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Revealing the invisible: In vivo imaging for photoaging therapies- review of the literature

Judit Korponai, Eva Remenyik, Emese Gellén *

Department of Dermatology, MTA Centre of Excellence, Faculty of Medicine, University of Debrecen, Hungary

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ABSTRACT

Background: Photoaging refers to the cumulative structural and functional changes in the skin caused by chronic exposure to ultraviolet (UV) radiation, distinct from chronological (intrinsic) aging. Among available interventions, photodynamic therapy (PDT) has demonstrated not only anti-tumor efficacy but also skin rejuvenating effects. To evaluate treatment outcomes objectively, modern non-invasive imaging technologies are increasingly applied in dermatology. This review aims to summarize the use of in vivo imaging tools—Antera 3D, VISIA complexion analysis system, optical coherence tomography (OCT), and reflectance confocal microscopy (RCM)—to assess the clinical efficacy of PDT and other interventions for photoaging.

Methods: A PubMed search was conducted up to May 2024. Eligible studies included human participants, a minimum follow-up period of three months, treatment of photoaged facial or décolleté skin, and an objective assessment using one of the four imaging modalities. Seventeen studies fulfilled the inclusion criteria.

Results: The reviewed imaging modalities demonstrated complementary strengths. The Antera 3D and VISIA systems provide rapid and reproducible quantification of wrinkles, pigmentation, and vascular changes. OCT enables cross-sectional analysis of the epidermis and dermis, particularly collagen density and dermo-epidermal junction architecture. RCM offers near-histological resolution of epidermal and superficial dermal structures, capturing cellular and extracellular matrix changes. These modalities confirmed clinically visible improvements in photoaging after PDT and other rejuvenation procedures.

Conclusion: PDT and other interventions can partially reverse the clinical signs of photoaging. In vivo imaging tools enhance objectivity in treatment monitoring. A multimodal imaging approach may represent the future standard for both clinical and research settings.

1. Introduction

Skin aging is a complex biological process driven by both intrinsic and extrinsic factors. Intrinsic (chronological) aging is genetically determined and occurs naturally over time, characterized by epidermal thinning, loss of dermal collagen and elastin, decreased vascularization, and reduced regenerative capacity. Clinically, it manifests as fine wrinkles, dryness, and loss of elasticity [1–3]. In contrast, extrinsic aging (photoaging) is caused by long-term exposure to ultraviolet (UV) radiation and other environmental factors such as smoking and pollution [4]. The direct and indirect DNA damage, reactive oxygen species (ROS), and release of inflammatory cytokines result in telomere shortening, oxidative stress, endoplasmic reticulum stress, chronic inflammation, and immunosuppression. All these lead to inhibition of type I and type III collagen synthesis, overexpression of matrix metalloproteinases-1, −3, −9, and −12 (MMPs), which contribute to extracellular matrix (ECM) and collagen degradation, and reduced collagen synthesis [5–10]. At the histological level, chronic UV exposure induces DNA damage, oxidative stress, upregulation of matrix metalloproteinases, and the degradation of collagen and elastin fibers, ultimately resulting in solar elastosis and increased risk of skin cancer [1, 11]. Photoaging typically affects sun-exposed areas of the skin—face, neck, décolleté, forearms, and hands—leading to coarse wrinkles, mottled pigmentation, telangiectasias, and actinic keratoses. Clinically, photoaging may manifest as the appearance of fine and deep wrinkles, vasodilatation, and mottled pigmentation. Depending on the extent of UV-induced damage and the protective reactions of keratinocytes and melanocytes, different signs of photoaging may predominate. Atrophic photoaging (AP) is characterized by fine wrinkles, erythema, telangiectasia, pigmentary changes, and a tendency to skin tumors, whereas

* Corresponding author.
E-mail address: emesegellen@med.unideb.hu (E. Gellén).

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Table 1
Comparative overview of imaging devices.

Imaging modality	Key strengths	Limitations	Typical clinical applications	Suitability for PDT/photoaging studies
Antera 3D camera	Quantifies pigmentation (melanin, hemoglobin). Measures wrinkle depth, texture, and pores. User-friendly, fast acquisition.	Limited depth. Mainly for cosmetic purposes.	Cosmetic/aesthetic practice. Evaluation of pigmentation, haemoglobin concentration, and wrinkles.	It can be used to document PDT-induced changes in pigment, haemoglobin concentration, and wrinkles.
VISIA system	High-resolution facial images under multiple light modes.	Mostly 2D surface analysis. Mainly aesthetic use.	Dermatology and cosmetology clinics. Analyzing wrinkles, pores, pigmentation, and redness.	Useful for follow-up and patient communication.
Optical coherence tomography	Cross-sectional visualization of epidermis, dermo-epidermal junction, and dermis (collagen organization). Can detect vascular changes	Limited penetration (~0.4–2 mm). Requires specialized equipment and expertise.	Research settings. Evaluation of collagen remodeling and vascularization.	It can be valuable for studies of PDT-induced remodeling.
Reflectance confocal microscopy	Near-histological horizontal imaging of the epidermis and superficial dermis. Visualizes keratinocytes, papillary dermis: detects elastosis and cellular changes.	Limited penetration depth (~250 μm). High cost and technical expertise required.	For research and specialized dermatology clinics. Diagnosis of pigmented lesions, cellular-level changes.	Powerful for mechanistic insights, less practical for routine PDT and other aesthetic procedures.

hypertrophic photoaging (HP) is characterized by deep, coarse wrinkles, a more homogeneous complexion, and fewer skin tumors [12,13].

