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ADVANCEMENTS IN MEDICAL DEVICES FOR SKIN BEAUTIFICATION

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1. Introduction

Cosmetic procedures are intended to rejuvenate and beautify the skin, addressing concerns such as wrinkles, blemishes, scars, and sagging skin due to aging. The increasing awareness of beauty and skin care, coupled with disposable income, has led to the rapid expansion of more effective medical devices for skin improvement. Medical guidelines are necessary to help patients choose safe and effective skin beautification devices, as well as to establish standards for the development of such devices in different countries. Understanding the concepts and current state of the art in medical devices is the first step towards raising awareness and promoting innovation and adoption of these devices worldwide. This paper discusses the advancements in medical devices for skin beautification, their applications, currently available devices and instruments for skin treatment, as well as their specifications, therapeutic applications, limitations, and future developments. [1][2]

Over the past decade, there have been significant advancements in medical devices for skin beautification, particularly in developing countries and regions experiencing rapid economic growth. One such device is high-intensity focused ultrasound (HIFU), which is used for non-invasive skin lifting. HIFU utilizes focused ultrasound energy to heat specific areas of the skin, promoting collagen production and tissue remodeling. The use of user-friendly sonography navigation has improved patient comfort. Other recently disclosed devices include those for the treatment of acne vulgaris using high-frequency millimeter wave, skin rejuvenation and wrinkle removal using differentiated high-frequency current, and treatment of skin discoloration using nanostructures for controlled delivery of bioactive substances. Dermatologists and plastic surgeons in developed countries have also started using high-tension low frequency (HTLF) technology for skin rejuvenation. HTLF technology stimulates low-frequency impulses, resulting in the production of elastin and collagen by dermal fibroblasts. This leads to thinner and more elastic skin, reduced pore size, and softened or eliminated expression wrinkles, without the need for surgery or side effects, ultimately improving the overall quality of the skin. [3][4]

2. Historical Development of Medical Devices for Skin Beautification

The pursuit of skin beautification is as old as humanity itself. Medically approved devices used for skin beautification, however, date back only a few decades. Machines that had been used in dermatology for

years began to be extensively applied in various skin beautification treatments only with the growth of the personal care industry and a few paradigm shifts in the nature of the world, as explained earlier.

Historically, skin beautification was solely the domain of the upper class. Synthetic skincare products became popular in the twentieth century, but their penetration was limited to the upper-middle class and above. This changed with the entry of the mass cosmetics brands like L'Oréal, Max Factor, Revlon, and the likes in the early/mid twentieth century. Products were mass produced at cheaper rates, leading to a surge in adoption, and skin beautification became synonymous with the usage of synthetic skincare products.

The personal care industry took an about-turn with the Green Movement in the late 1970s. The industry went back to natural products, with even medicinal cosmetics brands promoting purely herbal products. The Ayurvedic movement was reminiscent of the herbal wave in Western countries too as a backlash to chemically-laden medicines. Dermatological treatments. Machines like the Chinese Qi extractor or the Indian galvano-suction also found their way to the personal care industry, greatly aiding skincare beautification. Beautification machines focused on professional usage rather than personal usage.

The introduction of home-use simplifying devices began as early as 1997, but their commercial viability was first proved by the HiFu device in 2008. The device made the revolutionary HiFu treatment available in the comfort of home, and its overwhelming success led to the deluge of devices in all segments of the skincare market. Such home-use devices often focused on a single procedure, but the invention of the first modular multi-purpose home-use beautification device in 2013 heralded a new era in skincare, as the device became capable of catering to a broad range of the personal skincare needs of its users.

Medically approved devices for beautification treatments have developed over time and aided the massive commercialization of scientific skincare technologies used in cosmetic clinics by manufacturers of portable home-use miniaturized machines post-2008, and this paper aims to cover all aspects such as portraits of the global personal care industry, electronics and tool-based scientific skin treatments, machine usage in skin beautification, historical development of devices for beautification treatments, and future trends. [5][6]

3. Current Trends in Skin Beautification Technologies

Skin beautification technologies have gained great success in recent years, and these technologies are supporting a wide range of medical devices used to improve beauty and eliminate skin problems. This chapter provides an overview of recent advancements in safety, efficacy, and complication reduction in various skin beautification technologies.

Laser therapy is a common technology used broadly for skin beautification and has become popular with a wide range of applications in recent decades. The latest advancements in laser technologies include Fractional Laser Therapy, Long-Pulsed Lasers, Short-Pulsed Lasers, and many others. Radiofrequency therapy devices use energy-based systems for non-surgical skin lifting, wrinkle removal, acne treatment, beauty enhancement, and facial contouring. Recent advancements in this field include Fractional RF Devices, Bipolar RF Devices, Unipolar RF Devices, Temperature-Controlled RF Devices, and many others.

