Dermatology Practical & Conceptual

Advanced Skin Imaging Techniques for Patients with Skin of Color: Clinical and Technological Insights

Dorra Guermazi[1], Elie Saliba[1,2]

1 Department of Dermatology, Warren Alpert Medical School of Brown University, Rhode Island, USA

2 Department of Dermatology, Gilbert and Rose-Marie Chagoury School of Medicine, Lebanese American University, Lebanon

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Corresponding Author: Elie Saliba, MD, Department of Dermatology, Warren Alpert Medical School of Brown University, 593 Eddy St, APC 10, Providence, Rhode Island, 02905, USA. ORCID ID: 0000-0001-5994-3212. E-mail: elie_saliba@brown.edu

ABSTRACT

Introduction: Skin imaging has transformed dermatology by enabling non-invasive diagnosis, monitoring, and treatment of various skin conditions. However, imaging skin of color presents unique challenges and opportunities due to variations in melanin content and skin structure.

Objectives: By focusing on the unique aspects of skin of color, this review aims to promote equitable healthcare and encourage the adoption of advanced imaging technologies across all skin types.

Methods: This review paper provides a comprehensive overview of the current state of skin imaging technologies, including optical, non-optical, and hybrid modalities, and their specific applications in dermatology.

Results: We discuss the diagnostic complexities associated with skin cancers, inflammatory conditions, and infectious diseases in diverse skin tones, underscoring the need for tailored imaging techniques. The review also explores advances in artificial intelligence and machine learning, highlighting their potential to enhance image analysis and diagnostic accuracy for skin of color.

Conclusion: We address the technical limitations, biological variability, and ethical considerations in skin imaging, ultimately advocating for more inclusive research and development. Future directions include the development of innovative imaging modalities and personalized medicine approaches that consider the diverse spectrum of human skin.

Introduction

Background

The skin is the largest human organ and serves as a critical barrier and interface between the body and the external environment. The skin's appearance and characteristics vary widely among individuals, influenced by factors such as genetics, age, and environmental exposure. Among these variations, skin of color presents unique anatomical and physiological features, primarily due to differences in melanin content and distribution. Melanin, the pigment responsible for skin color, not only determines the visual appearance of the skin but also affects its response to external stimuli, disease manifestations, and healing processes [1].

Historically, dermatological evaluation relied on visual inspection and palpation. The introduction of photography in the 19th century enabled documentation of skin conditions. Major advancements occurred in the mid-20th century, with the emergence of dermatoscopy in the 1980s to enhance melanoma detection through visualization of sub-surface structures [2, 3]. In the 1990s, confocal laser scanning microscopy (CLSM) allowed for high-resolution in vivo cellular imaging.

Non-optical imaging methods like high-frequency ultrasound and MRI further expanded diagnostic capabilities by visualizing skin tumors and inflammatory conditions [4, 5]. In the 21st century, hybrid technologies such as photoacoustic imaging have combined optical and ultrasound modalities for improved visualization of vascular and pigmented lesions [2, 3]. Despite historical bias toward lighter skin tones in imaging research, recent efforts have aimed to improve representation and diagnostic equity for skin of color [4, 5]. Advances in digital dermatoscopy, multispectral imaging, and artificial intelligence (AI)-driven diagnostics continue to make skin imaging more precise, accessible, and inclusive [2, 3].

Importance of Skin Imaging

Skin imaging technologies facilitate early diagnosis, precise monitoring, and effective treatment of various dermatological conditions. Imaging techniques range from traditional methods like dermatoscopy to advanced modalities such as confocal laser scanning microscopy, ultrasound imaging, and emerging hybrid techniques [2, 4]. While these technologies have significantly improved dermatological care, their efficacy and accuracy can be influenced by the patient's skin tone. For instance, the higher melanin content in skin of color can affect the penetration and reflection of light-based imaging methods, potentially complicating the diagnosis and treatment of skin conditions [1, 5].

