Wound Healing Assessment Using Digital Photography: A Review

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ABSTRACT

Digital photography as a non-invasive, simple, objective, reproducible, and practical imaging modality has been investigated for the wound healing assessment over the last three decades, and now has been widely used in clinical daily routine. Advances in the field of image analysis and computational intelligence techniques along with the improvements in digital camera instrumentation, expand the applications of standardized digital photography in diagnostic dermatology such as evaluation of tumours, erythema, and ulcers. A series of digital images taken at regular intervals carries the most informative wound healing indexes, color and dimension, that may help clinicians to evaluate the effectiveness of a particular treatment regimen, to relieve patient discomfort, to globally assess the healing kinetics, and to quantitatively compare different therapies; however, the extent of underlying tissue damage cannot be fully detected. This paper is an introductory review of the important investigations proposed by researchers in the context of clinical wound assessment. The principles of wound assessment using digital photography were shortly described, followed by review of the related literature in four main domains: wound tissue segmentation, automated wound area measurement, wound three dimensional (3D) analysis and volumetric measurement, and monitoring and evaluation of wound tissue changes during healing.

Keywords: Wound Assessment, Digital Photography, Image Analysis, Wound Healing

1 Introduction

Wound assessment at regular intervals helps clinicians to evaluate the effectiveness of adopted treatment strategy and change it if necessary; however it is complex and multi-sided which includes wound appearance, identification of factors delaying healing, wound etiology, monitoring and prediction of healing rates, and wound documentation [1]. The gold standard is the wound biopsy which provides valuable superficial and depth information with the cost of increasing the wound area and impairment in the healing process [2]. In clinical arena, assessment methods have mainly been based on

measuring the two informative characteristics of the wound: dimension and colour [3]. The earliest methods used rulers, acetate sheets and alginate casts to measure the wound area and volume. However, the problem of direct contact to the wound, along with the poor precision due to subjective aspects of the measurement, made them less reliable [4]. In addition, automatic wound healing assessment, especially wound dimensional measurement would reduce the professionals' workload and costs, and improve the quality of patients' care [5]. Various simple and complex non-contact methods such as stereo-photogrammetry and structured light analysis were developed to reduce the measurement error rate to 0-3% and 3-5% respectively, to prevent wound contamination and to remove patient discomfort [6]. On the other hand, wound colorimetry which is based on the Red-Yellow-Black model, takes into account the ulcer's colour characteristics as a function of its clinical stage; however, it is more a measure of the clinicians' skills at cleaning up a wound than of the healing progress [7].

Significant advances in the field of digital image processing make the standardized digital photography as the most popular tool which considers both aspects of the wound for assessment of healing. Several successful attempts to classify wound tissue have been made through segmentation algorithms applied to various sets of features extracted from different colour spaces, with the aim of objectively monitoring the colour changes during healing [8-15] and automatically determining the wound volume and area [16-18]. All these proposed methods for assessing wound healing provide information only at the surface level and cannot be applied to all types of wound [2, 19]. This issue becomes more significant when dealing with chronic wounds such as diabetic foot ulcers (DFUs) which are notably different from acute wounds in that they can develop superficially or from within the deep tissue, depending on the nature of dominant risk factors [20]. This paper shortly describes the principles of digital photography, reviews the related studies that investigated the application of optical imaging in wound assessment, and enumerates limitations.

2 Clinical Assessment of Wound Healing

A thorough assessment of wound tissue should consider the following characteristics: size of the wound, edge of the wound, wound bed and colors, wound depth, surrounding skin, wound exudate, infection, and severity of pain. However, there is no universally established instrument applicable for all types of wounds which considers all above mentioned characteristics and satisfies all aspects of instrument validity, reliability, and measurement sensitivity. The quantitative assessment of chronic wounds still builds upon manual techniques and visual inspection to portray the wound physical appearance and the nature of tissues paved the wound bed [21, 22]. In practice, a wound is inspected on a weekly or fortnightly basis during replacement of dressing. The size of a healing wound tends to be reduced over time, while it is static or increasing in a deteriorating or non-healing wound [16]. Therefore, continuous measurement of wound size as a key indicator of healing and comparison of the recent wound's dimension with the current measurement may increase the likelihood of adopting effective treatment regimen, provide objective form of evaluation, help predict healing, enhance quality of patient care, contribute to more accurate communications between professionals, and enhance overall wound management [3, 16, 23-25]. Of the several contact and non-contact methods proposed for wound dimensional measurement, ruler based technique, transparent tracing, and computer assisted planimetry are most commonly used in clinical daily routine [16, 26, 27]. The modified ruler technique is simple, fast, and cheap, while its poor precision (25%) for wound with complex shape along with risk of

