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MAJOR ARTICLE

Using Thermal Imaging to Track Cellulitis

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Background. Cellulitis is a common soft tissue infection and a major cause of morbidity. The diagnosis is based almost exclusively on clinical history and physical exam. To improve the diagnosis of cellulitis, we used a thermal camera to track how skin temperature of the affected area changed during a hospital stay for patients with cellulitis.

Methods. We recruited 120 patients admitted with a diagnosis of cellulitis. Daily thermal images of the affected limb were taken. Temperature intensity and area were analyzed from the images. Highest daily body temperature and antibiotics administered were also collected.

We estimated a longitudinal linear mixed-effects model with a random intercept for the affected body area. All observations on a given day were included, and we used an integer time indicator indexed to the initial day (ie, t = 1 for the first day the patient was observed, etc.). We then analyzed the effect of this time trend on both severity (ie, normalized temperature) and scale (ie, area of skin with elevated temperature).

Results. We analyzed thermal images from the 41 patients with a confirmed case of cellulitis who had at least 3 days of photos. For each day that the patient was observed, the severity decreased by 1.63 (95% CI, −13.45 to 10.32) units on average, and the scale decreased by 0.63 (95% CI, −1.08 to −0.17) points on average. Also, patients' body temperatures decreased by 0.28°F each day (95% CI, −0.40 to −0.17).

Conclusions. Thermal imaging could be used to help diagnose cellulitis and track clinical progress.

Keywords. cellulitis; surveillance; thermal imaging.

Cellulitis is a common infection and a major cause of morbidity [1]. Cellulitis is a common reason for hospitalization, and hospitalizations for cellulitis have recently increased [2]. The median length of hospital stay for cellulitis is 3 days, contributing to a total cost of $3.74 billion annually [2]. Yet, despite the frequency of cellulitis, diagnosis is sometimes difficult to make, leading to both underdiagnosis and overdiagnosis [3]. A diagnosis of cellulitis is primarily based on physical exam, and the infection is often confused with other diseases that affect the skin, so overdiagnosis is common. Stasis dermatitis, contact dermatitis, deep vein thrombosis, and lymphedema share some similar symptoms with cellulitis and can be confused with the infection [4, 5]. For example, a study conducted by David et al. found that 28% of hospitalized patients initially diagnosed with cellulitis were misdiagnosed, with the most common actual diagnosis being stasis dermatitis [4]. To date, there is no definitive, point-of-care test to confirm cellulitis. Laboratory testing for a nonspecific inflammatory response may be helpful for confirming a diagnosis of cellulitis, however, some patients may have normal or elevated leukocyte counts, body temperature, and erythrocyte sedimentation rate (ESR) [6].

In addition to the absence of reliable tests to diagnose cellulitis, there is a similar shortage of methods to track the infection's evolution and, as a consequence, the effectiveness of treatment. The purpose of this study was to explore the feasibility of using thermal images to track changes in skin temperature among patients admitted to the hospital with the diagnosis of cellulitis. Currently, there are no standard approaches to measure the skin temperature of patients with cellulitis. Thus, we used a thermal camera, FLIR One for iOS, to determine the extent to which local skin temperature was elevated around the affected area. FLIR, Forward Looking Infrared, has been used in a variety of studies to measure skin temperature in septic shock, exercise, and burns [7–9]. Studies by Ko et al. and Li et al. in 2018 examined the use of thermal imaging to aid in the diagnosis of cellulitis and found that it could be helpful in distinguishing cellulitis from pseudocellulitis, but they did not follow patients over time [10–12]. The purpose of this study was to evaluate if (1) a FLIR camera can be used as an objective measure of skin temperature in patients with soft tissue infections and (2) the temperature and area of skin captured by the FLIR camera correlate with the clinical course of soft tissue infections in hospitalized patients.

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METHODS

Patients were screened in the University of Iowa Hospitals and Clinics Emergency Department (ED) by research assistants, who were alerted to the presence of possibly eligible patients by ED residents, physician assistants, or attending physicians. Patients with suspected soft tissue infections in 1 or more extremities were approached if they were at least 21 years old, were undergoing empiric treatment with intravenous antibiotics for a possible soft tissue infection determined by the health care provider, and were expected to be admitted to the hospital for at least 1 day. Some patients had abscesses as part of their cellulitis. Patients were not enrolled if they had any facial infections or infection on the torso, were non-English-speaking, were prisoners, were pregnant, or had an aversion to research studies. If they were not enrolled in the ED, they could also be enrolled on the unit where they were admitted.