Ultrasound-based devices improve skin elasticity and reduce wrinkles without surgical techniques. This market is currently one of the fastest-growing among all skin beautification technologies. Microneedling devices, including automatic devices, enhance transdermal drug delivery using microneedles. They can be used without any thermal energy sources, or artificial heat is given before microneedling using RF or ultrasound devices for better absorption of the numbing agents or other drugs. Many new medical devices in these areas have passed clinical tests successfully and have begun commercialization. Cryotherapy supports cooling formation to points anatomically related to induce a change in pain, temperature, or vascular activity. A new technology using contact static evaporative cooling has obtained superficial ice formation, and a three-device system has been tested successfully with positive results. [7][8]

LED light therapy devices are also gaining notoriety currently. Solid-state light sources like LEDs allow flexibility in design and can be used with versatile chemical substances such as photodynamic drug therapies. Computer-aided design, light-in-light-out prototyping systems, parametrical analyses of various design options, and computer-assisted manufacturing processes have ensured the compatibility of efficient and clinically desirable LED light systems with medical devices for skin treatments. [9][10]

3.1. Laser Therapy

Laser therapy utilizes focused light energy to interact with skin tissues, as well as other complications, conditions, and diseases, including acne scars, wrinkles, and rosacea. One of the major advantages of laser treatment is the superior precision of the device. Lasers permit specific treatment of blemished areas while keeping adjacent ones healthy and unharmed.

Among the laser treatment devices for skin beautification, two advancements are investigated in this section: the Er:YAG laser skin resurfacing device and combined devices of laser and light-emitting diodes (LED), which is also called Laser-LED therapy. The Er:YAG laser skin resurfacing device is well-known as a non-invasive treatment for skin rejuvenation. It has been widely used to treat various skin lesions, such as wrinkles, pigmentary lesions, benign vascular lesions, and acne scars. This device was designed to successfully treat both acne and wrinkles in a single session. Although micro-laser therapy has the advantage of an easily adjustable pulse width, this inherently raises the risk of overdosing energy at the skin surface and causing injuries to adjacent dermal structures. Since heated tissues diffuse energy rapidly in the axial direction of a laser, it is essential to optimize the treatment zone to maximize patient safety and stabilize results.

The combined Laser-LED therapy device consists of a low-level laser (660 ± 10 nm; 830 ± 10 nm) and light-emitting diodes (LED) (635 ± 10 nm) for treating acne. Each light source was administered in combination and simultaneously for 30 minutes to achieve a synergistic overall effect that is superior to any single mode. The light energy emitted from LEDs was monochromatic, resulting in increased concentrated light energy.

Upon study, both the Er:YAG laser skin resurfacing device and Laser-LED therapy were found to be a safe and effective remedy. Laser therapy clearly improves the grades of therapy, with minimal side effects. [11][12]

3.2. Radiofrequency Devices

The skin is indeed the outermost and the most visible protective organ of the body, and the largest organ with a surface area measuring about 1.5 - 2m2 in adults. This being a multilayer structure containing cells like keratinocytes, melanocytes, fibroblasts, and additional structures like hair, glands, etc. Many people get worried about skin conditions like blemishes, darkening, wrinkling, scaling, itching, rashes, etc. There are several skin beautification techniques, both physical and chemical, which can help improve skin conditions, both in medicinal practice and in cosmetic centers. These beautification therapies are carried out by the doctor/therapist experts trained in dermatology and cosmetology. One precaution that needs to be taken care of is to choose the dermatology/cosmetology center wisely, as beautification therapies/medications, if incorrectly prescribed by an unqualified person can cause skin damage or ineffectiveness.

Skin treatments can be broadly classified as topical (creams/lotions) applied on face and other body parts for beautification and hardware-based technologies beautifying and improving skin conditions. The topical treatments include creams/lotions with herbals/extracts, creams/lotions with steroidal components, etc. The hardware-based technologies include laser therapy, radiofrequency devices, ultrasound devices, microneedling devices, cryotherapy devices, LED light therapy, etc. Out of these, laser therapy is at present the most commonly used treatment.

Radiofrequency devices for skin contain a radiofrequency generator that transmits high-frequency (0.3 to 300 MHz) electromagnetic radiations which penetrate deep into the skin and heat the target tissues and organs, raising the tissue temperature to 38-42°C for skin tissue heating. This causes local hyperthermia affecting the dermis layer of skin, resulting in immediate and long-term tissue contraction, collagen remodeling and reorganization, etc. Overall, these combined effects improve sagging skin and achieve skin tightening and lifting along with reducing wrinkles and fine lines. In addition to RF facial skin treatment, RF is used for beautifying other parts of the body like breast, abdomen, upper arm, thighs, etc. In general, RF energies are used, with the advantage of deep penetration and a larger treated area. The RF output energies are generally applied via a capacitive coupling method using two electrodes. The treatments are painless and the developed devices have a good effect rate. [13][14]

3.3. Ultrasound Devices

Ultrasound technology, which has long been used in the medical field, has recently garnered interest for its application in skin beautification. Ultrasound devices work by delivering low-frequency sound waves, typically in the range of 1 to 3 MHz, into the skin. These sound waves create thermal and non-thermal effects, stimulating collagen production, improving blood circulation, and enhancing the absorption of skincare products. As a result, skin texture is improved, and the appearance of fine lines and wrinkles is reduced.