infection made it less reliable [4, 28]. Tracing is a more accurate 2D method for wound with irregular shape in which the wound is outlined on a transparent squared acetate sheet and next the wound area is calculated by manually counting the amount of included squares; however, it is a tedious task and has shown poor inter-rater reliability [27, 29, 30]. In addition, the problem of steam forms below the film blocks the visibility of wound's outline; increases the risk of cross-contamination and patient's discomfort [30]. So, the digital planimetry was proposed to speed up the area calculation through using a digital tablet wherein the tracing is placed on it and the border is outlined by a stylus pen. It is well documented that the results of acetate tracing and the digital planimetry are in agreement for wounds with an area < 10cm^2, while significant difference was reported for larger wounds. Moreover, using the second tracing automatically increases the error rate [27]. Colour also is an important parameter in wound care for two reasons: Firstly, wound colour may be used to classify wound tissue types (i.e. granulation, slough, and necrotic), guiding medical decisions like the type of dressing and prediction of possible complications; secondly, colour has been one way of identifying basic symptoms of inflammation [8]. The Red-Yellow-Black (RYB) model [31] is the commonly accepted tissue classifying method on the basis of colour used by clinicians and wound nurses, and is not limited to any specific wound type, such as pressure or diabetic foot ulcers. However, it is highly related to clinician's experience, time consuming, and irritating for patients. Advancement in the field of colour image processing along with advent of relatively cheap high quality compact digital camera, give rise to developing numerous 2D digital image analysis techniques for wound healing assessment. Here, the principles of digital imaging were described and the most successful attempts for area measurement and wound tissue classification using optical imaging were reviewed briefly.

3 Principles of Digital Imaging

Colourimetry, the measurement of colour, is a complex task. Ideally, a system with precisely known characteristics able to acquire images under exactly reproducible conditions is needed. Unfortunately it is very difficult to have perfect control over every aspect of the acquisition process like camera position and setup, lighting, and filters. Care has therefore to be exercised in order to eliminate as many variables as possible from the image acquisition process. Furthermore it is important that the images resulting from the acquisition process are of the highest quality and reveal as much information as possible about the problem at hand. Otherwise a range of post-acquisition digital image conditioning and filtering processes like noise reduction and colour correction may have to be used unnecessarily and it may become impossible to extract the required information [8]. An ideal image acquisition system consists of several sub-components (e.g. lighting box and filters) which are bulky and expensive; so, a single set of device including digital camera and colour checker would be used in case of achieving colour consistency by defining a protocol wherein all influential factors are specified and controlled as much as possible (Figure 1).
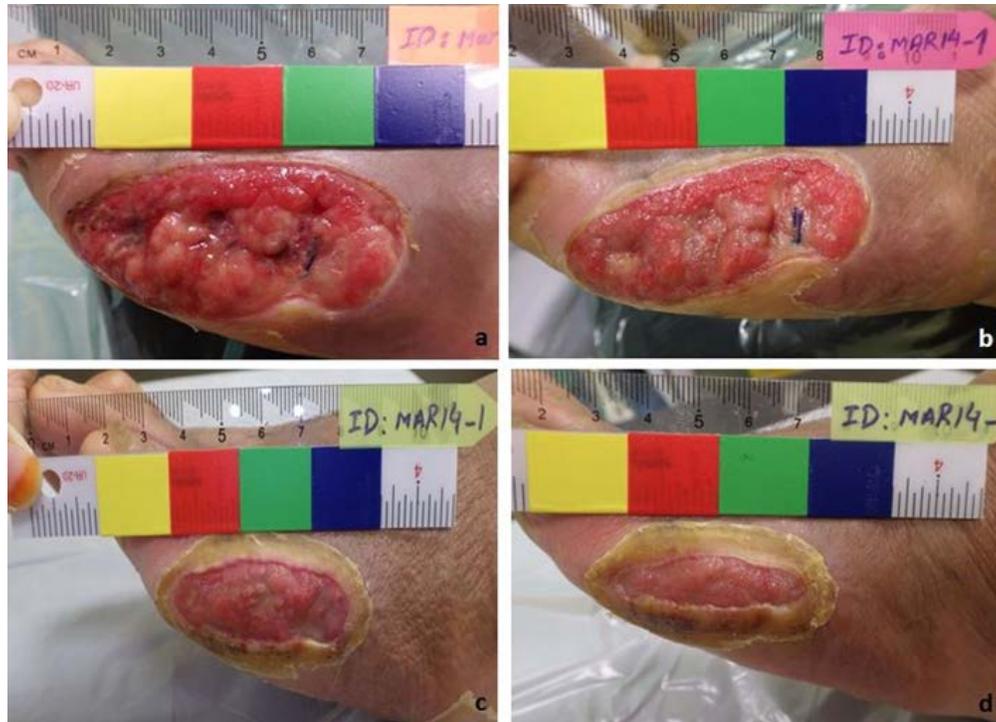
Figure 1. Optical images of a diabetic foot ulcer taken on (a) Day 7, (b) Day 14, (c) Day 21, and (d) Day 28 post-debridement in a controlled environment. As the wound images were taken under similar conditions with the same set of equipment, their colour characteristics were consistent and the subsequent colour corrections would be minimized.

