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A noncontact wound measurement system

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Abstract—The instrument described in this manuscript was developed to perform objective, quantitative measurements of wound healing, which will enable service providers to assess, improve, and individualize the treatment given to each wound patient. It was designed to produce measures that will enable the care provider to assess the current state of the wound as well as gain insight into the time course of the wound healing by comparing the series of wound data collected over time. The record provided by the instrument could also assist in legal defense; a need that, unfortunately, cannot be ignored. The system uses a structured lighting pattern captured on a digital photograph of a wound to calculate the area and volume of debrided wounds. We used plaster molds with spherical indentations to represent various wounds to evaluate the precision of the system. Results indicate that when at least 144 of the data points in the picture lie within the wound borders, the surface area and wound volume are repeatable and the precision is within ±3% of the calculated values based on the geometry of the spherical indentation.

Key words: *chronic wounds, digital image, processing, structured lighting, wound measurement.*

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INTRODUCTION

Chronic wounds such as pressure ulcers, stasis ulcers, and diabetic ulcers constitute a problem that affects approximately 20 percent of the hospitalized population in our country and limits the autonomy and quality of life experienced by—

- Persons with spinal cord injuries.
- Postpolio patients.
- The geriatric population.
- Persons with peripheral vascular disease, diabetes, or cardiac problems who require bypass surgery.
- Persons with birth defects such as spina bifida, cerebral palsy, or muscular dystrophy.

In addition to the cost in human suffering, a tremendous dollar cost also exists associated with the treatment of pressure ulcers. An estimated $10 billion is spent each year in the care of pressure ulcers [1].

Pressure ulcers are enormously significant to many persons with disabilities, particularly those with spinal cord injuries or those who are immobile for long periods. It is estimated that 25 percent of spinal cord injured persons will suffer from a pressure ulcer at some point in their lives [2]. Improving the treatment strategy by providing quantitative assessment measures for pressure ulcers and other chronic wounds would reduce cost and greatly improve the quality of life for those people who suffer from them.

Much research has been done on the etiology and treatment of pressure ulcers; however, treatment of pressure ulcers is limited in part by the lack of a noninvasive yet effective metric for assessing wound healing. Current clinical noninvasive technologies are limited not only to simple measurements of the wound area with the use of plastic templates but also to subjective visual evaluations. More objective methods of measuring wound healing may lead to more effective treatment of problem wounds. Assessing whether a wound is healing, worsening, or staying the same is often difficult because no fast, noninvasive, and reliable method for measuring wounds currently exists. If a reliable quantitative wound measurement system were available, caregivers would be able to speed wound healing by adjusting treatment modalities as the wound responds or fails to respond to treatment.

The most widely used wound assessment tools are plastic templates that are placed over the surface of the wound bed to permit the clinician to estimate the planar size of the wound. These templates range from a simple plastic ruler that provides a measure of the major and minor axes to more sophisticated devices such as the Kundin measuring tool, which provides an estimate of the surface area and volume of the wound based on assumptions about the geometry of a typical wound. In a similar approach, clinicians often place plastic films over the wounds and use a marker to trace around the border of the wound. The tracing is processed then with a planimeter to generate information about the surface area covered by the wound. These methods of wound assessment are low cost and relatively easy to use. Unfortunately, the assessment of the wound state depends highly on individual rater reliability [3].

Other methods are available that measure wound volume. These are often more useful measurements than surface area alone [3]. A technique that has been used clinically to assess wound volume involves filling the wound cavity with a substance such as alginate. A mold is made of the wound, and either the volume of the alginate cast can be measured directly with the use of a fluid displacement technique or the cast can be weighed and that weight divided by the density of the casting materials, which represents the wound volume. A variation of this technique for measuring wound volumes involves using saline. A quantity of saline is injected into the wound; the volume of fluid needed to fill the wound is recorded as the volume of the wound. These techniques have been described in various articles in the literature, and the relative merits and relative accuracy of each have been the subject of several studies reported in the literature. However, the contact methods of measuring a wound all share several significant problems:

- Potential for disrupting the tissue when contact is made.
- Risk of contamination of the wound site.
- Fluids may be spilled on the bed or clothing may become a vector for the spread of pathogens from the wound site to other patients or clinical staff.
- Failure to account for other information such as surface area, color, or presence of granulation tissue.

