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Advancements in non-laser energy-based devices in trichology: A comprehensive review

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ABSTRACT

Trichology has witnessed significant advancements in non-invasive techniques for managing various hair-related conditions, including androgenetic alopecia, female patterned hair loss, alopecia areata, chronic telogen effluvium, hirsutism, and hypertrichosis. Through a systematic literature search across databases such as PubMed and Google Scholar, we evaluated methods such as iontophoresis, electrotrichogenesis, intense pulsed light, scalp cooling therapy, photodynamic therapy, radio-frequency technology, oxygen therapy, and ultrasound. These methods hold promise in enhancing drug delivery, stimulating hair growth, preventing chemotherapy-induced alopecia, and reducing unwanted hair. By scrutinizing their mechanisms, applications, and recent research findings, this paper emphasizes the importance of customization based on individual needs. It highlights the promising outcomes of these approaches in terms of effectiveness, safety, cosmetic outcomes, and prospects in both trichology and esthetics. This article provides a comprehensive overview of the applications of these techniques, laying the groundwork for further research and the refinement of protocols in the field of non-laser interventions in trichology.

Keywords: Non-laser, Iontophoresis, Electrotrichogenesis, Intense pulsed light, Photodynamic therapy, Radiofrequency technology, Oxygen therapy, Ultrasound, Trichology

INTRODUCTION

The field of trichology has witnessed significant advancements in non-invasive techniques that help in hair growth promotion, especially in conditions such as androgenetic alopecia (AGA), female pattern hair loss (FPHL), alopecia areata (AA), chronic telogen effluvium, and management of unwanted hair in conditions such as hirsutism and hypertrichosis. Low-level light therapy is an established method and remains the only food and drug administration (FDA)-approved treatment for AGA. In addition, several non-laser approaches are employed, including iontophoresis, electrotrichogenesis (ETG), intense pulsed light (IPL), scalp cooling therapy, photodynamic therapy (PDT), radio-frequency (RF) technology, oxygen therapy, and ultrasound [Figure 1]. This article emphasizes the importance of non-laser techniques used in various indications in trichology.

A systematic literature search was conducted in databases such as PubMed and Google Scholar on non-laser methods in trichology, mainly focused on drug delivery, stimulating hair growth, preventing chemotherapy-induced alopecia (CIA), and reducing unwanted hair [Table 1].

IONTOPHORESIS

Iontophoresis is a specialized drug delivery technique that utilizes low electrical current to transport a drug into and through the skin. This method enhances the absorption of drugs,