4 Optical Imaging in Wound Assessment

Applications of digital photography in quantitative wound assessment can be categorized to four main domains: wound tissue classification, automated wound area measurement, wound three dimensional (3D) analysis and volumetric measurement, and monitoring and evaluation of wound tissue changes during healing.

4.1 Wound Tissue Classification using Digital Image Analysis

Tissue classification over the wound delineated from the image background, has been reported to be a complicated task. It is due to nature of the wounds with non-uniform combination of red granulation, black necrotic and yellow slough tissues that leads to colour ambiguity [10, 11, 32, 33]. Several successful attempts have been made to classify wound tissue through using segmentation algorithms applied to various sets of features extracted from different colour spaces, with the aim of objectively monitoring the colour changes during healing [5, 8-12, 14, 15, 32, 34-37]. Here, we tried to briefly review the most prominent investigations.

In a novel technique, the 3D RGB colour histogram was used for wound tissue classification, i.e. after computation of 3D RGB histogram of the manually delineated wound, a clustering technique was applied to cluster the histogram bins which lead to segmentation of the different tissue types within the wound site. Finally, segmented granulation tissue area was used as a quantitative measure for wound healing assessment [38]. Although the classification results were promising, the used un-calibrated wound image and insufficient number of wound images prevented the investigator from establishing

colour reproducibility and generalizing the proposed method. Moreover, reducing resolution of the RGB image, the way of selecting the seeds, and the order wherein the clusters created restricted the algorithm.

In another study, the slough tissue in 30 pressure ulcers was segmented and graded based on the hue value changes in HSI colour space after wound delineation performed by a semi-automatic method called adaptive spline technique, followed by calculation of amount of slough as a quantitative measure in wound healing assessment. The accuracy of colour assessment was compared with the clinicians' decision and 75% agreement was reported. However, it was concluded that the wound assessment just by optical images looks insufficient for clinicians as they normally consider the other parameters like pain, surrounding tissue, and wound odour. Also, the uncontrolled lighting condition appeared as 10% shift in red patches of colour checker which affected the reliability of the results for describing the minor changes in hue [9]. Meanwhile, the same team of researchers launched another study with the same protocol, but increasing the number of leg ulcers to 50. The results revealed that the red patches colour shift increased to 17%; so, calibration of hue values prior to wound analysis was suggested [12].

Three other investigations were used the support vector machine (SVM) for tissue classification in calibrated wound images. Firstly, Belem [8] studied the relationship between wound colour and inflammation that may be resulted from an infection. The manually delineated wound was automatically segmented in CIE L*u*v* into smaller regions, separating "healthy" and "non-healthy" tissues. Then, extracted statistical parameters were imposed to "brute force" approach to select the most successful ones for subsequent classification. Logistic regression (LR), support vector machine (SVM), and an artificial neural network (ANN) were utilized as classification engines which were compared against each other and the clinician's classification using the Kappa agreement estimator. Results demonstrated that SVM was the best performing classifier with more consistency in its judgment than most of the clinicians. The study outcomes were encouraging, but more information was required to guarantee causality between actual wound inflammation status and classification as the infection is not necessarily the sole cause.

