenated and deoxygenated hemoglobin in the microcirculation. Because large vessels or hematomas absorb the light completely, the only light collected by the sensors is light that is capable of passing through the microcirculation.\textsuperscript{26} This technology is similar to a pulse-oximeter through its use of light to solve for the percentage of oxygenated hemoglobin, but near-infrared spectroscopy is capable of sampleing tissue as deep as 3 cm below the skin, such as cerebral tissue and muscle.\textsuperscript{22,24,27-30} The depth of tissue penetration or the location of tissue oxygenation measurement is directly proportional to the distance or separation between the light source and the light receptor.\textsuperscript{22,24}

The purpose of the present study was to evaluate muscle oxygenation of the leg in the setting of acute compartment syndrome with use of near-infrared spectroscopy. We hypothesized that altered (decreased) muscle oxygenation would be correlated with the intracompartmental tissue perfusion gradient and that these responses could be detected with near-infrared spectroscopy.

**Materials and Methods**

After receiving institutional review board approval and individual patient informed consent, fourteen consecutive patients who were managed for an acute compartment syndrome after unilateral lower extremity trauma were recruited into this study. Treatment was provided at a Level-I trauma center between October 1, 2006, and March 1, 2009.

The study group consisted of consecutive patients with an acute compartment syndrome that had been diagnosed clinically and confirmed with intracompartmental pressure. The cohort consisted of patients between the ages of thirteen and eighty-five years with a unilateral leg injury. Exclusion criteria included bilateral lower extremity injury and previously diagnosed peripheral vascular disease or pulmonary insufficiency. The clinical diagnosis was based on pain out of proportion, pain with passive stretch of the toes and foot, and palpation of firm compartments. Intracompartamental pressure within 30 mm Hg of diastolic blood pressure was used for the confirmation of compartment syndrome and the threshold for surgical release through a four-compartment fasciotomy.\textsuperscript{10,13,14,16-18} All patients were diagnosed by the senior orthopaedic surgeon at the time of diagnosis prior to recruitment and were determined to require a fasciotomy for treatment.

Once the clinical diagnosis and treatment were determined, the patient was enrolled in the study. Near-infrared spectroscopy values were then recorded prior to intracompartmental pressure measurements to ensure that needle insertion did not influence the near-infrared spectroscopy values. All patients with a clinical diagnosis of acute compartment syndrome had at least one intracompartamental pressure reading within 30 mm Hg of the diastolic blood pressure.

Age, sex, race, body mass index, and blood pressure at the time of evaluation were recorded for each patient. The injury classification, the fracture location, the mechanism of injury, and the time from the injury to measurement were recorded. All measurements, including near-infrared spectroscopy values and intracompartmental pressure measurements, were obtained within one hour after the diagnosis of the compartment syndrome had been determined clinically. Near-infrared spectroscopy and intracompartmental pressure values were obtained after provisional reduction of the fracture in the emergency department. All splints and circumferential bandages were removed prior to measurement. The foot was maintained in a neutral position, with the heel placed on a rolled towel to prevent pressure in the posterior compartments. Intracompartamental pressures were obtained within 5 cm from the fracture. A Stryker pressure gauge (Stryker Surgical, Kalamazoo, Michigan), which employs a side port needle, was utilized to obtain the intracompartamental measurements. Intracompartamental pressures were obtained in the injured extremity for all four compartments of the leg including the anterior, lateral, deep posterior, and superficial posterior compartments. The compartment perfusion gradient was calculated as the diastolic blood pressure minus the intracompartmental pressure. Near-infrared spectroscopy values were obtained for both the injured side as well as the uninjured side. The data collection methods have been described in previous reports.\textsuperscript{30}

Near-infrared spectroscopy measurements were obtained as described by Shuler et al.\textsuperscript{30} Briefly, near-infrared spectroscopy measurements were obtained approximately 2 to 3 cm below the skin with use of the INVOS Cerebral Oximeter 4100 (Somanetics, Troy, Michigan). Measurements were obtained at the level of the middle part of the tibia for all four compartments. Near-infrared spectroscopy values represented a percentage of oxygenated hemoglobin and ranged from 25% to 95%. The device is precalibrated during the manufacturing process and does not require additional calibration prior to use.\textsuperscript{24,30,32}

