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REVIEW ARTICLE

Non-invasive techniques for wound assessment: A comprehensive review

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Abstract

Efficient wound assessment is essential for healthcare teams to facilitate prompt diagnosis, optimize treatment plans, reduce workload, and enhance patients' quality of life. In recent years, non-invasive techniques for aiding wound assessment, such as digital photography, 3D modelling, optical imaging, fluorescence and thermography, as well as artificial intelligence, have been gradually developed. This paper aims to review the various methods of measurement and diagnosis based on non-invasive wound imaging, and to summarize their application in wound monitoring and assessment. The goal is to provide a foundation and reference for future research on wound assessment.

KEYWORDS

imaging technology, mobile medical devices, wound assessment, wound diagnosis

Key messages

- Importance of Efficient Wound Assessment: Essential for timely diagnosis, optimized treatment plans, reduced workload, and improved quality of life for patients.
- Emergence of Non-Invasive Techniques: Recent developments include digital photography, 3D modelling, optical imaging, fluorescence, thermography, and artificial intelligence.
- Focus of the Paper: This review examines various methods for measurement and diagnosis based on wound images.
- Applications: Summarizes the use of these non-invasive techniques in monitoring and assessing wounds.
- Research Foundation: Aims to provide a basis for future studies in wound assessment.

1 | INTRODUCTION

Wound healing is a complex process that requires a certain amount of time to complete. In recent years, the issue of patients' wounds has garnered significant attention.[1] Delayed wound healing not only imposes a substantial burden on families and society but can also pose a risk to the patient's life.[2] Objective and precise documentation and assessment play a crucial role in aiding wound diagnosis and treatment. The advancement of smartphones, computer hardware, optics, and internet technologies has led to the emergence of studies on wound images. These studies have proven to be effective in wound management, from the acquisition of wound images to the analysis of their information.[3,4] By examining the visual characteristics of wounds, healthcare professionals can accurately evaluate the condition of the wound and surrounding skin, including factors like size, depth, and tissue type. The optical properties of a wound can reveal pathological changes in the underlying tissue, which is essential for determining the progression of the wound and the effectiveness of treatment. Quantifying these optical properties can enhance the accuracy of wound monitoring and enable precise wound management. However, the lack of standardized tools for wound image acquisition poses challenges for obtaining accurate images and for medical personnel to analyse and process them. In conclusion, while wound image-based analysis and processing techniques have garnered significant attention and shown promise for application, further research is necessary to effectively implement these techniques in clinical practice for comprehensive and efficient wound management. This review paper aims to summarize the research progress on acquisition tools and processing techniques for wound images, providing valuable references and guidance for the utilization of wound images in clinical settings. The advantages and disadvantages of various wound image imaging techniques are shown in Table 1.

2 | WOUND IMAGING TECHNOLOGY

2.1 | Digital photography

Digital photography has become an essential tool in wound recording and management, offering superior image

TABLE 1 Various wound imaging techniques.

Wound imaging technique	Imaging principle	Advantages	Disadvantages
Digital photography[4,7–10]	Digital photography captures a wound image through an optical lens, converts the optical signal into an electrical signal, and ultimately produces a digital image	High resolution; Immediacy; Storable and shareable; Non-invasive	Deep tissue assessment limitations; High environmental impact; Dependence on equipment; High operational skill requirements; Difficulty in data management
3D wound model[11–15]	The creation of a 3D wound model is accomplished through the steps of image acquisition (e.g., digital photographyetc.), data processing, 3D reconstruction	Precision; Visualization effect; Non-invasive	High equipment costs; High technical requirements; Long time consumption; Difficult in data management; High environmental dependency
Optical imaging[16–23]	Optical imaging utilizes the principles of reflection and transmission of light to capture images of wounds through optical devices such as cameras and lenses	High resolution; Real-time; Easy to operate; Low cost; Radiation-free	Limited imaging depth; Light dependence; Viewing angle limitations; High information processing needs; Inability to penetrate obstacles
High frequency ultrasound[24,25]	High-frequency ultrasound imaging utilizes the principles of reflection and transmission of sound waves to generate an image of a wound by sending high-frequency sound waves and receiving their reflected signals	High resolution; No radiation; Real-time imaging; Portability; Tissue characterization	Imaging depth limitations; Operator skill dependent; Gas interference; Field of view limitations; Resolution decay
Fluorescence imaging[26,27]	Fluorescence imaging is a technique that uses fluorescent signals to generate images, usually by injecting or applying a fluorescent dye to enhance the visualization of tissue	High sensitivity; High specificity; Real-time imaging; Deep imaging; Multiple imaging	Photobleaching; Operational complexity; Fluorescent background noise interference; High cost
Artificial intelligence[6,28,29]	Artificial intelligence in wound imaging focuses on analysing and processing images through machine learning and deep learning techniques	High efficiency; High consistency; High precision; Personalized medicine; High learning capacity	Data dependency; High technological threshold; Privacy and security issues; Ethical issues

