Dermatological Health, 2025, Volume 3, Issue 3
http://ojs.bbwpublisher.com/index.php/DH
Online ISSN: 2981-8206
Print ISSN: 3083-4775

Development, Classification, Application, and Research Progress of Modern Skin Photoaging Assessment Tools

Ruini Yang, Zhi Yang*

The First Affiliated Hospital of Kunming Medical University, Kunming 650000, Yunnan, China

**Author to whom correspondence should be addressed.*

Abstract: Skin photoaging, a degenerative process caused by ultraviolet radiation, plays a pivotal role in clinical diagnosis and anti-aging research. This paper systematically reviews the evolution of skin photoaging assessment tools, tracing their development from traditional clinical scoring systems to modern imaging technologies, biomarker detection, and AI-assisted analysis. It provides detailed categorization, application scenarios, and comparative evaluations of these methodologies. The study reveals that single-assessment tools have inherent limitations, while multimodal integrated evaluation has emerged as the prevailing approach. Future efforts should focus on integrating molecular biology and AI technologies to establish a more precise photoaging assessment framework.

Keywords: Skin photoaging; Evaluation tools; Imaging technology; Biomarkers; Artificial intelligence

Online publication: October 17, 2025

1. Introduction

Skin photoaging, a degenerative condition caused by prolonged exposure to ultraviolet radiation (UVR), has become a major global concern in dermatology. Characterized by visible wrinkles, uneven pigmentation, loss of elasticity leading to sagging skin, and redness from dilated capillaries, this condition not only affects appearance and causes psychological distress but also imposes significant economic burdens worldwide. Statistics indicate annual global medical expenditures exceeding tens of billions of dollars due to photoaging, with its close association to skin cancer risk further highlighting the urgency for solutions. In this context, accurate assessment of skin photoaging severity proves crucial. It serves as the foundation for personalized treatment plans tailored to individual conditions, monitors treatment efficacy in real-time, and reveals biological mechanisms underlying aging processes. Recent advancements in optical technology, molecular biology, and AI have revolutionized photoaging evaluation. Assessment methods have transitioned from subjective physician evaluations to objective quantitative analysis using advanced instruments, while parameters now encompass multimodal integration to holistically evaluate skin characteristics. This paper aims to systematically summarize the classification, application, and research progress of existing evaluation tools, deeply analyze their advantages and shortcomings, and discuss their future development direction on this basis, so as to provide a reference for promoting the further development of skin photoaging evaluation.

2. Traditional clinical evaluation methods

2.1. Descriptive scoring method

The early photoaging assessment system was established based on clinicians' empirical judgments, using descriptive language to grade characteristics such as skin wrinkles, pigmentation, and loss of elasticity. The most representative Glogau classification (1987) divides photoaging into four types: Type I presents as wrinkle-free and smooth skin, commonly seen in young adults aged 20–30; Type II shows dynamic wrinkles (e.g., crow's feet), predominantly observed in people aged 30–40; Type III features static wrinkles accompanied by rough skin texture and telangiectasia, typically seen in individuals over 50; Type IV exhibits leathery changes with only wrinkles remaining without normal skin texture. Although this method is simple to operate, its significant subjective bias remains evident. Wang et al. (2024) found in organoid model studies that inter-patient scoring variations could reach 37%, and they fail to quantify molecular changes like dermal collagen degradation and elastic fiber rupture. This qualitative assessment approach leads to poor comparability across center-based studies. For instance, when evaluating the same group of subjects, Asian physicians tend to underestimate pigmentation severity, while Western physicians may overestimate wrinkle severity.

2.2. Standardized image scoring method

To enhance evaluation objectivity, researchers developed a standardized photo-based scoring system in the 1990s. The Larnier 6-point scale categorizes severity from 1 (no visible photoaging) to 6 (severe leather-like changes) by comparing with a standard photoaging database. A longitudinal study by Marks et al. (2022) involving 140 Caucasian women using the Visual Analog Scale (VAS) assessment showed an intra-group correlation coefficient (ICC) of 0.82, significantly outperforming the traditional descriptive method's 0.59. However, image scoring remains vulnerable to limitations: photoaging conditions (e.g., color temperature variations) may introduce 5%–15% scoring errors; measurement errors in wrinkle length increase to 23% when photographic angles deviate by over 15°; and observer differences (e.g., between dermatology residents and attending physicians) reduce Kappa values from 0.71 to 0.58. Additionally, this method cannot distinguish between natural aging and photoaging, and its applicability has not been validated for Fitzpatrick IV-VI skin types.