For each enrolled research subject, thermal images were taken once daily until discharge using the FLIR One for iOS attached to an iPad. The affected area was uncovered, and photos were taken from at least 3 different angles to ensure that the entire area was captured. A large metal washer serving as a room-temperature fiducial marker was placed on an unaffected area to provide a control for the size and temperature of the affected area. Because the washers are made from zinc, which has a relatively low heat capacity, we constructed 2 washers joined by an insulating silicone adhesive to slow the transfer of heat from the patient's skin to the upper washer.

Data were also collected from the patients' electronic medical records (EMRs) including sex, body mass index (BMI), diagnoses using International Classification of Diseases, Tenth Revision, codes, highest temperature recorded during each day of the patient's hospitalization for cellulitis, and, if available, white blood cell count (WBC), ESR, and C-reactive protein (CRP). Specific antibiotics prescribed to treat the cellulitis were also noted. Demographic characteristics of the sample are given in Table 1.

Table 1. Participant Characteristics

	No. (Mean)	Standard Deviation
No. of participants	41	
Age	61.9	14.3
Sex		
Male	22	
Female	19	
Average BMI, kg/m^2	35.5	11.5
Affected limb		
Arms	6	
Legs	32	
Bilateral legs	3	
Average length of stay, d	6.1	2.1
Admission data		
Average admission WBC	11.5	5.9
Average admission body temperature	37.6	1.1
Average ESR[a]	48.4	35.6
Average CRP[b]	12.7	13.1

Abbreviations: BMI, body mass index; CRP, C-reactive protein; ESR, erythrocyte sedimentation rate; WBC, white blood cell count.

[a]Twenty participants had ESR measured.

[b]Twenty-six participants had CRP measured.

A total of 120 patients were enrolled in this study; 14 patients withdrew after enrollment, and 5 participants' photos were removed because cellulitis was originally suspected but other diagnoses were subsequently considered more likely (eg, venous stasis). These decisions were made via review of the medical record by the research team. Sixty additional participants were dropped from analysis because they had an insufficient number of thermal images (fiducial marker absent, part of affected area out of frame, or <3 days of images). A total of 41 patients correctly diagnosed with cellulitis who had a sufficient number of days of quality images and associated data were included in the analysis.

Thermal images were obtained from the FLIR radiometric camera system in JPEG/Exif format. The FLIR system saves 16-bit raw sensor data in the Exif header of a normal JPEG/Exif format file, from which we extracted a 240×320 thermal image in PNG format; the corresponding paired 480×640 visual spectrum image in JPEG format was also extracted from the original JPEG./Exif format file. Note that the thermal and visual images were taken together but through separate lenses, with a resulting degree of parallax between them. All image extraction operations were performed using the ExifTool photo manipulation utility [13].

Working only with the thermal image, we next masked out the portion corresponding to the (thermal) background using an implementation of Otsu's method [14]. We assumed that any remaining foreground must correspond to body parts, which are warmer than the ambient background.

Next, the Canny edge-detection algorithm was applied to the remaining foreground to identify edge segments along high gradient temperature differentials [15]. The resulting edge segments were then assembled into temperature contours, producing a thermal topology map of the affected portion of the extremity in 1°C increments starting from current body temperature. We used a generalized Hough transform to detect concentric ellipsoids corresponding to the (ambient temperature and therefore cooler) fiducial marker [16]. To allow meaningful comparisons across images, we used the major/minor axes ratio from the detected ellipsoids along with knowledge about the true dimensions of the fiducial marker to compensate for camera angle and distance to normalize and scale the measured area of the nested thermal contours.

The resulting values, representing the normalized and scaled areas of the nested contours from "coolest" to "warmest," provide a histogram-like "fingerprint" of the infection. We define the "severity" of the infection as the weighted sum of this histogram, and the "scale" of the infection as the lowest-temperature value in the histogram (the area of the outermost thermal contour). Both severity and scale were tracked over the course of the patient's hospital stay. All computation on images was performed in Python using the SciKit Image libraries [17].