resolution and colour reproduction. This enhances the efficiency and quality of wound tracking and management. The research on wound image dataset construction and intelligent wound assessment systems primarily focuses on acquiring wound image datasets through digital cameras and mobile electronic devices.[5,6] Moreover, wound images captured with smartphones have emerged as a valuable source of information for medical professionals to assess wound healing progress and identify abnormalities promptly.[7,8] Commonly used wound image capture software includes WoundZoom, PictZar, Motic Images Plus, etc. However, variations in camera models, settings, shooting methods, and environments can lead to differences in the quality and clarity of acquired wound images. The quality of these images directly impacts the assessment of wounds by medical personnel and the accuracy of intelligent wound assessment systems. Therefore, enhancing the quality of wound images is crucial.

2.1.1 | Methods to improve the quality of digital photography of wound images

Zhang et al.[9] developed an mHealth tool to enhance wound image quality, comprising a wound imaging and management app, custom colour reference stickers, and a smartphone holder to create a comprehensive wound image acquisition system. The system introduces two objective image quality parameters: colour checker detection rate and colour checker sharpness. These parameters offer direct feedback on image quality, enabling users to adjust shooting settings for optimal image quality in real-time acquisition. Chairat et al.[4] created a wound calibration chart as a reference point to address colour variations in wound images captured under different conditions. This chart assists users in calibrating image colour and scale, as well as developing an automated algorithm for wound colour and measurement calibration. To overcome challenges in acquiring wound images during clinical practice and maximize the utility of available images for further analysis, researchers have developed various image processing techniques. These techniques include histogram equalization and colour space transformation to address differences in smartphone images caused by lighting and location variations, These techniques include histogram equalization and colour space transformation, which address variations in smartphone images caused by differences in lighting and location. Histogram equalization improves image contrast, making features more discernible. Methods involved include calculating the histogram and computing the cumulative distribution function, among others. Additionally, colour space transformation enables more effective manipulation of image colours and properties, with methods such as defining colour spaces and applying conversion formulas, among others. A comprehensive understanding of these methods and their respective purposes can significantly enhance the quality and efficacy of image analysis tasks.[10] Through these image processing methods, it is possible to enhance existing wound image quality, extract important wound feature information, and address challenges related to low light and colour discrepancies in clinical settings. This work establishes a critical foundation for subsequent wound diagnosis and assessment.

2.2 | 3D wound model

Two-dimensional (2D) planar wound images captured by digital cameras or smartphones are currently considered to be one of the most cost-effective, non-invasive, and straightforward methods for obtaining wound images. However, due to the curvature of the human body surface and the three-dimensional nature of wounds, relying solely on 2D images may not provide a comprehensive representation of the wound's actual condition. For instance, details regarding the depth and volume of wounds may not be accurately captured. Traditional methods of measuring wound volume, such as inserting cotton swabs or using sterile objects to fill the wound, often result in additional damage to the wound and increase the risk of infection. The use of 3D wound data allows for the precise calculation of three-dimensional information about the wound area, making the assessment of wounds with the aid of a three-dimensional (3D) wound model a topic of significant interest among researchers.[11,12]