Because of the limitations of these techniques, noncontact methods based on photographic methods of wound measurement have been explored. These methods have the advantage that they do not require contact with the wound; thus, the potential for damaging the wound bed or contaminating the wound or surroundings is eliminated. Currently, available systems for making noncontact photographic measurements share one or more of the following characteristics that limit their utility:

- Expense.
- Equipment that is cumbersome in a clinical setting.
- Significant training time for the operator.
- Careful setup by the operator to obtain precise reproducible measurements.

The simplest photographic techniques are black and white Polaroid prints. Color photographs of wounds have been studied to determine the most effective type of film and lighting that can be used to document accurately the size of the wound and the status of the tissue in and around the wound. Tissue color and texture appear to provide clinicians with useful information about the health of the wound. However, flat photographs are inherently limited by the problems of projecting a three-dimensional (3-D) image into a plane. These problems are easily seen on maps of the earth, where the island of Greenland becomes almost the same size of the continent of South America when the 3-D globe is projected onto a 2-D surface. Another limitation of 2-D measurements is that wound healing frequently occurs through changes in depth rather than surface area; that is, the wound maintains an approximately constant surface area but heals through reduction in wound depth—which is not measured easily with 2-D techniques. With the development of biostereophotogrammetry as a field of interest, a number of investigators have explored the feasibility of adapting stereophotogrammetric techniques to assess wounds. However, the systems that have been described in the literature share the problems of cumbersome instrumentation and lengthy preparation time for setting up the equipment to make the photographic records.

A recent expansion of photogrammetry and its applications in robotics is the field of computer vision. This field has melded the desirable characteristics of photography, such as the capability to represent object color and texture, with computers creating accurate 3-D representations of objects and surfaces. Recently, the medical community has expressed much interest in applying machine vision to the measurement of skin wounds. The ready availability of digital cameras and the progressively decreasing cost of powerful personal computers (PCs) have made computer vision a financially viable option for automatically measuring parameters relating to wound healing.

Computer vision has proved successful in many measurement tasks ranging from automatic inspection of loaves of bread to measuring the size of brain tumors in radiography. By building on the technologies developed to provide robots with vision and depth perception, this project focused on merging 2-D area, circumference, reflectance, color, and texture analysis with 3-D-structured light-volume and surface-contour measurements so that wound healing could be accurately and objectively assessed. A system was developed that can be used clinically to characterize the healing of wounds by quantifying the wound size and determining the presence of granulation tissue with minimal operator prompting.

Commercial products such as the Advanced Wound Measurement System by Vision Engineering Research Group (VERG), Inc., use computers equipped with video frame grabbers to create digital images of wounds from videotapes. Clinicians then clinically assess the images on-line [4]. However, a substantial limitation of products currently available is that the practitioner is required to manually delineate the boundaries of the wound and the boundaries of different tissue types within the wound. Reduction of human involvement in wound assessment is necessary because determination of parameters, such as wound surface area, “must be completely automated in order to obtain a fully objective and reproducible measure and to avoid the loss of time due to an interactive delineation by a human observer” [5].

The automation is made possible with the use of “structured light” technology. Structured light is a recognizable pattern of light, such as dots, stripes, or fringes, projected from a light source whose position and orientation are known relative to the light sensing equipment. The requirements for computer vision with the use of structured light are that—

- Position and orientation of the illumination source are known.
- Illuminated points on the surface are identifiable.
- Position of the camera or other sensor is known so that the direction to the illuminated part of the surface can be computed.