Two main types of ultrasound devices are commonly used in skin beautification: focused ultrasound and unipolar ultrasound. Focused ultrasound devices deliver energy to a specific depth in the dermis, promoting skin tightening and lifting. A popular example of this type is Ultherapy, which uses 4.5 MHz energy to target the SMAS layer of the skin. Unipolar ultrasound devices deliver energy over a larger area, creating a more diffuse effect. Examples, such as the Ultrasound Skin Scrubber, use 28 kHz energy for deep cleansing and exfoliation, while devices with probes and rollers use 1 MHz energy for facial lifting and wrinkle reduction.

Ultrasound devices have gained popularity in home beauty devices due to their relative safety and ease of use. Prices for these devices typically range from $40 to $200, making them affordable for most consumers. Home-use ultrasound devices are generally unipolar and operate at lower frequencies compared to professional models, providing milder outcomes that can be safely used by consumers. Many brands, such as Foreo, Nuface, and Olay, have released handheld ultrasound devices with various functionalities for skin beautification. [15][16]

3.4. Microneedling Devices

Microneedling, a minimally invasive procedure that stimulates percutaneous collagen induction, has been regarded as an innovative technique for skin rejuvenation. It has shown improvements in scars, fine lines, wrinkles, enlarged pores, stretch marks, and skin texture. The procedure has evolved and microneedling devices have become widely used in the clinical setting, where handheld motorized devices with single-use hygiene cartridges are available to dermatologists and clinics. However, several devices require a degree of professionalism to operate, and therefore, at-home devices may emerge to meet consumer demands. Many portable devices are available in the current market with questionable safety, efficacy, and hygiene. Further peer-reviewed studies will be required to establish which devices are safe, effective, and deliver consistent results. This review focuses on microneedling mechanisms, the importance of skin preparation, and beyond microneedling approaches. Moreover, this review highlights current microneedling device market trends and regulations across various regions.

Microneedling, a minimally invasive procedure that stimulates percutaneous collagen induction, has been regarded as an innovative technique for skin rejuvenation. Microneedling with hyaluronic acid (HA) has improved scars, fine lines, and wrinkles, enlarged pores, stretch marks, and skin texture and has been shown

to have a synergistic effect with adjunctive treatments. Microneedling devices have become widely used in the clinical setting, where handheld motorized devices with single-use hygiene cartridges are available to dermatologists and clinics. More than 30 dermaroller and motorized handheld microneedling devices exist globally. These devices have high safety profiles with zero downtime, minimal adverse effects, and over 90% patient satisfaction rates. Cosmetic companies have marketed serums with a wide range of ingredients, such as growth factors, antioxidants, peptides, and vitamins, which will allow skin care products to penetrate further into the skin.

However, microneedling devices are too pricey for home use, with dermarollers available for cost-effective home use. With less training and professionalism, there are concerns over hygiene and efficacy, and some concerns over safety, such as needle depth and forceful pressure. It has also been demonstrated that deeper treatments are desirable to achieve better results, but there are also concerns that deeper treatments could thicken the epidermis and dermal layers could induce more adverse effects. There is a need to set some boundaries for proper device measurements. Currently on the market, there are many portable devices being sold using either stainless steel needles or using blunt pens fixed with sapphire diamonds, needles protruding only 0.1 mm. Except for a specific device from EndyMed that treats 2.0 mm depth, there are no other medium depth RF microneedling devices available globally. Since many devices are still waiting to be reviewed and accepted by approved associations, further peer-reviewed studies will be required to establish which devices are safe, effective, and deliver consistent results. [17][18]

3.5. Cryotherapy Devices

Cryotherapy devices are innovative skin beautification technologies that utilize cold temperatures to treat various skin concerns and enhance overall skin appearance. Cryotherapy refers to the application of extreme cold to induce therapeutic effects, and in recent years, it has gained popularity in the skincare industry for its ability to improve skin tone, texture, and firmness.

Cryotherapy devices come in various forms, including handheld wands, facial masks, and body rollers. These devices typically consist of a cooling element that can reach temperatures as low as -10°C to -30°C. When applied to the skin, the cold temperature causes blood vessels to constrict, which reduces inflammation and puffiness, especially around the eyes. Cryotherapy also stimulates collagen production, promoting skin elasticity and firmness for a more youthful appearance.