Digital imaging and morphometry are commonly utilized methods for reconstructing 3D models of wounds. Pavlovčič et al.[13] developed a 3D measurement system based on laser triangulation, which offers convenience and speed for measuring wounds in 3D. However, this method has only been validated for typical wounds and requires further improvement in terms of reproducibility and minimizing bias. While 3D wound image acquisition tools have shown significant benefits for wound characterization and monitoring, the impact of human factors cannot be overlooked. Inexperienced operators may result in a 3D wound model that does not accurately represent the actual wound. To address this issue, Tassanavipas et al.[14] utilized servo motors to stabilize the wound 3D scanner and implemented image processing techniques to calculate wound area and volume. This method was tested on wounds of various sizes, demonstrating its advantage in estimating the volume of larger wounds. As smartphone camera resolution improves, researchers have explored using smartphones for 3D wound measurement. This approach combines structure from motion (SFM), least-squares conformal mapping (LSCM), and image segmentation to extract and measure wound features, enhancing the convenience and accuracy of wound management.[15] Nevertheless, the effectiveness, accuracy, and feasibility of 3D wound modelling in real-world settings require further investigation and validation. Commonly used software and equipment for 3D wound imaging include Silhouette, Aranz Medical's SilhouetteStar, eKare inSight, and WoundVision Scout, etc.

2.3 | Optical imaging

Optical imaging techniques, including near-infrared spectroscopy (NIRS), hyperspectral imaging (HSI), and thermography, offer valuable quantitative data on the structure and chemical composition of skin tissues. These methods allow for the assessment of oxygen levels in wound tissues, evaluation of the microvascular system, monitoring tissue health, and analysing wound microbiology. By providing insights into tissue perfusion of wounds, these imaging tools equip clinical staff with valuable resources for in-depth wound analysis.[16,17]

2.3.1 | Wound imaging using near-infrared spectrum imaging technology

Near Infrared Spectroscopic Imaging (NIRSI) is a non-invasive optical imaging technique utilized to evaluate oxygen perfusion in skin and wounds. This involves placing a NIR light source and detector on the skin or around a wound to collect light intensity data. The analysis of light intensity variations allows for the calculation of parameters like oxygen saturation and tissue blood flow.[18] Some researchers have combined NIR spectroscopy with support vector machines (SVMs) to detect microorganisms in wounds, offering innovative approaches for microorganism identification.[19] However, NIR spectroscopic imaging can only provide information about the surface layer of tissues and cannot penetrate deeper into tissue conditions. Professional operation and data interpretation are essential for accurate and reliable results when using this instrument. Therefore, it is crucial that professionals handle the operation and interpretation of results when employing this technique.

2.3.2 | Wound imaging using hyperspectral imaging techniques

Hyperspectral imaging techniques involve using the visible and near-infrared spectra for imaging spectroscopy, which enables quick acquisition of information about the imaged tissue. This technique combines spatial and spectral wavelength data to convert received light intensity into an optoelectronic signal. It can quantitatively measure tissue oxygenation levels, making it valuable for assisted wound diagnosis. Various systems like OxyVu, TIVITA™, and Kent Camera have demonstrated significant potential for multispectral and hyperspectral techniques in wound assessment.[16]

2.3.3 | Wound imaging using thermal imaging technology

Elevated wound temperatures may indicate an inflammatory response or infection. Real-time monitoring of wound temperature allows for early detection of potential issues. Thermal imaging technology can measure the radiant heat of the body surface using infrared cameras,[20] This technology can provide valuable information about abnormal temperatures in the body or local tissues of the wound, which may be caused by ischemia, inflammation, or infection.[21] However, factors like water evaporation from the wound bed can distort thermographic images, and practical factors such as acute pain, blood volume, and certain medications or foods that affect blood flow may impact results. It is important to consider these practical factors to obtain an accurate thermographic image.