The topography of a surface can be determined through active triangulation repeated at many points on the surface. Each illuminated point can be considered the intersection point of two lines. The first line is formed by the ray of illumination from the light source to the surface. The second line is formed by the reflected ray from the surface through the focal point of the imaging device to a point on the image plane. Since the position and orientation of the light source and camera are known, the point on the surface can be computed through triangulation. The entire surface can be mapped by interpolating between multiple points on the surface. Multiple points are generated either by the algorithm sequentially computing the location of a single point that is scanned across the surface in multiple images or projecting a grid of points and processing the surface in a single image. It is also possible to make 3-D measurements with the use of stripes of structured light rather than discrete points.

The feasibility of measuring the volume of wounds with structured light-based computer vision was tested in the United Kingdom [6]. Testing on plaster model wounds indicated that computer vision could provide more precise wound volume measurements than either alginate or saline filling. Additionally, unlike the filling techniques, computer vision volume measurements provided information on the area, circumference, and depth of the wounds at the same time. One limitation of the equipment developed for the study was its lack of portability because of its large size. Also, since only plaster models of wounds were used, no efforts were made to use color, reflectance, or texture differences to distinguish between tissue types and no information was given on the capability of the equipment to quantify changes in wound size over time.

Computer vision using structured light has been used in dental work to measure the wear on dental filling materials over time [7]. The optical measurements provided high sensitivity to changes in tooth contour because of wear. A digital picture was taken immediately after a filling while a structured lighting pattern was projected on the tooth. The digital pictures were repeated during the wear period at intervals from 6 months to 3 years. Comparison of the image contour maps before and after wear clearly identified regions where wear was occurring.

Two-dimensional image processing is useful for assessing wound parameters, such as surface area, boundary contours, and color. Recent findings in 2-D computer vision for wound assessment include information regarding the selection of color variables that maximally discriminate between different wound tissues, information on the relationships between visual parameters such as color and reflectivity, and information on the objectivity and reproducibility of automatic measurements [8]. The instrument developed in this study can provide information on visually assessable information, such as the presence of necrotic material or granulation tissue, and can also document the RYB color code [9–11]. We took special care to ensure that all results were generalizable to persons regardless of levels of skin pigmentation.

Because of the successes of computer vision in related applications, the time is ripe for developing a wound measurement system that integrates into one system the visually perceivable parameters that are useful for assessing wound healing, including surface area, color, reflectance, volume, and texture. The 2-D image processing required to assess color and surface area already has been used to assess burn wounds and identify skin tumors [12,13]. Three-dimensional machine vision techniques have found limited application to the measurement of wound volume [2]. A new and powerful development that has been derived from this research is the fusion of 3-D surface measurement techniques used in industrial and robotics settings with the 2-D color- and texture-based image processing techniques that already have been applied to the automated measuring of wounds.

With the growing emphasis on treating persons with chronic wounds in skilled nursing facilities or in home-care environments, having quantitative, reproducible measures that can be used to document the efficacy of a treatment approach has become increasingly important. Such documentation can limit care provider liability and make timely changes in treatment strategy easier to justify in the managed-care environment. In the current environment, many gaps exist in the instrumentation that is available to quantitatively assess the status of a wound. The instrument described in this paper was developed to perform objective, quantitative measurements of wound healing that will enable service providers to assess, improve, and individualize the treatment given to each wound patient. It was designed to produce measures that will enable the care provider to assess the current state of the wound and gain insight into the time course of the wound healing by comparing the series of wound data collected over time.

The instrument was designed with the following goals in mind:

- Assess wound size by characterizing the surface area and volume without touching the wound.
- Be of a general utility for measuring all types of skin wounds, including pressure ulcers, stasis ulcers, and burn wounds.
- Provide measurements that are repeatable to within approximately 3 percent.
- Require less than 5 minutes to assess a wound, based on typical clinical staff time constraints.
- Be of a size and weight comparable to an ordinary hand-held camera so the device can be considered a portable instrument.

