INVITED REVIEW OPEN ACCESS

New Frontiers of Non-Invasive Detection in Scalp and Hair Diseases: A Review of the Application of Novel Detection Techniques

Meijiao Du[1,2] | Ying Wang[1] | Jing Wang[3] | Ying Xie[1,2] | Yonglong Xu[1,2] | Dingquan Yang[1]

[1]Department of Dermatology, China-Japan Friendship Hospital, Beijing, China | [2]Clinical Medical College, China-Japan Friendship Hospital, Beijing University of Chinese Medicine, Beijing, China | [3]School of Chemical and Materials Engineering, Jiangnan University, Jiangsu, China

Correspondence: Dingquan Yang (ydqlx@163.com)

Received: 14 September 2024 | **Revised:** 16 December 2024 | **Accepted:** 25 February 2025

Funding: The authors received no specific funding for this work.

Keywords: fungal microscopy | hair physiological indices | patch test | skin physiological function tests | trichoscopy

ABSTRACT

Objective: The aim of this paper is to review the current status and recent progress of the application of novel non-invasive testing technologies in the diagnosis, treatment, and care of scalp hair diseases in recent years, and to discuss their contribution to the improvement of scalp hair health management.

Methods: Through a literature review, the principles and current status of application of technologies such as trichoscopy, microbiological testing, scalp skin physiological function testing, hair physiological index testing, and hair product patch testing, and their specific roles in the management of scalp hair diseases were systematically sorted out.

Results: Trichoscopic intelligent analysis technology can quantitatively assess the hair growth status and provide an objective assessment of the efficacy of hair diseases; microbiological testing provides a laboratory reference for the rapid diagnosis of scalp diseases and clinical use of medication; scalp skin physiological function testing and hair physiological index testing are essential for a comprehensive assessment of the scalp environment and hair health. The patch test can effectively detect allergenic substances, which can help to safely select topical drugs and hair care products, avoid medical risks, and facilitate safety evaluation.

Conclusion: Novel non-invasive testing techniques provide powerful technical support for accurate diagnosis, personalized treatment, and safe care of scalp hair diseases, and show a broad application prospect. Future research should focus on improving the accuracy and detection efficiency of these techniques to meet the growing demand for scalp hair health management and to promote the development of this field in a more scientific and refined direction.

1 | Introduction

With the development of society and people's health awareness, the health of hair and scalp is getting more and more attention. Hair health is closely related to physical, mental, scalp, and hair follicle health, and the detection of scalp and hair physiological indicators has important clinical and scientific research value. Common scalp diseases include seborrheic dermatitis, scalp furuncle, psoriasis, alopecia folliculitis, sensitive scalp, and so forth. Hair diseases mainly include non-scarring alopecia such as androgenetic alopecia, resting hair, and pemphigus vulgaris, as well as scarring alopecia such as lichen planus, discoid lupus erythematosus, and scleroderma [1]. In addition to relying on history tracing, clinical examination, and clinical trials, the diagnosis of scalp hair disorders is commonly made by non-invasive testing techniques such as dermatological imaging techniques, microbiological testing, scalp, and hair physiological assays, as well as scalp hair pathology guided by dermatological imaging techniques.

To retrieve research advances in non-invasive testing techniques for hair disorders, we searched relevant literature from PubMed. We used the following search terms in conjunction with practical clinical scenarios: ("Scalp Diseases" OR "Hair Diseases") AND ("Trichoscopy" OR "Fungal microscopy" OR "Skin physiological function tests" OR "Hair physiological indices" OR "Patch test"). Only Journal articles written in English and published between January 1, 1984 and July 31, 2024 were included. The subjects were limited to Medicine and Health and we retrieved 84 articles. The limited number of studies on the theme is mainly due to a number of factors. On the one hand, it is difficult to obtain hair samples, and there are many challenges in microstructural research, as well as differences in samples at different stages of the growth cycle, and high technical thresholds for research on cellular and molecular changes at the microscopic level [2, 3]; on the other hand, there are limited research resources, and funding tends to be directed toward research on major diseases such as cancer and cardiovascular diseases, so there is insufficient funding for research on hair physiology, and there is a scarcity of specialized talents in the field, so it is necessary to attract multidisciplinary talents. In addition, the limitation of clinical application value, the lack of attention to the correlation between hair problems and diseases in the past, as well as the limited means of treatment for hair-related diseases, the difficulty of accurately evaluating their effects, and the ineffectiveness of therapeutic feedback have hindered the in-depth development of research on detection techniques for hair physiology and the growth of its volume [4, 5].

This review focused on scalp hair disorders, specializing in their diagnostic and follow-up methods. With the development of the field, there is an increasing variety of testing methods. We aim to systematize these methods, including diagnostic pathways such as physical tests and biochemical analyses, as well as follow-up methods for assessing the condition and efficacy of the disease, in order to provide guidance for clinical and research purposes, and to present the current status and trends in the field.