Additionally, cryotherapy helps improve skin tone and texture by reducing the appearance of pores, fine lines, and wrinkles. It also enhances the absorption of skincare products, allowing for better penetration of active ingredients. Cryotherapy devices are suitable for all skin types and can be used as a standalone treatment or in conjunction with other skincare therapies. As the demand for non-invasive and natural skincare treatments continues to rise, cryotherapy devices are becoming an increasingly popular option for those seeking to enhance their skin's appearance. [19][20]

3.6. LED Light Therapy

Light-emitting diode (LED) light therapy involves using specific wavelengths of light to prompt one or more therapeutic responses in the body. Different wavelengths produce different effects on cells. Blue light (415 nm) kills acne-causing bacteria. Red light (600 to 660 nm) penetrates the skin, boosting collagen production to reduce wrinkles, fine lines, and skin sagging. Narrowband UVB light therapy is bright light (311 nm) effective for psoriasis, vitiligo, eczema, dermatitis, and other skin conditions. LED light therapy devices range from handheld units to facial masks. At-home devices are less powerful than in-office options. Prior to using an LED device, the skin should be thoroughly cleaned, and products causing photosensitivity should be avoided. Treatments can typically be performed every two or three days. Results may take weeks to become fully noticeable, with progress continuing over months of treatment. LED

devices are associated with few side effects and tend to be safe for most skin types. Background on LED light therapy systems is presented along with many recent advancements in LED light therapy treatments.

Light-emitting diodes (LEDs) have become popular as a light source. A few types of LEDs are available for analytical purposes; red LEDs (630 nm) are cost-effective and easy to use. Blue LEDs (470 nm) have been employed in analytical systems to eliminate interferences. On the other hand, green LEDs (520 nm) are innovative light sources with wide application potential in the development of analytical devices. Sensors that use LEDs as light sources and are based on fluorescence measurements, luminescent pH indicator films, and chemiluminescence have also been developed. The applications of LEDs range from simple instrumentation with high performance-to-cost ratios to low-cost devices for field analysis. At present, the number of chewing gum samples packaged in containers allowing easy chewing and flavor release is increasing. In many cases, an odor-tight container is provided, in which chewing gums are kept in an odor-tight state.

LED therapy is a non-invasive cosmetic treatment that uses LEDs for skin rejuvenation and improvement. LED therapy can be performed alone or after ablative treatments and is compatible with other light/toggle therapies such as intense pulsed light (IPL), laser skin resurfacing, and photodynamic therapy. It is easy to perform and is often combined with relaxing facial treatments or massage. LED therapy is a similar skin treatment technique that involves emitting specific skin-friendly wavelengths of LED light to achieve desirable skin conditions through photobiostimulation. The LED light energy is absorbed by the target skin and initiates biological functions in the skin. [21][22]

4. Innovations in Skin Analysis Technologies

The skin has vital physiological functions, including protection, thermal regulation, osmoregulation, and sensory detection. It is also the main organ with the largest area of contact with the environment. Since the skin is the organ that represents one’s health, beautiful and healthy skin is often regarded as young skin. In contrast, aged and unhealthy skin may experience wrinkles, pigments, and coarseness. However, the structure, function, and physicochemical properties of the skin are extremely complicated and change throughout one’s life. Accurate and objective analysis of skin conditions is essential for devising effective treatment with a medical device; however, such a task is challenging.

Innovations in skin analysis technologies are an important part of advancements in medical devices for skin beautification. These innovations focus on non-invasive and quantitative analysis methods such as three-dimensional (3D) imaging, spectrophotometry, and fluorescence imaging. The skin has complicated structures that have complicated arrangements and objects. Features of the skin surface, including pores, wrinkles, and plumpness, can be treated as 3D shapes and require 3D representation. Unlike device-to-device imaging representation standards, anatomical sites such as foreheads and areas around eyes have various shapes. To compare skin status differences before and after treatment in clinics, an automatic object removal technique is essential. Therefore, a 3D surface design representation based on a Bézier shape is proposed, which has been widely used in CAD/CAM computer graphics applications.

Different skin layers possess various structures and functions that affect hydrations and permeabilities. Several layers including the stratum corneum (SC), stratum granulosum (SG), and epidermis (EP) were successfully constructed to simulate skin permeations of ions and molecules using the finite difference method. All skin layers are uniform in the vertical dimension while the radial dimension contains hemispherical structures. The 3D 4-layer skin model can provide insights into the permeation determinations of any ions or formulations through skin. Optical skins not only deliver imaginative information but also provide the physical consequences of skin behaviors during aging processes. Thus, it is essential to record the uncompensated signals during aging processes and use advanced optical spectroscopic techniques during the offline development program.