Over the past two decades, multiple therapeutic strategies have been developed to counteract photoaging, including topical retinoids, fractional laser resurfacing, microneedling, platelet-rich plasma (PRP) injections, and photodynamic therapy (PDT). PDT, originally devised for oncologic applications, has proven rejuvenating effects through the stimulation of epidermal and dermal remodeling. PDT involves the application of a photosensitizing prodrug (such as 5-aminolevulinic acid [ALA] or its methyl ester [MAL]), which is converted intracellularly into protoporphyrin IX (PpIX). Upon activation by a light source of a corresponding wavelength in the presence of oxygen, ROS are generated. These induce selective cytotoxicity in dysplastic keratinocytes and stimulate dermal remodeling, and clinical rejuvenation by the induction of new collagen synthesis, transforming growth factor β levels, reduction in elastotic material and matrix metalloproteinases, and activation of the local immune response [14,15]. Studies have demonstrated that ALA-PDT enhances antioxidant defenses through activation of the nuclear factor erythroid 2 (Nrf2) protein. Knockdown of Nrf2, on the other hand, impaired these positive effects, suggesting that Nrf2 plays a key role in ALA-PDT-mediated skin rejuvenation [16]. Repeated PDT sessions can yield long-term improvement in photoaging signs, sustained for up to two years [14]. Moreover, PDT with combined light sources could potentially lead to greater efficacy in the treatment of photodamage through the synergistic effect of different wavelengths of light with similar tolerability [17,18]. Enhancing the delivery of photosensitizing agents into the epidermis can be achieved through pre-treatment with retinol, a fractional laser, or microneedling [19–21]. Fractionated CO_2 and erbium ablative lasers are common types used in wrinkle reduction, acne scar treatment, and photoaging enhancement. They are also useful to increase drug delivery, like ALA during PDT [22–24]. These approaches may work synergistically to boost the efficacy of photodynamic therapy (PDT) by promoting collagen production [1,11,25].

While traditional clinical scales and subjective evaluations have been used to monitor outcomes, they are prone to inter-observer variability. The advent of non-invasive in vivo imaging technologies has revolutionized dermatologic assessment by providing objective, reproducible, and quantifiable parameters of structural and functional improvements [26]. These in vivo tools offer the possibility to perform real-time, easily reproducible, non-invasive diagnostic examinations of large areas of skin. Several such imaging techniques are becoming increasingly valid in the diagnosis of skin diseases, including reflectance confocal microscopy (RCM), optical coherence tomography (OCT), Antera 3D (Miravex, Limited, Dublin, Ireland) camera, VISIA® (CANFIELD Imaging Systems, Fairfield, NJ, USA), high frequency skin ultrasound (HFUS) and multispectral imaging (MSI) [26–28]. The development of modern digital imaging technology has made it possible to assess the condition of the skin and objectively analyze the effectiveness of cosmetic products and treatments used to improve photoaging [29].

Despite the rapid technological evolution of dermatologic imaging, the comparative clinical utility of different systems in evaluating photoaging treatments remains insufficiently synthesized. Most published reviews to date have focused on descriptive overviews or small subsets of imaging modalities, without critical analysis of their relative diagnostic precision or suitability for PDT-based rejuvenation assessment.

The present review, therefore, aims to summarize existing evidence on the use of four imaging systems—Antera 3D, VISIA, OCT, and RCM—in the evaluation of PDT and other photoaging interventions, and provide a comparative analytical synthesis of these modalities in terms of diagnostic capability, depth resolution, measurable parameters, reproducibility, and clinical applicability.

2. Methods

A systematic literature review was conducted to identify clinical studies that applied in vivo imaging systems to evaluate therapeutic outcomes of photoaging treatments. A comprehensive search was performed in the PubMed database up to May 2024 using the following search terms: photoaging, photodynamic therapy, Antera 3D, VISIA, optical coherence tomography (OCT), reflectance confocal microscopy (RCM), rejuvenation. Studies were included if they met the following criteria: human participants with photoaged or actinically damaged facial or décolleté skin, treatment using PDT or other rejuvenation interventions (e.g., retinoids, lasers, PRP), objective outcome assessment using one or more of the following imaging modalities: Antera 3D, VISIA, OCT, or RCM; and a minimum follow-up duration of three months post-treatment. Exclusion criteria were animal or ex vivo studies, case reports without imaging data, and studies relying solely on subjective clinical or histological evaluation without quantitative imaging.