2 | Dermatological Image Detection and Digital Image Analysis

2.1 | Clinical Application of Trichoscopy in Hair Diseases

Photography of hair/scalp is an important part of photo-documenting a patient with involvement in these areas. It poses its own difficulties and special posing and light requirements. Today, it is complemented with trichoscopy images (a method of hair and scalp evaluation that uses dermoscopic images for diagnosing hair and scalp diseases). Hair/scalp photography is essential for monitoring alopecia treatments [6]. Trichoscopy, serving as a non-invasive and efficient auxiliary diagnostic tool, provides information on the microstructure of the skin surface at the follicular unit's orifice, hair shaft morphology, hair root shape, perifollicular microvasculature, and the condition of the skin in the hair-bearing area [7]. This method is a commonly used and straightforward diagnostic technique for hair disorders. Trichoscopy allows for the observation of various features in hair diseases, such as variations in hair shaft diameter, follicular units, hair density, as well as perifollicular signs, enabling differentiation among various types of alopecia and staging of the condition. Trichoscopy can also be used to determine the proportion of hairs in the anagen and telogen phases by cutting hairs to a length of 1 mm and photographing them under standard conditions, and repeating the process 1 week later [8]. Characteristic dermoscopic features of androgenetic alopecia include hair diameter diversity greater than 20%, brown perifollicular pigmentation, and a decrease in the anagen/telogen ratio. During the active phase of alopecia areata, yellow dots, black dots, broken hairs, and exclamation mark hairs are observed. These typical dermoscopic features are valuable for the early diagnosis, differential diagnosis, staging, biopsy guidance, treatment evaluation, and prognosis of scalp and hair diseases. Trichoscopy also shows significant advantages in differentiating common scalp conditions, such as the vascular patterns in scalp psoriasis and seborrheic dermatitis, providing strong support for differential diagnosis [9]. Hair microscopy can be used to detect hair structure, and hair examination can accurately differentiate conditions such as trichorrhexis nodosa and pili annulati [10]. Regular dermoscopic monitoring of fixed target points allows for a standardized assessment of treatment efficacy and provides objective data for adjusting treatment plans. For example, Penha et al. regularly monitored terminal hair density on the frontal and vertex regions of the scalp in male patients with androgenetic alopecia, comparing the dynamic changes before and after treatment in the same area of hair loss to assess treatment effectiveness and they found that the percentile increase of terminal hair density in the vertex area, oral minoxidil therapy demonstrated superiority over topical minoxidil [11]. Overall, the clinical application of trichoscopy significantly enhances diagnostic and treatment capabilities for scalp and hair diseases.

2.2 | Digital Image Analysis for Hair

With the advancements in computer technology, digital imaging, and artificial intelligence, modern hair microscopy integrates digital imaging photography, computer technology, and computer-aided diagnostic systems to quantitatively assess and identify the area and characteristics of local target lesions, offering objective and quantifiable evaluation scores. In the frontier of hair digital image analysis, leading domestic and international companies have integrated hair analysis software into dermoscopic systems, capable of automated analysis of hair parameters. For example, with the *FotoFinder* dermoscopy TrichoScale software for hair growth analysis capable of analyzing three primary indices under standard hair shaving conditions: hair diameter, number, and density. Additionally, it can analyze terminal/vellus hair indices, follicular units, and empty follicles/yellow dots from various perspectives to assess hair growth conditions (Figure 1). It can be viewed as a modification of the classical trichogram. It combines standard epiluminescence microscopy with automatic digital image analysis for the measurement of human hair. The software quantifies the number of hairs and the anagen–telogen ratio within one operation. The use of TrichoScale initially involves shaving a scalp area (approx. 1.8 cm^2). After 3 days, hairs in the shaven area are dyed and a

FIGURE 1 | Evaluation of hair growth by *FotoFinder* dermoscopy Trichoscale.

digital photograph is taken at 20-fold magnification and saved. The TrichoScale software works on the basis that telogen hairs do not grow and uses this as a basis for calculation of the anagen–telogen ratio [12]. In the international market, there are other devices such as Canfield that have a similar function of automatically recognizing and measuring the relevant parameters of the hair. Domestically, companies with mature digital evaluation in the hair field, can use artificial intelligence automatic calculation functions to evaluate the aforementioned indicators and perform customized target area measurements based on demand. These technologies can manually mark yellow dots, white dots, or black dots to achieve quantification of hair image data.

Objective records with standardized trichoscopy have become an important component of efficacy trials of hair loss. However, Van Neste et al. found that such detailed measurement was developed separately from the global assessment of scalp hair in the clinic, and they proposed the first calibrated scoring methods used in clinical dermatology—the new Scalp Coverage Score (SCS) method and the Hair Mass Index (HMI) abacus, which, in combination with measurements of hair productivity, can take advantage of known calibrated test images and standardized labels, paving the way for future of artificial intelligence and deep learning research [13, 14]. Although hair digital evaluation is not yet standardized in China, it provides important references for the diagnosis and treatment of hair diseases and hair transplantation, aiding clinical diagnosis, treatment evaluation, and hair research. In the future, with continuous progress in image intelligent analysis technology and research, the diagnosis and management of scalp and hair diseases will become more efficient and precise.

3 | Scalp Microbiota Testing

The scalp and its appendages form a unique ecosystem, where interactions between fungi and bacteria are essential for maintaining microbial balance and scalp health [15]. The most abundant fungi on the healthy adult scalp are the Malassezia species, including Malassezia restricta and Malassezia globosa, while the most abundant bacteria belong to the Propionibacterium and Staphylococcus genera [16]. Positive Malassezia is a cause of dandruff and seborrheic dermatitis [17], and accurate fungal detection methods are relied upon clinically, including fluorescence staining, KOH wet mount, and fungal culture [18]. Fluorescence staining is widely used in the diagnosis of scalp fungal infections due to its rapidity, sensitivity, and specificity [19]. It allows for the observation of the presence of fungal spores or hyphae on the scalp and the measurement of fungal quantification, providing laboratory reference for rapid diagnosis and clinical medication indications. Fungal culture is the gold standard for diagnosing fungal infections, identifying the causative organisms through culture. Fungal testing combined with antimicrobial susceptibility testing can determine the pathogen's sensitivity to drugs, offering strong guidance for clinical treatment.

Traditional bacterial assays usually use a few empirical solid and liquid media in combination with Gram staining tests to directly observe the physiological behaviors and phenotypic characteristics of different bacteria in specific media and in combination with bacterial cultures as the gold standard for the identification of bacterial genera [20, 21]. Recent developments in microbiome technology have led to deeper research into scalp microbial communities. Studies have found that the relative abundance of Staphylococcus and Malassezia restricta increases in areas with dandruff, and bacteria are more closely related to dandruff than fungi [22]. Scalp microbiological testing is also significant in the diagnosis and prognosis of other scalp disorders, which are often accompanied by microbiological imbalance. Lin et al. found that the presence of Malassezia and Aspergillus was both found to be potential fungal biomarkers for SD, while Staphylococcus and Pseudomonas were found to be potential bacterial biomarkers [23]. Won et al. found that the higher proportion of *Corynebacterium* species and the lower proportion of *Staphylococcus caprae* among the *Staphylococcus* species were noticed in severe alopecia areata patients compared to healthy control or mild alopecia areata [24]. Choi et al. identified that increased diversity of the scalp microbiome and the relative abundance of Pseudomonas are associated with the severity of scalp psoriasis [25]. In bacterial-associated diseases, Ho et al. found that Propionibacterium acnes were associated with the expression of immune-responsive genes in hair follicles and it may be involved in the pathogenesis of AGA and follicular atrophy [26]. As well as balding folliculitis, a primary scarring alopecia with an unclear pathogenesis, cotton swab sampling and culture usually cultures Staphylococcus aureus, and antimicrobial treatments have a temporary favorable effect in most cases, so that there is a widespread belief in a link between the bacterium and the development of the disease [27].