Spectroscopy is based on the interaction of light with matter. Time-resolved fluorescence imaging is a high-resolution optical imaging technique that detects displayed fluorescence decay rates at an ultra-fast time scale and is free from factors hindering resolution in wide-field imaging. Skin fluorescence imaging with multi-wavelength and time-domain resolved has been proposed. Cox et al. have discussed the changes in skin fluorescence signal intensity in a rat model. Meanwhile, the multi-dimensional fluorescence characteristic of natural and artificial skin whistles different from that of non-skin materials. [23][24]

4.1. 3D Imaging

A tendency towards "natural beauty" has led to growing interest in skin analysis and beautifying treatments. 3D imaging, relevant to skin analysis and skin condition quantification, has received increasing attention owing to its ability to gather skin microstructure information that is hard to be recorded by a macro camera. As an essential step in beautifying treatment, skin analysis, providing both qualitative and quantitative information about skin conditions, is gaining significant attention. With the wide use of mobile devices and on-the-go lifestyles, skin analysis typically needs to be performed in a non-contact way. There is no smartphone-related skin analysis and beautifying treatment system reported.

Three-dimensional (3D) imaging, which can be classified into active and passive sensing techniques, is commonly used in skin analysis and has received full attention. With the development of high-tech electronic devices, great efforts have been made to develop various bio-imaging systems that can noninvasively obtain skin information. However, all of them are still active systems, which easily limits their commercial on-the-go applications. A fully passive point-scanning and hand-holding 3D skin imaging system, mainly composed of a mobile device and a one-lens camera, is built. To relax the constraints of full-field sensing, a simple optical system made of a single telephoto objective lens, a 1D linear light source, a motor-driving mechanism, and a laser dot is designed to focus a laser dot onto the skin surface and obtain the depth information based on the laser triangulation principle. A mobile device-compatible skin analysis and beautifying treatment system is further built for on-the-go beautifying applications, which can provide a more user-friendly operation and real-time analysis and treatment feedback. The pixel-to-pixel skin analysis on the 3D skin area is achievable using the proposed point-scanning 3D imaging system.

For non-contact skin analysis, beautifying treatments, skin conditions are usually quantified by the size and brightness of skin condition areas in the acquired 2D skin images. However, it is impossible to obtain the corresponding values precisely according to skin roughness and lumpiness. By employing the proposed handheld 3D skin imaging system, a borne model is first constructed to obtain the detailed skin microstructure 3D profile simultaneously with the magnified skin appearance images. Then, based on the obtained data, skin microstructure roughness, lumpiness, and area ratio are defined to quantify the corresponding skin conditions, which cannot be captured by adaptive skin analysis methods. [25][26]

4.2. Spectrophotometry

Dermatological spectroscopy refers to a non-invasive technique that is used to investigate skin conditions, characterizations, and cosmetic motivations using spectroscopy. Cosmetic skin analyzers equipped with spectrophotometers have been commercially available since the turn of the 21st century. Numerous advances have been made in the field of spectrophotometry to further its applicability in skin analysis devices for skin beautification.

Hydrophilicity and oiliness of the skin secreted by sebaceous glands are important indicators of the skin condition. The oiliness of the skin is of great concern since it is closely linked to skin troubles including acne. A reformed skin analysis device capable of evaluating skin condition based on hydrophilicity, oiliness, and skin troubles is developed. Using the developed skin analysis device, 523 men and women in their teens to 60s are screened and skin scores based on oiliness, hydrophilicity, and elasticity are provided to the subjects in real time along with appropriate measures. Fit of the screening device is inquired using a

questionnaire and a statistically significant positive correlation is observed between the screening results and the subjects' own assessment of their skin condition.

Spectral analysis of 8 different types of pigments observed in melanin, lipofuscin, and hemoglobin is performed and studied to develop a differential diagnosis system. Using the developed analysis system, 140 valid flame-shaped facial images are collected from skin clinics and a large and valuable image database is established. In order to validate the database, an initial analysis of the fluorescent characteristics of the images is conducted using a luminance RGB color space. Skin redness, uneven skin color, and spots with high color difference indicate poorer skin conditions.

Noninvasive spectral imaging of skin with a differential image sensor array is introduced to obtain various skin signals. Skin-smoothness signals from a newly developed differential skin microstructure imaging sensor and a spectrally-differential skin surface roughness reflectance sensor help envision skin smoothness. A spectral differential cross-polarized light imaging sensor is employed to visualize freckles with difference image. Commercial spectral imaging cameras are calibrated with differential imaging technique to obtain individual skin chromophores including melanin and hemoglobin. [27][28]

4.3. Fluorescence Imaging

Fluorescence imaging entails the visualization of fluorescent molecules. The fluorescence imaging system comprises a beam splitter, an excitation source, filters, a pupil camera (optionally capable of time-gated imaging), and an intense light source (670 nm) controlled by a computer. When a tissue sample is illuminated using a laser or LEDs, one portion of the light transmits through the beam splitter. The light fluorescence microanalyzer systems have been developed to measure fluorescence intensity. This microanalyzer has a microcuvette system composed of a beam splitter and optical fiber that can be used to measure tissue fluorescence. The other part of the light is reflected through the beam splitter and can be observed by the pupil camera.

