Burn Depth Estimation Using Thermal Excitation and Imaging

Fred M. Dickey*, Scott C. Holswade, and Mark L. Yee

Sandia National Laboratories, Albuquerque, NM 87185-0328

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ABSTRACT

Accurate estimation of the depth of partial-thickness burns and the early prediction of a need for surgical intervention are difficult. A non-invasive technique utilizing the difference in thermal relaxation time between burned and normal skin may be useful in this regard. In practice, a thermal camera would record the skin's response to heating or cooling by a small amount—roughly 5° Celsius for a short duration. The thermal stimulus would be provided by a heat lamp, hot or cold air, or other means. Processing of the thermal transients would reveal areas that returned to equilibrium at different rates, which should correspond to different burn depths. In deeper thickness burns, the outside layer of skin is further removed from the constant-temperature region maintained through blood flow. Deeper thickness areas should thus return to equilibrium more slowly than other areas. Since the technique only records changes in the skin's temperature, it is not sensitive to room temperature, the burn's location, or the state of the patient. Preliminary results are presented for analysis of a simulated burn, formed by applying a patch of biosynthetic wound dressing on top of normal skin tissue.

Keywords: Burn diagnostic, thermal imaging

1. INTRODUCTION

Accurate estimation of the depth of intermediate depth burns and the early prediction of a need for surgical intervention is difficult. Such an ability would be of significant utility in managing burn patients, and consequently has been the subject of numerous investigations.¹ Methods to compliment the experienced examiner's visual assessment have included burn wound biopsy,² topical application of methylene blue,³ ultraviolet induced fluorescence of injected fluorescein,⁴ ultrasound examination,⁵ laser Doppler flowmetry,⁶ thermography,⁷ light and reflectance of red, green, and infra-red light,⁸ and fluorescence of intravenously injected indocyanine green dye.⁹ None of these methods have enjoyed widespread acceptance because of their inability to accurately determine burn depth in intermediate depth wounds.

Several approaches to the problem of burn diagnostics based on thermal radiation or heat flow have been proposed. Mladick et al.¹⁰ were the first to report the application of static thermography to the assessment of burn wounds. Liddington and Shakespeare¹¹ address the timing aspects of the static thermographic approach. Their work is based on the assumption that detected infrared radiation is related to the cutaneous blood flow in the surface of the wound and indirectly gives information relating to burn depth. They also point out that evaporative cooling complicated the early studies. In their studies they used a non-permeable, infrared transmitting membrane to inhibit evaporative cooling. For deep wounds they conclude that thermographic information was relating to burn depth was lost after three days. Dittmar et al.¹² measures heat flow (thermal conductivity) for healthy, burned, and grafted skin. Their technique employs a contact probe. They report that during the first 24 hours partial thickness burns have high heat conductivity relative to healthy skin. During this period full thickness burns exhibit a lower than normal heat conductivity. They conclude that heat flow can be used to distinguish between deep partial burns and full thickness burns.

In the following we present an infrared technique for the assessment of burn wounds that is based on differences in heat clearance (return to equilibrium temperature) after a small heating or cooling of the surface layer. The heat clearance is measured using an infrared imaging camera. This approach thus differs from static thermographic approaches in that it records change in surface temperature due to a thermal stimulus. It should not be sensitive to initial skin temperature, which can vary due to environment, the burn's location, or the state of the patient.

* Correspondence: Email: fmDicke@sandia.gov; Telephone: (505) 844-9660; Fax: (505) 844-1214

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2. ANALYSIS

A simple analysis was used to estimate the magnitude of the effect of a burned layer raised to a temperature difference T . It is assumed that the blood flow in the healthy tissue provides a constant temperature boundary condition. This problem has an exact solution for the time-dependent temperature $U(t)$ (temperature difference above nominal)¹³. The solution is,

$$U(t) = T - 2 \cdot T \cdot \sum_{n=0}^{10} (-1)^n \left[1 - \operatorname{erf} \left[(2n+1) \cdot \frac{d}{2 \cdot \sqrt{k \cdot t}} \right] \right] \quad (1)$$

where d is the thickness of the burned layer, t is time and k is the thermal diffusivity. For burned tissue k was estimated to be $1.59 \times 10^{-7} \text{ m}^2/\text{s}$. The basis for a more detailed analysis can be found in the literature.^{14,15} Analysis appropriate for a laser induced temperature difference is given in Prah et al.¹⁶ Figure 1 is a plot of Eq. (1) for $d = 100$ and $300 \text{ } \mu\text{m}$.

Figure 1. Relaxation of surface temperature ($^{\circ}\text{K}$) as a function of time (seconds).

In the figure, the shorter duration curve corresponds to the case $d = 100 \text{ } \mu\text{m}$. This graph shows a clear temperature difference between the two burn thicknesses as time progresses. A thermal camera would thus be able to resolve the two burn thicknesses. The thermal camera should also be able to resolve the difference between burned and healthy skin. Although this analysis is simplistic, it qualitatively agrees with the experiments described below. Note that this simple model assumes that the heating or cooling was uniform throughout the burn layer.