In the 21st century, high-throughput sequencing technologies have rapidly enabled the discovery of more than 80% of previously unculturable bacterial species through sequencing, thus rapidly replacing traditional culture methods. High-throughput sequencing can be used to reveal features such as composition, distribution, and metabolic function of skin flora and explore the correlation between flora and disease, but there is a limitation of insufficient sequencing depth [28]. High-throughput sequencing can be used to reveal features such as composition, distribution, and metabolic function of skin flora and explore the correlation between flora and disease, but there is a limitation of insufficient sequencing depth. In contrast, the detailed classification and specific function of the unknown flora discovered by bacterial colony culture genomics can tap the diversity of skin flora in physiological state, and at the same time promote the study of skin commensal bacterial species and strain level in disease state, which shows a good prospect in the field of dermatological research [29].

4 | Skin Physiological Function Testing of Scalp

The ecology of the scalp is closely related to hair health. A healthy scalp has moderate sebum secretion, no dandruff, lesions, itching, or odor, and the hair is evenly colored and glossy [7]. Similar to facial skin, the scalp can exhibit erythema and scaling due to impaired barrier function, accompanied by symptoms such as stinging, itching, greasiness, and folliculitis. As age increases, internal moisture and nutrients on the scalp gradually diminish, and the skin barrier function declines, leading to symptoms like dryness and flaking associated with scalp aging. Therefore, testing scalp skin physiological functions helps to comprehensively assess scalp health and guide the diagnosis and treatment of scalp diseases. Currently, testing methods specifically for scalp skin physiological functions are scarce. Scalp physiological indicators are not yet mature because of the challenges of obtaining data from the scalp. Due to the complex anatomical structure of the scalp, its high hair density, hair follicles deep into the dermis, and dense distribution, which makes it difficult for many testing instruments to directly contact the surface of the scalp for accurate measurement. Factors such as the high sebaceous gland secretion of the scalp [30], the thickness and elasticity of the scalp skin, and the relative position of the scalp and the skull also increase the complexity of data acquisition, making the scalp even more difficult to fix the detection probe and ensure the consistency of the depth and range of detection.

Based on research on facial skin aging and the characteristics of scalp skin, skin physiological function tests used in dermatological treatment can be applied to the detection and diagnosis of scalp skin.

4.1 | Skin Physiological Indicator Detection Technology

Indicators for skin physiological function testing mainly include transepidermal water loss (TEWL), stratum corneum hydration (SCH)), skin hydration levels, skin sebum, epidermal pH, and skin elasticity.

TEWL is the amount of condensed water that diffuses through a fixed area of stratum corneum to the surface of the skin per unit of time, and is the primary indicator for assessing the degree of skin barrier damage. It is measured using a probe that is placed in contact with the skin surface and contains sensors that detect changes in water vapor density [31]. TEWL values increase when the skin barrier is damaged by physical, chemical, or pathological factors [32]. SCH is an important parameter for evaluating the severity and outcome of diseases related to water loss, with its detection principle based on dielectric constants to calculate the water content of the skin's epidermis. Three electrical parameters are mainly used to reflect SCH indirectly, including capacitance, conductance, and resistance. When the stratum corneum's water content is below 10%, it can lead to weakened skin barrier function [33]. Measurement of skin hydration is one of the indicators of skin condition, and it is one of the main factors affecting the degree and rate of skin absorption. In recent years, various electronic devices have been developed to measure it more objectively. These include the Corneometer (Courage+Khazaka, Cologne, Germany), which measures skin capacitance, and the DermaLab Combo hydration probe (HP; Cortex Technology, Hadsund, Denmark), which uses the skin conductance for the evaluation [34]. Skin sebum prevents water loss and resists aging. The most commonly used detection method is the lipid tape method, in which a tape coated with an adhesive material is applied to the skin, and when oil is encountered, the light transmittance of the tape is increased, and then the sebum secretion can be quantitatively determined by an image analysis program. The epidermal pH is important for maintaining skin barrier function, and single-glass rod measurement circuits are by far the most common method of measuring skin surface pH. Skin elasticity reflects the degree of skin aging. The principle of measuring skin elasticity is based on suction and stretching, creating a vacuum on the skin surface to draw the skin into a specific testing probe. A non-contact optical testing system measures the depth of the skin drawn into the probe, with software analysis determining the skin's elastic properties.

4.2 | Association of Abnormal Physiological Indicators With Disease

When TEWL increases, the stratum corneum's water content decreases, skin hydration is weakened, sebum content is too high

TABLE 1 | Skin diseases associated with impaired skin barrier.

Indicator	Variations	Related skin diseases
TEWL	High	Atopic dermatitis, ichthyosis, psoriasis, eczema, contact dermatitis, and so forth.
SCH	Low	
Skin hydration	Low	Itchy, peeling, cracked skin, premature aging, barrier dysfunction, and atopic dermatitis.
Skin sebum	High	Acne, rosacea, seborrheic dermatitis, and so forth.
	Low	Psoriasis, atopic dermatitis, ichthyosis, and so forth.
epidermal pH	High	Dry, itchy, senile, and inflammatory skin diseases.

or too low, epidermal pH is too acidic or alkaline, and the scalp skin becomes lax or thin, it indicates impaired scalp skin barrier function and aging. When the skin barrier is defective, it can lead to a series of symptoms such as dryness, flaking, itching, and so forth, and in serious cases, it can cause a variety of skin diseases (Table 1). In clinical treatment, scalp skin physiological indicators can be tested to assess scalp health and monitor the changes in indicators before and after treatment to observe medication effects, guiding treatment plan adjustments and providing a scientific basis for the diagnosis and treatment of scalp diseases. Therefore, scalp physiological function testing has important application value in the diagnosis, treatment, and care of scalp diseases, with broad prospects for application.

