Development of a Thermal and Hyperspectral Imaging System for Wound Characterization and Metabolic Correlation

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Monitoring and treatment of wounds remains a very personal activity. A patient is often seen by multiple individuals who subjectively document the wound healing process. The metabolic needs of wound healing are also not well understood. A collaboration between APL and The Johns Hopkins University School of Medicine was therefore formed to study the metabolic needs of wound healing. A mid-wave IR thermal and seven-band visible/near-IR hyperspectral imaging system has been developed to provide a novel approach to documenting and characterizing the progress of wound healing and local wound metabolic activity. This article summarizes the development of the imaging system and gives a detailed system description.

INTRODUCTION

Proper wound characterization can help identify appropriate treatment. One problem with wound characterization is the subjectivity of the process. For example, monitoring the progress of wound healing (wound progression) is often the responsibility of many people who may see the patient during a series of visits over time. Though there is a standard set of metrics for wound characterization, some of those metrics are subjective. In addition, measurement of wound depth and structure often requires invasive methods such as the application of a specialized gel to create a three-dimensional (3-D) mold of the wound volume for future comparison. With current noninvasive imaging technologies, it is believed that some quantitative metrics can be derived to document wound progression.

A collaboration was formed between staff from APL and staff from The Johns Hopkins University School of Medicine (SOM) at the Bayview Medical Center to address some issues relating to wound characterization and treatment. In particular, the APL team is developing an image acquisition system and imaging tools to analyze and record wound progression. The SOM team is studying the metabolic costs associated with wound healing and the treatment of bedridden patients with pressure ulcers. Data from this study will be used to correlate local metabolic activity associated with wound healing to a patient's metabolic needs.

The goal of this collaborative effort is threefold: (1) to provide new tools and methods for monitoring wound progression and associated metabolic activity, (2) to improve the ability to predict the healing response of a wound resulting from changes in dietary intake and the patient's metabolic activity, and (3) to provide an enhanced understanding of these metabolic relationships so that these tools and methods can lead to improvements in wound care.

The team believes that the metabolic needs of healthy people differ from those of people with wounds. Hospital dieticians use metabolic prediction equations[1–6] to determine the appropriate caloric needs of a patient and prepare a patient's meals accordingly. These equations were developed based on healthy people of normal weight and may not represent the true needs of a bedridden patient with pressure ulcers. Therefore, the metabolic portion of this study will investigate the true metabolic needs of patients with pressure ulcers at various stages of healing.

Thermal and hyperspectral imaging techniques were chosen because of technological developments in these areas and their noninvasive nature and transportability. Advancements in hyperspectral imaging (HSI) have shown that oxygenation saturation level changes can be detected within wavelengths of 400–900 nm,[7–9] and tissue oxygenation plays a central role in tissue metabolism as well as the processes of tissue repair and healing.

Similarly, thermal imaging can be used to monitor metabolic activity as a result of corresponding changes in blood flow characteristics and metabolic processes. A key objective for the future will be to develop correlations between the metabolic measurements made by the imaging techniques and those made by traditional methods such as blood composition, metabolic cart measurements, and dual-energy X-ray absorptiometry (DEXA) scans.

Wound progression is currently monitored manually. The National Pressure Ulcer Advisory Panel (NPUAP) developed the Pressure Ulcer Scale for Healing (PUSH) tool that outlines a five-step method of characterizing pressure ulcers.[10] This tool uses three parameters to determine a quantitative score that is then used to monitor the pressure ulcer over time. The parameters are wound dimensions, tissue type, and the amount of exudate or discharge present after the dressing is removed.

A wound can be further characterized by its odor and color. Currently, all descriptions of wounds are somewhat subjective and noted by hand by either the attending physician or the nurse. A system to noninvasively characterize wound progression and record the data digitally would minimize human error and provide an objective, electronic history of the healing process.

This article, which summarizes the development of the imaging system and provides a detailed system description, is organized in the following manner. The design approach and system requirements are presented first, followed by detailed descriptions of the hardware and software components of the imaging system. The image analysis techniques completed to date are then presented. The article concludes with a description of a patient study and possible applications of this system.