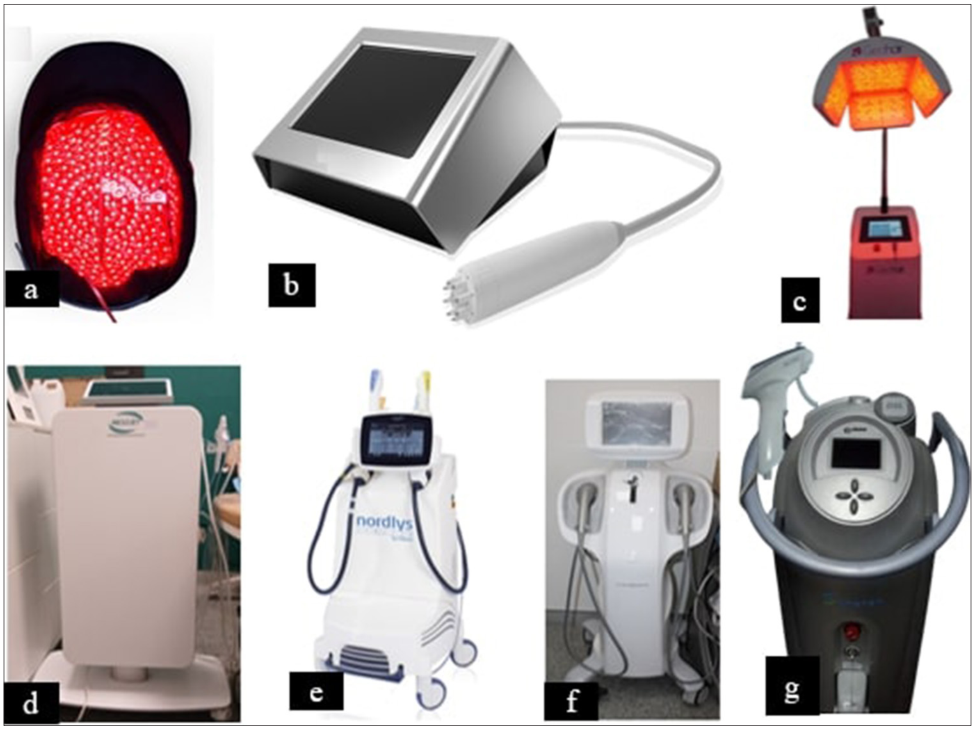

Figure 1: Non-laser devices in trichology. (a) Electrotherapy; (b) iontophoresis; (c) photodynamic therapy; (d) oxygen therapy; (e) intense pulsed light; (f) ultrasound; and (g) radiofrequency. Radiofrequency image courtesy: Dr. M Ramesh, Department of Dermatology, Kempegowda Institute of Medical Sciences Hospital, Krishna Rajendra Road, Visveswarapura Puram, Bangalore, India.

Table 1: Non-laser methods used in trichology.

Method	Indications	Application
Iontophoresis	AGA	Improves hair growth
Electrotrichogenesis	AGA	Hair regeneration and regrowth
Scalp cooling	Chemotherapy-induced alopecia	Preventing or minimizing hair loss during chemotherapy
PDT	AA, AGA Unwanted body hair	Hair regrowth Hair removal
RF	AA, AGA, MPHL, FPHL Unwanted body and facial hair	Hair regrowth Hair removal
Oxygen therapy	AGA and telogen effluvium Adjuvant treatment- Hair transplantation surgery	Hair regrowth Minimizing post-surgical follicle shedding
IPL	Hirsutism Unwanted facial hair	Unwanted hair removal and hair reduction
Ultrasound	Abnormalities in hair follicles Detection of HS AGA	Diagnosis of follicular structures Diagnosis of HS Hair growth

IPL: Intense pulsed light, AGA: Androgenetic alopecia, PDT: Photodynamic therapy, RF: Radiofrequency, AA: Alopecia areata, MPHL: Male pattern hair loss, FPHL: Female pattern hair loss, HS: Hidradenitis suppurativa

particularly uncharged molecules through the electroosmosis process. Hair follicles, which extend deep into the dermis, provide a transappendegeal pathway with lower resistance compared to the stratum corneum, enabling deeper and more effective drug absorption.

Iontophoresis has been used in transporting various therapeutic agents. Studies have demonstrated its efficacy in delivering drugs such as minoxidil sulfate (MXS), chitosan nanoparticles loaded with MXS, and growth factor cocktails to treat conditions like androgenic alopecia.[1-5] These agents are effectively targeted to specific sites within the skin, enhancing treatment outcomes while minimizing systemic side effects.

The application of a small electrical current causes ions of the drug to migrate through the skin, driven either by anodal or cathodal stimulation. This process induces muscular stress, enhancing the contractile capacity, dilation of pores and facilitating the absorption of the active ingredients.[6] These mechanisms significantly improve the absorption of active ingredients into the targeted areas, such as hair follicles and follicular infundibula.[1]

Recent advancements in iontophoresis device technology have focused on improving usability, effectiveness, and patient comfort. Wei *et al.*[7] designed a portable drug delivery device for treating AGA. This device includes a drug container, an iontophoretic stimulation part, and a rechargeable part which performed well and enhanced drug delivery. Effective drug penetration through iontophoresis has been demonstrated, with a synergistic effect of combining iontophoresis with sonophoresis, showing ×10 enhancement in transdermal drug penetration in Franz-type cells and hairless mouse skin.[8] To address discomfort and attachment difficulties caused by common metal electrodes, Wei *et al.* designed a carbon-silicon electrode.[9] This electrode reduces pain, increases conductance, and improves hair coverage by allowing hair to be voided for attachment. Ongoing research continues to refine these devices, aiming to optimize functionality and safety while expanding their applicability in clinical settings. The clinical studies on iontophoresis are summarized in Table 2.