Seventeen eligible studies were identified and analyzed. The results are summarized according to the imaging system applied. For each modality, treatment type, study design, and main outcomes were extracted.

3. Results

A total of seventeen clinical studies met the inclusion criteria, covering a spectrum of interventions ranging from topical retinoids, platelet-rich plasma (PRP) and plasma gel injections, to photodynamic therapy (PDT), fractional CO_2 and Er: YAG laser-assisted rejuvenation, and combined multimodal approaches. Each study utilized one or more non-invasive imaging systems—Antera 3D, VISIA, OCT, or RCM—to objectively evaluate post-treatment changes. Collectively, these studies

Table 2
Anti-aging treatment results measured by the Antera 3D camera.

Authors	Device	Treated condition	Treatment	Clinical data	Results	Conclusion
Goberdhan LT at al [28]	Antera 3D, Miravex© camera	Photodamaged skin	0.5 % retinol	$N = 23$ patients Age: 45 to 68 years old Fitzpatrick skin type: II–IV Duration: 12 weeks (Controls at weeks 4, 8, and 12)	Skin texture—parameters decrease at weeks 4, 8, and 12 ($p \leq 0.004$). Wrinkles (2-mm filter) —Decrease in overall size, depth, width, and maximum depth at weeks 4, 8, and 12 ($p \leq 0.0004$). Pores—Decrease in volume, index count, and density at weeks 4, 8, and 12 ($p < 0.02$). Melanin—Decrease in the average level of melanin, affected area, and hyperconcentration at weeks 4, 8, and 12 ($p < 0.02$). Redness -At week 4, the hemoglobin parameter showed a nonsignificant increase, and at week 8, a significant increase. At week 12, the hemoglobin decreased close to the baseline level.	Topical retinol 0.5 % cream improves photoaging.
Kim J et al. [33]	Antera 3D, Miravex© camera	Photodamaged skin	MLV-RAL0.05 %/0.1 % (multilamellar vesicle containing retinaldehyde) cream on one randomized side of their face. Retinol 0.05 %/0.1 % cream on the opposite side.	$N = 22$ females Mean age: 49.6 years Duration: 8 weeks Evaluation: weeks 4 and 8	Wrinkle depth was reduced by 23.7 % on the side treated with MLV-RAL 0.05/0.1 %, while it was reduced by 10.27 % on the side treated with retinol 0.05/0.1 % after 8 weeks of treatment. Significant improvement was observed in wrinkle depth ($P = 0.001$) on the MLV-RAL 0.05/0.1 % treated side compared to the retinol 0.05/0.1 % treated side.	The application of MLV-RAL0.05 %/0.1 % cream improved wrinkles.
Cantisani C et al. [30]	Antera 3D, Miravex© camera	Actinic keratosis (AK) grade I–III, including subclinical lesions or fields of actinic damage	Daylight-PDT with 16 % MAL cream.	$N = 331$ patients Mean age: 73 years Fitzpatrick skin types: I–III Evaluation: baseline and every 3 months	A general reduction of inflammation was observed in 310 patients, evaluated through hemoglobin concentration and the intensity of the red color. A general homogenization of skin color (melanin) was observed in 314 participants. Wrinkle reduction occurred in 309 cases.	DL-PDT is an effective, easily implementable, well-tolerated treatment option that involves little pain and reduces the number of AKs while improving photoaging.
El-Domyati M et al. [34]	Antera 3D, Miravex© camera	Photodamaged skin in the periocular area	Carboxytherapy alone on the right hemiface or combined with fractional CO_2 laser on the left hemiface	$N = 25$ females Mean age: 49.1 ± 5.4 years Evaluation: baseline and 4 months post-treatment	In terms of texture and pigmentation, the left side (combined) showed significant improvement compared to the right side ($P < 0.05$). There was no significant difference in wrinkle improvement between the two sides ($P > 0.05$).	Carboxytherapy is more effective in improving photoaging when combined with a fractional CO_2 laser.
Diab HM et al. [35]	Antera 3D, Miravex© camera	Photodamaged skin of the periorbital area	PRP (platelet-rich plasma) was injected into the right hemiface (Rt) and plasma gel on the left hemiface (Lt)	$N = 40$ females Mean age: 32.48 ± 5.27 years Treatment: two sessions, 4 weeks apart (week 0 and week 4) Follow-up: until week 16	In the periorbital wrinkles, significantly better results were achieved on the plasma gel-injected side compared to the PRP-treated side after the second session. The improvement achieved could not be sustained in the following 3 months after either treatment. The average melanin concentration showed no significant improvement on either the PRP or the plasma gel-treated side.	Although both procedures are effective for periorbital rejuvenation, the plasma gel showed significantly better results in the short term.

demonstrated that imaging-based assessment consistently detects structural and chromophoric (melanin, hemoglobin concentration) improvements following anti-photoaging interventions. However, differences in measurement depth, resolution, and analytic scope among the four modalities determined their diagnostic strengths and limitations. To allow for comparison, the key advantages and limitations of the imaging devices are synthesized in a comparative overview table (Table 1).