DESIGN APPROACH

The Thermal and Hyperspectral Imaging System (THSIS) requirements were specified by the developers with three functional constraints: the system (1) would be used in a hospital, (2) could be operated by a minimally trained user, and (3) would be transported occasionally between APL and Bayview Hospital. These constraints required the system to be transportable and maneuverable for easy setup and positioning, to have a minimal-sized footprint, to meet Bayview Hospital's electromagnetic interference safety requirements, and to consider patient interactions.

In addition, the THSIS prototype was proposed with the intention of leveraging the research developments of an APL project on thermal imaging and a student design project on HSI that resulted from a joint program with JHU's Biomedical Engineering Department.[11] Some designs from the student project, in addition to physical hardware, were leveraged into the design of THSIS.[12] Some of the thermal imaging software tools developed for APL's Dynamic Infrared Radiometric Imaging (DIRI) system are being considered for THSIS imaging analysis. In addition, lessons learned from the DIRI system design have been applied toward the design of THSIS.

Other design considerations included the desire to procure and integrate as many commercial off-the-shelf products as possible. To minimize integration time, National Instruments LabVIEW software was selected as the development environment for the data acquisition software. Another consideration was to minimize system costs; consequently, trade-offs were made during system development.

Because THSIS was intended to acquire hyperspectral and thermal images in addition to collecting measurements of wound volume, four cameras were needed: an IR camera to provide thermal images, two monochrome cameras to provide the hyperspectral data and stereoscopic views, and a color camera to document the wound and provide a color reference for the physicians. In addition, as a consideration for patient interaction, it was determined that the THSIS unit could be no closer than 2 ft from the patient. Because of the anticipated wound sizes, the cameras were fitted with wide-angle lenses to maximize the field of view at the 2-ft distance. This distance constraint, in addition to the number of cameras, presented the biggest mechanical design challenge. To further complicate this design, the monochrome cameras had to be situated at a specific separation distance for stereoscopic imaging and had to allow enough space to accommodate two filter carriages that contained the hyperspectral filters.

Finally, there was a desire to develop a phantom that could emulate a wound and normal tissue from a thermal and hyperspectral perspective. In addition to its utility as a calibration tool for the imaging systems, the phantom would provide a method to quantify THSIS performance. However, development of this phantom was not within the scope of the project and it was decided that a visually accurate phantom would suffice as a calibration tool. This phantom has no intrinsic IR properties. Hence, the phantom images in the IR realm are the result of reflected and/or incident energy from the environment.

HARDWARE SYSTEM CONFIGURATION

The specific cameras used for the THSIS prototype (Fig. 1) were an Indigo IR camera (a mid-wave IR camera with a Stirling cooled indium antimonide sensor) for radiometric imaging, two monochrome PixeLINK cameras for stereo-hyperspectral imaging, and one color PixeLINK camera to provide reference images for physicians.[13] A Bitflow Roadrunner frame grabber card was used to capture the IR images, whose dimensions were 320 pixels wide $\times$ 256 pixels high with a 12-bit pixel depth. The color image dimensions were 1024 pixels wide $\times$ 1280 pixels high with 8 bits per pixel (bpp) of red, green, and blue. Because of IEEE 1394 Firewire bandwidth limitations, the monochrome image dimensions were set at 1024 pixels square, with a resolution of 10 bpp. A portable PC housed the data acquisition software that controlled the peripherals and interfaces with the operator. These peripherals are described in detail in the following section. Briefly, two Class II laser pointers were used for positioning, two lamps were used for lighting, and a motor driver was used to actuate the motor, which in turn moved the filters. A National Instruments (NI-6503) digital input/output (I/O) card was used to interface the software to the hardware components.