ETG/ELECTROTHERAPY

ETG is a method that enhances the influx of calcium ions into dermal papilla cells through voltage-gated transmembrane ion channels. This mechanism facilitates ATP synthesis in mitochondria, activates protein kinases, and stimulates protein synthesis and cell division. The overall effect of ETG is thought to regulate the secretion of various hair growth factors, promote the proliferation of hair follicles, extend the anagen stage, and ultimately contribute to the regeneration

Table 2: Summary of various studies on Iontophoresis in drug delivery in trichology.

Drug deliver	Drug delivery method	Result and conclusion	Reference
Antipyrine and sodium salicylate- as model drugs	Iontophoresis+ultrasound	10 folds penetration enhancement with combination method	Watanabe *et al.*[8]
L-Ascorbic acid 2-phosphate sesqui-magnesium salt hydrate water-soluble vitamin (Ap-Mg)	Iontophoresis with carbon silicon electrode	*In vivo* experiment showed effective and comfortable treatment in AGA	Wei *et al.*[9]
L-Ascorbic acid 2-phosphate sesqui-magnesium salt hydrate water-soluble vitamin (Ap-Mg)	Portable drug delivery device using iontophoresis	*In vitro* study showed that negative ion stimulation had the best results.	Wei *et al.*[7]
MXS (99%)	Anodal iontophoresis	Enhanced follicular 5-fold the amount of drug delivery of MXS. Potential treatment for alopecia	Gelfuso *et al.*[1]
Chitosan encapsulated MXS (99%) microparticle	Microencapsulation and iontophoresis	Increased (6-fold) drug accumulation in the hair follicles	Gelfuso *et al.*[2]
MXS-loaded chitosan Nanoparticle (200 nm)	Nanoencapsulation and iontophoresis	the best method for directing MXS at the hair follicles, helps to avoid possible side effects	Matos *et al.*[3]
GFC-basic fibroblast growth factor, vascular endothelial growth factor, keratinocyte growth factor-2, stem cell factor, insulin-like growth factor-1, superoxide dismutase-1, noggin peptide, fibroblast growth factor 9, and fibroblast growth factor 5-short	Iontophoresis on scalp using headset	Absorption of GFC including FGF5s following iontophoresis Increased hair count and was effective for patients with AGA	Ro *et al.*[4]
GFC solution-basic fibroblast growth factor, insulin-like growth factor 1, vascular endothelial growth factor, stem cell factor, keratinocyte growth factor 1, superoxide dismutase 1, fibroblast growth factor 9, fibroblast growth factor 5-short, and noggin peptide	Microneedling on scalp	Increased hair density and diameter in AGA patients with no side effects.	Ro *et al.*[5]

AGA: Androgenetic alopecia, MXS: Minoxidil sulphate, GFC: Growth factor cocktail, FGF5s: Fibroblast growth factor 5-short of hair. It is a non-invasive, physically-based approach that plays a crucial role in regenerative tissue engineering through the application of alternating electric fields.[10] Various studies explore the efficacy of electrical stimulation (ES) methods. The use of pulsed electrical fields (PEFs) in promoting hair regrowth has gained significant attention in recent studies. Maddin *et al*.[11] reported a remarkable 66.1% increase in hair count over 36 weeks, attributing this effect to the electrophysiological impact on quiescent hair follicles and increased cell mitosis. Furthermore, the application of pulsed electrostatic fields, known as ETG, in breast cancer patients undergoing chemotherapy exhibited promising results in hair retention, suggesting potential improvements in treatment compliance and psychosocial well-being.[12] However, despite promising results, ETG awaits approval from the US Food and Drug Administration, necessitating further randomized double-blind trials.[13]

Khan *et al*.[14] explored the use of PEF to stimulate hair follicles, demonstrating a significant increase in anagen follicles following treatment in Sprague–Dawley rats. Another innovative approach involves the self-powered omnidirectional motion-activated and electric stimulation device (m-ESD), a universal wearable device designed to harness random body motions for hair regeneration.[10] The m-ESD showcased impressive outcomes, including longer and denser hair after 3 weeks compared to conventional treatments such as minoxidil (Mx), Vitamin D3, and normal saline. This nonpharmacological, self-powered wearable device not only accelerated hair growth but also addressed genetic keratin disorders, offering a promising solution for hair loss.