DEVICE DESIGN AND TESTING

We mounted a digital camera (Kodak DC120) to an aluminum frame (**Figure 1**). Four 3.0 mW red laser diodes were mounted so that each emitted light through a 0.036-in. pinhole waveguide that split each laser beam into an 8×8 grid. These four 8×8 grids make up a larger 16×16 grid that is projected onto the wound. By projecting an image with known geometry onto the wound and using distortions in the image, one can perform surface area and volume calculations. For this task to be accomplished, a digital picture of the wound and grid is temporarily stored in the camera and then transferred to a PC for analysis with the use of both commercial and custom-written software.

The equipment must be calibrated before it can be used to measure wounds. Calibration involves creating files that describe how the structured light pattern changes as the distance from the surface being imaged to the camera image plane changes. This process requires a moveable platform for the camera and laser projector. As the

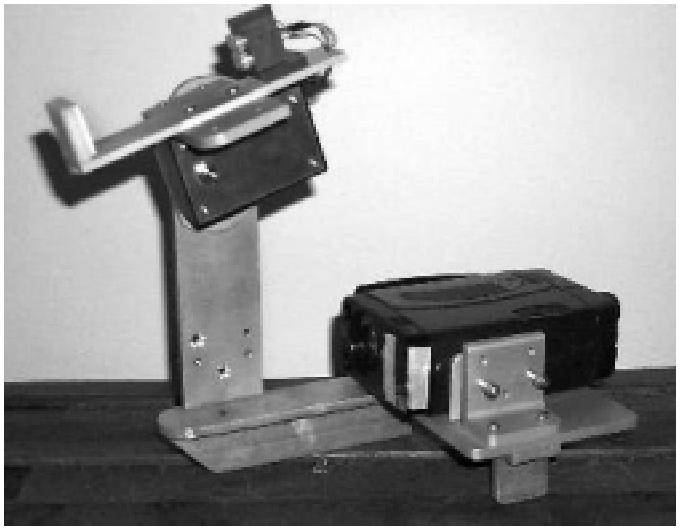

Figure 1.
Camera system configuration.

camera is moved toward the vertical plane (**Figure 2**), the image of each beam, a dot on the surface, moves upward. The vertical location of each dot will depend on the distance between the camera and the surface. For each beam, then, the equation is $z = Ay + z_0$, where z is the distance between the camera and imaged surface and y is the vertical location of the dot. Careful measurements are required to calibrate the camera-laser setup and to estimate the limits of accuracy. The vertical location of the dot is directly measurable from the digital images as a pixel count. However, conversion from pixel count to metric distance depends on pixel density on the image, and pixel density varies with z. Pixel density was found to be nearly constant across the entire surface, at all distances from the camera (varying with z but not with location at a given z).

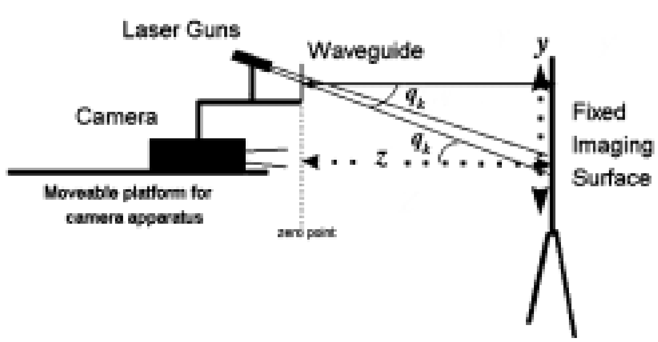

Figure 2.
Camera calibration geometry.