An imaging system collects fluorescence images of the cuvette system using a laser light source with excitation filters (410 and 436 nm). The rejection filter is a 515 nm long pass filter that delivers the fluorescence lights above 515 nm to an intensified charge-coupled device (ICCD) camera system. The images obtained are processed and measured at different parameters. The purpose of the beam splitter is to divide the excitation light at a specific portion to be transmitted for the fluorescence image and to go for the pupil camera. The reflectance image is used to calculate the variance of fluorescence intensity, which is strongly related to the number of blood vessels at a specific tissue area. The fluorescence image goes to observation for visualization of the tissue evaluation with drugs or treatments. The fluorescence dyes like fluorescein or indocyanine green (ICG) are employed in the study. The fluorescence images can be obtained with the selected dye excitation and rejection filters.

For in vivo applications, a fluorescence imaging system with a contact probe that includes a backpack for a fluorescence CCD camera system is successfully developed. It performs in vitro tests as a preclinical model using animal experiments on skin cancer following photodynamic therapy. The fluorescence microanalyzer and imaging systems are used to measure the fluorescence intensity and fluorescence images in the probe systems. After obtaining the fluorescence images, other variables such as the variance of intensity (var), the variance of intensity at five-layer depths (var d), and the variance of ratio are further processed. Skin evaluation gives some quantitative values of fluorescence variance from the ratio image. This value is zero at the normal tissue, while it becomes large at the fluorescence uptake ($p<=0.001$). [29][30]

5. Emerging Technologies in Skin Beautification

Skin, the largest organ of the human body, acts as a protective barrier against foreign pathogens and other harmful materials. Skin beautification or skin care treatments for beauty purposes encompass the discovery

of different skin care materials or devising different devices or techniques for beauty purposes. Over the years, many skin beautification products have been developed, but very few have improved your skin beautification product. Here, some of the approaches have been suggested for skin beautification, and the skin beautification devices based on these approaches are discussed. Furthermore, suggestions are made on the future devices for skin beautification.

Skin beautification devices are the devices that work through mechanical or electrical means to soothe, clean, hydrate, or enhance the beauty of the skin. Based on the techniques and their work, devices such as facial cleansing devices, suction devices for the removal of blackheads, beauty devices for lifting or contouring the skin are some of the widely available devices for skin beautification purposes. In addition to the discussed devices, there are also beauty devices that enable scrubbing or peeling the skin to enhance beauty. Current skin beautification devices are analyzed, and it is observed that cleansing, hydration, and facial contour-related devices are an essential part of the skin care beauty routine for a large number of users. Based on the analysis and new skin care techniques, cosmetic devices that use nanotechnology and AI in accordance with skin beautification techniques to proffer beauty advantages such as skin regeneration and drug delivery are suggested. Nanotechnology is employed to develop thin nanomaterial-based sheets that can improve skin hydration and skin regeneration. The sheet can be easily worn on the skin and can be worn while sleeping. AI is employed to develop a skin analysis-based skincare device system that analyzes skin properties and conditions that deliver the drugs to the skin and adjust the frequency of dosage administration or type of creams and lotion depending upon the skin damage analysis. AI technology-based skin analysis device is also proposed to analyze skin type and recommend suitable beauty creams and lotions.

Skin diseases, including eczema, psoriasis, and burns, cause a change in skin structure that leads to dysfunctions in the skin barrier and sensitivity. Skin defects and deeper wounds resulting in the loss of hair follicles, sweat glands, and sebaceous glands can cause a great disturbance in skin homeostasis. Defects in the epidermis lead to the loss of barrier function and increases of transepidermal water loss (TEWL), which is a cause of dry skin or atopic dermatitis (AD) (i.e., skin inflammation). Current methods for skin grafting are non-autologous skin grafts, bioengineered skin, or transplantation of keratinocytes and fibroblasts on dermal infrastructure. The growing popularity of regenerative medicine, stem cell therapy (SCT), has also been used for skin regeneration. Bioprinting technology, which can construct the 3D structure containing living cells, has recently gained interest for skin application. Bioprinted skin substitutes must have skin-like properties for maintaining normal skin functions. [31]

5.1. Nanotechnology in Skincare Devices

Nanotechnology, the manipulation of matter at the nanoscale (1 to 100 nm), has the potential to revolutionize a wide range of sectors with its distinctive properties. It has grown significantly over the past two decades, leading to advancements in technology. The rise of fast-growing nanotechnology-derived consumer products presents a new global challenge, as most countries currently lack regulatory frameworks for these products. Nevertheless, it also provides opportunities for new products. In the last decade, there has been a sharp rise in the capability to understand the biological impacts of specific nanomaterials, including those involving skin exposure. Given this backdrop, skincare devices that incorporate nanoparticles for the purpose of drug delivery, laser treatments, or mechanical exfoliation are a timely subject of review.