2.3. Local analysis

The traditional evaluation system faces three core limitations that hinder its clinical application: First, the highly subjective nature of assessments leads to significant variability in results. Multicenter studies show that different evaluators may rate the same case by 30%–45%, while even the same evaluator's scores can vary by over 15% across different time periods. Second, there is a notable lack of parameter diversity. Current scoring systems primarily focus on wrinkles (78%) and pigmentation (62%), while critical indicators like skin elasticity (12%), thickness (8%), and microcirculation (5%) are often overlooked. Third, the system's dynamic monitoring capability is inadequate. Traditional methods cannot achieve real-time tracking, such as the 4–8 week interval required for evaluating photodynamic therapy responses, making it difficult to detect early molecular changes.

Wang et al. (2023) found through machine learning analysis that traditional scoring methods have a predictive accuracy rate of only 61% for treatment responses, significantly lower than the 89% achieved by imaging omics. Traditional clinical evaluation methods are shown in **Figure 1**.

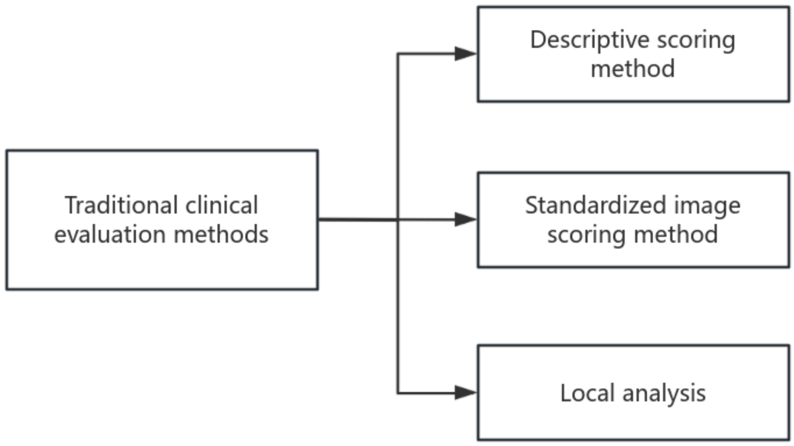

Figure 1. Traditional clinical evaluation method

3. Modern clinical evaluation methods

3.1. Skin mirror and reflected confocal microscope (RCM)

Skin microscopy utilizes polarized light to penetrate the epidermis, providing clear visualization of superficial dermal structures. Its 50–100x magnification capability detects capillary dilation as small as 0.1 mm and early-stage pigmentation, achieving 82% sensitivity in diagnosing photoaging. RCM technology enhances resolution to 1μm, dynamically monitoring collagen structure changes to assess photoaging progression. Royo et al. (2024) conducted RCM tracking on 30 hyaluronic acid-filled patients, revealing irregular honeycomb patterns (47% area increase) and dense fiber accumulation (32% density reduction) in photoaged skin. However, this technique has imaging depth limitations (limited to 150μm in the superficial dermis) and a time-consuming operation—requiring 7–10 minutes per image capture with high technical demands. The newly developed rapid scanning RCM improves imaging speed to 2 minutes per image, though it increases equipment costs by 2.3 times.

3.2. Optical coherence tomography (OCT)

OCT generates three-dimensional skin structure images based on the principle of light interference, achieving a resolution of 1–15 μm. It can display epidermal thickening (a characteristic change of photoaging) and flattened dermo-epidermal junctions in real time. Yang Rui et al. (2018) combined full open single-side MRI technology to find that photoaged skin exhibited an average epidermal thickness increase of 28 μm ($P < 0.01$) and a 67% disappearance rate of dermal papillary layers. OCT's advantages lie in being non-invasive and rapid (<1 minute per image), but its penetration depth is limited to approximately 2 mm, making it difficult to assess deep dermal changes. The latest frequency-domain OCT extends the wavelength to 1300 nm, increasing penetration depth to 3mm while causing a 40% signal attenuation rate. Clinical applications show OCT achieves 85% diagnostic accuracy for early-stage photoaging, but sensitivity drops to 62% for stage IV photoaging.