Laser dots have diameters of 12 to 16 pixels with typically fuzzy boundaries. They are round, but "circular" or "elliptical" would be too precise. Occasionally, a dot has a protrusion or an indentation. Ghosts were common. Because of the irregular shape of most wounds and the ghosting of the laser dots, we did not attempt at this stage to automatically capture the location of the dots. Rather, we digitized the dots on screen by point-and-click using a mouse. For capture to be facilitated, a button on the application interface caused interpolation of the last three entered points to fill out a grid: the first two points must be on a diagonal that defines the grid dimensions, and the third defines the far point of the interpolation. Points can be deleted or moved as well as added. **Figure 3** shows part of a screen during data capture. White "×" marks are on points outside the wound area, and white "+" marks are on points inside the wound area. A study of the images and process showed that, with care, laser dot centers could be manually located to about two pixels. Closer accuracy is doubtful primarily because of the fuzziness of the dots. Point location is thus accurate to about 0.0045 in. (0.11 mm). Using the calibration protocol, one can determine the height of each laser point above an arbitrary horizontal reference line and the slope of each laser beam (**Figure 2).**

Image Enhancement

As noted, locating the center of a laser dot manually is not straightforward. Computed relocation was provided

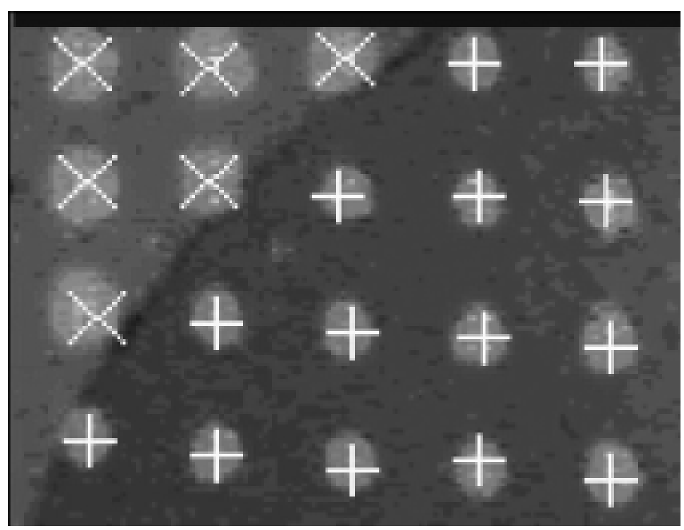

Figure 3.
Illustration of data capture.

as two search algorithms: the first relocates on color and the second relocates on brightness. The color algorithm searches the 5- × 5-pixel neighborhood of the pixel, where the digitized point is currently located. It computes the average color and the deviation from the average. We found anomalous pure white points to invalidate the computation from time to time, so we excluded these. Then the 19- × 19-pixel neighborhood was examined, and the coordinates of all points whose color fell within range of the original color were used to compute a new location for the digitized point. Repeated application tends to migrate the point to a fixed location.

The brightness algorithm computes the brightness of all points in a 17- × 17-pixel neighborhood, and the coordinates of the points in the brightest 33 percent were used to relocate the point. As in the case of the color algorithm, repeated application tends to converge to a point. Arbitrarily, we chose the neighborhood sizes 5, 19, and 17; we took no effort to optimize these numbers.

When we modified the calibration files using these algorithms, the intrinsic root-mean-square (rms) error decreased by a factor of 2, from 0.025 to 0.0125 in. This suggests that locating pixels with this method is accurate.

Wound Area Calculations

Wound area is calculated by summing areas associated with each laser dot within the wound. The area at each dot is computed as the product of cross-section lengths in the horizontal (*x*) and vertical (*y*) directions. The cross-section length is the average of two approximations: a bilinear approximation and a circular approximation. Each laser dot interior to a wound is surrounded by eight immediate neighboring dots. The four dots in the *x* and *y* directions are used in the approximations. **Figure 4** illustrates the approximating algorithms in a cross-section view. Three dots in the *x* or *y* direction are shown projected onto the surface of a wound. Bilinear approximation is accomplished by connecting the central dot with the other two dots by two straight lines in either *xz* or *yz* space. The distance across the surface of the wound in cross section is then approximately the combined length of these lines. The lengths to be associated with the central point are computed by bisecting the lines.