5 | Physiological Indicator Testing of Hair

Hair, composed mainly of keratin, has unique mechanical properties and structural characteristics. Healthy hair appears smooth and shiny, without scalp flakes or dandruff, has appropriate thickness, moderate softness and hardness, good elasticity and resilience, is dark and dense, and does not exhibit abnormal hair loss [35]. Hair growth and physicochemical properties vary with race, gender, age, and can also be influenced by mental state, nutritional factors, scalp function, systemic diseases, and other intrinsic factors. Additionally, hair dyeing, bleaching, perming, UV exposure, and excessive washing can change the hair's physicochemical properties. When hair ages, it can show signs such as split ends, lack of gloss, dryness, thinning, and breakage [36]. The appearance of hair can reflect its internal physical and chemical properties, so physiological and pathological testing of hair can explain the external changes in hair under different disease states, providing a reference for hair care and personalized treatment plans.

Common physiological testing content of hair includes morphological features (such as color, thickness, curl, and quality), physical properties (such as elasticity, extensibility, and strength), and chemical composition (such as proteins, lipids, moisture, minerals, and trace elements). Research has shown that hair performance is closely related to its moisture retention, gloss, elasticity, and strength [37, 38]. Hair diseases are diverse and include but are not limited to hair loss, graying, and hair shaft abnormalities, often accompanied by changes in hair structure and function, and their pathological manifestations are varied and complex [39, 40]. Hair physiological indicator testing can comprehensively evaluate hair performance and explain the molecular mechanisms behind hair damage, aging, and graying.

5.1 | Microscopic Observation of Hair Shaft

The microscope is a valuable non-destructive analytical technique for observing the microstructure of hair (Figure 2). Through optical microscopy, one can observe whether the hair's pigment distribution is even and whether the appearance is smooth, including the presence of nodes. However, optical microscopy has limited resolution for many subtle structures, and electron microscopy can provide higher-resolution images of hair microstructure. Scanning electron microscopy can obtain high-resolution images of the hair's outer surface (with a resolution of about 10 nm) [41], observing the morphology and spacing of the hair cuticle and cortex, including the number and size of cuticle loss, cuticle edge integrity, and cortex erosion. Although scanning electron microscopy can also observe the hair cross-section to determine protein loss and melanin deficiency [42], it still cannot fully observe the internal microstructure of the hair. Transmission electron microscopy can compensate for this by providing ultra-high-resolution structures (about 0.2 nm resolution) of hair cross-section images after secondary sampling and staining [41], such as the electron-dense A-layer, outer and inner keratin layers observed under transmission electron microscopy [43].

5.2 | Mechanical Property Testing of Hair Shaft

Hair's mechanical properties include strength, extensibility, and elasticity, which are important standards for assessing hair health. Due to the complexity of hair material, its mechanical properties require multiple indicators and different testing methods for systematic characterization [37]. The common indicators for assessing hair's mechanical properties are tensile properties, often tested using a single-fiber tensile tester to obtain a hair stretching curve, with parameters such as breaking strength, Young's modulus, and elongation rate used for evaluation. The higher the tensile strength value, the less likely the hair is to break. Hair's extensibility is proportional to its tensile resistance, while hair elasticity refers to the ability to return to its original state after being stretched without breaking. Poor elasticity makes hair prone to dryness and frizz. Hair's mechanical properties depend on the structure of hair and the molecular arrangement of hair keratin. In the chemical bonds and non-covalent bonds of hair fibers, hydrogen bonds, and disulfide bonds play a crucial role in maintaining tensile properties, and the content and changes in keratin's secondary structure are closely related to changes in mechanical properties. For example, perming changes the hair's internal keratin secondary structure, transforming the α-helix into random coils, reducing tensile properties [44].

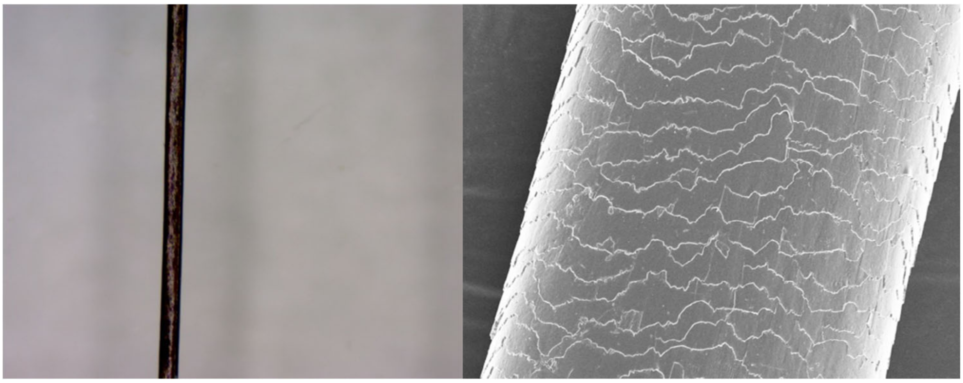

FIGURE 2 | Microscopic images of healthy black hair in light microscopy (left) and scanning electron microscopy (right).

Therefore, hair's mechanical properties can also reflect changes in its chemical structure.