We distinguished between two types of acute compartment syndrome: clinical compartment syndrome (which constituted a criterion for inclusion in the study) and ischemic compartment syndrome (referring to the presence of a perfusion gradient of ≤10 mm Hg within a compartment). A diagnosis of clinical compartment syndrome was based on physical examination and an intracompartmental pressure within 30 mm Hg of the diastolic pressure as initially described by Whitesides\textsuperscript{30,33} and confirmed by multiple other authors.\textsuperscript{14,34,35} This threshold was advocated in order to perform fasciotomies prior to muscle ischemia, which, when main-
tained for extended periods, results in permanent muscle necrosis. However, altered perfusion has been shown to occur once the intracompartmental pressure nears diastolic pressure. Matava et al. showed, in a canine study, that intracompartmental pressure within 20 mm Hg of diastolic pressure resulted in no signs of tissue necrosis whereas intracompartmental pressure held within 10 mm Hg of diastolic pressure resulted in substantial necrosis on pathological examination and loss of contractility on gross examination. This threshold was clinically confirmed by Prayson et al. in a series of patients with isolated lower extremity trauma who were managed nonoperatively without complication. More than half of the patients were shown to have perfusion pressures as low as 20 mm Hg, and more than 80% were found to have perfusion pressures within 30 mm Hg of diastolic pressure at some point during the evaluation period. Therefore, because near-infrared spectroscopy measures oxygenated hemoglobin concentrations, a change in concentration would not be expected until the intracompartmental pressure was within 10 mm Hg of diastolic pressure. A perfusion pressure of ≤10 mm Hg

### TABLE I Intracompartmental Pressures and Near-Infrared Spectroscopy Values Across Compartments for Fourteen Patients with Unilateral Lower Extremity Trauma and Acute Compartment Syndrome With Ischemia* Compared With Literature-Based Values for Comparable Injury Without Acute Compartment Syndrome

<table>
<thead>
<tr>
<th>Trauma with acute compartment syndrome* (no. of patients)</th>
<th>Anterior Compartment</th>
<th>Lateral Compartment</th>
<th>Deep Posterior Compartment†</th>
<th>Superficial Posterior Compartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intracompartmental pressure, injured leg (mm Hg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>99</td>
<td>92</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>35.9</td>
<td>37.7</td>
<td>28.6</td>
<td>20.8</td>
</tr>
<tr>
<td>Range*</td>
<td>57 to 170</td>
<td>55 to 176</td>
<td>58 to 135</td>
<td>61 to 115</td>
</tr>
<tr>
<td>Near-infrared spectroscopy, injured leg (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>45</td>
<td>46</td>
<td>56</td>
<td>49</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>14.3</td>
<td>13.4</td>
<td>13.5</td>
<td>14.1</td>
</tr>
<tr>
<td>Range</td>
<td>15 to 66</td>
<td>15 to 62</td>
<td>36 to 75</td>
<td>22 to 69</td>
</tr>
<tr>
<td>Near-infrared spectroscopy, uninjured leg (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>55</td>
<td>56</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10.8</td>
<td>11.3</td>
<td>7.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Range</td>
<td>41 to 76</td>
<td>38 to 76</td>
<td>54 to 75</td>
<td>45 to 85</td>
</tr>
<tr>
<td>Near-infrared spectroscopy difference‡ (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>−10.1</td>
<td>−10.1</td>
<td>−9.4</td>
<td>−16.3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>11.6</td>
<td>7.4</td>
<td>10.8</td>
<td>15.8</td>
</tr>
<tr>
<td>Range</td>
<td>−26 to 8</td>
<td>−25 to 1</td>
<td>−24 to 4</td>
<td>−47 to 3</td>
</tr>
<tr>
<td>P value§</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0003</td>
</tr>
<tr>
<td>Trauma without acute compartment syndrome* (n = 26)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near-infrared spectroscopy difference (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>+14.2</td>
<td>+14.9</td>
<td>+17.2</td>
<td>+13.7</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>7.7</td>
<td>7.7</td>
<td>6.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Range</td>
<td>5 to 34</td>
<td>5 to 37</td>
<td>2 to 28</td>
<td>5 to 28</td>
</tr>
</tbody>
</table>