To analyze the data just described, we conducted a longitudinal regression analysis to explore 3 different relationships in the measurement of cellulitis across the hospital stay: (1) changes in thermal image, expressed in terms of severity and scale (described above) across the stay, and (2) the change in body temperature recorded across time. For both of these outcomes, we used a linear mixed-effects regression model that included a subject-specific random intercept. For the models exploring the first 2 relationships, we regressed the respective scale, severity, or temperature value on an integer time value indicating the day of the hospital stay (ie, 1 for the first day, 2 for the second day, etc.). If multiple images were available for a given day, we used mean daily values of severity and scale in the

Table 2. Models of Severity and Scale Over Time

	Severity		Scale	
Coefficient	Estimate	95% CI	Estimate	95% CI
Intercept	53.70	(11.12 to 96.31)	7.30	(5.65 to 8.93)
D	−1.63	(−13.45 to 10.32)	−0.63	(−1.08 to −0.17)

Table 3. Model of Participant Body Temperature Over Time

Coefficient	Estimate	95% CI
Intercept	99.89	(99.41 to 100.36)
D	−0.28	(−0.40 to −0.17)

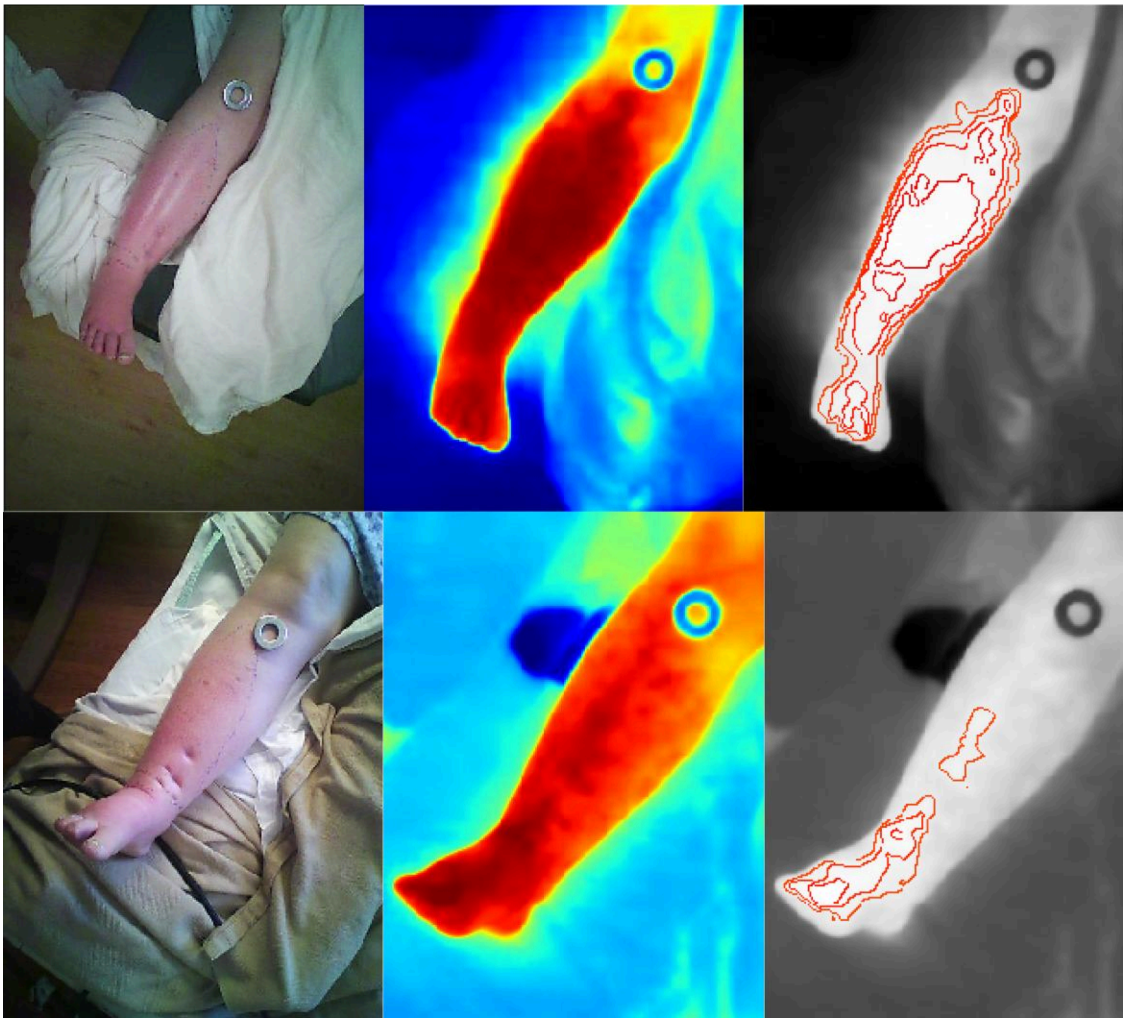

Figure 1. Photos and thermal images of a patient's leg, 2 days apart.