The above analysis neglects cooling by radiation (as well as convection). To check on the validity of neglecting radiation cooling, the surface radiation cooling of a slab of tissue of thickness l was calculated. Under simplifying assumptions, which include ignoring radiation effects from beneath the surface, this problem also has an exact solution. The solution is,

$$t(T) = \frac{-\rho \cdot C \cdot l}{(4 \cdot \sigma \cdot T_0^3)} \cdot \left[\ln \left[\left(\frac{T - T_0}{T + T_0} \right) \cdot \left(\frac{\Delta T + 2 \cdot T_0}{\Delta T} \right) \right] - 2 \cdot \operatorname{atan} \left(\frac{T}{T_0} \right) + 2 \cdot \operatorname{atan} \left(\frac{\Delta T + T_0}{T_0} \right) \right] \quad (2)$$

where T is temperature, t is time, ρ is the material density, T_0 is the absolute temperature, ΔT is the applied temperature difference, C is the specific heat and σ is the Stefan-Boltzman constant. A plot of Eq. (2) for $l = 100 \mu\text{m}$ is given in Figure 2. A thicker burn layer would cool at an even slower rate.

Figure 2. Radiation cooling of a slab (temperature T in $^{\circ}\text{K}$, time $t(T)$ in seconds).

The derivation of Eq. (2) assumes that conduction of heat in the slab is negligible, a conservative assumption. Consequently, the actual cooling rate due to radiation would be even less than that exhibited in Figure 2. At this level of analysis, it thus seems reasonable to neglect radiation effects, since they occur on seconds-long time scales. Convection effects, on the other hand, are far too complicated to be included at this initial analysis. Convection effects would thus have to be controlled or possibly exploited in an operational system.

3. EXPERIMENT

Although actual burn experimentation was not possible, the thermal imaging concept underwent preliminary testing. A burned area was simulated by applying a patch of biosynthetic wound dressing on top of normal skin tissue. The dressing acted as a dead skin layer. The dressing was a porcine derived xenograft under the trade name "E•Z Derm," manufactured by Brennen Medical. We measured the thickness of one sample with a micrometer, and it varied from about $120 \mu\text{m}$ to $200 \mu\text{m}$. It was difficult to get the patch to adhere to the skin, so we used some hand lotion to get good contact. The patch was allowed to dry to the point that the infrared camera no longer displayed a visibly noticeable difference between the patch and the surrounding skin. This was done to ensure that evaporation didn't affect the temperature of the patch.

Both heating and cooling of the skin were explored. Heat was provided by a heat gun used in electronics work. Cooling was provided by a can of compressed CO_2 gas. The thermal camera responded to radiation from $8\text{-}12 \mu\text{m}$, and its output was recorded on S-VHS tape. For each run, the camera viewed the skin at normal temperature, the heating or cooling process, and the relaxation of the skin after the removal of the heating or cooling. Analysis indicated that the temperature differences between the patch and the skin should occur on short time scales. We didn't expect to visually notice much of a difference, and we planned on image processing of the tape to recover the data. Unfortunately, this meant that we wouldn't know if the experiment were successful until well afterward. We thus tried several different heating and cooling times, with the aim of finding the best combination during data reduction. Some problems with the cooling technique were noticed during the experiment, however. The compressed gas did not flow evenly enough to uniformly cool the sample area, and some improvement over the stock delivery nozzle would be necessary for good results.

4. DATA REDUCTION FOR IR IMAGES

The following is a description of the image processing methods used on the IR images. The images display a $120\text{-}200 \mu\text{m}$ thick xenograft patch on a male arm after the application of hot air from a heat gun. The images were obtained by recording the video output of an IR camera on S-VHS videotape. Selected image frames from the videotape were later digitized using a frame grabber. This was done by pausing the videotape at the desired frames and then digitizing them one at a time. Use of

Figure 3. Thermal image of skin patch with no thermal stimulus.

the videotape introduced small artifacts (horizontal lines) into the images due to pausing the tape. Convolution with a 3x3 smoothing kernel was used to reduce the effects of the artifacts. All images were smoothed prior to being used in any computations. For comparison purposes, Figure 3 shows a thermal image of the patch with no thermal stimulus.

We expected to see two types of thermal behavior similar to that shown in Figure 1. Areas of normal skin should have returned quickly to equilibrium, as shown by the solid curve in Figure 1, and areas covered by the patch should have returned to equilibrium more slowly. The data actually revealed three types of behavior: the normal skin response and then two distinct responses for the xenograft patch. Some parts of the patch became quite hot and remained hotter than normal skin several seconds after the application of heat stopped, probably due to adhesion problems with the patch to the skin. The edges of the patch exhibit this behavior most markedly. If plotted on the time scale of Figure 1, this "hot spot" response would be a nearly horizontal line across the top of the plot. Other parts of the patch cooled off faster than these "hot spots," but also cooled off more slowly than normal skin. This is the expected response for the patch shown by the dashed curve in Figure 1. Two different image processing methods have been applied to the images in order to highlight both types of phenomena.