*Includes compartments with a perfusion gradient (diastolic blood pressure minus intracompartmental pressure) of ≤10 mm Hg (indicating ischemia). †Data were unavailable for the deep posterior compartment of five patients. ‡The near-infrared spectroscopy difference is defined as the near-infrared spectroscopy value for the injured leg minus the near-infrared spectroscopy value for the uninjured leg. §Signed rank test for near-infrared spectroscopy difference between injured and uninjured compartments ≠ 0.
was considered to be the indication of an ischemic compartment syndrome and was used to differentiate between patients with clinical indications for fasciotomy and those expected to show hypoperfusion.

With regard to outcomes, all patients in the current study received a two-incision four-compartment fasciotomy. There were no signs of muscle necrosis, and all patients had viable tissue at the time of fasciotomy, with the exception of one patient who required débridement of the anterior compartment musculature because of necrosis at the time of fasciotomy. The near-infrared spectroscopy reading over this compartment was 47% and was 29 percentage points below that for the contralateral, uninjured side.

Six postoperative wound complications occurred, including hypergranulation and numbness over split-thickness skin grafts. Three patients required irrigation and débridement because of wound infections, and one of those patients ultimately went on to have a nonunion of the fracture that necessitated revision surgery. One patient required physical therapy to resolve an equinus contracture. An additional patient had a foot drop due to nerve injury associated with the original injuries and ultimately required a rotational flap for wound coverage. Three patients ultimately were lost to follow-up after the immediate postoperative period.

### Statistical Analysis

Intracompartmental pressure and near-infrared spectroscopy values were summarized as means, standard deviations, and ranges across compartments. Differences in near-infrared spectroscopy values between the injured and uninjured sides were tested for significance with use of the signed rank test. The perfusion gradient was calculated for each compartment as the difference between the diastolic blood pressure and the intracompartmental pressure. A negative value for the perfusion gradient indicates that the compartment pressure exceeded the diastolic blood pressure. The relationship of the perfusion gradient to the near-infrared spectroscopy difference was characterized with use of graphical methods and Spearman correlation.

**Figs. 1-A through 1-D** Scatter plots showing a positive linear correlation between the perfusion gradient (the diastolic blood pressure minus the compartment pressure) and the near-infrared spectroscopy (NIRS) difference (the value for the injured leg minus the value for the uninjured leg) for the four lower extremity muscle compartments. **Fig. 1-A** Anterior compartment ($r = 0.82$, $p = 0.001$). **Fig. 1-B** Lateral compartment ($r = 0.65$, $p = 0.016$). **Fig. 1-C** Deep posterior compartment ($r = 0.67$, $p = 0.049$). **Fig. 1-D** Superficial posterior compartment ($r = 0.62$, $p = 0.018$). The asterisks (*) indicate observations in which the compartment pressure exceeded the systolic blood pressure (see Statistical Analysis).
rank correlation. Because we expected that a linear decrease in near-infrared spectroscopy values with a decreasing perfusion gradient would level off beyond a threshold of very high compartment pressures with absent perfusion, we chose to exclude compartments in which the intracompartmental pressure exceeded the systolic blood pressure from the correlation analysis only. This decision resulted in the exclusion of two measurements in two compartments (in the same patient). These compartments were shown for reference on all scatter plots with use of distinct symbols; however, they were excluded from all correlation statistics and regression calculations.