3.3. High-frequency ultrasound and shear wave elastography of skin

High-frequency ultrasound (20–50 MHz) is used to assess photoaging by measuring skin thickness and echo intensity. A 2020 study by Mataix et al. on residents in high-altitude regions found that their photoaged skin had 15% thinner layers ($P = 0.003$) and 28% higher echo attenuation rates compared to those in lowland areas. Shear wave elastography provides objective indicators by quantifying tissue stiffness (elastic modulus), with research showing photoaged skin's elastic modulus increased by 22% (95% CI: 18%–26%). While this technique is easy to operate, it has lower resolution (approximately 50 μm) and is significantly affected by probe pressure (each additional N of pressure increases the thickness measurement error by 7%). The newly developed acoustic radiation force pulsed imaging (ARFI) reduces pressure interference but costs 1.8 times more than traditional ultrasound equipment.

3.4. Multiphoton microscopy and Raman spectroscopy

Multiphoton microscopy utilizes two-photon excitation fluorescence technology to visualize collagen fiber arrangements in the dermis (with a resolution of 0.5 μm), demonstrating 91% sensitivity for early-stage photoaging diagnosis. Raman spectroscopy quantifies advanced glycation end products (AGEs) by detecting molecular vibration patterns. A.F.M. P et al. (2021) found that carboxymethyl lysine (CML) levels in photoaged skin were three times higher than those in naturally aged skin ($P < 0.001$), suggesting Raman spectroscopy could serve as a molecular biomarker for photoaging. However, this technique requires expensive equipment (over 2 million yuan per unit) and specialized operation (training period>6 months). The latest portable Raman probes can reduce detection time to 30 seconds per spot, but at the cost of a 40% decrease in spectral resolution. Modern clinical evaluation methods are shown in **Figure 2**.

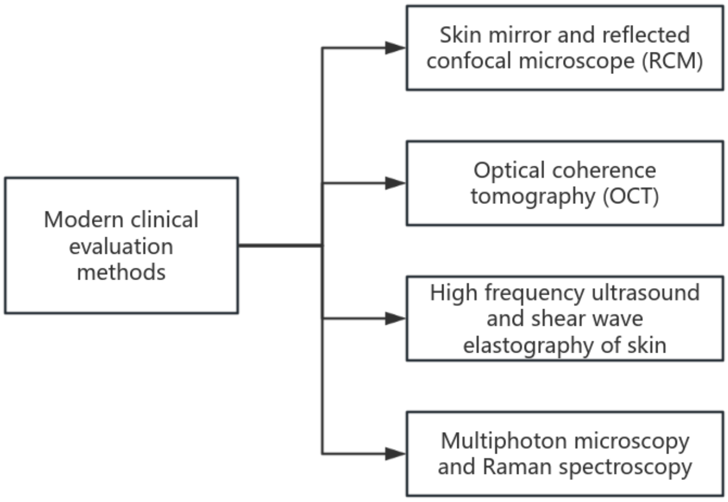

Figure 2. Modern clinical evaluation methods

4. Development and classification of skin photoaging assessment tools

4.1. Visual assessment

Visual assessment, the most intuitive method for evaluating skin photoaging, involves trained professionals observing visible changes in skin appearance to determine severity. Key indicators include skin laxity (sagging, elasticity loss), wrinkle quantity/depth (dynamic/static), pigmentation spot size/distribution, and capillary dilation visibility. Widely used in dermatology, it offers simplicity and cost-effectiveness, requiring only basic tools for rapid screening in large-scale health surveys. However, limitations persist: subjective interpretation varies with observer expertise, reducing consistency. Early-stage photoaging changes may escape detection due to low sensitivity, and the lack of quantitative data hinders precise severity tracking or treatment efficacy evaluation. Despite these drawbacks, it remains practical for preliminary assessments across healthcare levels [1–2].

4.2. Visia skin detection system

The Visia Skin Detection System, a non-invasive tool utilizing advanced optical imaging technology, plays a vital role in skin photoaging assessment. This system employs multispectral imaging to comprehensively analyze various critical skin indicators. It not only evaluates surface conditions but also captures deep-layer visual information, delivering detailed reports on spots, wrinkles, texture, pores, UV-induced pigmentation, brown spots, redness zones, and porphyrin deposits [3]. Through this comprehensive data, dermatologists can more accurately assess photoaging severity and potential issues, providing robust evidence for developing personalized treatment plans.