Literature Selection and Appraisal

We conducted a targeted literature search to identify relevant articles on skin imaging modalities, artificial intelligence applications, and equity considerations in dermatology. Sources were selected based on their relevance to the topic, with a focus on peer-reviewed studies, reviews, and consensus guidelines published in English. While this is not a systematic or scoping review, efforts were made to include diverse perspectives and recent advancements.

Although many imaging technologies are described in the literature, few have been rigorously validated across diverse skin tones. For example, dermoscopy and high-frequency ultrasound have been well studied, while newer modalities like photoacoustic imaging and AI-driven tools have often relied on preliminary or retrospective data. Notably, there remains a lack of standard imaging protocols and prospective validation studies specifically for skin of color.

Purpose of the Review

This review focused on the intersection between skin imaging technologies, artificial intelligence, and dermatological equity, with an emphasis on their application to skin of color (SoC). Rather than offering a broad survey, it critically examined how diagnostic tools, particularly AI-driven and noninvasive imaging modalities, perform across diverse skin types. It identified key limitations in dataset diversity, algorithmic bias, and the lack of standardized imaging protocols for melanin-rich skin. By synthesizing evidence across modalities and highlighting underexplored gaps, the review aimed to advance a central thesis: achieving diagnostic equity in dermatology requires not only technological innovation but also a fundamental redesign of how imaging tools are developed, validated, and deployed for all skin tones.

How Imaging Technologies Shape Dermatological Insight

Optical Imaging

Optical imaging techniques use light to visualize skin structures and offer both high resolution and noninvasiveness. These methods are widely used due to their ability to provide detailed images of the skin surface and superficial layers.

Dermatoscopy

Dermatoscopy uses a handheld device with a magnifying lens and a light source to examine skin lesions. This technique enhances the visualization of subsurface structures, aiding in the early detection of melanoma and other skin cancers. Dermatoscopy is particularly useful for evaluating pigmented lesions and vascular structures, which can appear differently in skin of color [6].

Confocal Laser Scanning Microscopy (CLSM)

CLSM provides real-time, high-resolution imaging of the skin at the cellular level. By using a laser to scan the skin and a pinhole to eliminate out-of-focus light, CLSM produces clear images of the epidermis and upper dermis. This technique is valuable for diagnosing skin cancers, inflammatory conditions, and infections. Its ability to visualize individual cells and cellular structures makes it a powerful tool for both research and clinical practice [7].

Multiphoton Microscopy

Multiphoton microscopy (MPM) is an advanced optical imaging technique that uses multiple photons to excite fluorescent molecules within the skin. This method allows for deeper penetration and reduced photodamage, making it suitable for long-term imaging of living tissues. MPM is particularly effective in studying the dynamic processes of skin physiology and pathology at the molecular level [2, 8].

Non-Optical Imaging

Non-optical imaging techniques rely on other forms of energy, such as sound waves or magnetic fields, to visualize deeper skin structures. These methods are used for assessing conditions that affect the deeper layers of the skin and underlying tissues.

Ultrasound Imaging

High-frequency ultrasound (HFUS) uses sound waves to create detailed images of the skin and its underlying structures. HFUS is widely used to evaluate skin tumors, measure skin thickness, and monitor wound healing. This technique is non-invasive and widely accessible, and it provides real-time imaging, making it a valuable tool in dermatology. Additionally, the integration of color Doppler imaging with HFUS enhances the evaluation by providing information on blood flow within the skin and its underlying structures, further aiding in the diagnosis and management of vascular-related dermatological conditions [9]. This combined approach offers comprehensive insights into both the anatomical and functional aspects of skin health.

Magnetic Resonance Imaging (MRI)

MRI uses strong magnetic fields and radio waves to produce high-contrast images of the skin and subcutaneous tissues. While MRI is more commonly used for internal organs, it can be adapted for dermatological purposes, particularly for evaluating large or deep skin tumors and inflammatory conditions. MRI offers excellent soft tissue contrast, which is beneficial for detailed skin assessments [2].