5.3 | Spectroscopic Characterization Techniques

Spectroscopic characterization techniques are important for analyzing the types and valence states of elements in hair, molecular structures and configurations, and chemical bond interactions within materials. They provide molecular-level explanations and scientific basis for the development of modern hair care products [45]. Currently, common spectroscopic characterization techniques for hair include infrared spectroscopy, Raman spectroscopy, x-ray photoelectron spectroscopy, and x-ray fluorescence spectroscopy. Infrared spectroscopy is the most common characterization method, where various chemical bonds in hair can absorb infrared light and produce absorption peaks. Based on characteristic peaks in the spectrum, different groups such as peptide bonds, amino groups, methyl groups, methylene groups, and other functional groups in hair can be identified and used for quantitative analysis of lipids and keratin. Since hair's infrared characterization is unaffected by melanin and requires no special sample preparation, infrared spectroscopy is the most convenient method among hair spectroscopic characterization techniques. Some functional groups, such as disulfide bonds, which are not prominent in infrared signals, can produce absorption peaks in Raman spectroscopy, compensating for infrared spectroscopy limitations and being commonly used in hair spectroscopic characterization. x-ray photoelectron spectroscopy can accurately quantify surface elements in hair, mainly simple elements such as C, O, N, S; x-ray fluorescence spectroscopy has a deeper detection depth than the former, commonly used to analyze heavy elements above Na [45].

The combined application of these spectroscopic techniques is an important means to study the internal structure and molecular changes of hair. However, currently, hair physiological indicator testing is mostly used in hair care and hair product development, and it is relatively rare in clinical treatment. In the future, hair physiological indicator testing will become more diversified and precise. On the one hand, it is necessary to delve into the molecular structure and function of hair, revealing the pathogenesis of hair diseases; on the other hand, it is essential to develop more efficient and convenient testing technologies for differential research on hair disease states and physiological states, revealing the essence of therapeutic effects. Additionally, interdisciplinary collaboration should be strengthened to apply research findings in hair physiology and pathology to clinical practice, contributing more to the hair health industry.

6 | Patch Testing

Patch testing, also known as skin patch testing, is a diagnostic method to determine the presence of an allergic reaction by applying suspected allergenic substances to the skin and observing the skin's reaction after a certain period. This method is widely used to diagnose various allergic skin diseases and is the gold standard for diagnosing allergic contact dermatitis, effectively identifying contact allergens [46]. Allergic contact dermatitis is very common worldwide and has garnered global attention. Data indicates that at least 1%-3% of women are allergic to cosmetics, and allergic contact dermatitis is very common, affecting one in five people [47]. Since allergic contact dermatitis has a latency period and specificity, and most patients are unaware of their allergens, allergens can be easily overlooked in product use and prone to recurrence. Identifying the cause through patch testing is an effective way to prevent allergic contact dermatitis. For instance, the American Contact Dermatitis Society proposed the clinical practice model of thin-layer rapid-use epicutaneous testing in 2010, which can test an average of 62 allergens for subjects and is popular among dermatologists and allergists [48]. It has formed a commercial model and is being promoted nationwide [49].

The scalp is a common site for contact allergies, with contact allergens including hair care products, medications, and scalp contact medical devices. The most common allergens in hair care products include fragrances, preservatives, hair dyes, and surfactants, and so on. Isothiazolinone preservatives, widely used in cosmetics and household detergents, can cause contact dermatitis despite their low toxicity and have become one of the main allergens in European countries [50]. P-phenylenediamine in hair dyes is a common allergen, accounting for 35.8% of allergic reactions caused by hair care products [51]. In medications, commonly used topical drugs such as minoxidil solution can cause local scalp itching, increased dandruff, or dermatitis. Rungsima et al. found that Minoxidil itself was identified as the primary allergen in 74.7% of the 99 patients with patch-test-confirmed ACD to minoxidil-based topical treatments, with propylene glycol being the next most common allergen at 17.1%.

Other allergens identified included estradiol, butylene glycol, methylchloroisothiazolinone/methylisothiazolinone, canrenone, and latanoprost [52]. Besides drugs, many metals have immunogenic activity and can cause certain allergic reactions, with the most common metal allergy symptoms being nickel/nickel alloy-induced allergic contact dermatitis [53]. Nickel metal is widely present in medical devices that directly contact the scalp, such as smear-type medication applicators and microneedles. It is worth noting that microneedles are made of diverse materials, including glass, metal, silicon, and polymers, and patients may have allergic reactions to specific materials used in microneedles, including but not limited to metal components [54]. It is evident that allergenic components in hair care products, medical devices, and hair treatments such as shampooing, dyeing, and perming is widespread. Therefore, caution should be exercised when using such medical devices, assessing the patient's allergy history and potential risks, and patch testing is also applicable for the precise selection of external products for hair diseases.

Given the close relevance of hair care product use to everyone, with a wide variety of products, diverse sources, and complex ingredients, it is necessary to guard against the occurrence of scalp contact dermatitis. With patch testing for hair care products, protective measures can be taken based on the results to select products free of allergens, thereby minimizing adverse reactions. For products with a high sensitization rate that are essential for use, the results from patch testing with combination therapies can provide solutions to prevent or reduce irritation or sensitization. Moreover, patch testing accounts for potentially sensitizing chemicals in shampoos, hair dyes, perming solutions, and hair conditioners, assessing their potential for scalp irritation and allergy, thus aiding patients in identifying allergens and avoiding products with irritating or sensitizing components. In summary, patch testing for hair care products, as an effective method for detecting scalp allergens, plays a significant role in the diagnosis and treatment of hair disorders. Conducting patch tests for hair care products can help select safe drugs and hair care products to prevent or reduce irritation or allergies, offering patients more precise, and personalized solutions, improving treatment outcomes and patient satisfaction, and supporting the health management of patients with hair conditions.

7 | Conclusions

This article comprehensively reviewed the application of novel non-invasive detection techniques in scalp and hair disorders, highlighting their pivotal role in disease diagnosis, treatment, and care. Trichoscopy, with its non-invasive and efficient attributes, offers intuitive and precise evidence for the diagnosis of hair disorders, demonstrating remarkable advantages particularly in differentiating alopecia types, evaluating therapeutic responses, and managing health outcomes. Direct microscopic examination of the scalp for fungi enables visual assessment of fungal infections affecting scalp hair, while direct immunofluorescence clearly identifies fungal spores or hyphae. Furthermore, microbial culture combined with drug sensitivity testing facilitates the identification of pathogenic microorganisms and corresponding sensitive antibiotics.