Nonparametric methods were employed because of the small sample size; symmetric distributions were confirmed graphically. All statistical tests were two-sided, with the level of alpha set at 0.05. A pre-study power analysis indicated that fourteen patients would provide 80% power at an alpha of 0.05 to detect a simple linear correlation between the near-infrared spectroscopy difference and the perfusion gradient within individual compartments, assuming a true population correlation coefficient of $r = 0.65^{36}$.

**Source of Funding**

Funding was provided by Somanetics and Stryker in the form of equipment donation only.

**Results**

Fourteen male patients with a mean age of 37.4 years (range, fifteen to sixty-two years) were managed for an acute compartment syndrome and participated in the study. Six injuries were on the right side, and eight were on the left. The skeletal injuries consisted of eight tibial shaft fractures (including four in the proximal third of the tibia, three in the middle third, and one in the distal third) and six tibial plateau fractures (including one Schatzker type-III, one Schatzker type-V, and four Schatzker type-VI fractures). The mechanisms of injury included six motor-vehicle accidents, four falls from a height, three pedestrian-automobile accidents, and one gunshot wound. The average time from the injury to measurement was eleven hours (range, five to twenty-eight hours). At the time of evaluation, the mean systolic and diastolic blood pressures were 135 mm Hg (range, 92 to 192 mm Hg) and 72 mm Hg (range, 55 to 100 mm Hg), respectively. Eight patients were black, four were white, one was Hispanic, and one was Asian. The mean body mass index was 26.6 kg/m² (range, 22.4 to 31.9 kg/m²). Five patients were intubated at the time of enrollment.

The mean intracompartmental pressure for all compartments of the injured legs was $79 \pm 33.0$ mm Hg (range, 21 to 176 mm Hg). The intracompartmental pressure was >30 mm Hg in all compartments but two (both in the same patient). Thirty-eight compartments had a perfusion gradient of $\leq 10$ mm Hg (indicating ischemia). Among ischemic compartments, near-infrared spectroscopy values in the anterior, lateral, deep posterior, and superficial posterior compartments of the injured limbs were decreased by an average 10.1%, 10.1%, 9.4%, and 16.3%, respectively, in comparison with the corresponding compartments of the uninjured leg (Table I). Most compartments exhibited near-infrared spectroscopy deficits relative to the uninjured leg (Figs. 1-A through 1-D), and every patient in the present study showed a deficit in at least one compartment. The near-infrared spectroscopy values relative to the uninjured leg (the near-infrared spectroscopy value for the injured leg minus the near-infrared spectroscopy value for the uninjured leg) were positively correlated with the compartment perfusion gradient (the diastolic blood pressure minus the intracompartmental pressure) within each compartment (anterior compartment, $r = 0.82$, $p = 0.001$; lateral compartment, $r = 0.65$, $p = 0.016$; deep posterior compartment, $r = 0.67$, $p = 0.049$; and superficial posterior compartment, $r = 0.62$, $p = 0.018$) (Figs. 1-A through 2).

The first five patients who were enrolled did not have near-infrared spectroscopy measurements for the deep posterior compartment because we had not devised a way to perform the measurements for that compartment until before the sixth patient was enrolled.

**Discussion**

The body’s response to injury is to increase blood flow to the site of trauma$^{12,39-42}$. Near-infrared spectroscopy measurements reflect a weighted venous arterial average in the capillary bed of soft tissues. Sandegård and Lewis studied vasodilation and hyperemia associated with trauma and injury$^{40,41,47-48}$. The finding of increased near-infrared spectroscopy values in the setting of trauma is consistent with these previous reports and was confirmed in previous studies of injured patients without an acute compartment syndrome$^{44,30}$.