Terahertz Imaging

Terahertz imaging uses terahertz radiation, a type of electromagnetic wave with frequencies between 0.1 and 10 terahertz, to penetrate the skin and visualize its internal structures. This technique is still in the experimental stage but shows promise for noninvasive skin cancer detection and other dermatological applications [10]. Terahertz imaging can differentiate between various tissue types based on their water content and molecular composition.

Hybrid Imaging Techniques

Hybrid imaging techniques combine multiple modalities to leverage their respective strengths, providing comprehensive and complementary information about the skin.

Photoacoustic Imaging

Photoacoustic imaging (PAI) combines optical and ultrasound imaging to produce high-resolution, high-contrast images of skin structures. In PAI, pulsed laser light is absorbed by the skin, causing thermoelastic expansion and generating ultrasound waves. These waves are then detected to create images. PAI is particularly useful for visualizing blood vessels, melanin, and other chromophores, making it suitable for assessing vascular and pigmented lesions, especially in skin of color, though there are still some biases present [11].

Optoacoustic Imaging

Similarly to PAI, optoacoustic imaging uses laser-induced ultrasound waves to create detailed images of the skin. This technique provides high contrast and resolution and is effective for visualizing both superficial and deeper skin layers. Optoacoustic imaging is valuable for studying skin cancer, vascular anomalies, and other dermatological conditions [12].

Overall, the advancements in skin imaging modalities have significantly enhanced the ability to diagnose, monitor, and treat various skin conditions (Figure 1).

Clinical Impact and Gaps in Skin Imaging Applications

Diagnosis of Skin Diseases

Melanoma and Non-melanoma Skin Cancers

Detecting melanoma and non-melanoma skin cancers in individuals with darker skin tones is challenging due to variations in lesion appearance and pigmentation, and most of the data we have to date are from white patients [13, 14]. Traditional imaging methods, which often rely on color contrast between lesions and surrounding skin, may not be as effective in detecting early-stage cancers or distinguishing malignant from benign lesions in darker skin tones. Advanced imaging technologies have been developed to address these challenges, as was discussed with the many examples given in Section 3 on 'Imaging Modalities'. These techniques enable dermatologists to visualize structures beneath the skin's surface, enhancing the

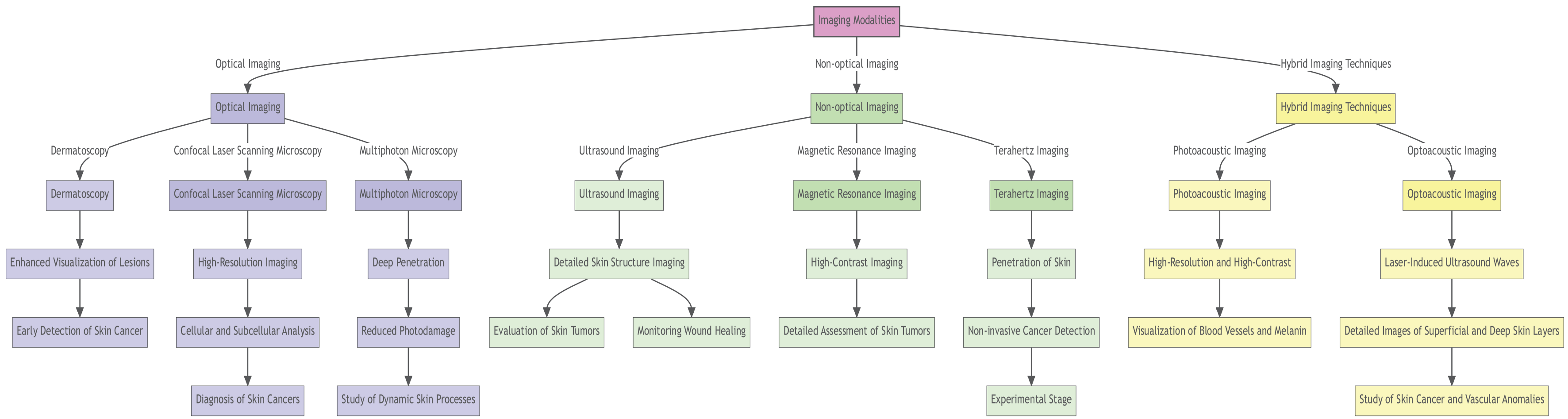

Figure 1. Key Imaging Modalities in Dermatology. This flowchart illustrates the primary imaging modalities used in dermatology, categorized into optical, non-optical, and hybrid techniques.