3.1. Antera 3D camera

The Antera 3D (Miravex, Limited, Dublin, Ireland) camera is a new in vivo imaging device that uses multiple LED lights, multi-directional illumination of the skin, and advanced software reconstruction to instantly display tiny details of the skin invisible to the naked eye in 3D on a computer screen [30,31]. The camera can produce 3D images using 7 different wavelengths of light from several different light sources, where its software performs a multispectral analysis of the epidermis and dermis. It analyses the colorimetric properties of the skin: concentrations of hemoglobin and melanin chromophores, as well as topographic features such as wrinkle depth, texture, pores, and volume [32]. Therefore, it provides three-dimensional surface reconstruction and spectral analysis of pigmentation, vascularity, and wrinkle morphology.

Five studies employing the Antera 3D system were identified [28,33,30,34,35]. Despite variations in treatment protocols, consistent patterns of improvement were noted in wrinkle depth, pigmentation

Table 3
Anti-aging treatment results measured by the Visia.

Authors	Device	Treated condition	Treatment	Clinical data	Results	Conclusion
Goberdhan LT et al. [28]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Photodamaged skin	0.5 % retinol	$N = 23$ patients Age: 45 to 68 years old Fitzpatrick skin type: II–IV Duration: 12 weeks (Controls at weeks 4, 8, and 12)	VISIA showed clinical improvements in color, texture, appearance of lines/wrinkles, and skin tone unevenness at weeks 4 and 12 compared to baseline.	Topical retinol 0.5 % cream improves photoaging.
Wanitphakdeedecha R et al. [40]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Photodamaged skin	0.1 % kinetin cream	$N = 100$ Thai patients Age range: 35–65 years Kinetin cream was applied twice daily for 12 weeks, with follow-up visits at weeks 4, 8, and 12.	Significant improvement was observed in UV spots ($P = 0.047$) and redness ($P = 0.008$). Facial wrinkles ($P = 0.228$) and skin texture ($P = 0.975$) improved, but not significantly, at week 12.	The short-term application of Kinetin (0.1 %) cream was found to slightly improve cutaneous facial photo-damage.
Lin et al. [41]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Photoaging skin with melasma	Picosecond lasers with a diffractive lens array	$N = 10$ Asian women with melasma Mean age: 46.5 years Fitzpatrick skin type: IV Treatment: 3–5 laser sessions at 4-week intervals Evaluation: baseline, 12 weeks, 20 weeks, and 1 year post-initial treatment	Spots significantly alleviated at weeks 12 and 20 compared to before treatment, but this improvement was no longer observed after one year. Wrinkles showed significant improvement, while skin texture exhibited minimal changes during the one-year follow-up. Pores, UV spots, and porphyrins improved at weeks 12 and 20 compared to the baseline, but regressed by the one-year follow-up. Brown spots significantly improved at week 12, but this improvement was not sustained in later check-ups.	Picosecond lasers with a diffractive lens array provide short-term improvements in photoaging.
Sun Y et al. [42]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Photoaging skin	Electrode pin fractional radiofrequency (FRF)	$N = 20$ females Mean age: 54.4 ± 3.3 years Fitzpatrick skin types: III–IV Treatment protocol: first pass 240 V, 10–12 ms; second pass 220 V, 25–30 ms; three fractional RF (FRF) treatments at 4-week intervals Follow-up: 12 weeks	The average wrinkle percentile (58.8 ± 10.2) increased to 79.0 ± 8.4 at the 12-week follow-up.	The FRF treatments can effectively reduce wrinkles.
Wardhani pH et al. [43]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Facial rejuvenation in Indonesian skin	Picosecond 755-nm laser	$N = 20$ patients Mean age: 44 years Fitzpatrick skin types: III–V Treatment: two sessions at 4-week intervals Evaluation: baseline and 4 weeks after the second session	Significant improvement in wrinkles ($p < 0.001$), pigments ($p < 0.001$), and textures ($p < 0.001$).	The picosecond laser (755 nm) is effective for facial rejuvenation for a short time.
Perez Davo A et al. [44]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Facial photoaging skin in Caucasians	High concentration formulation (retinol 0.5 %, EDA extract 0.5 %, and niacinamide 4 %) and a transition cream (retinol 0.02 %, EDA extract 0.8 %, and niacinamide 3 %) on the face, for three months.	$N = 22$ Age range: 45–65 years Fitzpatrick skin types: III–IV Evaluation: baseline, week 4, and week 12	The number of wrinkles showed a continuous decrease at week 4 ($p = 1.000$) and at week 12 ($p = 0.010$). The wrinkles significantly decreased by week 12.	This anti-aging treatment demonstrated objective and subjective effectiveness in reducing wrinkles during the 90-day observation period.
Rivera Z et al. [45]	VISIA® (Canfield Scientific Inc., Fairfield, NJ)	Photoaging skin of melasma	1064-nm QS-Nd: YAG laser	$N = 64$ Venezuelan women with melasma Mean age: 45.5 ± 14.7 years Treatment: eight weekly sessions	The dark brown spots significantly decreased ($p < 0.005$) after 8 weeks of treatment.	Eight weeks after treatment with the Q-switched 1064 nm Nd: YAG laser mode, improvement in