In the second research, Automatic segmentation of wound region was performed using multi-dimensional histogram sampling technique that provided efficient set of feature vectors for as an input for SVM classifier. It was concluded that 3D colour histogram sampling, produced more discriminatory set of features for SVM classifier than those of one dimensional histogram which improved the accuracy of wound area segmentation by 20-30% [10]. However, such an approach failed to generate a contour as fine as the manual one traced by clinicians.

In the third study, the wound images were imposed to an unsupervised segmentation method before classification to increase the robustness of tissue labelling. Then the colour and texture descriptors (i.e. average, standard deviation, skewness, and kurtosis) were calculated in perceptually uniform colour spaces La*b* and LC*h* to design a SVM classifier with 88% successive overlapping scores. Finally, the unsupervised segmentation method was applied on test-samples, followed by classifying the regions. The results indicated that the classification performance was 75% and 60% for granulation and slough tissues respectively [33]. However, the classification error was greater than 50% for necrosis and the proposed approach required preliminary manual region of interest selection [14].

Zheng, Bradley [32] proposed a new technique to classify the wound bed tissues in leg ulcers using three 2D histograms of RGB pixel distribution values as an input for case-based retrieval , KNN classifier. The outcomes demonstrated that for binary classification, the accuracy ranged 86.2-99.45%, while for multi-class segmentation was 87.2%, higher than 77.6% obtained in study performed by [38].

Galushka, Zheng [5] used eighteen texture features extracted from co-occurrence matrix of each RGB channel and eighteen RGB colour features as an input for case-based classifier (CBR) to identify wound tissues. Two groups of experiment (i.e. three and six classes) were recruited to assess the accuracy. The results indicated that the textural features were less effective in multi-class segmentation, 58.3% and 54.4% accuracy for 3-class and 6-class respectively, than the colour features with accuracy of 89.93% and 86.8%. Such a drawback was due to the small size of region of interest which inevitably reduced the accuracy of classifier.

A hybrid design based on Bayesian classifiers and neural networks was used for automatic tissue classification in wound images. A region-growing approach and a mean shift strategy were designed for effective region segmentation wherein texture and color features were extracted. Then, a set of k-multilayer perceptrons was trained with inputs consisting of texture and color patterns, and outputs consisting of categorical tissue classes were determined by clinical experts. At the end, a Bayesian committee machine was formed by training a Bayesian classifier to integrate the classifications of the k neural networks, and the results of the classifications were improved using specific heuristics based on the wound topology. The results of binary cascade strategy showed the highest classification accuracy rate by specificity = 94.7%, accuracy = 91.5%, and average sensitivity = 78.7% [14]. Except granulation tissue, there were significant differences in sensitivity among the proposed approaches to classify the other tissue types, made each approach more or less appropriate to classify a particular tissue type.

A database including 74 different chronic wounds was imposed to Bayesian and SVM classifiers for automatic tissue classification. Firstly, the recorded RGB wound images were converted to HSI color space, followed by wound delineation through fuzzy-divergence-based thresholding. Then, set of color and texture features were selected as an input for aforementioned classifiers. The research outcomes revealed that the SVM showed higher accuracy for slough, granulation, and necrotic tissues by 90.47%, 86.94%, and 75.53%, respectively [11].

4.2 Wound Area Measurement Using Digital Photography

Digital photo planimetry has become increasingly popular for wound healing assessment wherein series of well-obtained digital images taken from the same region of an ulcer along with dimensional measurements can be applied as a yardstick to monitor the effectiveness of a treatment strategy [3, 4, 39-41]. In the context of wound's perimeter, area, and volume measurement, delineation in which details of the surrounding area is isolated from the wound information, is one the most important image processing steps; however, there is no single algorithm in existence that works perfectly for all types of wounds due to "the nature of the wounds". Manual delineation is tedious and is liable to two major criticisms: bias measurements and repeatability through using several observers [16]; therefore, several automated and semi-automated methods were developed to define the region of interest (ROI). The fully automated approaches failed to show acceptable performance as single algorithm cannot deal with all affecting factors like shape and type of wound, definition of wound edges, and type of dressing. So,

numerous semi-automatic algorithms which require some user interaction were proposed: active contour modelling [16, 42], contour detection using histogram segmentation [10], region growing for edge detection [43], clustering approaches [44], and texture analysis [16, 44, 45]. Once the wound boundary has been outlined, the circumference and area are measured in terms of lengths and pixel areas, respectively. Here, the most successful attempt for area measurement was reviewed shortly.