detection of subtle morphological changes associated with malignancy. By improving diagnostic accuracy, these technologies improve the chances that individuals with skin of color receive timely and appropriate treatment, thereby reducing disparities in cancer outcomes, which can be seen in Figure 2 below.

One such example is below, in a study done by Wang et al., where "melanoma moulages" were used to evaluate melanoma detection rates in training medical students in different skin types [15]. Though they did not find a significant difference in detection rates between whites and African Americans, they concluded that it is essential to educate students to consider sun exposure history and sun protection practices regardless of skin color [15].

Psoriasis and Eczema

Psoriasis and eczema can present differently in individuals with diverse skin tones, affecting both diagnosis and treatment strategies [16]. Skin imaging techniques such as high-resolution photography and optical coherence tomography help dermatologists assess the severity of these conditions and monitor response to therapy. For instance, psoriatic plaques may appear thicker or exhibit different patterns of erythema in darker skin tones compared to lighter skin tones [17]. By capturing detailed images of the affected areas, these technologies assist in tailoring treatment plans that take into account these variations, thereby optimizing outcomes for patients of all skin types.

Figure 3 is an example of psoriasis presentation in different skin colors [18, 19]. In fair-skinned individuals, psoriasis typically appears red or pink with a silvery-white scale, while Hispanic individuals may exhibit salmon-colored psoriasis with a silvery-white scale, and in African American patients it may appear violet with a gray scale. On dark skin, psoriasis can also be dark brown and may be more challenging to detect [20].

Infectious Diseases

The presentation and imaging outcomes of infectious dermatological diseases, such as fungal infections or viral rashes, can vary significantly based on skin color. Traditional imaging methods may struggle to differentiate between different types of skin lesions in individuals with darker skin tones due to similarities in color and texture. Advanced imaging modalities, including fluorescence microscopy and multispectral imaging, enhance the visualization of pathogens or inflammatory responses within the skin. By providing detailed insights into disease progression and treatment efficacy, these technologies aid dermatologists in improving the accuracy of diagnoses and guide appropriate therapeutic interventions for patients with skin of color.