The approximation is made in both the *x* and *y* directions. It is then possible to estimate an area associated with each point by two methods, circular and linear fitting. When the area is computed from these two approximations and compared to the actual area of a known

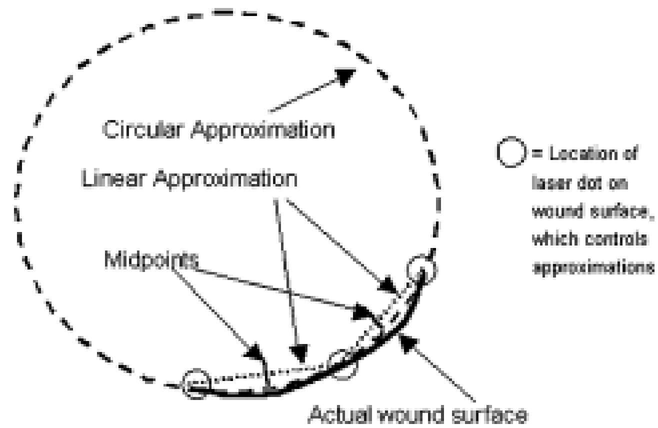

Figure 4.
Interpolation geometry for wound area and volume calculations.

geometry, the errors associated with the process can be tabulated as shown in the **Table**. We generated the information in the **Table** using data collected on wound models, which had known spherically shaped indentations of varying size. Images were taken at various distances. The defect size and distance from the camera determined the number of points falling inside the defect area. The **Table** also illustrates that accuracy reaches about 1 percent when 100 or more laser dots are in the wound area.

We identified four sources of error: (1) deviation from the mathematical model just described, (2) overlap and gaps in the areas associated with the points, (3) mislocation of laser dots during digitizing, and (4) error inherent in the discretization of the wound surface, or “Border Error.” **Figure 4** clearly indicates that computed lengths will deviate from actual lengths on the wound surface. In the general case, the flatter the wound surface, the more accurate both the bilinear and circular approximations will be, but the calculations are made with the nonflat cases specifically in mind. From **Figure 4**, one can see that the computed areas from point to point are likely to overlap and to have gaps. In addition, mislocations of laser beam centers will cause some, probably very small, errors in area calculations. Perhaps the largest source of error is the Border Error caused by the discretization of the wound surface. As long as points are randomly located with respect to the border of the wound, this will be a random error, but a wound with straight sides, such as might be caused by mechanical incision, could produce a biased area computation. If the wound has straight sides, the image should be captured so that

Table.
Error percentage as a function of the number of points in the wound bed.

No. Points	Area Error	Volume Error
16	4.13	15.61
22	5.81	–5.66
24	8.79	–24.53
28	–4.96	–7.51
32	2.83	5.66
32	–4.13	–1.73
34	4.13	–1.73
39	7.83	–7.93
40	4.13	4.05
45	–2.17	–10.49
60	–12.61	–8.95
102	–3.41	–5.66
109	0.00	2.43
109	–0.28	2.43
112	–3.12	2.43
118	0.57	–2.96
120	–0.85	–0.27
133	–5.62	–19.15
138	0.28	–0.27
139	0.28	1.73
144	1.26	–2.26
152	1.40	2.60
154	0.00	–3.99

the dots do not track along one of the sides. A row or column of dots should cross the border of the wound at an angle. In addition, the image, whatever its shape, should include points both inside and outside the wound over the entire surface of the wound. The outside points are important in estimating (however inaccurate) the location of the wound border, as well as estimating the prewound surface for volume computation.

Volume Calculation

Volume estimation requires estimation of the original skin surface. Skin surface is approximated by the equation

$$z = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 y^2 + a_5 xy .$$

Coefficients a_i are estimated by a least squares fit to the points outside the wound area. This assumes that the wounded part of the body was originally smooth and had only simple curvature in two orthogonal directions, as would be expected for the thigh or upper arm. Areas such as the side of the neck or between the shoulder blades might deviate from this assumption. Fortunately, the residual error in the least squares fit is a quantitative measure of the suitability. Swelling around the wound, of course, would cause a problem. If swelling goes up or down, it will change the volume calculation regardless of any change in the wound itself, and the residual error will be irrelevant to the suitability of the mathematical model. The method should be applied only to stable wounds, if the volume calculation is to be used at all.