The importance of testing scalp skin's physiological functions cannot be overlooked in comprehensively evaluating scalp health status and barrier function. The detection of hair growth physiological indicators provides a multidimensional assessment of scalp and hair health. Patch testing for hair care products effectively screens for sensitizing agents, aiding in the safe selection of hair care products and topical medications, thereby mitigating medical risks and contributing to the safety evaluation and quality control of these products.

In conclusion, the continuous innovation and refinement of novel non-invasive detection techniques have introduced novel perspectives and strategies for the diagnosis, treatment, and health management of scalp and hair disorders. Although scalp skin physiological function testing and hair growth physiological indicator assessment are yet to achieve widespread clinical adoption, their significance in comprehensively and multi-dimensionally assessing scalp and hair health cannot be underestimated. Future research should delve deeper into exploring the applications of these novel non-invasive techniques in scalp and hair disorders, enhancing the standardization, digitization, and intelligentization of scalp and hair health assessments. Ultimately, this will propel the development of scalp health management practices.

8 | Limitations

References to works done in Asia only is a limitation, which might narrow the research perspective and affect its generalizability given the unique regional context. Additionally, due to space limitations, not all retrieved research results could be incorporated, potentially compromising the comprehensiveness of the literature review and related discussions. Despite these drawbacks, the study still provides valuable insights within its set scope. However, future research that encompasses a more diverse range of references and includes all relevant results is essential to strengthen the overall quality and applicability of the work. The article only outlined various non-invasive testing techniques without comparing them to traditional testing methods, and the failure to address potential challenges in clinical practice, such as cost and accessibility, are also limitations of this article.

Ethics Statement

The ethical statement is not applicable since this study is a summary based on published literature. The images we have quoted are only used to exemplify the functions of trichoscopy and hair shaft detection and do not involve personal patient information.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further information could be acquired by contacting with the corresponding author.

References

1. A. Alessandrini, F. Bruni, B. M. Piraccini, and M. Starace, "Common Causes of Hair Loss—Clinical Manifestations, Trichoscopy and Therapy," *Journal of the European Academy of Dermatology and Venereology* 35, no. 3 (2021): 629–640, https://doi.org/10.1111/jdv.17079.

2. R. Araújo, M. Fernandes, A. Cavaco-Paulo, and A. Gomes, "Biology of Human Hair: Know Your Hair to Control It," in *Biofunctionalization of Polymers and Their Applications*, ed. G. S. Nyanhongo, W. Steiner, and G. Gübitz (Springer, 2011), 121–143.

3. R. Paus and G. Cotsarelis, "The Biology of Hair Follicles," *New England Journal of Medicine* 341, no. 7 (1999): 491–497, https://doi.org/10.1056/nejm199908123410706.

4. E. A. Olsen, "Female Pattern Hair Loss," *Journal of the American Academy of Dermatology* 45, no. 3 Suppl (2001): S70–S80, https://doi.org/10.1067/mjd.2001.117426.

5. K. N. Richards and R. M. Rashid, "Problems in Pattern Alopecia," *Journal of Cosmetic Dermatology* 11, no. 2 (2012): 131–133, https://doi.org/10.1111/j.1473-2165.2012.00607.x.

6. P. Pasquali, "Special Considerations: Hair Photography," in *Photography in Clinical Medicine*, ed. P. Pasquali (Springer International Publishing, 2020), 241–244.

7. Group on Medical Aesthetics and Cosmetology CAoAM. Management of Scalp Health: A Chinese Expert Consensus Statement (2022). *Chinese Journal of Dermatology* 2022;55(10):843–849, https://doi.org/10.35541/cjd.20220253.

8. M. Saitoh, M. Uzuka, and M. Sakamoto, "Human Hair Cycle," *Journal of Investigative Dermatology* 54, no. 1 (1970): 65–81, https://doi.org/10.1111/1523-1747.ep12551679.

9. J. Golińska, M. Sar-Pomian, and L. Rudnicka, "Diagnostic Accuracy of Trichoscopy in Inflammatory Scalp Diseases: A Systematic Review," *Dermatology* 238, no. 3 (2022): 412–421, https://doi.org/10.1159/000517516.

10. L. Rudnicka, M. Olszewska, A. Waśkiel, and A. Rakowska, "Trichoscopy in Hair Shaft Disorders," *Dermatologic Clinics* 36, no. 4 (2018): 421–430, https://doi.org/10.1016/j.det.2018.05.009.

11. M. A. Penha, H. A. Miot, M. Kasprzak, and P. Müller Ramos, "Oral Minoxidil vs Topical Minoxidil for Male Androgenetic Alopecia: A Randomized Clinical Trial," *JAMA Dermatology* 160, no. 6 (2024): 600, https://doi.org/10.1001/jamadermatol.2024.0284.

12. R. Dhurat and P. Saraogi, "Hair Evaluation Methods: Merits and Demerits," *International Journal of Trichology* 1, no. 2 (2009): 108, https://doi.org/10.4103/0974-7753.58553.

13. D. J. Van Neste, D. H. Rushton, G. E. Westgate, L. Duteil, K. Roegies, and V. V. Ronsse, "A Segmental Approach to Scoring Hair Density From Global Images: Introducing the Scalp Coverage Scoring Method for Clinical Trials and Practice," *Nature Cell and Science* 2, no. 2 (2024): 59–67, https://doi.org/10.61474/ncs.2023.00014.

14. D. Van Neste, T. Leroy, and E. Sandraps, "Validation and Clinical Relevance of a Novel Scalp Coverage Scoring Method," *Skin Research and Technology* 9, no. 1 (2003): 64–72, https://doi.org/10.1034/j.1600-0846.2003.00368.x.

15. H. Li, B. N. Goh, W. K. Teh, et al., "Skin Commensal Malassezia Globosa Secreted Protease Attenuates Staph Crocus Aureus Biofilm Formation," *Journal of Investigative Dermatology* 138, no. 5 (2018): 1137–1145, https://doi.org/10.1016/j.jid.2017.11.034.

16. C. Clavaud, R. Jourdain, A. Bar-Hen, et al., "Correction: Dandruff Is Associated With Disequilibrium in the Proportion of the Major Bacterial and Fungal Populations Colonizing the Scalp," *PLOS ONE* 8, no. 10 (2013): e58203, https://doi.org/10.1371/annotation/bcff4a59-10b7-442a-8181-12fa69209e57.