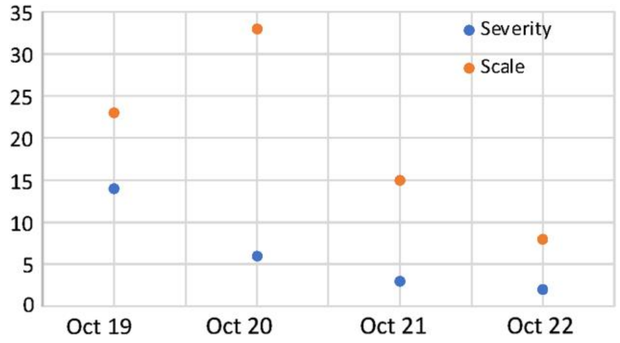

Figure 2. Measures of severity (heat) and scale (size) for the patient in Figure 1 over time.

regression model. For the third relationship (ie, between body temperature and severity/scale), we regressed the body temperature recorded each day on the mean severity/scale values for that day both with and without a day indicator.

RESULTS

Our first analysis compared the change in thermal imaging values across the stay. We looked at both the daily change in severity and scale. For each additional day the patient stayed, we estimated that on average the measure of severity decreased by 1.63 units (95% CI, −13.45 to 10.32) and the measure of scale decreased by 0.63 (95% CI, −1.08 to −0.17) (Table 2).

Our second analysis looked at the change in body temperature readings abstracted from the patient's medical record across the stay. We found that, on average, patient temperature readings decreased by 0.28°F each day during the hospital stay (95% CI, −0.40 to −0.17) (Table 3).

Figure 1, below, is an example of 1 patient's photos that were captured on 2 different days during their hospital stay. Although the patient's leg does not appear to be improving based on a visible spectrum image (left-most panel), the severity and scale captured by the thermal camera show how the affected area is decreasing (right-most panel). Figure 2 gives the measurement of both scale and severity over time for the same patient.

Although not a specific goal of this project, we were also able to identify necrotic tissue with our thermal camera. Figure 3*A* is an example of a patient whose toe, although red and swollen, was actually necrotic. In general, areas of higher heat corresponded to visible areas of erythema. However, in some cases, early in the clinical course, it was clear that heat extended beyond areas of observable erythema (Figure 3*B*). In contrast, detected warmer areas would recede before the prior corresponding erythema (Figure 3*C*). Finally, in cases where it was difficult to perceive red discoloration of skin, that is, in people with darker skin, increased skin temperatures were easy to identify with a thermal image (Figure 3*D*).

DISCUSSION

Our results demonstrate that readings abstracted from a thermal camera may be useful for tracking the clinical course of cellulitis over time. Not surprisingly, we found that at the time of admission, the skin temperature of affected areas was elevated compared with the surrounding area. However, the skin registered a higher thermal region that extended beyond the area of erythema at the beginning of the illness and over time receded faster than the area affected by erythema. Although erythema often lingers after other symptoms of cellulitis have decreased [18], the most common symptoms of cellulitis—erythema, edema, pain, and warmth—are not generally reported to occur in any particular order [10, 19–22]. Our measures of scale and severity estimated from data obtained from thermal images improved over the hospital stay. Given the difficulty of differentiating cellulitis from other diagnoses associated with erythema and edema, our results demonstrate how thermal imaging could be used to augment other signs and symptoms to improve diagnostic accuracy.

Thermal imaging applied to the diagnosis of cellulitis promises many positive benefits. First, while thermal cameras are expensive, prices are decreasing, and the model we used was only a few hundred dollars. Furthermore, although we attached our camera to an iPad, the same camera could be attached to a smartphone, making the device extremely portable for convenient bedside use. Given the emerging ubiquity of mobile computing devices, thermal cameras that attach to such devices promise to make this approach widely available. A third advantage is that very little training is needed. Also, with further modification of our software, quantitative results could be available in real time. Finally, thermal imaging is noninvasive and is not associated with any discomfort. While engaging patients' perceptions of our research approach was not a purpose of this study, several patients asked to see the daily images. Multiple patients commented that they found the images useful and that the images helped them to understand the disease that led to their hospitalization. Thus, thermal images could also enhance patients' understanding of their disease.

