Figure 7. Mean water concentration comparing burn and local control sites of deep partial-thickness burns, demonstrating an increase in water concentration within the burn site at detector positions 1 (*$P_{.023}$) and 2 (**$P_{.032}$) but not at 3 ($P_{.129}$).

range of 350 to 1100 nm and, consequently, only the second overtone of water can be used.

Studies have been published in the cosmetic dermatology literature using NIR technology to assess the effects of different moisturizers or dehydrating solutions on the skin. NIR successfully differentiated the treatment regimens, but these studies were primarily interested in the hydration of the stratum corneum and not necessarily what is occurring in the deeper tissues.\textsuperscript{20,22} Kilpatrick et al allowed full-thickness porcine skin to be exposed to various relative humidity situations (100, 75, and 11% relative humidity). Overall, as relative humidity is lowered, there should be less water found in the skin. After 3 days of exposure to the humidity conditions, the water content of the skin was measured with an NIR device. They found that the higher the humidity, the greater the area under the absorbance band (the greater the amount of water in the tissue).\textsuperscript{41} Stamatas et al used a histamine injection model, which is used by dermatologists to mimic cutaneous edema. In this model, histamine injections are given to human subjects, and the edema reaction becomes noticeable in a dose-dependent fashion. In this study, NIR technology could measure the increasing levels of edema formation as the dose of histamine was increased.\textsuperscript{24} Our group used a rodent reverse McFarlane flap model to demonstrate the NIR’s ability to detect changes in edema. In this model, it has been well described that

Figure 8. Superficial partial-thickness burn. A, Digital photograph of burn region; B, NIR water image of burn region showing an increase in water in the burn site; C, Local control site showing no increase in water concentration. The superficial vasculature is also visualized in this image, as shown by the red arrow.
the proximal portion of the flap closest to the pedicle experiences an early rise in edema vs the distal region that desiccates. NIR technology measured an immediate increase in water up to 12 hours after flap elevation in the proximal zone, which declined back to baseline levels by 48 hours. The distal region experienced a 10% drop in water content after flap elevation, and this level continued to decline until 48 hours or the endpoint of the study. Overall, the spectrum of water has been so well elucidated that there is no debate over the fact that the 970-nm region represents an OH stretch and, consequently, a measurement of water content.

The ability of a noninvasive technology to assess edema has many applications in medicine. Specifically, the ability to measure water (edema) would enable an understanding of the pathophysiology of burn wound edema by its ability to track changes in water content over time. It could be used to assess end points of resuscitation and prevent an over resusciation of the patient and the complications associated with “fluid creep.” Crookes et al have been successful at determining the end points of resuscitation in trauma patients with NIR devices. End points are important in burn resuscitation but, more importantly, the debate continues about the usage of hypertonic saline, albumin, and other regimens to control edema formation and, at the same time, ensure adequate perfusion of the end organs. Finally, controlling edema in the chronic wound during rehabilitation is important in the functional recovery of the patient. However, it is difficult to assess treatment regimens when there is no gold standard for the noninvasive measurement of water content. A device that can measure edema would allow us to objectively evaluate many of the tools used to treat edema and determine the ones that are efficacious. The ability to assess end points of resuscitation, the type of resuscitation regimen, and a proper assessment of edema treatments has applications beyond the field of burns. In this study, NIR spectroscopy documented changes that occur between a burn wound and a healthy unburned region based on water content alone. The control sites or healthy unburned regions, when compared, showed no differences in water content at any of the detector positions. Eleven healthy unburned subjects were used to determine baseline levels of water content. Mean water content was lower in normal unburned patients than that measured in the local control sites of a burn patient. This suggests that the area surrounding the burn region also experiences the local effects of the burn wound, even in small TBSA injuries. Clinically, there was no noticeable edema at the control sites during the study period, which indicates that NIR point spectroscopy can detect changes in water content or edema that are not visible with the naked eye. This finding is consistent with our previous work using NIR to assess hydration in a rodent reverse McFarlane flap model. NIR technology was able to demonstrate these changes in the flap with accuracy as early as 5 minutes after surgery but did not become clinically apparent for 12 hours.

