Advancing Dermatologic Imaging: AI, AR, and New Technologies

Juliana P. Costa*

Department of Dermatology, Atlântico University of Health Sciences, Porto, Portugal

Introduction

The field of dermatology is undergoing a profound transformation driven by advancements in imaging technologies that offer unprecedented insights into skin structures and pathologies. Optical coherence tomography (OCT) and high-frequency ultrasound (HFUS) are at the forefront of this revolution, providing non-invasive, real-time visualization capabilities that significantly enhance diagnostic accuracy and treatment monitoring for a wide range of skin conditions. These sophisticated tools enable clinicians to differentiate between benign and malignant lesions with greater precision and to meticulously plan surgical interventions. Furthermore, the burgeoning integration of artificial intelligence (AI) with these imaging modalities promises to elevate diagnostic capabilities to new heights, potentially ushering in an era of personalized dermatological care by refining the interpretation of complex imaging data and identifying subtle diagnostic markers that might otherwise be overlooked. [1]

High-frequency ultrasound (HFUS) has emerged as an indispensable technique for the detailed evaluation of both dermal and subcutaneous lesions. Its capacity to penetrate and visualize structures beneath the skin's surface provides critical diagnostic information for a variety of conditions, including lipomas, dermatofibromas, and even early-stage melanomas, often negating the necessity for invasive biopsies. The remarkable resolution achieved by contemporary HFUS devices permits an in-depth examination of lesion composition and vascularity, which is instrumental in guiding therapeutic decision-making and tailoring treatment plans to individual patient needs. [2]

Reflectance confocal microscopy (RCM) is steadily expanding its role in in vivo dermatological diagnosis, offering cellular-level resolution without the need for tissue excision. This technique is particularly adept at the real-time assessment of melanocytic lesions, non-melanoma skin cancers, and various inflammatory dermatoses. By providing detailed cellular and subcellular information, RCM contributes significantly to improving diagnostic accuracy, thereby reducing the incidence of unnecessary biopsies and enabling more effective guidance of treatment strategies. [3]

Artificial intelligence (AI) is rapidly becoming an integral component of dermatologic imaging, equipping practitioners with powerful analytical tools for lesion characterization. Machine learning algorithms, meticulously trained on extensive datasets of dermoscopic and OCT images, are now demonstrating exceptional accuracy in classifying skin lesions, detecting subtle indicators of malignancy, and even predicting therapeutic outcomes. This AI-driven paradigm holds the potential to markedly enhance diagnostic efficiency and democratize access to expert-level interpretations, making advanced dermatological assessment more widely available. [4]

Multiphoton microscopy (MPM) offers a distinct advantage by enabling label-free, high-resolution imaging of skin structures in vivo, making it exceptionally well-suited for evaluating skin aging, inflammatory processes, and wound healing dynamics. Its unique ability to visualize vital components like collagen and elastin fibers without the requirement of exogenous contrast agents positions MPM as an ideal tool for in-depth studies of extracellular matrix remodeling and for informing the development of cosmetic and regenerative therapies. [5]

The ongoing evolution of advanced dermoscopic imaging techniques, encompassing both polarized and non-polarized light methodologies, continues to refine the established diagnostic criteria for skin neoplasms. Innovations in digital dermoscopy, coupled with sophisticated image processing capabilities, are facilitating more objective lesion analysis, improving the documentation of findings, and significantly enhancing the efficacy of telemedicine consultations for a broad spectrum of dermatological conditions. [6]

Augmented reality (AR) is emerging as a novel and impactful tool within dermatologic procedures, particularly for the critical phases of surgical planning and precise lesion mapping. By seamlessly overlaying real-time imaging data directly onto the patient's anatomical structures, AR technology can substantially improve the precision of tumor excisions, facilitate the intricate steps of Mohs surgery, and serve as a powerful educational aid for teaching complex dermatological techniques to trainees. [7]

Infrared thermography provides a valuable non-contact method for assessing thermal signatures associated with inflammation and vascular changes in various dermatological conditions. Its sensitivity in detecting subtle temperature variations makes it a beneficial tool in the management of conditions such as rosacea, psoriasis, and certain inflammatory infections, thereby serving as a complementary diagnostic and monitoring modality. [8]

Photoacoustic imaging (PAI) represents an innovative hybrid approach that synergistically combines optical excitation with ultrasound detection to yield both functional and structural information about biological tissues. Within dermatology, PAI is demonstrating significant promise for visualizing subsurface blood vessels, assessing tissue oxygenation levels, and mapping melanin distribution, offering potential for the early detection of skin cancers and the monitoring of treatment efficacy. [9]

The strategic integration of multi-modal imaging platforms, which cohesively combine techniques such as OCT, HFUS, and RCM, is paving the way for a more comprehensive and holistic assessment of skin lesions. This synergistic approach capitalizes on the distinct strengths of each individual modality, yielding complementary information that collectively enhances diagnostic certainty and optimizes patient management strategies, particularly in cases of complex or ambiguous der-

matological presentations. [10]