4.1. Case I: Hot Spots

To handle the first case (hot spots), a short sequence of images approximately 0.5 second apart was used. This is due to the fact that the hot spots took a long period of time (several seconds) to cool down to the temperature of normal skin. A control image (prior to application of heat) was also used. We define the following:

- Im_0 : control image (prior to heat)
- Im_1 : image immediately after heat application was halted
- Im_2 : image approx. 0.5 sec after Im_1
- Im_3 : image approx. 1.0 sec after Im_1

The following is then computed:

$$\text{result}_1 = (Im_1 - Im_0) + (Im_2 - Im_0) + (Im_3 - Im_0) \quad (3)$$

The result is shown in Figure 4, as an overlay over the initial image of Figure 3. This is essentially a crude integration of the sample's temperature response over time, with the initial temperature as a baseline. Pixels that represented hot spots would

Figure 5. Case II results. Dark overlay indicates areas detected by data reduction.

It is noted that this processing will indicate pixel changes of any kind, not just those due to temperature variation. There are two extraneous causes of changing pixel values. One cause is artifacts introduced by the VCR/videotape. A second cause is slight arm motion.

4.3. Final processing

Both $result_1$ and $result_2$ are then thresholded and added together to produce the final image, which indicates all areas of skin that did not cool off at the same rate as normal skin. Figure 6 shows the final results. These areas are highlighted by the overlay on top of the control image (Figure 3). The final result corresponds well with the xenograft patch.

We note that some areas near the edge of the arm are highlighted. These areas are undoubtedly due to the extraneous causes of changing pixel values, namely VCR artifacts or slight arm motion. Finally, the remnant evaporative cooling visible in the initial image of Figure 3 merits discussion. This visible area should not have affected the results. Examination of Equations 3 and 4 reveal that these data reduction techniques only recorded *changes* in the surface temperature. In future work, evaporative effects could be eliminated by the use of a non-permeable membrane.¹¹ However, since actual burned tissue might display evaporative cooling anyway, future studies might benefit by including it.

5. CONCLUSION

Actual burn tissue would tend to consist of a continuous range of burn depths, and thus should exhibit a range of times in returning to thermal equilibrium. Data reduction could then consist of integrating the thermal response for each pixel, with the total value corresponding to burn depth. The techniques used in this work were selected to highlight specific patterns of thermal response. Similar techniques could also be used in a clinical setting where the goal is only to identify those areas that require surgical intervention.

The thermal imaging technique is based on monitoring the skin temperature transient response after heating or cooling of the surface layer. Analysis has shown that this technique may record a significant difference between burned and viable tissue. It has applications both in initially determining burn depth and in providing a feedback mechanism for debridement. Although actual burn experimentation was not attempted, a burned area was simulated. Using suitable data reduction, the technique recorded a difference between the simulated burn area and the surrounding tissue. These initial results show promise, and warrant more detailed clinical studies with actual burn tissue.

Figure 4. Case I results. Dark overlay indicates areas detected by data reduction.

have large values for this case. The overlay thus represents parts of the image that did not cool off within the first second after heat application was halted.

4.2. Case II: Differential Cooling

This was the expected response for the patch, as shown by the dashed curve in Figure 1. Besides discriminating between this response and the normal skin response, the data reduction algorithm had to discriminate against the "hot spot" response. The model of Equation 1 indicated that the normal skin should have returned to equilibrium by 0.1 second, so this algorithm began at 0.1 second after heat application to discriminate against the normal skin response. A sequence of images approximately 0.033 second (one frame time) apart was used to discriminate the differential cooling response from the "hot spot" response. We define the following:

Im_{0A} : image approx. 0.1 sec after heat application was halted

Im_{1A} : image approx. 0.033 sec after Im_{0A}

Im_{NA} : image approx. $(N \cdot 0.033)$ sec after Im_{0A}

The following is then computed:

$$\text{result}_2 = (Im_{0A} - Im_{1A}) + \dots + (Im_{0A} - Im_{NA}) \text{ up to } N=12 \quad (4)$$

Figure 5 shows the results. As stated above, Im_{0A} is taken when the normal skin has reached an approximate thermal steady state. All subsequent images should show little variation in pixel values for normal skin. The xenograft patch cools off at a slower rate than normal skin, so subsequent images will show variation in pixel values for the patch. Thus, subtraction of Im_{1A} from Im_{0A} results in brighter pixels where cooling is still taking place 0.033 sec after Im_{0A} , while pixels will be dark wherever the temperature remained constant (either from cooled normal skin or "hot spot" areas). Subtraction of Im_{NA} from Im_{0A} results in brighter pixels where cooling is still taking place $N \cdot 0.033$ sec after Im_{0A} while pixels will again be dark wherever the temperature remained constant. The images are added together to perform a crude integration of the changing pixel values over time. Bright pixels indicate where the temperature changed during the interval from 0.1 sec after heat application was halted up to 0.5 sec after heat application was halted. Dark pixels indicate where the temperature remained constant. Therefore result_2 indicates which areas of the patch had a longer cooling time than normal skin (but not as long as the "hot spots") over the first 0.5 sec after heat application was halted.

Figure 6. Combined thermal results. Dark overlay indicates areas detected by data reduction.

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