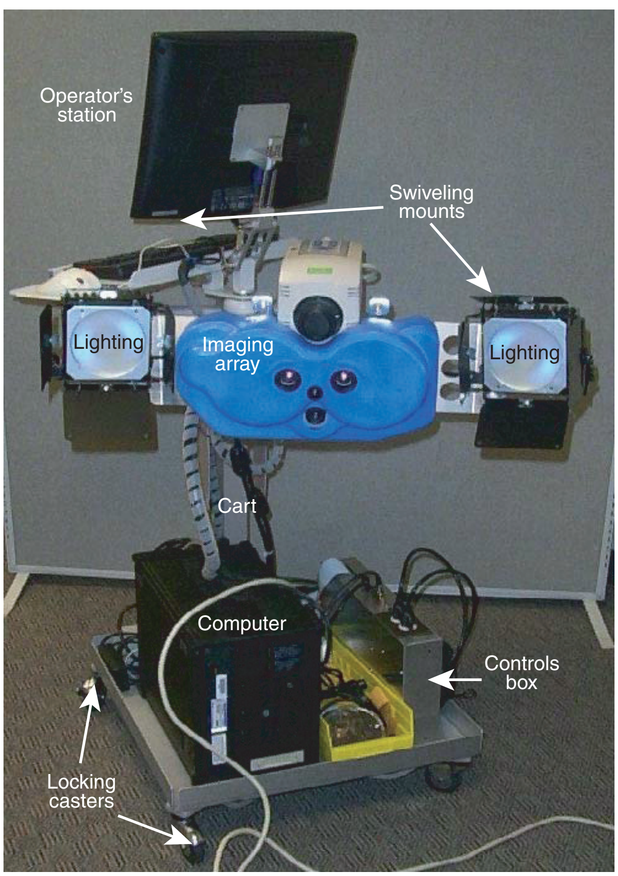

Figure 1. System overview.

As noted earlier, part of the design approach was to leverage an HSI prototype from a student project, which included some hardware components (the stepper motor, motor driver, and power supply) that were reused for the THSIS prototype. Because THSIS is intended for use in a hospital setting, strict requirements were placed on the chassis design. To meet these system requirements, the Over the Bed Stand cart from Pryor Products was procured to house the equipment listed. This cart was selected for its ample storage space underneath a cantilevered swiveling sensor mount, hydraulic lift capability for raising and lowering the sensor mount from ≈2.7 to 4.0 ft, and large locking, low durometer rubber casters. The sensor platform could also be easily adjusted because its friction swivel mount, with 200° of lateral motion, gives a range of options for positioning the cart relative to the patient. The imaging array was mounted at the end of the cantilevered arm on the pivot. The computer and the electronics box were located below the imaging array, and the operator's controls were mounted on an adjustable platform just above the hydraulic lift mechanism.

The greatest mechanical design challenge was the integration of the four cameras. The principal constraint in the camera layout was the need for spacing the stereoscopic cameras approximately 3 in. between their lenses' centerlines. Placing the heavy IR camera over the cart support structure and mounting the other cameras below the IR camera achieved the optimal camera spacing while maximizing the shared viewable area of each of the cameras. Figure 2 shows the experimentally calculated field of view of all four cameras at a 2-ft distance from the face of the IR camera lens. The shared imaging area corresponded to roughly 5 $\times$ 9 in.

The lenses for all cameras were set to focus on a subject approximately 2 ft away. To consistently place the cart at this distance, a noninvasive measuring system was needed and achieved by using two industrial laser pointers that would converge to a point at a distance of