The most successful method was based on a Snake active contour model proposed by Jones and Plassmann [16] in which the manual delineation was adjusted as the initial solution and the final contour was obtained using piece-wise B-spline arcs and minimax principle. Despite of the fact that it produced significant results; it is very complex and failed in case of wounds with vague boundaries and existence of red and dark spots near the inner and outer sides of wound edges, is not robust against small changes in lighting, and any artefacts like shadow or piece of dressing in the image can also upset such a system.

As a result, manual wound delineation through using simple and fast software equipped with accurate scaling mechanism is still the first choice of professionals in everyday clinical routine. For instance, a digital planimetry software called Pictzar was developed using calibrated optical images and its accuracy, intra and inter-rater reliability was assessed on a database consisted of 200 images of the wounds with varying aetiologies. The accuracy and reliability mean value for small wounds ($<4cm^2$) were reported as 98% and 94% respectively [30].

4.3 Wound 3d Analysis And Volume Measurement

Despite of valuable information obtained from 2D measurement of wounds, it is insufficient for comprehensive assessment of wound healing and for detection of deep tissue changes. Moreover, area measurements do not show initial changes in deep ulcers wherein the healing improves by growth of granulation tissue from the wound's bed [29]. Traditional measurement of wound volume is limited to estimation of wound depth using sterile cotton tip and combine with area information through mathematical formula, filling the wound with saline and measuring the volume of the saline dispensed from syringe, and applying wound mould made of silicon rubber and weighing alginate moulds. These approaches increase the rate of contamination; and are inaccurate with error rate 10-40% and 5-15% for depth estimation using the cotton tips and wound moulds, respectively [46-48]. Several approaches tried to develop non-invasive volume measurement applying wound 3D reconstruction including photogrammetry [39, 49], structured light analysis [4, 17, 34, 50], and industrial 3D digitiser [18, 51].

4.3.1 Wound 3d Analysis Using Stereo-Photogrammetry

Wound stereo-photogrammetry was introduced by Bulstrode, Goode [28] where the wound depth was obtained by capturing the wound images in two different angles, followed by a matching algorithm trying to find the corresponding points in two images and computing the point depth based on the distance between corresponding points in the pair of images. It was reported that such a measurement tool has the highest accuracy among volume measurement approaches with the error rate less than 3%; however, it is costly and impractical in clinical application. Another investigation was used three progressive scan video cameras mounted on a triangle frame and a light projector placed at the centre of the rig holding the cameras called MEDPHOS (Medical Digital Photogrammetric System) measure volume of the pressure sores in which image triplets were acquired from the wound, followed by generation of three digital surface models that then combined to increase the reliability of generated

surface model. Finally, the volume of the wound, the space sandwiched between the measured surface of the wound and the original healthy skin surface, was calculated [49]. Another research team worked on the same setting with a novel strategy in characterizing the point correspondences along with their performance evaluation resulted in 96.8% robust 3D point reconstruction [39]. Apart from high accuracy level, it failed to measure the moist wounds with flat surface due to presence of reflection. Moreover, the calibration stage should be done by a trained operator and the fixed observation distance limited the field of view for large size wounds.

4.3.2 Wound 3d Analysis Using Structured Light

Using the colour coded structured light in wound assessment was proposed by Plassmann [29] which was then commercialized as MAVIS I (Measurement of Area and Volume Instrumentation System) in 1998, wherein a set of 70 parallel beams of varying colours was projected onto the wound surface and recorded by a CCD camera. Then a computer calculated 3D map of the wound from the position information of the focal points of projector and camera, and from the intersection points of the stripes of light with the wound surface. The error rate of this instrument was 3-5% for wounds with the size of 0.5-30 cm^2, but it was expensive and needs trained operator. The newer prototype, MAVIS II, was introduced in 2006 that equipped to a reflex digital camera with special dual lens optics to record two images from different view-angles which removed the needs for exact camera positioning, made the prototype portable in clinical environment, and simplified image capturing; however, it was still costly.