Most studies performed to date have compared partial-thickness injuries with full-thickness injuries with respect to edema formation and resorption. It is well documented that edema forms more rapidly in a partial-thickness injury compared with the full-thickness injury. The superficial vasculature is also visible in both the burn and control regions.
burn wounds, and peak edema tends to reach higher levels. However, little is known about the differences that may exist between a superficial and a deep partial-thickness injury. In this study, both burn types show high levels of water, but the deep partial-thickness wounds actually showed a 23% increase in water concentration compared with 18% in superficial partial-thickness burn wounds. The fact that superficial partial-thickness burns had less water than deep partial-thickness burns might suggest that superficial burns start the resorption process earlier or do not accumulate the same amount of edema as their deep counterparts at this time point. This is secondary to an intact lymphatic system that can resorb the accumulated edema fluid more rapidly. This finding is consistent with the literature, because full-thickness injuries do not resorb edema fluid as quickly with high levels of edema remaining at 48 hours, and 25% of the edema still remain 1 week after injury. Deep partial-thickness burn wounds seem to behave in the same manner with a limited capacity to resorb edema fluid quickly.

Water content in the burn wound varied depending on the detector position. The detectors are organized strategically to collect transmitted light from certain regions of the skin and subcutaneous tissue. Detectors 1 and 2 are the superficial and deep dermal detectors, with detector 3 at the subcutaneous tissue detector. Overall, the superficial detector showed less water content (15%) compared with the deeper tissue detectors (23%). This suggests that a greater amount of edema forms in the subcutaneous tissue, when compared with the dermis. Papp et al. used the dielectric constant to show in a porcine burn model that water content was increased in the subcutaneous fat over the other skin layers and compared with preburn levels. The greatest increase in subcutaneous water content was found in the partial-thickness injuries compared with the superficial- or full-thickness burns. Therefore, the increase in water concentration in the subcutaneous layer may be an important differentiating feature of burn depth.

This study represents our preliminary clinical experience with the NIR technology. There are several limitations of this study. The small sample population samples size reflects the nature of a pilot study. Our aim was to prove or disprove that NIR spectroscopy has potential as a noninvasive measure of edema in a clinical environment. Large TBSA burns were excluded, because they are resuscitated with varying levels of fluids, and this would have had an impact on the amount of edema accumulation. Differences in edema formation could have then been attributed to the varying levels of fluid given and would have added a confounding variable. In this study, we wanted to establish baseline results in a nonfluid resuscitated patient population before adding variables into the data processing. Data were collected from the burn wounds and local controls at the time point 48 hours after burn injury. This time point was chosen based on the referral patterns to our center for small TBSA injuries, and also, because at 48 hours, burn patients have reached their peak edema levels and should be in the plateau or the slow resorption phase. It is well known that edema formation is affected by time, burn depth, fluid resuscitation type, and volume, and our future work in this area will investigate these variables.

The study goal was to prove that NIR technology is capable of measuring water concentration and, therefore, edema. An additional finding from this study is the fact that edema levels could be used to differentiate partial-thickness injuries. This adds strength to our hypothesis that water content is an important variable when assessing burn depth using NIR spectroscopy and should be used in conjunction with oxyhemoglobin and deoxyhemoglobin variables. Future support for this statement comes from our early porcine burn studies, where a multivariate analysis using the three variables, water, oxyhemoglobin, and deoxyhemoglobin, dramatically improved the robustness of the NIR assessment of depth.

A noninvasive monitor of edema is instrumental in improving our knowledge of burn edema pathophysicsology. Without this knowledge, it is difficult to monitor the effects of current or new therapeutics, thereby limiting potential advances in this area. NIR holds promise as a new noninvasive, portable clinical tool to quantify edema in vivo. A tool that has the capacity to measure edema possesses medical applications that extend well beyond the field of burn wound physiology.

**REFERENCES**


27. Isengard HD. Water content, one of the most important properties of food. Food Control 2001;12:395–400.