The third column of the **Table** shows the volume error as a function of the number of points inside the wound. Clearly, the error tends to decline with a number of points. With more than 100 dots in the wound area, the error is about 2.5 percent. To further study the sensitivity of the system, we constructed a cylinder 0.75 in. in diameter, with a piston to measure volume at various piston settings. With this apparatus, we determined that with about 100 points inside the area, changes in depth of 0.01 in. (0.25 mm) were detectable. This is approximately the limit of accuracy of the system as calculated based on the physical characteristics and geometry of the system.

CLINICAL EVALUATION

Informed consent was received from 48 people to photograph over 100 wounds. We were careful to ensure that participants with various skin pigmentations participated in this project. The wounds were of various sizes, anatomical locations, and stages of healing. They were photographed in several different hospitals with different amounts of ambient light (although we attempted to keep ambient light at a level approximating 5 to 10 lm). The wound images were stored in digital format and then taken to a laptop computer for processing.

Adobe PhotoShop was used to enhance the distinction between the three areas of the digital picture: the laser dots, the wound, and all nonwound area. A simple procedure, which takes less than 5 minutes, was developed for the enhancement process. All enhancement procedures were performed on a copy of the original photograph, thus preserving the original for subsequent visual inspection. The enhancement procedures were designed to sequentially achieve three goals: (1) clarify the distinction between the laser dots and the rest of the photo, (2) select the laser dots, and (3) clarify the distinction between the wound and all nonwound area.

Clarifying the distinction between the laser dots and the rest of the photo can be done in one of two ways, depending on the pigmentation of the skin surrounding the wound. For wounds from fair-skinned individuals, the entire photograph was darkened which blended the background somewhat and allowed the bright red laser dots to stand out. For wounds from individuals with darker skin, we could alter the photograph by increasing the dominance of blue and by converting the red into pink. These steps provide pink laser dots on a blue background. The exact process is available from the authors and only involves opening a dialog box in Adobe PhotoShop. No specialized knowledge of photography is required to process these photographs. The laser dots can then be selected based on their color, because it is consistent, both within a single laser dot and from one dot to another. Using the “magic wand” tool, the user selects a typical laser dot. Then the software is able to find all portions of the photograph of similar color. The exact pixel the user selects is a certain color, which is assigned a number. The user can set the tolerance or width of the band of acceptable colors. He or she may have to perform a small amount of clean-up to individually select a couple of faded or fuzzy laser dots or to unselect an alias.

Once all the relevant laser dots are selected (those in and surrounding the wound), the inverse is selected and copied. The inverse, which is the entire photograph except for the laser dots, is copied into a new document. The former locations of the laser dots are now represented by blank (white) space, which provides a subtle, but important, difference from the original photo. In the original, the laser dots were of a consistent red color; in this paper, the spots representing the laser dots are all exactly the same color, in this case white. This uniformity in color improves the accuracy and ease of use of the analysis software. The laser dots are not all the same size after this procedure, but that is not important. The only important piece of information is the location of the centroid of the laser dot. Therefore, if some dots are large and others small and if some dots appear as an annulus instead of a circle, the calculation is not affected. **Figure 5** shows an intermediary image from the process directly after the laser dots had been selected.