Hwang *et al*.[15] investigated the potential of micro-current ES in promoting hair regrowth by applying it to human hair follicle-derived papilla cells. The study revealed promising results, including enhanced cell proliferation, migration, and modulation of cell cycle progression. In addition, Yan *et al*.[16] explored ES with a PPy-modified electrode upregulated trichogenic gene expression in human dermal papilla cells (hDPCs), which increased gene expression and the number of hairs in cells of the transplanted mice (with ES) compared to untreated cells (without ES).

These studies provide valuable insights into non-pharmacological approaches for hair regenerative medicine; further investigations are warranted to establish the long-term efficacy and viability of these techniques, particularly in clinical applications for various types of hair loss. Table 3 presents a comprehensive overview of various studies on the effectiveness of electrical stimulation methods in promoting hair growth.

SCALP COOLING

Scalp cooling therapy has emerged as a pivotal preventive measure against CIA for cancer patients. Developed in the 1970s, this globally adopted technique utilizes vasoconstriction and hypothermia to minimize blood flow and drug uptake by hair follicles, demonstrating consistent efficacy with success rates averaging 50–70% over the past two decades.[17]

The cornerstone of this therapy is a sophisticated, self-contained, and electrically powered refrigeration unit. This unit circulates a glycol-based fluid through channels within a cap, enabling precise control and maintenance of scalp temperature throughout the treatment course. The cap is equipped with sensors strategically placed at the front and back to monitor scalp temperature, with an additional sensor preventing temperatures from dropping below freezing. Any deviations from the default temperature range are promptly identified and corrected by the feedback loop established through the sensors. This closed-loop system ensures real-time monitoring and intervention, guaranteeing that the scalp temperature is maintained within the optimal range of 3–5°C throughout the entire treatment process.[18,19] Scalp cooling therapy has gained widespread acceptance, being implemented in over 30 countries.[20] Its consistent success rates and the technological advancements incorporated into the device underscore its relevance in contemporary cancer care.[17]

CIA is a distressing side effect of cancer therapy that impacts the emotional well-being of patients. Several studies have explored the effectiveness and safety of scalp-cooling devices in preventing or minimizing hair loss during chemotherapy. A prospective observational study conducted by Kate *et al*.[21] demonstrated that scalp-cooling devices were particularly effective in reducing CIA in patients treated with taxane-based chemotherapy compared to anthracyclines. The study, involving 100 patients, reported minimal adverse events (AEs), highlighting the safety of these devices.

Bülow *et al*.[22] further delved into the relationship between subcutaneous temperature and hair preservation. Their findings suggested that maintaining subcutaneous temperatures below 22°C with scalp cooling techniques could prevent hair loss, attributing the success to the metabolic effects of the process. This metabolic impact was reinforced by a more recent study conducted by Carbognin *et al*.,[23] who reported a 68.0% success rate in preventing alopecia in breast cancer patients with varying chemotherapy regimens.

A randomized clinical trial by Nangia *et al*.[24] involving 182 women with breast cancer provided robust evidence supporting the efficacy of scalp cooling. The study demonstrated a 50% significant reduction of hair loss with scalp cooling. Similarly, a study in Italian oncology units by Gianotti *et al*.[25] involving 220 female breast cancer patients undergoing curative chemotherapy reported a 68% success rate in scalp cooling, with high rates of success in both taxane-based and combined anthracyclines and taxanes chemotherapy.

Table 3: Overview of studies on electrical stimulation for hair regeneration.