Thermal imaging has several different uses and a wide range of applications for skin and soft tissue infections. First, thermal imaging can help with the initial diagnosis of cellulitis. In addition, because the systematic symptoms of cellulitis such as elevation of temperature, chills, and groin pain precede the development of erythema and edema [23–25], thermal imaging might help clinicians make the diagnosis of cellulitis faster. In addition, erythema is difficult to detect in patients with darker skin tones [26], and we have shown that thermal imaging could help in this case as well. A second use case is to track the

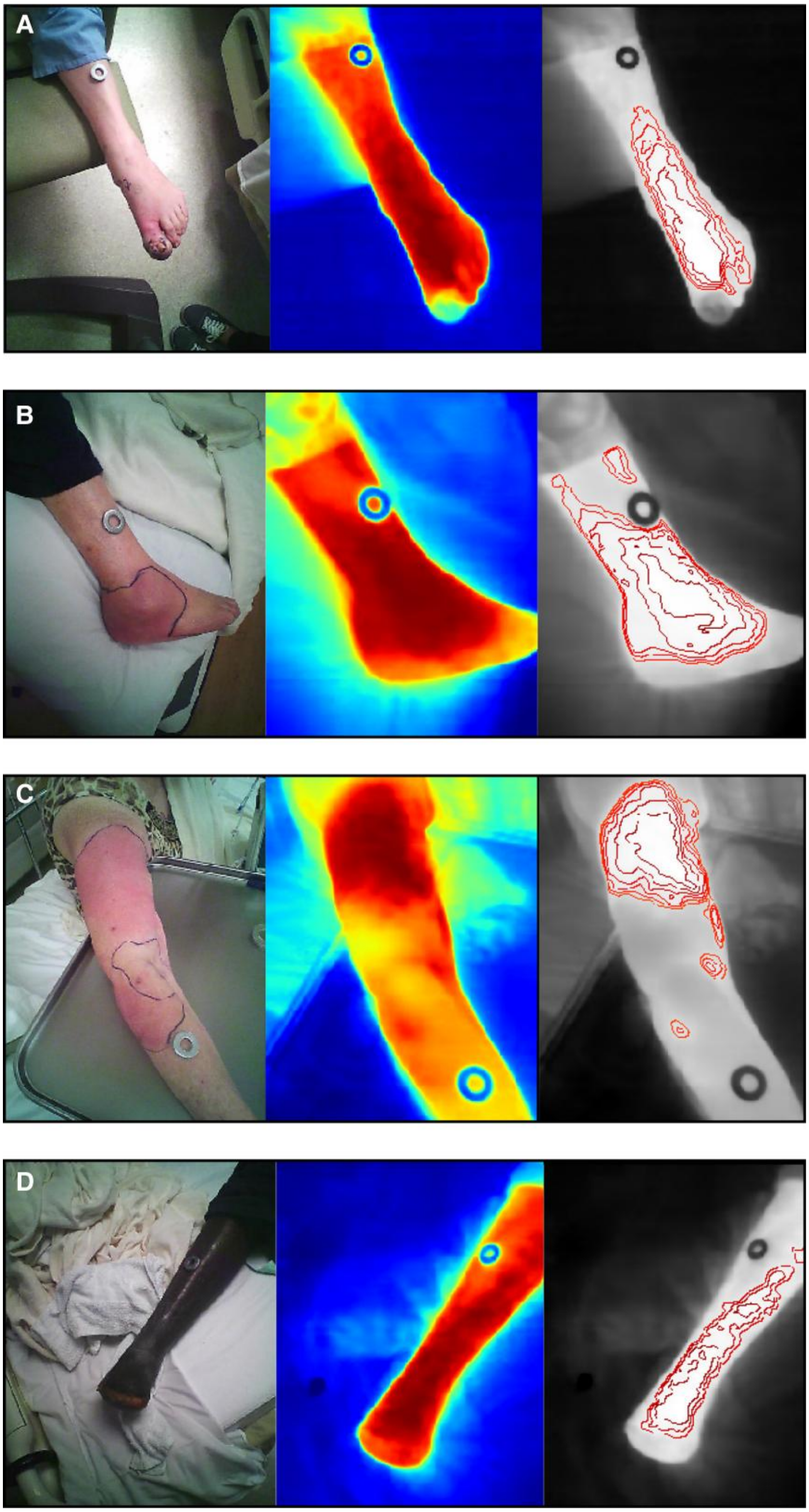

Figure 3. Patient with a necrotic toe (*A*). Early in the clinical course, heat extended beyond areas of observable erythema (*B*). Late in the clinical course, detected warmth receded before the corresponding erythema (*C*). A patient with darker skin: Erythema is difficult to see, but increased skin temperatures were easily identified (*D*).