(*continued on next page*)

Table 3 (*continued*)

Authors	Device	Treated condition	Treatment	Clinical data	Results	Conclusion
				Evaluation: baseline and 8 weeks post-treatment		melasma was observed in the patients.

homogeneity, and vascular parameters (Table 2). In summary, the results of the studies indicate that the Antera 3D camera provides rapid, reproducible quantification of macroscopic photoaging parameters, particularly wrinkles and pigmentation. Its utility lies in clinical trials and cosmetic monitoring, where topographic and chromophore mapping allow early detection of therapeutic benefit. However, as it captures only surface reflectance data, it cannot visualize dermal remodeling or collagen reorganization directly. Thus, Antera 3D is optimal for surface-level evaluation, complementing deeper imaging modalities.

3.2. VISIA

The VISIA (New Jersey, USA) camera system is a state-of-the-art in vivo tool for photo documentation and analysis of facial skin [29]. The VISIA system is a widely used and efficient non-invasive imaging tool that captures high-resolution photographs of the skin and offers valuable insights into its overall condition [36]. Using the device, it is possible to perform accurate and reproducible basic dermatological examinations and provide objective evidence of the effectiveness of treatments to improve photoaging [37]. It is widely used in dermatology, aesthetics, and the cosmetics industry. It utilizes three distinct lighting modes: standard incandescent light, ultraviolet (UV) light, and polarized light. The system includes a high-resolution camera with 15 megapixels that features automatic focusing capabilities [38]. The system analyzes skin images to assess and measure various dermatological concerns. It provides comparative data by matching each individual's results with those of peers who share a similar skin type and age. Using standard flash illumination, the VISIA device can detect features such as pore size, wrinkles, surface texture, and skin imperfections and compare them to the skin type of age-matched controls. The UV light source is used to detect UV spots and porphyrin. The absorption of UV light by epidermal melanocytes allows the identification of solar lentigos. Porphyrin, produced by Propionibacterium acnes, accumulates in hair follicles and sebaceous glands and fluoresces under UV light. Cross-polarised flashlight helps to identify brown spots and red areas. Canfield's proprietary RBX (Red/Brown/X) technology identifies skin melanin and hemoglobin chromophores. Cross-polarized light, unlike UV light, can detect melanin content in the deeper layers of the skin. Hemoglobin levels indicate the degree of redness of the skin, which can be mapped to monitor for erythema, telangiectasia, and vascular lesions [39].

Seven studies using VISIA for objective analysis of photoaging treatments were identified (Table 3) [28,40–45]. Analyzing the results of the studies, VISIA's strengths include standardized reproducibility, large population databases, and multi-spectral analysis, enabling comparison across treatment timepoints and subjects. However, it primarily reflects surface optical changes and cannot capture subsurface histological improvement. VISIA is therefore best suited for longitudinal documentation and quantitative cosmetic evaluation, while microstructural insights require OCT or RCM correlation.

3.3. OCT (Optical coherence tomography)

Optical Coherence Tomography (OCT), originally introduced for skin imaging by Welzel et al. in 1997, has been under development for nearly three decades and shows promising potential for future applications. While it is routinely utilized in ophthalmology, it has not yet been fully integrated into everyday dermatological diagnostics. OCT is a cutting-edge imaging technique primarily employed in dermatology to identify non-melanoma skin cancers, especially basal cell carcinoma (BCC) and actinic keratosis (AK), as well as various inflammatory skin conditions. In recent years, it has also gained popularity in aesthetic and cosmetic research to evaluate treatment outcomes. The device enables acquisition of cross-sectional, en face, and 3D images of skin at depths ranging from 0.4 to 2.0 mm, with optical resolution between 3 and 15 μm [46]. OCT enables detailed visualization of tissue architecture by utilizing light wave interference, eliminating the need for surgical intervention. It captures real-time digital images of the skin, allowing for the evaluation of both the epidermis and the upper dermis, as well as associated blood vessels and skin appendages. This technology provides a non-invasive method for diagnosing various skin conditions, monitoring disease progression, and assessing the outcomes of anti-aging treatments.