Device	Study design	Outcome	Hypothesis/Observation	Author
Pulsed electrostatic field	A study of 73 white men with male pattern baldness aged 19–49 was conducted, with participants randomly assigned to treatment or control groups.	Treatment group showed a 66.1% increase in hair count over 36 weeks.	Unclear mechanism, but believed to involve an electrophysiologic effect on quiescent hair follicles, causing increased cell mitosis through calcium influx.	Maddin *et al.*[11]
ETG	Thirteen women underwent adjuvant ETG and breast chemotherapy treatment, measuring hair loss and quality of life, twice weekly with pulsed electrostatic field for 12 min.	12 of the 13 patients had good hair retention both during and after chemotherapy, with no reported side effects due to ETG.	ETG's potential to reduce chemotherapy-induced hair loss in CMF regimes warrants further investigation through a randomized controlled trial, potentially expanding to other alopecia-inducing chemotherapy regimens.	Benjamin *et al.*[12]
Electrical Stimulation (AC Voltage Pulses)	Impact of various electrical stimuli settings on hair growth by examining changes in hDPCs *in vitro* and molecular changes in a rabbit animal model.	Low voltage (3.5 V) and frequency, induced *in vitro* proliferation of hDPCs, enhancing Wnt/b-catenin, Ki-67 antigen, phospho-extracellular regulated kinase, and phospho-Akt expressions. Animal model showed hair regrowth in stimulated areas.	Electrical stimuli induce Wnt/b-catenin and MAPK pathways in hair follicles, suggesting ideal conditions for accelerated hair development, which may differ in cells, animals, and human tissues.	Sohn *et al.*[26]
PEF	Sprague–Dawley rats treated with PEF and histological analysis to determine the percentage of anagen follicles, following a Taguchi experimental design.	At optimal doses increased anagen follicles by 5.05-fold, indicating a dose-dependent shift in hair cycle from telogen to anagen.	PEF stimulation, shifts hair cycle from resting telogen to active anagen, focusing on dose-dependent growth and optimizing treatment parameters, with voltage being the most influential.	Khan *et al.*[14]
PEFs (m-ESD)	Universal wearable, m-ESD as a nonpharmacological approach for hair regeneration, tested on Sprague–Dawley rats and nude mice.	Device enhanced hair regeneration, resulting in higher follicle density and longer shaft length in rats and improved keratin disorder alleviation in genetically defective mice.	m-ESD, an effective strategy for nonpharmacological hair regeneration, utilizing physiologically appropriate alternating electric fields generated by random body motions.	Yao *et al.*[10]
MCS	The effects of MCS on human HFDPC and a telogenic mouse model, examining cell proliferation, migration, and growth factors.	MCS significantly impacts HFDPC proliferation, migration, cell cycle progression, and Wnt/β-catenin pathway activation, promoting hair growth in telogenic mice models, indicating increased growth factors in developing hair follicles.	MCS would have promoted hair growth in HFDPC and a telogenic mouse model, potentially offering a non-pharmacological treatment for alopecia.	Hwang *et al.*[15]
ES	the impact of electrical stimulation with a PPy-modified electrode on HFDPC *in vitro*, assessing trichogenic gene expression, and transplanting the activated cells into mice for hair generation evaluation.	PPy-modified electrodes upregulated and enhanced trichogenic gene expression in hDPCs, generating double the number of hairs in mice transplanted	Suggests that a PPy-modified electrode-based electrical stimulation could restore trichogenic activity in hDPCs, improve hair generation in mice and a potential method for hair regeneration therapy.	Yan *et al.*[16]

ETG: Electrotrichogenesis, PEF: Pulsed electrical fields, m-ESD: Motion-activated electric stimulation device, MCS: Micro-current electrical stimulation, HFDPC: Hair follicle-derived papilla cells, PPy: Polypyrrole, ES: Electrical stimulation, hDPCs: Human dermal papilla cells, CMF: Cyclophosphamide, methotrexate and 5-fluorouracil, AC: Alternating current, MARK: Mitogen-activated protein kinase

The comprehensive review by Wim *et al.* (2011)[27] synthesized findings from 58 scalp cooling publications, emphasizing the reversibility of CIA in many chemotherapy regimens and its cost-effectiveness. The article called for further research on scalp cooling methods and advocated for its accessibility in all hospitals for suitable patients.