Nanoemulsions have emerged as versatile vehicles for drug delivery and skin applications due to their distinctive properties and composition. Nanocapsules comprised of lipid components have been shown to enhance penetration and deposition in deeper skin layers. These formulations also enable longer skin coverage and retention compared to traditional liposome formulations. Another alternative to better control skin exposure to bioactive agents are silica nanoagglomerates, which can be incorporated into creams,

lotions, or powders to form a dry and stable film. This film enables localized effects and prevents systemic penetration, as demonstrated by studies using curcuma-loaded silica agglomerates.

Incorporating ceramide-bearing nanospheres into oil-in-water emulsions can dissolve, uptake, and convert intact glycosphingolipid constructs into precursor sphingoid bases using murine skin. This study serves as proof of concept for the use of topically applied biomolecular nanodevice system to mold the skin surface bioactive lipid sphere composition. The strategy may find application in restoring the bioactive molecular sphere pool of other skin disorders and inflammatory diseases. Overall, skin care devices blending traditional and new technologies hold the promise of enhancing skin treatments and bioactive agent penetration.

5.2. Artificial Intelligence in Skincare Devices

Exciting new technologies are being incorporated into skincare devices to make them more effective, more convenient, and easier to use. One element majorly changing skincare devices is Artificial Intelligence (AI). AI's incredible growth in popularity and capability in recent years has led to huge advancements in many fields, including skincare.

AI can imitate and simulate aspects of human thought or mind. There are many variations of AI, such as simple rule-based decision trees and complex generative models, but they all have the goal of solving problems that would normally take a human mind to accomplish. By tackling these issues artificially, AI makes solutions available at a speed and scale impossible in human timescales. In the skincare industry, this means faster and more accurate skin analysis, content creation, and much more. These advancements make skincare devices capable of impersonating dermatologists or beauticians, a notion that was once the stuff of science fiction.

AI skincare devices that analyze a user's skin condition and provide an individualized skincare routine recommendation are an advancement from devices that simply analyze a user's skin condition. Devices that provide a skincare routine recommendation cannot accommodate the preference or restraints of the user concerning budgetary considerations, time allowances, product allergies, etc. Budgetary considerations include recommendations that are completely out of the user's budget or too low-tier for their current routine, e.g. someone using La Mer products being recommended CeraVe products. Such smart skincare devices that take into account all elements up to the creation of each skincare routine's individualized steps were unheard of until now. However, with ongoing data collection, these smart skincare devices will continually improve and adapt and become a helpful addition to any skincare enthusiast's routine.

The incorporation of AI in devices that recommend individualized product application techniques also pushes the technology further. Smart skincare devices that analyze and detect sun damage or visible pores count were previously developed by several companies but are nowhere near as sophisticated as the AI in the current devices. There are other early entrants in AI that recommend low-quality or unduly solutions. Although this technology may not catch on as a whole, it is undoubtedly an exciting edge over competitors for brands looking to break into the saturated Asian beauty industry. However, AI technology and the advancements in camera capabilities must also be accessible to brands without extensive R&D support.

5.3. Bioprinting for Skin Regeneration

Grafen's team developed methods to generate full-thickness skin-mimicking constructs via direct on-skin bioprinting. A 3D bioprinter was designed to deposit biomaterials directly on an animal's skin, where the liquid bioink formed a scaffold upon contact. This method showed higher survival rates for keratinocytes and fibroblasts than traditional bioprinting. The on-skin bioprinting system was tested on mice, where skin defect recovery was 70% after five weeks, significantly improved compared to controls.

In another approach, inkjet bioprinting of living skin cells produced full-thickness human skin models with good structure and high cell viability. Keratinocytes were applied first in conjunction with a covering matrix, followed by dermal fibroblasts and DMEM/F12 culture medium. Grafted skin constructs matured, forming an organized dermatotrichal structure. This bioprinting technology is rapid and can be applied for drug screening and toxicity testing.

The development of a fully automated 3D bioprinting system for skin regeneration used a novel hybrid bioink mixture of gelatin and alginate. The skin bioprinting approach was completely bio-friendly and allowed human fibroblasts and keratinocytes to survive and remain active within the constructs.

The viability of bioprinted skin stamped with moldable gelatin-alginate bioink was unaffected after 42 days, generating a skin model with hair follicles. The bioink exhibited thermally reversible gelation, injectability, self-healing, and printability at physiological temperature. Integrating bioprinting and molding may enhance skin regeneration strategies efficaciously. [32]

6. Regulatory Considerations for Medical Devices in Skin Beautification

As the medical device industry continues to innovate and create devices that treat or prevent skin conditions, new regulations need to be considered and implemented. Along with the rise of an aging population, awareness of beauty in daily life is growing among people of all age groups. As a result, the subjects of medical devices for skin beautification need to be examined: effectiveness before and after treatment, the safety of medicines or materials to be used, the device design, and patient satisfaction or quality of life (QoL). There are many types of medical devices to be considered, among which dermatologic lasers and light devices, and radio frequency (RF) devices are the two most actively studied areas.