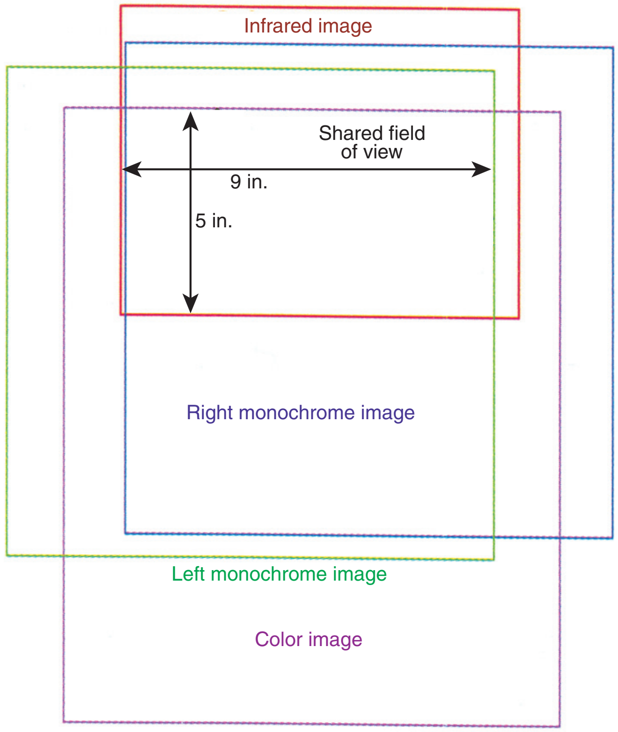

Figure 2. Alignment of camera fields of view.

2 ft. By using this method, setup and patient positioning time was significantly reduced.

Because of the requirement for repeatable lighting conditions, high color temperature photographic lighting was obtained and fixed to the imaging array. The lights were affixed to the camera array, aligned to always illuminate the same position, and focused to create more even illumination. This arrangement was designed to eliminate virtual hot spots in the images, especially when the flood setting was used with the diffusion filters.

To obtain the hyperspectral frequency information, seven narrow bandpass interference filters centered at various wavelengths between 535 and 940 nm were placed in front of the monochrome stereoscopic cameras (Fig. 3). To minimize the physical size of the imaging array, two filter wheels were selected that were moved using a simple gear train. A stepper motor was used to turn a pinion to advance the filter wheels. Since the ratio between the two pinions and the two filter wheels was 8:1, eight filters were allowed. Eventually, however, the stepper motor proved to be unreliable at consistently positioning the filter wheels. To overcome this issue at minimal cost, a microswitch with a lever was used in conjunction with the stepper motor to correctly position the filters.

The controls box under the imaging array contained the necessary circuitry to interface the National Instruments board used by the data acquisition software to the hardware peripherals: stepper motor, motor driver,

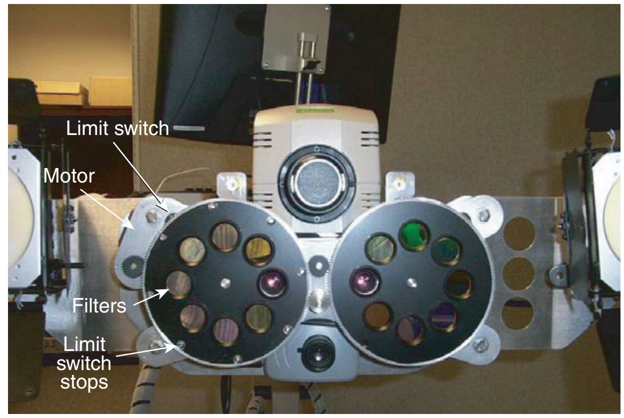

Figure 3. Filter wheels, each with seven filters as well as a filter bypass.

microswitch, positioning lasers, and light sources. A 38-V power supply was used to power the stepper motor and motor driver. A 5-V DC-DC converter was used to convert 38 V to 5 V to power the lasers and the limit switch. Two relays were used to activate the positioning lasers, and a Crydom relay was used to activate the light sources, which use standard 120-V AC power. Figure 4 shows the details of the controls box.[14–16]

Finally, the overall appearance of the camera array was designed to look nonthreatening. The cover also acted to hide the gears, the CCD (charge coupled device) cameras, and filters, thus preventing a possible safety hazard and providing protection for the optics.

SOFTWARE OVERVIEW

The THSIS hardware was controlled by a data acquisition application written in LabVIEW and C. The application was organized into functional modules that were implemented as dynamically linked libraries (DLLs) in C/C++ and as sub-virtual instruments (subVIs) in LabVIEW. The first two modules used DLLs and subVIs, while the last two used only LabVIEW. The four major modules were the visible wavelength camera