While safety concerns and the potential for scalp metastases limit the utilization of scalp cooling use in the US, recent research, as highlighted by Kruse and Abraham,[28] has demonstrated its effectiveness, especially with taxane-based chemotherapy. However, logistical challenges such as device availability and insurance coverage remain hurdles that need to be addressed for widespread adoption.

The reviewed studies collectively suggest that scalp-cooling devices are effective in preventing or reducing CIA, with encouraging success rates and minimal AEs reported [Table 4]. Further research and efforts to overcome logistical challenges are necessary to make this approach widely available, ensuring it becomes an integral component of holistic cancer care.

PDT AND MICRONEEDLING

PDT is a novel approach involving the application of a topical photosensitizer, exposure to light, and oxygen to eliminate damaged cells, leaving normal skin unaffected selectively.[29] In a study targeting static AA, PDT was administered to six patients who had previously undergone unsuccessful treatments. Despite limited overall success, one patient experienced complete regrowth after four sessions, particularly notable in AA of the beard, an area not previously explored with PDT. This suggests a potential differential response in beard hair AA, warranting further investigation.[30]

AGA, characterized by hereditary hair loss, traditionally relies on pharmaceuticals and, of late, various regenerative medicine applications for treatment. A study using red laser light, blue light-emitting diode (LED) light, and a photo cosmetic product called photoactive showed enhanced hair growth in AGA, reducing the need for professional treatments and promoting hair reconstruction.[31] Another investigation using mice skin tissues explored a low-cost PDT system for laser-assisted hair removal. The study revealed that methylene blue selectively absorbed by hair follicles, coupled with a low-power continuous-wave helium-neon laser, successfully damaged hair follicles, offering a more promising outcome compared to traditional laser-mediated methods.[32]

In the context of moderate to severe AA, a therapeutic combination of PDT with 5-aminolevulinic acid (ALA) and microneedling demonstrated efficacy in a study involving 41 patients. The synergistic approach yielded complete hair regrowth in some cases and improvement in others, providing a potential avenue for AA treatment.[33]

However, not all studies have reported positive outcomes. A pilot study utilizing a microneedle roller to enhance the trans-epidermal drug delivery system for treating AA did not result in hair growth or changes in histologic findings. This suggests that the effectiveness of PDT for AA may vary and necessitates further exploration with different parameters.[34]

Similarly, the combination of microneedle treatment system (MTS) and methyl 5-aminolevulinic acid-PDT for extensive AA did not yield positive results in a study involving six patients. Despite prior resistance to conventional therapies, none of the patients achieved hair regrowth in either the MTS or non-MTS areas. The study underscores the need for additional investigations with varied drug-delivery systems and in-depth microscopic analysis.[35]

Finally, in a randomized clinical study evaluating the efficacy and safety of ALA-PDT for AGA, the treatment was found to be safe and tolerable. However, no significant difference in hair density was observed between the ALA-PDT-treated and red-light therapy-treated halves of the scalp. This suggests the need for further research to determine the efficacy of ALA-PDT as a viable treatment option for AGA.[36]

In conclusion, while PDT shows promise in addressing various forms of hair loss, the outcomes vary across different conditions and treatment modalities. Further research is crucial to refine protocols, understand optimal parameters, and establish the effectiveness of PDT in specific types of alopecia.

RF

RF devices generate an electric current within an electromagnetic field with a frequency ranging from 3 kHz to 300 mHz. Once the current reaches tissue, it encounters the tissue impedance, resulting in the conversion of electric energy to heat energy. The generated energy depends on the energy flowing through the impedance of the target tissue. RF devices are classified as monopolar (single electrode tip) and bipolar (two electrodes applied to the skin).[37] Studies have explored various RF modalities such as bipolar, monopolar, and microneedling RF, highlighting their efficacy and safety for different treatments.[38]

USE OF RF IN HAIR REMOVAL

Elos technology combines bipolar RF with optical energy (e.g., lasers or IPL) for effective hair removal. The optical energy targets melanin in the hair shaft, converting it into heat, while the RF energy emits heat to the surrounding tissue, further heating the hair follicle. This combination allows for lower levels of both energies, making the treatment safer and more comfortable. The synergy between optical and RF energy ensures better destruction of hair follicles,

Table 4: Summary of scalp cooling studies on chemotherapy-induced alopecia.