The Visia skin assessment system excels in four key areas: comprehensive analysis of surface imperfections and deep structural changes, objective digital evaluation minimizing human error, quantitative metrics enabling precise tracking, and visual reports enhancing provider-patient communication. This integrates holistic insights, facilitates treatment adjustments, and encourages patient engagement in skincare [4].

While the Visia skin testing system demonstrates multiple advantages, it faces notable limitations. The primary constraint lies in its high cost, with substantial upfront expenses for equipment procurement and significant ongoing investments required for maintenance and upgrades [5]. These financial burdens make it challenging for grassroots medical institutions to adopt the system, thereby limiting its widespread implementation at the primary healthcare level. Operational complexity also poses challenges, as mastering the system's interface and interpreting test results requires specialized training in optical principles and dermatological theories. This demands high professional competence from operators, which increases operational complexity. Furthermore, the system's sensitivity to ambient lighting conditions means that improper lighting environments may compromise image quality and result in inaccurate assessments. Therefore, maintaining stable and suitable lighting conditions during testing significantly elevates operational complexity and technical requirements [6].

4.3. Other evaluation methods

4.3.1. Molecular biology assessment

Molecular biology evaluation tools play a central role in the study of skin photoaging, providing a powerful means to further explore the intrinsic molecular mechanisms of skin photoaging. In recent years, many studies have made a series of breakthroughs by using advanced molecular biology techniques.

A study by Gu Y et al. (2025) focused on the substance Isovitexin. Through rigorous experiments, they discovered that Isovitexin can effectively alleviate photoaging in skin caused by oxidative stress by inhibiting cellular aging processes [1].

Wang Y et al. (2025) investigated stem cell-derived exosomes from human adipose tissue. Their study demonstrated that these exosomes can reduce mitochondrial DNA loss through the PINK1/Parkin-mediated autophagy pathway. As the powerhouses of cellular energy, mitochondria play a vital role in maintaining the normal physiological functions of skin cells [7].

4.3.2. Cell biology evaluation

Cell biology evaluation tools focus on the direct observation of skin cells under the action of ultraviolet radiation and other factors, which can directly reflect the cellular effects of skin photoaging.

Hu C et al. (2025) conducted research focusing on recombinant human collagen injections. Experiments revealed that these injections regulate the skin's local immune microenvironment through immunomodulatory mechanisms, reducing inflammation-induced skin damage. Simultaneously, they enhance collagen production and increase elastic fiber content in the skin, effectively addressing issues like skin laxity and wrinkles caused by photoaging [8].

Wu L et al. (2025) innovatively developed a thermosensitive hydrogel transdermal delivery system for salvianolic acid B to address skin photoaging. As a novel drug carrier, this hydrogel undergoes phase transition under body temperature conditions, enabling precise drug release [9].

4.3.3. Biochemical evaluation

Biochemical assessment tools mainly detect biomarkers related to skin photoaging to quantitatively assess the degree of skin photoaging. These biomarkers can reflect the physiological and pathological changes in the skin after exposure to ultraviolet radiation.

A study by Han B et al. (2025) demonstrated that spirulina polysaccharides exhibit significant protective effects against UV-induced skin photoaging. Biochemical analysis revealed that these compounds regulate intracellular redox balance, reduce oxidative stress products, and enhance antioxidant enzyme activity, thereby mitigating UV-induced oxidative damage to skin cells [10].

Ma Y et al. (2025) investigated the protective effects of carotenoids against skin photoaging. As a crucial natural antioxidant, carotenoids play a vital role in eliminating free radicals and reducing photodamage within the skin. Through biochemical evaluation methods, the study revealed that carotenoids regulate signaling pathways in skin cells and inhibit the release of inflammatory factors [11].

4.3.4. Histological evaluation

Histological evaluation tools use microscopes and other equipment to observe the skin tissue section, which can directly present the histopathological changes caused by skin photoaging, and provide an important basis for an in-depth understanding of the histological characteristics of skin photoaging.