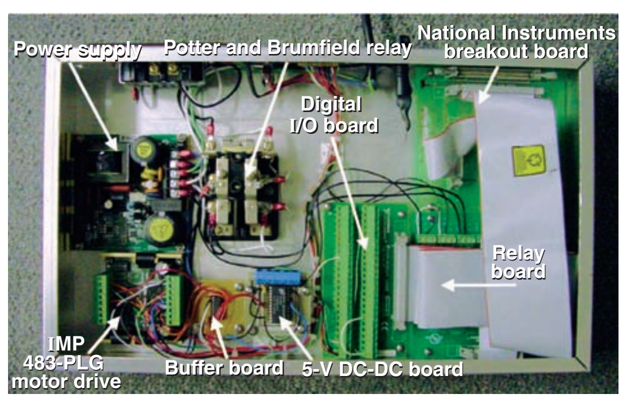

Figure 4. Internal view of the HSI electronics box.

module, the IR camera module, the digital input/output (DIO) module, and the graphical user interface (GUI) module. Because all DLLs were wrapped in LabVIEW, it was possible to have a layered approach that presented a single language interface at the highest level while hiding complexity and facilitating re-use of the code.

Visible Wavelength Camera Module

The visible wavelength camera module, used to control the PixeLINK cameras, is based on the camera-controlling DLL provided by the manufacturer. This OEM-supplied DLL is wrapped with a layer written in C that provides a simplified interface to the DLL's functionality and performs data conversions required to interface with LabVIEW. The resulting DLL is in turn wrapped by a LabVIEW subVI. The module's input consists of a camera control structure, a thumbnail size specification, and a filename for data storage. This control structure determines the image resolution, exposure time, and other camera hardware settings. A thumbnail of these images is displayed by the GUI.

IR Camera Module

The IR camera module reads a monochrome image from any industrial camera attached to the Bitflow frame grabber hardware. In this case, the Bitflow frame grabber was initialized with the Indigo IR camera parameters. A thumbnail image scaled down to 8 bits is generated by this module and passed to the GUI module. The IR module has thumbnail size, false color, and filename inputs but does not require camera control parameters since these are constant and stored in an OEM-specific configuration file.

DIO Module

The DIO module controls the National Instruments DIO hardware. Since the I/O hardware is also a National Instruments product, LabVIEW drivers are available and no DLL is required. Of the 24 available I/O lines, THSIS uses 5 for motor clock control, motor direction control, motor limit switch sense, laser control, and illumination control. The motor clock drives the optical filter stepper hardware at a rate of approximately 1 kHz. Except for the motor limit switch sense line, all other functions provide simple binary control lines that are used as input to the power supply and other hardware subsystems. The limit switch line accurately positions the filter wheels, provided that they are always rotated in the same direction. For this reason, the DIO module allows the user to rotate the filter wheels in only one direction; if the user desires to go backward by one filter, the module will spin the wheels forward rather than simply rotating backward. This design was an acceptable choice because of cost limitations.

GUI Module

The GUI is the highest level of software. It calls the other three modules and controls the process of data acquisition and machine motion. The GUI is designed for the nontechnical user with minimal training and consists of two steps: patient identification and data acquisition. Consequently, the GUI presents only two control panels to the user during a session, which reflect the needs of each step.

The Patient ID & Settings panel allows the user to choose or create new patient profiles and is displayed automatically at application startup or when a session has been completed and the software is ready for the next patient. The user may display this panel at any time to make changes to any settings as well as exit the application at any time. The settings on this panel allow a patient ID and wound ID to be selected or created and acquisition parameters to be specified. The acquisition settings box allows the user to choose which actions are applied during the acquisition process; defaults can be applied using the adjacent button. The state of this control is saved when data acquisition begins and is restored when the same patient is chosen in the future. The text window at the bottom of the panel shows the system log; once a patient has been selected, the log history for that patient is loaded. Finally, the user presses the Acquire Images button at the bottom to move to the data acquisition panel.