Near-infrared spectroscopy has previously been utilized in the setting of acute compartment syndrome (although with use of a different device than the one used in the present study). Characterization of the perfusion gradient in each individual compartment can be helpful in determining early ischemia in the setting of injury. Near-infrared spectroscopy values and perfusion gradient were shown to be nonparametrically correlated within an individual compartment and between compartments. This conclusion was based on a study with a small sample size. Additional research is necessary to verify the findings and determine the role of near-infrared spectroscopy in the setting of acute compartment syndrome.
study). An initial animal study involving an infusion compartment syndrome model in pigs showed that near-infrared spectroscopy values were inversely related to intracompartmental pressures. A follow-up study demonstrated the responsiveness of near-infrared spectroscopy in the setting of both hypotension and hypoxemia. In a simulated model involving human volunteers, near-infrared spectroscopy was shown to be more sensitive to an ischemic condition measured with nerve conduction studies when compared with perfusion pressure. Last, in a study of patients with an established acute compartment syndrome, near-infrared spectroscopy values were decreased at the time of initial measurement and rebounded after fasciotomy.

While the technology of near-infrared spectroscopy has been available for almost two decades, its application for the diagnosis of acute compartment syndrome has been impeded by many factors. First, a publicly available device that provides measurements deep enough to sample leg tissue has not been readily available until recently. Previous near-infrared spectroscopy devices required timely calibration through the induction of ischemia and reperfusion in order to establish 0% and 100% saturation levels. Early devices utilized a single depth of penetration to sample hemoglobin saturation. Newer near-infrared spectroscopy devices utilize multiple levels of sampling to isolate deeper tissue values. In addition, the ability to access the deep posterior compartment was not appreciated prior to the recent description by Shuler et al. The lack of measurements for the deep posterior compartment in the first five patients was due to the fact that we had not determined this possibility until before the sixth patient was enrolled. Last, the lack of consideration for the hyperemic response to trauma resulted in an underappreciation of the ability of near-infrared spectroscopy to reflect perfusion changes.

In order to interpret near-infrared spectroscopy values in the setting of an acute compartment syndrome, normal values for both an uninjured patient and an injured patient without compartment syndrome must be established. It has been shown that lower extremity trauma causes a predictable increase in near-infrared spectroscopy values in the absence of compartment syndrome and that the corresponding compartment of the contralateral leg offers an excellent internal reference value for near-infrared spectroscopy when evaluating the hyperemic response to injury. Shuler et al. demonstrated that lower extremity trauma resulted in an average 15 percentage point increase in near-infrared spectroscopy values (hyperemia) across compartments among twenty-six patients with unilateral injuries who never had development of a compartment syndrome and that the near-infrared spectroscopy values of the injured limb were greater than those of the uninjured limb in every compartment of every patient (minimum difference, +2%).

In contrast, most compartments of our comparably injured patients with an acute compartment syndrome exhibited a deficit in near-infrared spectroscopy values when compared with the values for the contralateral, uninjured leg, with normalized near-infrared spectroscopy values decreasing significantly in proportion to compartment perfusion gradients (Figs. 1-A through 2). These results suggest that if there is an absence of hyperemia in a patient with lower extremity trauma or fracture, the clinician should be concerned about impaired blood flow in the injured leg. Lack of hyperemia may be a sign of vascular injury or compartment syndrome. These findings have implications when considering the pathophysiology of compartment syndrome. It has been shown that a hyperemic response follows lower extremity trauma among patients who do not have development of compartment syndrome; accordingly, it seems that the natural course of posttraumatic acute compartment syndrome includes an initial phase of hyperemia prior to the increase in intracompartmental pressure sufficient to induce impaired perfusion.

Notably, there were two patients in the present study who demonstrated both hyperemia and hypoperfusion at the same time. While limited conclusions can be drawn from just two examples, some insight can be obtained from these patients. The first patient had perfusion pressures of 1 and 3 mm Hg in the anterior and lateral compartments, respectively, compared with perfusion pressures of 37 and 34 mm Hg in the superficial and deep posterior compartments, respectively. The compartments consistent with acute compartment syndrome (the anterior and lateral compartments) had a −1% near-infrared spectroscopy value in comparison with the uninjured leg, whereas the superficial and deep posterior compartments had values of +18% and +8%, respectively, when compared with their contralateral counterparts. This patient demonstrated hyperemia in compartments with adequate perfusion pressure (>20 mm Hg) while also showing an absence of hyperemia in compartments with poor perfusion (<10 mm Hg). In addition, the findings for this patient demonstrate how near-infrared spectroscopy is able to differentiate between individual compartments with different perfusion characteristics in the same leg.