In another study, the structured lights were produced by using LCD projection system and a CCD camera, to reconstruct the 3D surface of five wound phantoms with depth of 4-10 mm and width of 15-25 mm. The results were compared with the manual measurement and Saline infusion. Among three methods, the structured light showed the best repeatability (<10%) when the wound sides were not steep; however, the outcomes cannot be achieved through clinical practice due to the small number of studied wounds and complexity of real ulcers like DFUs which was not modelled in used phantoms [50].

Another original approach in 3D assessment of skin wounds was initiated by Albouy, Lucas [52] and then improved by Treuillet, Albouy [3] in which the wound 3D model was obtained from un-calibrated images recorded by a handheld digital camera with free zooming. In particular, an original matching scheme and self-calibrating algorithm were used to produce a dense and precise reconstruction from two colour images. It was demonstrated that the best configuration for image acquisition was between 15° and 30° for vergence of stereo-pair with global precision 3%.

4.4   Monitoring Wound Tissue Changes Using Digital Photography

Camera images were also utilized in quantitative assessment of tissue changes during the wound generation and healing procedures, i.e. the healing kinetics was evaluated though analysis of colour images over time. In an investigation with the aim of studying a new drug, four 8 mm skin blisters were induced on the forearms of eight healthy subjects; then the optical images of the wound site were recorded between day 1 and day 12. Two healing indices that were built on the wound area and colour changes were used as criteria for tissue comparison during healing. The results revealed that the mean of chromatic green (g) in rgb colour space, which is less sensitive to the intensity compared to the RGB colour space, showed the greatest ratio of variance among the other colour features [41].

In another research, the colour images were taken from induced pressure ulcers on the porcine with the aim of grading the wounds in terms of their severity. The outcomes demonstrated that visible colour changes in hue channel of Hue-Saturation-Value (HSV) colour space may be used as a criterion for distinguishing the wound severity provided that the elapsed time from the injury was known. Also, correlation analysis with histological information indicated that it can be used to evaluate the effectiveness of treatment regimen. However, the proposed method was not able to determine the grade of wound severity for wound older than 30 minute [40].

Optical images of donor sites, one treated with topical alginates and the other with petrolatum gauze, in 10 patients were taken from day 6 to day 12 post graft removal every 2 days. Then, the meaningful parameters measuring the wound colour and homogeneity changes were extracted; and those that had significant changes over time were selected to construct the linear healing function. The performance of the healing function was compared with the results of principal component analysis (PCA) [36].

Also, the induced pressure ulcers in guinea pigs were photographed by digital camera and scanned by high-frequency ultrasound scanner at day 3, 7, 14, and 21 to assess the pressure sore generation and healing processes. Then, the colour and textural features that significantly changed with time were extracted from optical and HFU images; respectively, followed by grouping into five categories as inputs for multi-layer perceptron neural network to classify the examination days. The results revealed that the features extracted from camera images were not able to distinguish the day 14 from day 21, and the HFU features were not able to differentiate days 3 and 21. However, information fusion of both imaging modalities using a fuzzy integral was able to differentiate all classes and would be applied as a viable tool for assessing the generation and healing processes in pressure ulcers. One major limitation of the study was the difference between real chronic and induced wounds in terms of severity, depth, and patient's characteristics which definitively changed the time pattern used in the study [19].

5 Limitations

All above reviewed studies were in agreement that the digital photography can be utilized as a non–invasive, quantitative, fast, and cost–effective technique in wound healing assessment; however, it is not able to depict the full extent of underlying tissue damage. Most of the studies evaluated the healing in acute experimental wounds induced on pigs or human wherein the wound severity, depth, size, and the healing phase sequential order were not necessarily follow the pattern in chronic wounds. In addition, the wound images should be taken under controlled environment which is impractical in everyday clinical practice; otherwise colour analysis and wound dimensional measurement will subjected to high error rate and produce grossly incorrect results. Also, much work still needs to be done to arrive at a reliable and simple calibration system that affects image data quality only minimally and is still easy to use.

6 Conclusion

Optical imaging has great potential for non–invasive and quantitative wound assessment by targeting the monitoring of healing progress. It can also be combined with the other imaging modalities like high frequency ultrasound imaging to provide comprehensive and accurate information on tissue dimensional and structural changes that may ameliorate patient discomfort by adopting proactive treatment regimen. Further work, however, is required to diminish the dependency on expert clinicians

and operator by developing standard protocols for wound border delineation and wound colour image calibration.

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