Multiple studies have shown that OCT can effectively detect the features of photodamaged skin and monitor their changes in response to rejuvenation therapies. Improvements in chronically UV-damaged skin can be evaluated based on alterations in the spatial distribution, alignment, density, and optical properties of collagen [47]. In OCT images, the appearance of the facial skin may vary, but the epidermis and dermo-epidermal junction (DEJ) remain identifiable. In cross-sectional OCT imaging of healthy skin, the stratum corneum is most clearly visible when the skin is moist, appearing as a broad, low-reflectivity band containing distinctly bright eccrine sweat glands. Beneath this layer, other epidermal layers can be seen as a variable band with a granular texture. The boundary between the epidermal thickness (ET) and dermal thickness (DT) is marked by the DEJ. The skin's blood supply is supported by two horizontal dermal plexuses, which also nourish the epidermis through diffusion. Dynamic OCT (D-OCT) allows for the visualization of vascular networks, which may be visible at different depths depending on the scan and the epidermal thickness. In normal skin, cross-sectional D-OCT images display dermal papillary loops as small dots near the DEJ, while en face D-OCT images reveal clearly defined and organized vascular patterns [48].

Four studies applied OCT or D-OCT for the objective assessment of rejuvenation treatments (Table 4) [28,49–51]. OCT excels in quantifying structural dermal restoration—notably collagen density and DEJ regularity—which correlate closely with true biological rejuvenation. Its quantitative output (e.g., attenuation coefficient, vascular signal density) provides objective metrics beyond visual evaluation. Limitations include equipment cost, trained observer, and restricted imaging depth (~2 mm).

3.4. RCM (Reflectance confocal microscopy)

The RCM, which is a suite of in vivo optical devices, can also be used successfully as a tool to objectively assess the efficacy of treatments to improve photoaging. The RCM is structurally composed of a light source, a condenser, objective lens, a detector, and a pinhole, which collects light from the plane in focus. Technically, the RCM allows very high resolution imaging of cells (axial resolution 3–5 μm, lateral resolution 1 μm), but can only visualize them at a depth of 250 μm, thus helping to assess the level of the papillary dermis or upper reticular dermis. There are two commercially available reflectance confocal microscopy devices: a wide-field probe system (VivaScope 1500, Lucid, Incorporated, Rochester, NY, USA; currently Mavig GmbH, Munich, Germany) and a portable, handheld version (VivaScope 3000, Mavig, Germany) [52]. RCM displays epidermal and dermal changes of

Table 4
Anti-aging treatment results measured by the OCT.

Authors	Device	Treated condition	Treatment	Clinical data	Results	Conclusion
Goberdhan LT et al. [28]	D-OCT (VivoSight, Michelson Diagnostics, UK)	Photodamaged skin	0.5 % retinol	$N = 23$ patients Age: 45 to 68 years old Fitzpatrick skin type: II–IV Duration: 12 weeks (Controls at weeks 4, 8, and 12)	The ET showed a significant decrease at week 8 ($p = 0.032$) and at week 12 ($p < 0.0001$). The DEJ contour was detectable in more participants at week 12 (95.7 %). The number of non-homogeneous collagen fibers significantly decreased, while the number of homogeneous collagen fibers significantly increased at week 12 ($p < 0.0001$). There was a significant increase in the attenuation coefficient at week 12 ($p < 0.001$) and in collagen density at weeks 4, 8, and 12 ($p < 0.03$). Significant increases in vascularization were observed at 300 μm at weeks 4 and 12 ($p < 0.02$), as well as at 500 μm at weeks 4, 8, and 12 ($p \leq 0.003$). There was also a significant increase in the number of vessels at weeks 4 and 12 at both 300 μm and 500 μm depths ($p < 0.025$).	Topical retinol 0.5 % cream improves photoaging.
Hendel K et al. [49]	D-OCT (VivoSight, Michelson Diagnostics, UK)	Photodamaged décolleté skin	Fractional 1927 nm thulium laser (TL) alone and combined with MAL-PDT with red light-emitting diode light.	$N = 12$ female Age: 18 years or older Fitzpatrick skin type: I–III Evaluations: at baseline and 12 weeks	The ET increased with the application of combined TL-PDT treatment ($P = 0.047$), while the roughness scores did not improve significantly with any intervention ($P > 0.850$).	The combination of TL and PDT is more effective in improving photoaging.
Gawdat HI et al. [50]	OCT RTVue Premier (Optovue Medical Industries, Fremont, CA, USA)	Photodamage face skin	During the split face treatment, one side of the face (Area A) was treated with mesotherapy (MRS FACE, mesologica_, MRS Lift solution, Jakarta Barat, Indonesia), while the other side of the face (Area B) was treated with autologous PRP (platelet-rich plasma).	$N = 20$ female Age: 35–55 years Fitzpatrick skin type: III-IV Each patient received six sessions at two-week intervals. Evaluations were conducted 1 month and 6 months after the last treatment.	Compared to the baseline, the mesotherapy-treated side showed a significant increase in both ET ($P = 0.003$) and DT ($P = 0.005$). Similarly, the PRP-treated side also demonstrated a significant increase in both ET ($P = 0.002$) and DT ($P = 0.001$). Surface irregularity improved on both sides. There was no difference between the two areas in the final ET and DT ($P > 0.05$).	PRP and mesotherapy are effective for skin rejuvenation.
Moftah N et al. [51]	OCT RTVue RT100 CAM (Optovue Inc, Fremont, CA, USA)	Nasolabial folds (NLFs) Intraoral approach on one side of the face (experimental side) and cutaneous extraoral approach on the other side (control side)	Fractional non-ablative Er: YAG (2940 nm) laser SMOOTH mode.	$N = 13$ Egyptian women Age: 35–60 years Fitzpatrick skin types: III–IV Each patient received 5 laser sessions at one-month intervals. Evaluation of NLFs was performed at baseline, 2 weeks after the last session, and 4 months after the last session.	Two weeks after the last treatment, there were no significant differences in ET ($p = 0.38$) and DT ($p = 0.27$) between the intraoral and extraoral sides. Four months after the last treatment, there was a significant difference in DT between the two sides ($p = 0.03$), while there was no significant difference in ET measurements ($p = 0.07$).	The intraoral Er: YAG laser in SMOOTH mode shows better results in rejuvenating nasolabial folds compared to the extraoral application.