The second patient had two compartments with perfusion pressures of >30 mm Hg and two compartments with pressures between 20 and 30 mm Hg. Near-infrared spectroscopy values were elevated in the two adequately perfused compartments demonstrating hyperperfusion. The two compartments with borderline perfusion with gradients between 20 and 30 mm Hg did not show hyperemia and the near-infrared spectroscopy values were roughly equal to those for the uninjured side. The findings for this patient with a borderline acute compartment syndrome suggest that compartment perfusion transitions from hyperemia to hypoperfusion as perfusion pressure drops from 30 to 10 mm Hg, consistent with previous studies. These longitudinal trends have not been directly documented, however, and our cross-sectional study design did not afford us the opportunity to observe the pre-ischemic condition of all of the patients. This conjecture warrants further study.

The hyperemia associated with trauma may account for some of the inconsistencies in the literature surrounding acute compartment syndrome. In previously described models
of compartment syndrome in which perfusion and intracompartmental pressures have been correlated, a hyperemic response associated with traumatic events has not been considered\textsuperscript{12,17,18,56,57}. In order to adequately reproduce the compartment syndrome model, the traumatic influences and associated hyperemic response must be understood and accounted for when analyzing the pressure and perfusion relationship.

White et al. reported no difference in clinical outcomes between patients with intramuscular pressures above and below the absolute 30-mm-Hg threshold\textsuperscript{16}. McQueen and Court-Brown showed that asymptomatic patients had intracompartamental pressures of as high as 50 mm Hg without development of a compartment syndrome\textsuperscript{16}. In a study of patients without compartment syndrome who were managed without fasciotomy, Prayson et al. reported perfusion pressures of $<20$ mm Hg in $>50\%$ of the enrolled patients\textsuperscript{23}. The existence of hyperemia in response to trauma may play a protective effect in patients with low to moderate intracompartmental pressures and may explain some of the disconnect found between model studies (lack of hyperemia) and clinical studies (presence of hyperemia). Of note, the only study to investigate the possible effects of traumatized tissue on perfusion was that by Heppenstall et al., who hypothesized that the ability of traumatized tissue to tolerate elevated intracompartamental pressures was actually decreased\textsuperscript{12}.

The present study had limitations. Because measurements were obtained at standardized locations, the possibility of different pressures and variable perfusion along the compartment may not have been appreciated\textsuperscript{1}. In addition, the near-infrared spectroscopy measurements were obtained for only a short period of time, roughly sixty seconds, which limits the information that can be obtained concerning a continual monitoring system. Although the patients in the present study were racially varied, our sample size was too small to evaluate or account for the potential influence of variable skin pigmentation on any correlation between near-infrared spectroscopy values and intracompartmental perfusion pressures. In addition, while no attempts were made to exclude female patients, previous studies have shown no difference in the response to trauma between the sexes\textsuperscript{30}. In the first five patients, a reading for the deep posterior compartment was not obtained. Because an isolated deep posterior compartment syndrome was not encountered in the present study, it is difficult to determine with certainty the ability of the device to isolate the deep posterior compartment.

The present study was designed to determine the potential for near-infrared spectroscopy to detect decreased perfusion in the setting of an acute compartment syndrome. While the pooled data suggest that the point at which the near-infrared spectroscopy values for both legs become equal is consistent with roughly 10 mm Hg of perfusion pressure, the definition of a critical point was outside of the scope of the present study. Additional studies examining the relationship of intracompartamental pressure and near-infrared spectroscopy values in a continual fashion are indicated. The present study examined near-infrared spectroscopy in patients with an existing compartment syndrome. The next studies should incorporate continual readings for patients as they progress through the development of an acute compartment syndrome in order to identify a critical threshold. This task should be performed through animal and human models as well as blinded observational studies of injured patients. The value of the near-infrared spectroscopy technology is its ability to monitor perfusion over extended periods and to respond in real time. ■

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