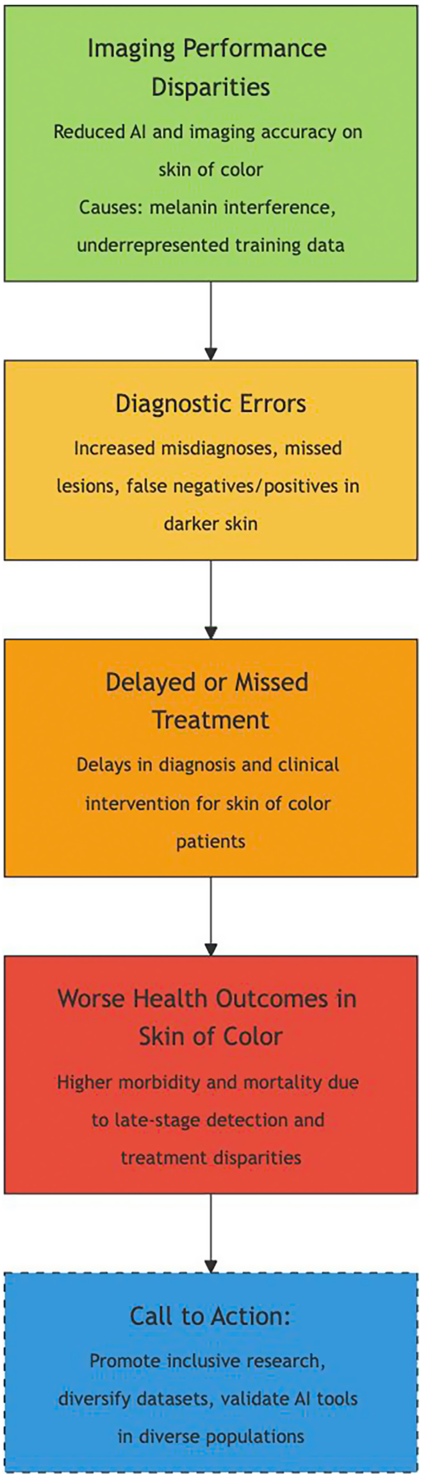

Figure 2. Clinical Impact Funnel Diagram.

Monitoring and Treatment

Wound Healing

The process of wound healing can vary in individuals with darker skin tones, presenting challenges in assessing tissue repair and identifying complications such as hypertrophic scars or keloids [21, 22]. Imaging techniques such as digital photography and ultrasound imaging enable dermatologists to monitor wound progression and evaluate treatment outcomes. These technologies provide objective measurements

Figure 3. On light skin, psoriasis typically appears red or pink (A) [18], while on dark skin, it often looks violet (B) [19].

of wound size, depth, and healing rates, facilitating early intervention and personalized care for patients of all skin types.

Laser Therapy Guidance

Laser treatments for dermatological conditions must be carefully tailored for individuals with darker skin tones to minimize the risk of adverse effects such as post-inflammatory hyperpigmentation or hypopigmentation [23]. Advanced imaging modalities, such as laser speckle imaging and thermal imaging, assist dermatologists in targeting treatment areas accurately and monitoring skin response in real time. By optimizing laser parameters based on individual skin characteristics, these technologies can enhance treatment efficacy and safety for patients of diverse ethnic backgrounds.

Cosmetic Dermatology

Aging and Pigmentation Analysis

Assessing skin aging and hyperpigmentation in diverse populations requires a nuanced approach to imaging [24, 25]. Techniques such as skin surface photography and spectrophotometry enable dermatologists to quantitatively measure melanin content and assess changes in skin texture and elasticity over time. These technologies capture detailed images of facial lines, wrinkles, and pigmentary changes, enabling personalized treatment planning and enhancing cosmetic outcomes for patients with diverse skin tones.

Scar and Wrinkle Assessment

Scars and wrinkles may appear differently in individuals with darker skin tones compared to lighter skin tones, necessitating specific imaging techniques for accurate assessment [25]. Modalities such as 3D skin imaging and laser scanning microscopy provide detailed visualizations of scar depth, texture, and vascularity [24]. By evaluating collagen deposition and tissue remodeling processes, these technologies help dermatologists select appropriate treatment modalities, including laser therapy or topical agents, to improve the appearance of scars and wrinkles in patients of all skin types.

Ultimately, skin imaging technologies play an increasingly important role in dermatology for their ability to enhance diagnostic accuracy, guide therapeutic interventions, and improve cosmetic outcomes across diverse patient populations. By addressing the unique challenges associated with skin of color, these advanced techniques ensure equitable access to high-quality care and personalized treatment strategies, thereby advancing dermatological practice towards more inclusive and effective patient management. We have illustrated a conceptual framework in Figure 4 below.

Barriers to AI Equity in Skin Imaging

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) and machine learning (ML) are increasingly utilized to enhance the analysis and interpretation of skin images, particularly in populations with diverse skin tones [26]. Algorithms trained on extensive datasets encompassing varied pigmentation levels and dermatological conditions enable more accurate detection and classification of skin lesions, including melanomas and other skin cancers. By learning from a broad spectrum of skin types, these AI models improve diagnostic precision and reduce disparities in healthcare outcomes.