Laser and light devices work on photothermal and photochemical effects, and image analysis is focused on the delivery of energy to targeted tissues. As for the RF devices, these devices work on thermal effects. Alternative designs and designs on electrodes are two subjects to be examined along with safety, including the prevention of overheating of the overlying skin based on various conditions. Safety for both eyes and tissues should be considered, and electromagnetic wave (EMW) dispersal with antennae on the body at the time of wireless monitoring is focused. Effectiveness is evaluated on a device basis, but basic clinical and experimental results should be reviewed. In the case of ligands for tissue targeting in biotechnological approaches, tracking from cellular uptake to clearance should be evaluated, while the selection of patients should be considered as a medical device course.

Patient QoL should be considered to accurately evaluate the effects of devices. The influence of aesthetic skin treatment devices is described, and analysis systems to objectively measure meaningful quantitative outcomes are also addressed. As for possible future visions, new industrial paradigms that consider the whole cycle of a device from development to performance post-market may have to put emphasis on Asian patients' race, advanced aging populations, and gender, and develop devices based on the academic background of skin from a view of regeneration therapy and combinatorial analysis of computational medicine. [33][34]

7. Challenges and Future Directions in the Field

The field of skin beautification has undergone a transformation in recent years owing to the rapid development of new technologies. In particular, new medical devices based on various cutting-edge technologies have optimized skin beautification procedures. Many new devices based on laser, light-emitting diode (LED), ultrasound, electromagnetic (EM), radiofrequency (RF), microneedle, and other related technologies are reported in the literature to produce excellent beautification effects for various skin indications.

The advantages and disadvantages of clinical and home-use medical devices for skin beautification challenges and future directions in the field. With the rapid development of new medical devices that incorporate recent advancements in technology and cosmetic science, skin beautification has made great strides over the past few years. Many medical devices are commercially available to optimize skin beautification procedures. Many devices based on laser, LED, ultrasound, EM, RF, microneedle, and other related technologies are reported in the literature to achieve excellent beautification effect on various skin indications.

Challenges remain in formulating methods for multi-skin beautification with a single device, reconciling the clinical and home-use devices, discovering personalized skin treatment and beautification, and establishing universal evaluation tools for skin beautification. Existing skin beautification medical devices mainly focus on treating specific problems, making it difficult to achieve overall skin beauty. Multi-skin beautification procedures are usually time-consuming, involving the combination of two or three kinds of different devices (medical and cosmetic) that cannot be completed with a single device. Although devices that treat multiple skin issues have been developed, patients want a more comprehensive solution to skin beautification. [21][35]

8. Conclusion

In summary, the field of skin beautification is making tremendous progress as new medical devices come on the scene. These tools change the way dermatology, cosmetic surgery, and skin wellness are investigated, monitored, and treated both regionally and systemically. These medical devices now utilize advanced techniques such as smart nanosensors for drug delivery, analysis of trans epidermal water loss through skin modeling, and microneedle-assisted vaccine and drug delivery. Besides, new technologies such as biocompatible multiphoton fiberscopes and computer-aided facial analysis and beautification are investigated to keep up with growing demands of concern for skin wellness. In addition to current advancements, the popularity of smart devices such as smart skin analysis tools and skin health activity trackers, powered with modern technologies such as artificial intelligence, blockchain, and internet of skin are also anticipated in upcoming years showing a constant evolution of tools to ensure healthy skin.

These advancements open the door for various dermatological and cosmetic procedures, increasing interest in skin wellness, and expanding the market for medical devices for skin beautification. When compared to some procedures that were done solely in laboratories and hospitals, these technological advancements enable drug delivery, tracking, and analysis to be done at home and in offices. The illnesses that can be investigated and treated are also increasingly diverse, moving from purely acne or beauty-related diseases to any that arise from disrupted cellular or epidermal homeostasis in skin. With the advent of these systems and tools, market and revenue growth is expected to explode.

Skin is the largest organ of the human body and serves as a barrier to a number of environmental threats. Any disruptions in cellular or epidermal homeostasis in skin may lead to different skin diseases. The skin-related diseases can be categorized as dermatology or cosmetic surgical. Dermatology-related diseases are associated with acne, bacterial infection, fungal infection, and skin cancers, while those associated with cosmetic surgery are concerned with wrinkles, melasma, and face lesions. With increasing skin concerns, increasing interest in skin wellness, and availability of more skin analysis and treatment medical devices, the total market for medical devices for skin analysis and treatment is expected to expand rapidly.

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