In order to enhance wound assessment accuracy, researchers have integrated optical imaging with other techniques. Liu et al.[22] developed a 3D morphologic multiview hyperspectral imaging system, demonstrating its technical feasibility for analysing tissue properties in three dimensions. Chang et al.[23] introduced a multimodal system for pressure injury assessment, incorporating five sensing modalities for comprehensive wound evaluation. This system is user-friendly, suitable for non-specialized caregivers, and applicable in various settings. While optical imaging offers benefits like noninvasive monitoring of wound healing and assessment of tissue properties, challenges such as technological integration complexity, equipment costs, and ease of operation must be considered in implementation.

2.4 | High frequency ultrasound

Advanced imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), and high-frequency ultrasound (HFU) imaging have been shown to be useful in understanding the healing of wounds and the tissues underneath them. Compared to CT and MRI, which are expensive and expose patients to radiation, ultrasound, as a non-invasive, quantitative and reproducible imaging modality, provides visualization of the epidermis, dermis, etc., and studies have demonstrated that HFU imaging can be used as a non-invasive, quantitative, reliable, and cost-effective technique for the assessment of wound healing.[24] The team of Mohafez et al.,[25] in the treatment of wounds in patients with diabetic feet in which ultrasound scanning technique was utilized and images of wounds were captured on the 7th, 14th, 21st and 28th day after wound debridement. By analysing the images, they observed and recorded the characteristics of the echostructure and intensity changes of the wound tissue during the wound healing process, thus developing a new method for quantitatively assessing wound healing in ulcerated diabetic foot. Ultrasound instruments are highly useful in the field of wound care due to their portability, non-invasiveness, and reproducibility, but the accuracy of their image analysis relies to a certain extent on the experience and skill level of the medical staff, and it requires a physician to have profound anatomical knowledge as well as a wealth of clinical experience to correctly select the wound area, which increases the subjectivity of the assessment. Although high-frequency ultrasound has shown unique advantages in the assessment of wounds such as ulcers, it is still understudied in acute surgical wounds, and more research is needed to confirm its broad validity and to explore how it can be combined with other imaging methods to improve the accuracy of wound assessment results.

2.5 | Fluorescence imaging

2.5.1 | Advantages of fluorescence imaging technology in identifying bacterial distribution in wounds

In a wound, inactive or bacteria-rich tissue not only hinders wound healing, but can also reduce the effectiveness of topical antimicrobials. Therefore, wound debridement is a crucial aspect of wound care when necessary. Challenges in recognizing and managing wound debridement may arise due to variations in expertise and experience. Fluorescence imaging techniques can be utilized to assess the bacterial load in tissues. By leveraging bacterial autofluorescence, fluorescence imaging stimulates the wound tissue and bacteria to emit distinct fluorescent signals, enabling the visualization of potentially harmful bacteria that are not visible to the naked eye. Common pathogens in wound infections such as Staphylococcus aureus and Pseudomonas aeruginosa can be identified under fluorescent imaging conditions by their specific fluorescent colours. This allows medical professionals to accurately quantify the distribution of bacterial colonies within the wound, leading to a more objective assessment of wound bioburden. Such insights can aid in determining the appropriate scope and depth of wound debridement, enhancing its precision and effectiveness. Additionally, changes in the number of colonies over time can serve as indicators of the infection status and the impact of clinical interventions on the wound.

2.5.2 | Development and challenges of fluorescence imaging technology in wound bacterial detection

Zheng et al.[26] developed a bacterial autofluorescence detection imaging system using a low-cost LED and a smartphone to quickly detect common bacteria in wounds, However, in vitro bacterial experiments have not yet been conducted to validate the device's feasibility. Ottolino-Perry et al.[27] created a handheld portable autofluorescence imaging device for wound bacteria detection, combining traditional clinical signs and symptoms assessment. Their study on 33 patients with diabetic foot ulcers demonstrated that autofluorescence image-guided wound swabs maximized bacterial load sampling, suggesting AF imaging as an objective approach to wound care. Despite the benefits of fluorescence imaging like real-time monitoring and non-invasiveness, potential drawbacks include interference from other microorganisms and the large size of imaging devices, limiting portability for wound monitoring. Further scientific research and technological advancements are needed.