The Acquisition panel (Fig. 5) is displayed upon request, given that all patient information has been entered. The manual control box allows the user to manipulate any of the hardware devices for testing, focusing, or patient positioning. When ready, the GO button is pressed, which starts the acquisition process. The process can be stopped at any time by using the STOP button. As each type of data is acquired, it is displayed on one of the four thumbnail image windows,

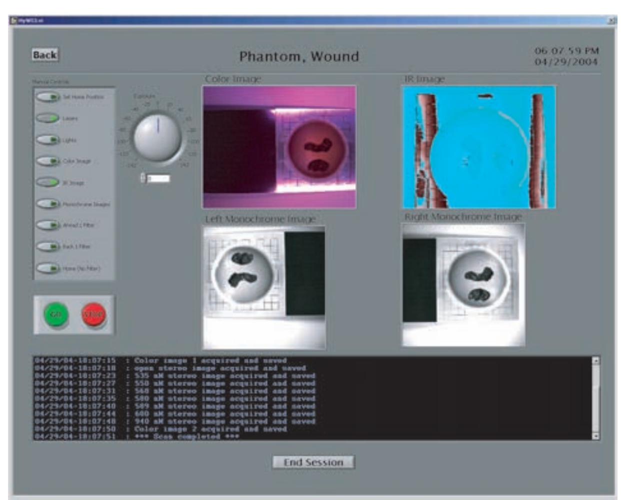

Figure 5. The GUI Acquisition panel.

and the log is updated by the action that took place. Because of chassis constraints, the PixeLINK cameras were mounted at either +90° or –90° relative to the IR camera; therefore, the images are displayed accordingly on the GUI. New data sets can be repeatedly acquired by pressing GO for the same patient. Once the session is complete, the user presses the End Session button, and the patient information panel is shown with all fields blank, ready for the next patient.

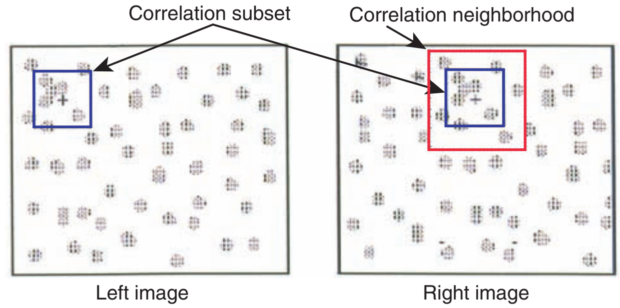

Figure 6. FLASH stereo correspondence.

VOLUME ESTIMATION AND CAMERA CALIBRATION

As mentioned earlier, current methods of measuring wound volume are extremely invasive. Since it is possible to derive depth from stereo-image pairs, it was decided to see if this technique could be applied to estimating wound volume. The problem of rapidly and automatically generating a dense set of stereo correspondences between two images is difficult. To solve this problem for applications in cartography and terrain elevation map generation, APL has developed a set of algorithms and software, named FLASH[17,18] (Fast Local Area Stereo Height), as well as a topographic photogrammetry tool called MICE[19,20] (Multiple Image Coordinate Extraction). Both FLASH and MICE are being used in the THSIS application.

Deriving Depth from Stereo

Depth information can be obtained from a scene if two images are taken from slightly different vantage points. This is one of the bases of human binocular depth perception. Several steps must be taken to accomplish this in addition to merely acquiring a pair of images. First, the cameras must be calibrated by imaging some scene with known geometrical content. Second, image points in one image must be matched to the corresponding points in the other image. If 3-D information for only a few points is desired, the matching is usually done manually. For this application, a dense set of points is needed to measure the wound shape and volume. Finally, the image correspondences are used to calculate the 3-D coordinates of the real-world points. Since MICE was originally developed for topographic photogrammetry, it was modified for close-range application (which requires a different coordinate system) and used both for camera calibration and 3-D point computation. MICE also computes error estimates for all calculated quantities.

Stereo Correspondence

A simplified version of the way that FLASH generates stereo correspondences is illustrated in Fig. 6. Small subsets are taken from the left image and used as templates for a matched filter that is run over some search neighborhood in the right image. The center of the location of the best match in the right image is taken to be the correspondent of the center of the subset from the left image. This operation is carried out repeatedly using templates taken from (centered around) every pixel in the left image, which is a computationally intensive process. Larger templates generate fewer false matches but produce a lower resolution in the resulting depth map as a result of the necessary averaging over template-sized areas.