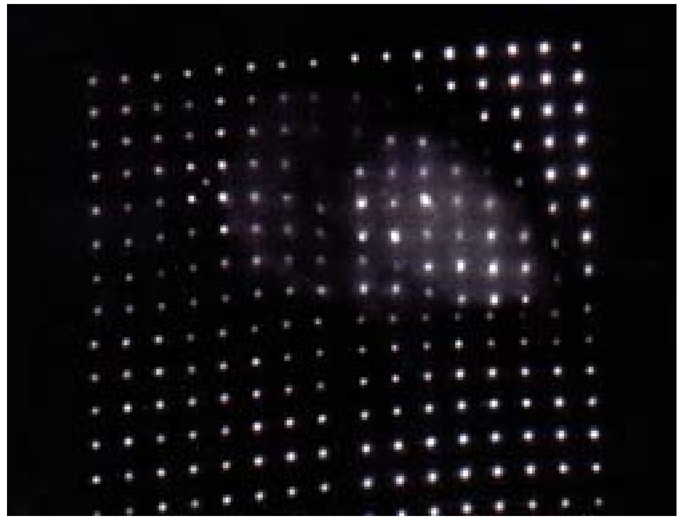

Figure 5.
Typical wound.

We then enhanced the photographs to exaggerate the distinction between wound and nonwound. For individuals with fair skin, we lightened the photographs and then viewed them using shades of green with the red and blue minimized. These green photographs more clearly exhibited the borders of the wound than did the original photograph. Removal of the red and blue left the wound black and the rest of the photograph green. For photographs of individuals with dark skin, both the red and green were accentuated while the blue was minimized. This procedure also left the nonwound area green, but colored the wound red. In either case, the wound could easily be distinguished from the nonwound without difficulty. **Figure 6** demonstrates this distinction.

The modified copy of the photograph was saved as a bitmap and then opened in the analysis software. The analysis software has an automated procedure for finding the laser dots and then locating the centroid of the dot. Once the laser dots were located, the user simply selected the dots inside the wound by pointing and clicking with the mouse, and the software calculated the surface area and volume of the wound in either metric units (cm^2 and cm^3) or English units (in^2 and in^3). These data could then be saved. Sequential photographs can be used to quantify wound healing in both volume and surface area.

CONCLUSIONS

The noncontact wound measurement system developed in this project has been shown to be an effective

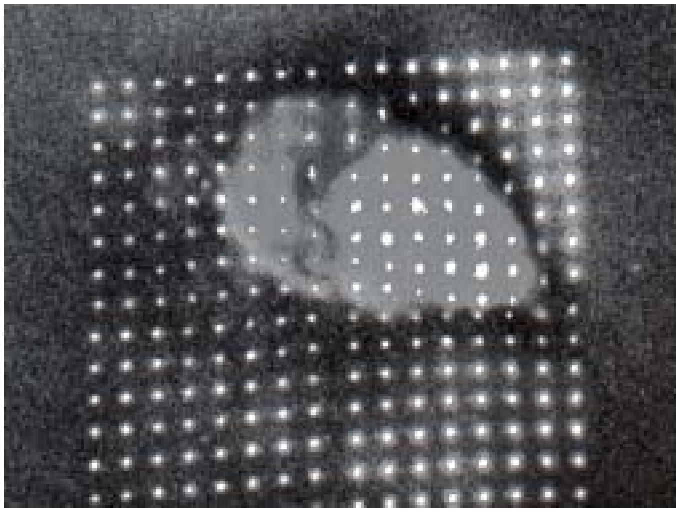

Figure 6.
Enhanced wound.

device for measuring surface area and volume of wounds, and it meets or exceeds the goals set at the beginning of the project. The combination of commercial and custom-designed software allows for processing and analysis of a digital copy of the photograph, leaving the original copy untouched for subsequent visual examination. The acquisition of the photograph takes very little time, especially if it coincides with the changing of the dressing on the wound. The portability of the device allows photographs to be taken almost anywhere. Once the image has been captured with the digital camera, the processing of the photograph takes less than 5 minutes. A trained computer operator must sequentially follow a series of predefined actions first in Adobe PhotoShop and then in the custom-designed wound measurement software. The time and effort to acquire and process an image are small, especially when compared to the clinical value of the information regarding whether the wound is healing or not. Future research will be needed to determine the explicit limitations of this device (wound size, location, etc.) as well as to determine other applications of this technology. The feasibility for using this device as a noncontact measure of wound surface area and volume has been demonstrated.

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