Intervention	Participants	Findings	Adverse events	Conclusion/ recommendation	Author
Scalp-cooling devices during taxane-based chemotherapy	100 patients	Effective in reducing chemotherapy-induced alopecia, rare adverse events, no serious device-related events	Chills (7%), Chills with headaches (6%)	Scalp cooling is effective with acceptable safety.	Kate *et al.*[21]
Evaluation of subcutaneous temperature below 22°C using a technique	10 subjects	Linear relationship between epicutaneous and subcutaneous temperatures, 80% success rate	-	Metabolic effect contributes to hair preservation.	Bülow *et al.*[22]
Randomized clinical trial comparing scalp cooling vs. control in breast cancer patients	182 women	48 out of 95 women with cooling had successful hair preservation, early study termination for efficacy	-	Scalp cooling likely reduces hair loss after the fourth chemotherapy cycle in breast cancer.	Nangia *et al.*[24]
Scalp cooling in clinical practice for early-stage breast cancer patients	220 patients	68% success rate, 89% success with taxane-based chemotherapy, 78% with anthracyclines and taxanes	20 patients discontinued for other reasons	Scalp cooling is well-tolerated and effective in clinical practice.	Gianotti *et al.*[25]
Overview of chemotherapy-induced alopecia and scalp cooling	Review of 58 publications	CIA is reversible, cost-effective, no exaggerated concerns about malignant cell protection	-	Scalp cooling should be available in every hospital for suitable patients.	Wim *et al.*[27]
Evaluation of Dignicap® in preventing alopecia in breast cancer patients	178 patients	68.0% success rate, no difference between dose-dense or standard schedules, 70.2% patient satisfaction	28.1% early discontinuation	Dignicap® is effective and well-tolerated.	Carbognin *et al.*[23]
Evaluation of scalp-cooling devices in Japanese breast cancer patients	48 patients	More patients in scalp-cooling group had no alopecia, improved hair volume recovery	-	Scalp-cooling devices are effective and safe for Japanese patients.	Kinoshita *et al.*[39]
Randomized controlled trial in non-metastatic breast cancer patients	-	SC significantly improved hair preservation and regrowth rates, lower hair loss in SC group	-	SC warrants wider usage in preventing<50% hair loss after CT.	Bajpai *et al.*[40]
Prospective cohort study on a scalp cooling system	122 patients	67 of 101 patients had 50% or less hair loss, better quality of life measures	-	Further research needed for anthracycline regimens and long-term measures.	Rugo *et al.*[41]
Effectiveness of scalp cooling in preventing chemotherapy-induced alopecia	Literature search of 32 relevant studies	Effectiveness depends on chemotherapy type, dose, and temperature, personalized approach needed	-	No clear cutoff point for effectiveness.	Komen *et al.*[42]
Study on Penguin Cold Cap system™	70 patients	81% protection from hair loss, comparable or better than other methods	-	The system is well-tolerated and effective.	Katsimbri *et al.*[43]
Study on scalp cooling in early breast cancer patients	79 patients	39.3% hair preservation, no differences in QoL between regimens	-	Scalp cooling should be available for chemotherapy patients.	Smetanay *et al.*[44]

(*Contd...*)

Table 4: (*Continued*).