17. J. Luis and T. C. W. Borda, "Seborrheic Dermatitis and Dandruff: A Comprehensive Review," *Journal of Clinical and Investigative Dermatology* 3, no. 2 (2015): 1–10, https://doi.org/10.13188/2373-1044.1000019.

18. S. M. Dass, E. V. Vinayaraj, K. Pavavni, A. Pallam, and M. S. Rao, "Comparison of KOH, Calcofluor White and Fungal Culture for Diagnosing Fungal Onychomycosis in an Urban Teaching Hospital, Hyderabad," *Indian Journal of Microbiology Research* 2, no. 3 (2015): 148, https://doi.org/10.5958/2394-5478.2015.00004.7.

19. J. Shao, Y. Song, Y. Zhou, Z. Wan, R. Li, and J. Yu, "Diagnostic Value of Fluorescein-Labeled Chitinase Staining in Formalin-Fixed and Paraffin-Embedded Tissues of Fungal Disease," *Medical Mycology* 58, no. 1 (2020): 66–70. (1460-2709 (Electronic)).

20. S. Bascomb and M. Manafi, "Use of Enzyme Tests in Characterization and Identification of Aerobic and Facultatively Anaerobic Gram-Positive Cocci," *Clinical Microbiology Reviews* 11, no. 2 (1998): 318–340, https://doi.org/10.1128/cmr.11.2.318.

21. G. M. Carlone, M. J. Valadez, and M. J. Pickett, "Methods for Distinguishing Gram-Positive From Gram-Negative Bacteria," *Journal of Clinical Microbiology* 16, no. 6 (1982): 1157–1159, https://doi.org/10.1128/jcm.16.6.1157-1159.1982.

22. Z. Xu, Z. Wang, C. Yuan, et al., "Dandruff Is Associated With the Conjoined Interactions Between Host an D Microorganisms," *Scientific Reports* 6, no. 1 (2016): 24877, https://doi.org/10.1038/srep24877.

23. Q. Lin, A. Panchamukhi, P. Li, et al., "Malassezia and Staphylococcus Dominate Scalp Microbiome for Seborrheic Dermatitis," *Bioprocess and Biosystems Engineering* 44, no. 5 (2021): 965–975, https://doi.org/10.1007/s00449-020-02333-5.

24. E. J. Won, H. H. Jang, H. Park, and S. J. Kim, "A Potential Predictive Role of the Scalp Microbiome Profiling in Patients With Alopecia Areata: Staphylococcus Caprae, Corynebacterium, and Cutibacterium Species," *Microorganisms* 10, no. 5 (2022): 864, https://doi.org/10.3390/microorganisms10050864.

25. J. Y. Choi, H. Kim, H. Y. Koo, et al., "Severe Scalp Psoriasis Microbiome Has Increased Biodiversity and Relative Abundance of Pseudomonas Compared to Mild Scalp Psoriasis," *Journal of Clinical Medicine* 11, no. 23 (2022): 7133, https://doi.org/10.3390/jcm11237133.

26. B. S. Ho, E. X. P. Ho, C. W. Chu, et al., "Microbiome in the Hair Follicle of Androgenetic Alopecia Patients," *PLOS ONE* 14, no. 5 (2019): e0216330, https://doi.org/10.1371/journal.pone.0216330.

27. O. M. Moreno-Arrones, C. Garcia-Hoz, R. Del Campo, et al., "Folliculitis Decalvans Has a Heterogeneous Microbiological Signature and Impaired Immunological Response," *Dermatology* 239, no. 3 (2023): 454–461, https://doi.org/10.1159/000529301.

28. P. B. McKinzie and M. E. Bishop, "A Streamlined and High-Throughput Error-Corrected Next-Generation Sequencing Method for Low Variant Allele Frequency Quantitation," *Toxicological Sciences* 173, no. 1 (2020): 77–85, https://doi.org/10.1093/toxsci/kfz221.

29. T. Govil, M. Paste, D. Samanta, et al., "Metagenomics and Culture Dependent Insights Into the Distribution of Firmicutes Across Two Different Sample Types Located in the Black Hills Region of South Dakota, USA," *Microorganisms* 9, no. 1 (2021): 113, https://doi.org/10.3390/microorganisms9010113.

30. F. Pouradier, C. Liu, J. Wares, et al., "The Worldwide Diversity of Scalp Seborrhoea, as Daily Experienced by s Even Human Ethnic Groups," *International Journal of Cosmetic Science* 39, no. 6 (2017): 629–636, https://doi.org/10.1111/ics.12425.

31. H. Alexander, S. Brown, S. Danby, and C. Flohr, "Research Techniques Made Simple: Transepidermal Water Loss Measurement as a Research Tool," *Journal of Investigative Dermatology* 138, no. 11 (2018): 2295–2300.e1, https://doi.org/10.1016/j.jid.2018.09.001.

32. Y. Momota, K. Shimada, A. Noguchi, et al., "The Modified Corneocyte Surface Area Measurement as an Index of Epidermal Barrier Properties: Inverse Correlation With Transepidermal Water Loss," *Veterinary Dermatology* 27, no. 2 (2016): 67, https://doi.org/10.1111/vde.12287.

33. T. C. Chou, T. S. Shih, J. C. Tsai, J. D. Wu, H. M. Sheu, and H. Y. Chang, "Effect of Occupational Exposure to Rayon Manufacturing Chemicals on Skin Barrier to Evaporative Water Loss," *Journal of Occupational Health* 46, no. 5 (2004): 410–417, https://doi.org/10.1539/joh.46.410.

34. J. H. Park, Y. Choi, Y. J. Jung, et al., "Skin Hydration Measurement: Comparison Between Devices and Clinical Evaluations," *Annals of Dermatology* 36, no. 5 (2024): 275, https://doi.org/10.5021/ad.23.103.

35. R. D. Sinclair, "Healthy Hair: What Is It?," *Journal of Investigative Dermatology Symposium Proceedings* 12, no. 2 (2007): 2–5, https://doi.org/10.1038/sj.jidsymp.5650046.