photoaging in horizontal sections with a high detail approaching histopathological resolution, and allows the diagnosis of melanoma and other pigmented lesions using a contrast source of melanin pigmentation. RCM images show regular polygonal keratinocytes in the stratum spinosum and granulosum of intact young skin, referred to as the 'honeycomb pattern', and identifiable structures include junctional connections between keratinocytes, dark cytoplasm and nuclei of keratinocytes, regular-structured dermo-epidermal junction, and thin reticulated collagen fiber networks. In chronically sun-damaged skin, RCM images show more irregularly shaped keratinocytes (with mild dyskeratosis, variable cell size and shape, and sometimes poorly defined cell borders) with irregularly pigmented areas (patchy pigmentation

Table 5
Anti-aging treatment results measured by the RCM.

Authors	Device	Treated condition	Treatment	Clinical data	Results	Conclusion
Shin MK et al. [53]	Vivascope 1500 (Lucid, Incorporated, Rochester, NY, USA)	Photoaging	Fractional laser (Fraxel Re: fine, Solta Medical, Hayward, CA, USA)	$N = 11$ Korean women Mean age: 26.8 years Fitzpatrick skin types: III–IV Treatment session: 1 Energy level: 20 mJ with 8 passes Measurement time points: pre-treatment, and 3 days, 7 days, 2 weeks, and 4 weeks post-treatment	The total number of dermal papillae showed a significant decrease until 1 week after treatment ($P = 0.04$), but 4 weeks after treatment, the total number of dermal papillae showed a significant increase ($P = 0.01$).	The skin rejuvenation effects of fractional laser last longer than 4 weeks.
Sun W et al. [54]	Vivascope 1500 (Lucid, Incorporated, Rochester, NY, USA)	Photoaging	IPL (Lumenis One, Lumenis Co., Santa Clara)	$N = 10$ Chinese women Mean age: 45.7 years Fitzpatrick skin types: III–IV Five treatment sessions at 4-week intervals, with a 1-month follow-up	The thickness of the stratum corneum showed no significant difference ($p = 0.322$). The minimum epidermal thickness ($p = 0.002$) and the thickness of the basal layer ($p = 0.018$) significantly increased. The density of dermal papillae at the DEJ significantly increased ($p = 0.035$), while the capillary diameter significantly decreased ($p = 0.035$).	The rejuvenating effects of IPL on human skin were observed using RCM.
Guida S et al. [55]	Vivascope 1500 (MAVIG GmhB, Munich, Germany)	Photoaging: pigmentary changes of the skin and wrinkles on the décolleté and face	Laser device: Discovery PICO Laser Type: Frequency-doubled Nd:YAG picosecond laser (PSL) Optics: Fractional micro-lens array	$N = 10$ patients Mean age: 58.2 ± 5.9 years (range 49–63) Follow-up: 4 months Number of sessions: 3, monthly intervals Treatment areas: Décolleté (preliminary phase); face (full treatment)	RCM evaluation showed significant improvements in photoaged skin: Epidermis: marked reduction of mottled pigmentation ($p = 0.001$) DEJ: decrease in polycyclic papillary contours Upper dermis: increase in long bright collagen fibers, indicating dermal remodeling	1064-nm Nd:YAG PSL effectiveness in the treatment of skin photoaging signs.

indicating the presence of clusters of light-coloured keratinocytes in a honeycomb pattern). At the dermo-epidermal junction, polycyclic papillary structures suggest epidermal elongation and hyperplastic changes. However, due to limited laser penetration depth, RCM cannot visualize alterations in the reticular dermis, leaving deeper sun-induced elastotic damage undetected. Polycyclic papillary contours appear in the dermo-epidermal junction, indicating elongation of the epidermis and hyperplasia. RCM is unable to assess changes in the reticular dermis due to the depth of laser penetration; thus, the extent of sunlight-induced elastosis of the deeper dermal layers is hidden [12].