Liu J et al. (2025) investigated the effects and mechanisms of collagen peptides and elastin peptides on UV-induced photoaging in skin cells. Through detailed histological analysis of skin tissues, they demonstrated that UV radiation causes collagen and elastic fiber damage with disordered alignment, leading to loss of skin elasticity and firmness [12].

4.3.5. Imaging evaluation

Imaging evaluation tools play an increasingly important role in skin photoaging assessment due to their non-invasive advantages. Optical coherence tomography (OCT) is a representative imaging technology.

Guida S et al. (2025) conducted a comparative study integrating OCT with other non-invasive imaging modalities to analyze atrophic and hypertrophic skin photoaging. OCT technology provides high-resolution cross-sectional images of skin tissues, clearly revealing structural changes across different layers. Through comprehensive analysis of these images alongside other imaging features, the research revealed distinct characteristic patterns in OCT-derived images for various types of photoaged skin [13].

4.3.6. Exosome biology evaluation

Exosome biology assessment tool, as an emerging research direction in recent years, has been increasingly valued in the study of skin photoaging. Exosomes are small vesicles secreted by cells, which can carry a variety of bioactive molecules and play an important role in intercellular communication.

Li K et al. (2025) demonstrated the crucial role of exosome lncRNAs in regulating apoptosis and inflammation during UV-induced skin photoaging. The study revealed that UV radiation alters the expression profiles of lncRNAs in skin exosomes. These abnormally expressed lncRNAs influence apoptosis and inflammatory responses by modulating downstream signaling pathways, thereby contributing to the development of skin photoaging [14]. This discovery provides a novel perspective for understanding the intercellular communication mechanisms underlying skin photoaging.

Liu L et al. (2025) conducted an in-depth investigation into the activation mechanism of the 5'-tiRNA-His-GTG-mediated JNK pathway in skin photoaging. The study demonstrated that 5'-tiRNA-His-GTG, as a novel small-molecule RNA, can be delivered between cells via exosomes to activate the JNK pathway, triggering a series of cellular responses that ultimately lead to skin photoaging [15]. This research further enriches the content of exosome biology evaluation in skin photoaging studies, providing theoretical support for developing novel exosome-based assessment methods and therapeutic strategies. The development framework of the skin photoaging assessment tool is shown in **Figure 3**.

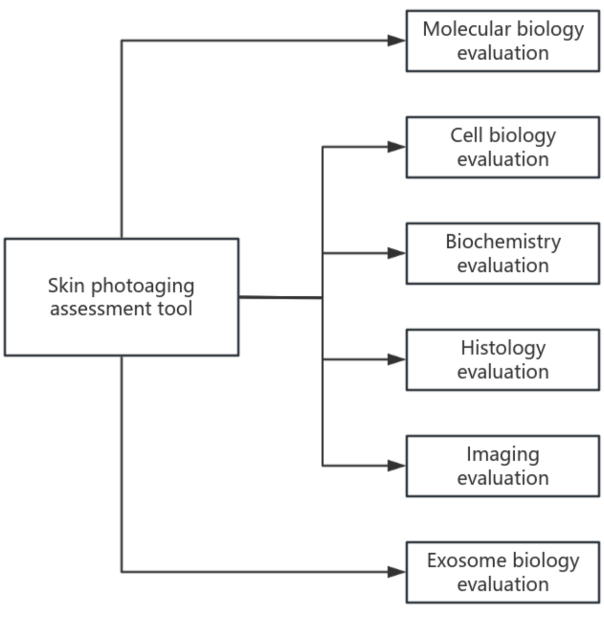

Figure 3. Development framework of skin photoaging assessment tools

5. Conclusion

The evaluation tools for skin photoaging have evolved through a developmental journey from subjective descriptions to objective quantification, and from single-parameter measurements to multimodal integration. Traditional clinical scoring methods, while easy to operate, remain highly subjective. Modern imaging technologies, though non-invasive and high-resolution, come with higher costs. Biomarker detection can reveal molecular mechanisms but requires invasive sampling. Artificial intelligence has enhanced analytical efficiency and accuracy. Moving forward, integrating molecular biology with engineering technology will enable the development of more sensitive, specific, and user-friendly assessment tools, providing scientific evidence for the prevention and treatment of photoaging.

Disclosure statement

The authors declare no conflict of interest.

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