2.6 | Artificial intelligence

Intelligent programs and software based on Artificial Intelligence have garnered considerable interest in recent years for their ability to assist remotely in the diagnosis and management of wounds. By leveraging computer science, these programs can more accurately assess wound characteristics and improve strategies for diagnosing and managing wounds in patients. These intelligent tools are crucial in remote wound management, encompassing tasks such as wound segmentation, classification, and measurement.[6,28]

Cazzolato et al.[28] introduced the UTrack framework, which can be utilized on a standard mobile device with a regular camera, without requiring an internet connection or specialized sensors or cameras. The framework aids in capturing photographs, segmenting, and measuring wounds. Currently, the device performs these tasks solely on mobile devices; however, future iterations could potentially allow healthcare professionals to manage and visualize data from multiple patients and offer appropriate guidance recommendations. Ahmad Fauzi et al.[29] presented a segmentation tool designed to identify various types of wound tissues, including granulation, putrefied, and charred tissues. The innovative approach involves segmenting wound images for feature recognition using a four-dimensional probabilistic map of wound characteristics. The study's results indicate that the tool is more effective in segmenting granulation and crusted tissues, but less accurate in segmenting carrion, possibly due to the fragmented nature of carrion distribution, leading to confusion with other tissue types. An analysis conducted among clinicians providing true value annotations revealed the complexity of wound segmentation and feature recognition. Despite clinicians' extensive experience, differing opinions on the boundaries and tissue types of the same wound highlight the necessity for a tool with standardized operation specifications to aid in the diagnosis and treatment of wounds. The efficacy of intelligent software algorithms heavily relies on the availability of rich, high-quality data. In wound management, high-quality image data plays a crucial role in training algorithms. These algorithms analyse features like shape, colour, texture, and the surrounding skin of a wound to accurately assess and diagnose new wound conditions. This, in turn, provides decision support for healthcare professionals.

3 | THE FUTURE OF WOUND IMAGING IN WOUND MANAGEMENT

3.1 | Wound healing monitoring of the future: smart image analysis combined with wearable technology

Wound healing is a complex and dynamic process influenced by factors such as skin condition and the presence of other pathologies. Advances in image processing technology are expected to enable comprehensive monitoring of the wound healing process through detailed analysis of wound images. By leveraging artificial intelligence and deep learning algorithms, the wound image diagnostic system can extract more accurate features, perform diagnostic analysis, and predict wound healing time through big data analysis. Moreover, the integration of wearable devices will enhance wound monitoring by enabling real-time and continuous data collection, thereby supporting personalized wound management. These mobile medical devices can effectively monitor wound healing, reduce healthcare costs, and allow for remote analysis of wound images by healthcare professionals without the need for frequent hospital visits. Patients can receive expert attention remotely and some devices even offer real-time wound assessment and diagnosis, empowering patients to stay informed about their own wound healing progress.

3.2 | Challenges and future development trends of wound image acquisition

Wound images play a crucial role in wound assessment and treatment, yet the process of acquiring these images remains a challenge. Medical professionals, whose primary focus is not data acquisition, may capture wound images of the same patient using different standards, leading to inconsistencies. Moreover, data imbalance is common in medical wound images due to variations in colour patterns, lighting, intensity, and edges caused by differences in imaging equipment, shooting distance, and angle. Despite obstacles like data privacy, device compatibility, and cost hindering the widespread use of wound imaging tools, the increasing demand for healthcare and the shift towards patient-centered care highlight the advantages of utilizing wound images in remote wound management. Some researchers leverage mobile devices with built-in cameras and portability to collect data (images and textual information) for wound monitoring.[30] The integration of multiple techniques, such as fluorescence imaging and ultrasound imaging, is crucial for comprehensive wound analysis, uncovering key indicators that may be missed by individual imaging methods. An ideal wound imaging device should prioritize ease of use, affordability, and accuracy to deliver real-time feedback to healthcare providers and patients. Developing such a device will necessitate multidisciplinary collaboration and a focus on integrating diverse imaging modalities, which will likely be a prominent trend in future research and development of tools for assessing wound images.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Specific data related to the findings of this study, including detailed measurements and results, can be shared upon request, provided that the request complies with the ethical guidelines and privacy regulations of our institution.

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