Wearable Skin Imaging Devices

Advancements in miniaturization and sensor technology have led to the development of wearable skin imaging devices. These portable devices allow for noninvasive, real-time monitoring of skin conditions and treatment responses. Designed to be worn comfortably by patients, wearable devices provide dermatologists with continuous access to high-resolution skin images, facilitating remote consultations and personalized treatment adjustments [27]. Their accessibility and convenience make them invaluable tools in managing chronic dermatological conditions, promoting patient engagement, and improving overall care outcomes across different ethnicities.

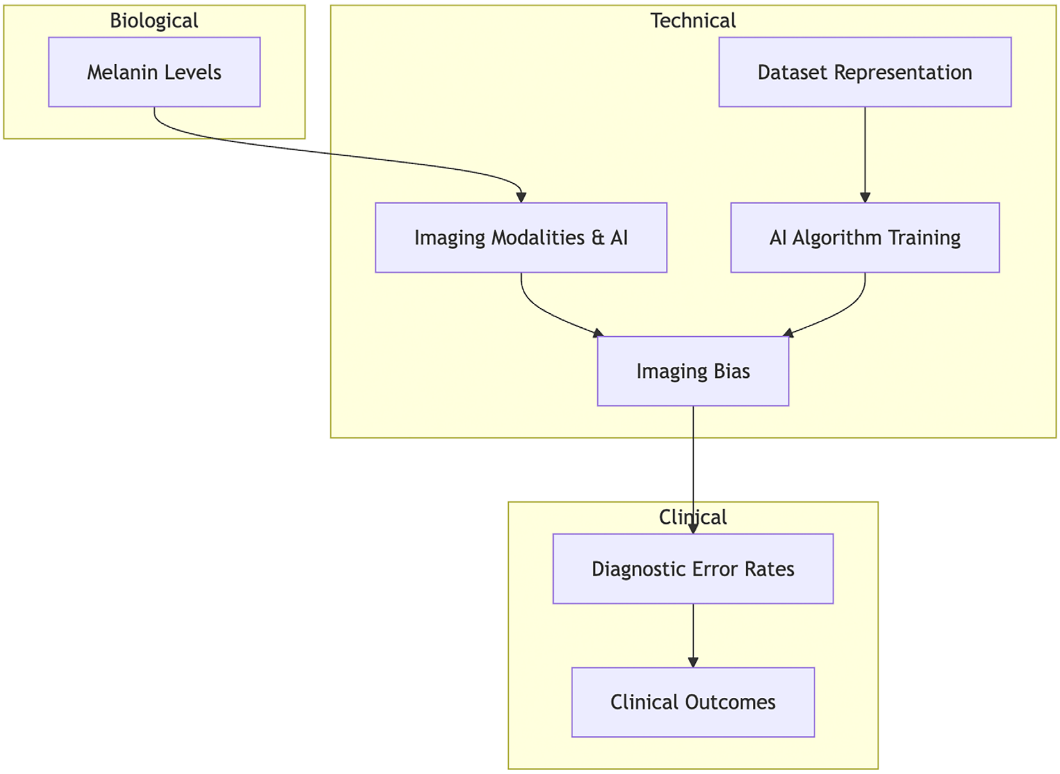

Figure 4. Conceptual Framework: interplay and directional relationships between AI, bias, melanin, and errors.

Portable and Point-of-Care Devices

Portable and point-of-care skin imaging devices are transforming dermatological practice by enabling rapid assessments in various clinical settings. These handheld devices, equipped with advanced optics and imaging modalities, deliver high-quality images of skin lesions and abnormalities [28]. Dermatologists can use these devices for on-the-spot evaluations during patient consultations, dermatology clinics, or community health screenings. Their ability to provide instant feedback and image documentation enhances diagnostic efficiency, supports timely interventions, and fosters equitable healthcare delivery for individuals with diverse skin tones [28].

Challenges and Limitations

One of the primary technical challenges in skin imaging, especially for darker skin tones, is achieving sufficient resolution and depth penetration [29]. Traditional imaging techniques may struggle to capture detailed structures and abnormalities in deeper layers of melanin-rich skin [30]. This limitation can affect the accuracy of diagnostic assessments and treatment monitoring, requiring advancements in optics and imaging modalities tailored to diverse pigmentation levels.