To circumvent this problem and to speed up the massive amounts of required processing, FLASH uses a variety of techniques and special algorithms. These include matching at a multiplicity of resolutions (hierarchical matching) and with a succession of gradually decreasing template sizes. The initial template sizes are chosen to be large enough to make false matches unlikely. After a correspondence has been found in the right image for every pixel in the left image, the right image is warped into partial alignment with the left image and the process is repeated with a smaller template and a smaller search area. The process is then iterated using progressively smaller template sizes until the desired resolution is reached. FLASH also uses a variety of techniques designed to detect and/or damp out errors that might arise in the process and produces an error map along with the desired list of stereo correspondences.

Camera Calibration Example

A calibration grid was used to determine the camera calibration parameters. By marking points of known locations in several images of the scene taken from different vantage points with each stereo camera, all of the necessary camera calibration parameters can be determined. These parameters include the stereo camera separation and relative alignment, as well as each camera's principal distance, image center coordinates, and optical distortion parameters.

NEXT STEPS

Now that the THSIS prototype has been developed, a patient study, designed by the Bayview team, will be conducted to measure the resting metabolic rate (RMR) of selected patients. Fifty patients over the age of 50 with stage III and IV sacral/ischial pressure ulcers will be recruited from the Johns Hopkins Geriatrics Center to participate in this investigation. We will measure RMR via open circuit spirometry using a portable metabolic cart in the patient's room. Actual RMR values obtained from the metabolic cart will be compared to predicted values for wound patients using published prediction equations. Metabolic assessments will be repeated monthly for 3 months (baseline, 30 days, 60 days, 90 days). DEXA scans will also be used to track changes in body composition and to examine the relationship between body composition variables and metabolic rate in patients with pressure sores. THSIS images will be used to track thermal and hyperspectral changes in the wound to enable development of correlations between local wound metabolic activity and total patient metabolic activity. Physical activity patterns will also be monitored using 3-D accelerometers. A Bayview Medical Center dietitian will calculate the energy intake that patients are consuming before and after the sores heal. Visual characterization of wound progress will be supervised and documented by an expert in wound care.

THSIS is currently a prototype imaging system with a set of off-line analysis tools. If proven effective, the next steps are to improve THSIS by miniaturizing it and by developing real-time decision aids for treatment and triage. With these improvements, THSIS can be used for several other applications besides wound characterization in correlation with metabolic activity. For example, THSIS can be used by pharmaceutical companies to noninvasively study tumor drug efficacy since studies indicate that a growing tumor has increased metabolic activity. THSIS can also be employed by the medic in the field. Using only the hyperspectral component, images of a soldier's wound can be taken and transmitted to a wound specialist for consultation while immediate decision aids are provided to the medic. Similarly, emergency medical technicians and paramedics can use it as a real-time decision aid for treatment and triage. Nurses can also use THSIS during at-home visits for documenting wound progression. Off-line expert wound consultation is always available through image transmission.

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ACKNOWLEDGMENTS: This work was sponsored through the U.S. Army Medical Research and Materiel Command by the Technologies for Metabolic Monitoring and Julia Weaver Fund, which includes the Juvenile Diabetes Research Foundation, as well as NASA and NIH/NIDDK. This grant enabled a collaborative effort with Ross E. Andersen (Co-PI), William B. Greenough III (Co-PI), and Param M. Dedhia from The Johns Hopkins University School of Medicine. The award number is DAMD17-02-1-0723 and the U.S. Army Medical Research Acquisition Activity (820 Chandler St., Fort Detrick, MD 21702-5014) is the awarding and administering acquisition office. This article does not necessarily reflect the position or the policy of the government, and no official endorsement should be inferred. We thank the following people for their contributions to this project: Wil Chung for developing the thermal image analysis tools, Eric N. Piazza for investigating current hyperspectral imaging techniques that will be applied toward THSIS data analysis, Russell L. McCally for his assistance with filters and reflectance issues, John C. Murphy for his contributions on the reflectance issues and DIRI system development, and Paul J. Biermann and Steve Main for the phantom fabrication. Special thanks to the Principal Investigator, Stuart D. Harshbarger, for his vision and guidance.

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