36. C. Fernandes, B. Medronho, L. Alves, and M. G. Rasteiro, "On Hair Care Physicochemistry: From Structure and Degradation to Novel Biobased Conditioning Agents," *Polymers (Basel)* 15, no. 3 (2023): 608, https://doi.org/10.3390/polym15030608.

37. Y. Wu, M. Bian, Z. Yue, K. Chang, and J. Wang, "Scientific Foundations of Hair and Scalp Care (III) Mechanical Properties of Human Hair," *Journal China Surfactant Detergent & Cosmetics* 53, no. 03 (2023): 260–270, https://doi.org/10.3969/j.issn.1001-1803.2023.03.003.

38. Y. Wu, L. Ma, T. Chen, K. Chang, and J. Wang, "Scientific Foundations of Hair and Scalp Care(I) Effects of Moisture on the Properties of Hair and the Study on Moisturizing Efficacy," *China Surfactant Detergent & Cosmetics* 53, no. 01 (2023): 8–15, https://doi.org/10.3969/j.issn.1001-1803.2023.01.002.

39. K. Wan, L. Ma, T. Chen, K. Chang, and J. Wang, "Scientific Foundations of Hair and Scalp Care (VI) Characteristics and Regulation of Scalp Sebum," *China Surfactant Detergent & Cosmetics* 53, no. 06 (2023): 634–641, https://doi.org/10.3969/j.issn.2097-2806.2023.06.004.

40. C. Fang, L. Ma, T. Chen, K. Chang, and J. Wang, "Scientific Foundations of Hair and Scalp Care(VII)the Causes of Hair Graying and the Methods to Make White Hair Turn Black," *China Surfactant Detergent & Cosmetics* 53, no. 07 (2023): 748–756, https://doi.org/10.3969/j.issn.2097-2806.2023.07.003.

41. S. L. Koch, S. R. Tridico, B. A. Bernard, M. D. Shriver, and N. G. Jablonski, "The Biology of Human Hair: A Multidisciplinary Review," *American Journal of Human Biology* 32, no. 2 (2020): e23316, https://doi.org/10.1002/ajhb.23316.

42. D. Van Neste and D. J. Tobin, "Hair Cycle and Hair Pigmentation: Dynamic Interactions and Changes Associated With Aging," *Micron (Oxford, England: 1993)* 35, no. 3 (2004): 193–200, https://doi.org/10.1016/j.micron.2003.11.006.

43. N. P. Khumalo, R. P. Dawber, and D. J. Ferguson, "Apparent Fragility of African Hair Is Unrelated to the Cystine-Rich Protein Distribution: A Cytochemical Electron Microscopic Study," *Experimental Dermatology* 14, no. 4 (2005): 311–314, https://doi.org/10.1111/j.0906-6705.2005.00288.x.

44. A. Kuzuhara, "Analysis of Structural Changes in Permanent Waved Human Hair Using Raman Spectroscopy," *Biopolymers* 85, no. 3 (2007): 274–283, https://doi.org/10.1002/bip.20646.

45. K. Chang, L. Ma, T. Chen, and J. Wang, "Scientific Foundations of Hair and Scalp Care(II)Spectroscopic Techniques for Hair Characterization," *China Surfactant Detergent & Cosmetics* 53, no. 02 (2023): 140–148, https://doi.org/10.3969/j.issn.1001-1803.2023.02.003.

46. V. Mahler, A. Nast, A. Bauer, et al., "S3 Guidelines: Epicutaneous Patch Testing With Contact Allergens and D Rugs—Short Version, Part 1," *Journal der Deutschen Dermatologischen Gesellschaft* 17, no. 10 (2019): 1076–1093, https://doi.org/10.1111/ddg.13956.

47. B. L. Adler and V. A. DeLeo, "Allergic Contact Dermatitis," *JAMA Dermatology* 157, no. 3 (2021): 364, https://doi.org/10.1001/jamadermatol.2020.5639.

48. R. A. Schleichert, S. G. Hostetler, and M. J. Zirwas, "Patch Testing Practices of American Contact Dermatitis Society Members," *Dermatitis* 21, no. 2 (2010): 98–101.

49. L. G. Rodriguez-Homs, J. Taylor, B. Liu, et al., "Patch Test Practice Patterns of Members of the American Contact Dermatitis Society," *Dermatitis* 31, no. 4 (2020): 272–275, https://doi.org/10.1097/der.0000000000000513.

50. O. Aerts, A. Goossens, J. Lambert, and J. P. Lepoittevin, "Contact Allergy Caused by Isothiazolinone Derivatives: An Overview of Non-Cosmetic and Unusual Cosmetic Sources," *European Journal of Dermatology* 27, no. 2 (2017): 115–122, https://doi.org/10.1684/ejd.2016.2951.

51. E. M. Warshaw, M. C. Goodier, J. G. DeKoven, et al., "Contact Dermatitis Associated With Skin Cleansers: Retrospective Analysis of North American Contact Dermatitis Group Data 2000–2014," *Dermatitis* 29, no. 1 (2018): 32–42, https://doi.org/10.1097/der.0000000000000330.

52. R. Kiratiwongwan, W. Boonchai, and S. Kanokrungsee, "Allergic Contact Dermatitis to Topical Preparations Containing Minoxidil: A Systematic Review and Individual Participant Data Meta-Analysis," *Dermatitis* Published online June 17, (2024), https://doi.org/10.1089/derm.2024.0092.

53. M. G. Ahlström, J. P. Thyssen, M. Wennervaldt, T. Menné, and J. D. Johansen, "Nickel Allergy and Allergic Contact Dermatitis: A Clinical Review of Immunology, Epidemiology, Exposure, and Treatment," *Contact Dermatitis* 81, no. 4 (2019): 227–241, https://doi.org/10.1111/cod.13327.

54. M. M. Almutlq and A. E. Bukhari, "Growth Factors and Microneedling in Alopecia Areata: A Narrative Review," *Skin Appendage Disorders* 10, no. 2 (2024): 92–98, https://doi.org/10.1159/000534636.