Moreover, the cost of advanced skin imaging technologies poses a significant barrier to equitable access, particularly in resource-limited settings. High-end imaging devices and AI-driven diagnostic systems may be prohibitively expensive for many healthcare facilities and patients [31]. Ensuring affordability and availability of these technologies across diverse socioeconomic backgrounds is essential to reducing disparities in dermatological care and improving health outcomes.

Future Directions

Emerging Technologies

A new computing method for four-dimensional (4D) spectral-spatial imaging in photoacoustic imaging (PAI), as discussed in section 3, has been developed to enable quantitative analysis and to optimize both structural and functional imaging of skin. This method accounts for the heterogeneous optical and acoustic properties of skin tissues, improving the accuracy of single-spectrum and multispectral imaging solutions [32]. The evolution from 2D to 3D and 4D imaging technologies represents a significant advancement in dermatological imaging. These technologies enable dermatologists to capture detailed three-dimensional representations of skin structures and dynamics over time [33]. By visualizing changes in skin texture, volume, and vascularization, 3D and 4D imaging enhance diagnostic accuracy and treatment planning, particularly for complex dermatological conditions and cosmetic procedures.

Table 1. Conceptual Heatmap Showing AI and Imaging Performance Across Skin Tones.

Imaging Modality / AI Model	Light Skin (Fitzpatrick I–III)	Medium Skin (Fitzpatrick IV)	Dark Skin (Fitzpatrick V–VI)
Dermoscopy AI	High (>85%)	Moderate (75-85%)	Low (<70%)
Clinical photography AI	High (>85%)	Moderate (70-80%)	Low (<65%)
Multispectral imaging AI	Moderate (75-85%)	Moderate (75-85%)	Moderate (70-80%)
Confocal laser scanning microscopy (CLSM)	High (90%)	High (85-90%)	Moderate (75-80%)
High-frequency ultrasound	High (85-90%)	Moderate (75-85%)	Moderate (70-80%)
Photoacoustic imaging AI	Moderate (80%)	Moderate (75-80%)	Moderate (70-80%)

Equity and Ethical Considerations

Despite technological progress, dermatological imaging and AI tools often lack equitable representation. Studies show that only 10–20% of images in major dermatology datasets represent Fitzpatrick skin types IV–VI [34] (Table 1). Many AI models trained on these datasets perform poorly on darker skin, risking misdiagnosis and delayed care [35]. Moreover, over 60% of AI dermatology studies fail to report skin type or race [36], limiting transparency and reproducibility.

These disparities raise ethical concerns around algorithmic bias and unequal access to innovation. Ensuring equity requires standardized reporting, deliberate inclusion of diverse skin tones in datasets, and a commitment to inclusive research design.

Research and Development Needs

Future research efforts should prioritize inclusivity in the development of skin imaging technologies. This includes expanding datasets to encompass diverse skin tones and conditions, ensuring that AI algorithms and imaging modalities are robust across different ethnicities [26]. By addressing biases and enhancing accuracy in diagnostic algorithms, researchers can mitigate disparities in dermatological care and promote equitable access to advanced imaging technologies worldwide.

Conclusion

The integration of skin imaging technologies has had a profound impact on dermatology and healthcare at large. By improving diagnostic accuracy and treatment outcomes, these technologies have reduced disparities in dermatological care and enhanced patient satisfaction. They have also streamlined clinical workflows, allowing for more efficient patient management and resource allocation in healthcare settings.

Looking ahead, the future of skin imaging in dermatology holds promising prospects for further innovation and advancement. Emerging technologies such as 3D and 4D imaging, along with enhanced data integration and AI applications, may enhance clinical practice, though further validation in diverse populations is needed. These developments will facilitate more personalized medicine approaches, improve predictive modeling, and continue to ameliorate dermatological care, ultimately improving the quality of life for patients worldwide.

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AI tools were minimally utilized in the Abstract and Conclusions sections to enhance sentence clarity.

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