Description

The field of dermatologic imaging is witnessing a paradigm shift, with advanced technologies like optical coherence tomography (OCT) and high-frequency ultrasound (HFUS) leading the charge in revolutionizing the diagnosis and management of skin conditions. These non-invasive, real-time visualization tools are instrumental in distinguishing between benign and malignant skin lesions, closely monitoring treatment responses, and meticulously planning surgical procedures, thereby improving patient outcomes. The incorporation of artificial intelligence (AI) into these imaging platforms is further enhancing diagnostic accuracy and paving the way for personalized dermatological care, offering a more tailored approach to patient management. [1]

High-frequency ultrasound (HFUS) plays a crucial role in the assessment of dermal and subcutaneous lesions, providing critical subsurface visualization that aids in diagnosing conditions such as lipomas, dermatofibromas, and early-stage melanomas. This technology often obviates the need for invasive biopsies, streamlining the diagnostic process. The high resolution of modern HFUS devices allows for detailed characterization of lesion composition and vascularity, which directly informs therapeutic decision-making, enabling dermatologists to select the most appropriate treatment strategies for their patients. [2]

Reflectance confocal microscopy (RCM) is increasingly recognized for its utility in in vivo dermatological diagnosis, offering cellular-level resolution without the necessity of tissue excision. RCM excels in the real-time evaluation of melanocytic lesions, non-melanoma skin cancers, and inflammatory dermatoses, providing detailed morphological information. Its application demonstrably improves diagnostic accuracy, reduces the reliance on unnecessary biopsies, and facilitates more effective guidance of treatment plans. [3]

Artificial intelligence (AI) is rapidly being integrated into dermatologic imaging workflows, providing powerful tools for lesion analysis. Machine learning algorithms, trained on extensive datasets of dermoscopic and OCT images, have shown remarkable accuracy in classifying skin lesions, identifying subtle indicators of malignancy, and predicting treatment responses. This AI-driven approach promises to enhance diagnostic efficiency and broaden access to expert-level interpretation, democratizing advanced dermatological assessment. [4]

Multiphoton microscopy (MPM) provides label-free, high-resolution imaging of skin structures in vivo, which is highly beneficial for evaluating skin aging, inflammation, and wound healing processes. Its ability to visualize essential components like collagen and elastin fibers without the need for exogenous contrast agents makes it an ideal technique for studying extracellular matrix dynamics and informing cosmetic or regenerative therapeutic strategies. [5]

Advanced dermoscopic imaging techniques, including polarized and non-polarized light methods, continue to refine diagnostic criteria for skin neoplasms. Innovations in digital dermoscopy, enhanced with advanced image processing capabilities, allow for objective lesion analysis, improved documentation of findings, and more effective telemedicine consultations for dermatological conditions, bridging geographical barriers in patient care. [6]

Augmented reality (AR) is emerging as a significant tool in dermatologic procedures, particularly for surgical planning and lesion mapping. By overlaying real-time imaging data onto the patient's anatomy, AR enhances the precision of tumor excisions, facilitates complex procedures like Mohs surgery, and improves the educational experience for those learning advanced dermatological techniques. [7]

Infrared thermography offers a non-contact method for assessing inflammation and vascular changes in dermatological conditions. Its capacity to detect subtle temperature variations is particularly valuable in managing conditions such as rosacea, psoriasis, and inflammatory infections, serving as a complementary diagnostic and monitoring tool that provides objective thermal data. [8]

Photoacoustic imaging (PAI) integrates optical excitation with ultrasound detection to furnish both functional and structural information about tissues. In dermatology, PAI is being explored for its capability to visualize blood vessels, oxygenation status, and melanin distribution, showing considerable promise for the early detection of skin cancers and the monitoring of therapeutic responses. [9]

The integration of multi-modal imaging platforms, which combine techniques like OCT, HFUS, and RCM, is leading to a more comprehensive assessment of skin lesions. This synergistic approach leverages the unique strengths of each modality, delivering complementary information that significantly boosts diagnostic certainty and optimizes patient management strategies, especially in complex dermatological cases. [10]

Conclusion

This review explores advancements in dermatologic imaging technologies, including optical coherence tomography (OCT), high-frequency ultrasound (HFUS), reflectance confocal microscopy (RCM), multiphoton microscopy (MPM), dermoscopy, and photoacoustic imaging (PAI). These techniques offer non-invasive, high-resolution visualization of skin structures, aiding in the diagnosis of various conditions from benign lesions to skin cancers. The integration of artificial intelligence (AI) and augmented reality (AR) is further enhancing diagnostic accuracy, surgical planning, and personalized treatment approaches. Infrared thermography is highlighted for its utility in assessing inflammation and vascular changes. The combination of multiple imaging modalities provides a comprehensive understanding of skin lesions, leading to improved diagnostic certainty and patient management.

Acknowledgement

Conflict of Interest

None.

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Address for Correspondence: Juliana, P. Costa, Department of Dermatology, Atlântico University of Health Sciences, Porto, Portugal, E-mail: j.costa@auh-derm.pt