Three studies were included that utilized RCM for quantitative analysis of photoaging treatment response (Table 5) [53–55]. The results of the studies also confirm that RCM uniquely captures cellular-level evidence of rejuvenation—restoration of the "honeycomb pattern," epidermal regularity, and papillary dermal reorganization. Its diagnostic granularity bridges the gap between optical imaging and histopathology. However, its shallow penetration limits visualization of deep reticular dermis, and acquisition requires operator expertise. Consequently, RCM serves best as a research and validation tool complementing OCT's deeper assessment and VISIA/Antera's macroscopic quantification.

Dermoscopy, although not the main focus of this review, deserves mention as a cost-effective and widely accessible tool. It is highly valuable for detecting actinic keratoses and early photoaging signs, but lacks the quantitative reproducibility of the advanced imaging modalities reviewed here.

4. Discussion

Reviewing the currently available literature, data support and highlight the growing role of non-invasive imaging systems in objectively evaluating the efficacy of interventions for photoaging. The use of these in vivo tools can contribute to the optimization of treatments and the development of new technologies, helping dermatologists and aesthetic practitioners to choose the most effective and safest anti-aging treatments. These modern imaging technologies provide the opportunity for quick and non-invasive assessment of skin condition, which helps not only in treating existing skin problems but also in future prevention.

Various imaging techniques, such as Antera 3D, Visia, OCT, and RCM, offer information from different perspectives about the extent of skin aging, changes in collagen synthesis, and the development of potential skin lesions. Antera 3D is particularly useful for the quantitative evaluation of pigmentation and wrinkle depth, making it a practical choice for monitoring changes in texture and chromophores related to treatment. VISIA provides standardized photographic documentation and percentile rankings against age and skin-type-matched cohorts, offering a patient-friendly way to visualize progress. However, Antera 3D and VISIA devices' diagnostic reach ends at the skin surface, and the absence of depth-resolved information limits their ability to confirm biologic repair. Therefore, they are ideal for routine clinical documentation and high-throughput quantification in cosmetic and dermatologic practice. Altogether, they excel in detecting early surface-level changes perceived by patients and serve as cost-effective monitoring tools. OCT allows visualization of epidermal and dermal microarchitecture, including collagen remodeling and vascularization, making it valuable for mechanistic studies. RCM provides near-histological resolution of the epidermis and papillary dermis, capturing subtle cellular changes, but its high cost and limited penetration depth restrict routine use. Therefore, OCT and RCM are research-grade instruments, capturing subsurface and microscopic events that validate the physiologic impact of treatments.

The results of research and clinical studies conducted by the scientific community further strengthen the significance of these tools in measuring the effectiveness of anti-aging treatments. Overall, these tools complement each other rather than competing with each other. In aesthetic dermatology, the Antera 3D and VISIA systems are more accessible and cost-effective for everyday use, whereas the OCT and

RCM systems are better suited to specialized research or mechanistic investigations. Although not the primary focus of this review, dermoscopy remains the most widely available and inexpensive technique and could serve as a practical addition to more advanced systems. Another important observation is that, although the literature consistently shows objective improvements in skin parameters, the heterogeneity of treatment protocols and imaging methodologies makes direct comparisons between studies difficult. Future work should therefore aim to establish standardized imaging protocols and validated outcome measures to facilitate meta-analyses and clearer clinical guidelines.

It is expected that these tools will become even more integrated into everyday clinical practice in the future, enabling more accurate diagnoses and personalized treatments. These will not only promote a youthful appearance of the skin but also contribute to its overall health and protection.

5. Conclusion

Modern non-invasive imaging systems are useful tools for assessing the outcomes of photoaging therapies, including PDT and others. Their use enhances the objectivity of treatment evaluation, supports personalized therapy planning, and contributes to the development of novel interventions. Practical systems such as Antera 3D and VISIA are more suited to routine clinical and cosmetic settings. Advanced modalities like OCT and RCM offer mechanistic insights into structural and cellular-level changes, making them valuable for clinical research. Dermoscopy, although less quantitative, remains an important adjunct for screening and follow-up in routine dermatology. Integrating these tools into both clinical and research practice can improve the monitoring of therapeutic efficacy, optimize treatment strategies, and advance the prevention and management of photoaging.

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Declaration of competing interest

The authors have no conflict of interest.

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