progression or improvement of cellulitis over time. We found, as previously reported [18], that skin temperature of affected areas decreases before decreases in erythema and edema, but we also found that warmth increases before erythema. Thus, the decrease in skin temperature is a leading indicator, and our ability to track skin temperature will provide an early indicator of improvement. Conversely, if the thermal signature continues to increase, this may be an indication that current antibiotic therapy is failing. While not tested in this study, future work may demonstrate whether thermal imaging can effectively be used to document treatment failures. In addition, in the process of our work, we were able to delineate a necrotic toe associated with a severe infection. Thus, thermal imaging may have utility for identifying skin changes associated with necrotizing fasciitis, as well as other diseases such as frostbite, earlier than with clinical exam alone. Finally, another use case may be in the early detection of surgical site infections. Patients with surgical site infections often present with erythema and edema, and thermal imaging may help detect cases sooner, or may help differentiate between an infection and erythema associated with normal wound healing. With thermal imaging, diagnosis, treatment, and overall management could become much more efficient, decreasing the overall cost.

While our preliminary work is extremely encouraging, in general, our work to date is associated with limitations. First, we did not collect any data outside normal, routine care. Ideally, we would like to correlate our daily thermal images with other daily laboratory results. Many patients had blood drawn on admission, but not on a daily basis. The second limitation is that while it is easy to tell if a patch of skin is hot, it is much more difficult to estimate the size of the affected area consistently. Here, the use of the fiducial marker, when it could be detected in the image, provided the means to estimate not only the relative size of the infected area, but also a crude measure of inclination with respect to camera angle. Even so, because affected extremities are not planar surfaces, the resulting scaling and normalization are themselves necessarily approximations, an especially important consideration when edema may be present. In addition, having different research assistants working on the project helped us understand that standardization of the approach to taking images across days is important; some patients were removed from the analysis because of poor marker placement or poor framing of the affected area. For each patient, we tried to get photos from different angles to understand how variation and technique might affect the size of the area measured. We would recommend taking images that capture the greatest affected area. Fourth, thermal imaging, like any test, should not be used in isolation: Diagnosis and tracking of cellulitis also require a physical exam. Finally, we did not intentionally follow patients with red skin without elevated temperature, for example, patients with stasis or heart failure, to determine how imaging changed in this patient group. We only included patients with cellulitis. Future studies should include patients with both cellulitis and other causes of red skin, for example, statis dermatitis.

We believe more work needs to be done to identify the most clinically important values that can be extracted from thermal images. We can estimate how much warmer affected skin is compared with nonaffected skin, and we can also measure the size of warmer affected areas. More work needs to be done to determine which and to what extent these 2 measures change over time. For example, is it more important for the maximum skin temperature to decrease or for the warm areas to shrink? In 1 anecdotal case, a patient with cellulitis improved in all but 1 area, and in this case, the patient had developed an abscess that needed surgical drainage. In another anecdotal case, the toe, while red and swollen, was cold on our thermal image, providing evidence that the patient needed a partial amputation (Figure 3*A*).

In conclusion, despite our limitations, our work shows the potential promise of thermal imaging for helping to not only aid in the diagnosis of cellulitis, but also track the clinical improvement or lack of improvement for patients suffering from cellulitis. Ultimately, thermal imaging could inform therapeutic approaches or decisions to admit or discharge patients with cellulitis.

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Author contributions. All authors have edited the manuscript. J.A.A. wrote the first draft of the "Methods" and "Results" sections; A.M.S. supervised the data analysis and implemented the image analysis tool; A.C.M. analyzed the data. J.T.H. interpreted the data; A.P.C. interpreted the data; L.A.P. supervised data collection; P.M.P. designed the study, interpreted the data, and wrote the first draft of the "Background" and "Discussion" sections.

Patient consent. This human-subjects-research study was approved by the University of Iowa Institutional Review Board (HawkIRB). All participants provided written informed consent.

Data availability. The data are not publicly available.

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