Intervention	Participants	Findings	Adverse events	Conclusion/ recommendation	Author
Feasibility study on Paxman scalp cooling device	30 patients	Increased hair loss and distress in most participants, low success rate	Grade 3 alopecia led to most discontinuations	Paxman device showed limited effectiveness in this study.	Dilawari *et al.*[45]
Study on scalp-cooled patients in Dutch hospitals	1411 patients	Positive results for most regimens, lower use of head cover, factors influencing head cover use	-	Scalp cooling results were positive, especially after paclitaxel treatment.	Van den Hurk *et al.*[46]
Study on scalp cooling preventing chemotherapy-induced alopecia	-	52% cases effective, increased well-being in successfully cooled hair, additional distress in unsuccessful cases	-	Additional support recommended for unsuccessful cases.	Van den Hurk *et al.*[47]
Study on Paxman device in breast cancer patients	131 patients	Successful hair preservation in 102 women, 7% adverse events related to device use		Scalp cooling is effective with minimal adverse effects.	Vasconcelos *et al.*[48]
Systematic review of scalp cooling devices in breast cancer patients	Review of 755 articles	Significant improvement in hair protection, potential side effects should be considered	Headache, dizziness, scalp pain, neck pain, coldness, heaviness of the head, skin rash, nausea, overtightened strap	Implementation should be guided by potential side effects.	Wang *et al.*[17]

CIA: Chemotherapy-induced alopecia, CT: Computed tomography, SC: Scalp cooling, QoL: Quality of Life

effectively reducing hair growth and making the treatment suitable for various skin types and hair colors. Kincaid *et al.*[49] mentioned the utility of bipolar and monopolar RF devices for effective hair removal. Studies emphasize the promising outcomes achieved by combining bipolar RF with IPL, showcasing long-term removal of body and facial hair. The chromophore-independent energy delivery of RF renders it suitable for treating lighter-colored hair and individuals with darker Fitzpatrick skin types.[49]

USE OF RF IN HAIR GROWTH

RF can also stimulate hair growth on its own. RF energy increases blood flow to the scalp, enhancing the delivery of nutrients and oxygen to hair follicles, which promotes healthier and stronger hair growth. It also stimulates collagen and elastin production, strengthening hair follicles and improving scalp health.

Microneedling RF involves penetrating the skin and releasing RF currents from needle tips, creating RF thermal zones (RFTZ) in the dermis without damaging the epidermis. This process induces thermal and mechanical injury, releasing of releasing growth factors and activating stem cells, contributing to hair regeneration. Studies indicate that RF exposure induces the expression of insulin-like growth factor-1 in dermal papilla cells, promoting hair growth.[50] Further research includes RF-based treatments for conditions such as eyelash regrowth,[51] AGA,[52] FPHL,[53] and male pattern hair loss,[54] highlighting the potential of RF in enhancing hair regrowth and hair health. The key findings of RF studies are summarized in Table 5.

In summary, RF technology in dermatology has gained significant attention for its dual capabilities in both hair removal and hair growth, depending on the specific RF modality employed.

OXYGEN THERAPY

Oxygen therapy focuses on delivering pure oxygen to the dermis and epidermal layers through devices such as the X2 Exea. These devices allow the flow of up to 96% pure oxygen to reach the skin's superficial layers, aiding absorption by the dermis and epidermis. Oxygen supply becomes crucial for hDPCs, which are vital for hair growth and regeneration. Park *et al.*[55] propose that continuous oxygen supply is essential for hDPC survival and regrowth,

Table 5: Summary of key findings of RF in hair applications.

Study	Focus	Key findings	Implications
Kincaid *et al.*[49]	Overview of RF devices in cosmetic dermatology	Reports dualistic nature of RF devices, with studies favoring hair removal (15 out of 19). Bipolar RF with IPL effective for long-term removal. Monopolar RF used for eyelash removal. Fractional RF stimulates hair growth in alopecia patients.	Preliminary evidence supports bipolar and monopolar RF for hair removal, while fractional RF emerges for hair growth. More studies needed for efficacy, mechanisms, and parameters.
Yoon *et al.*[50]	RF radiation effect on dermal papilla cells	1,763 MHz RF stimulates hair growth *in vitro* by inducing IGF-1 in dermal papilla cells. Enhanced hair shaft elongation observed in *ex vivo* cultures.	Suggested RF exposure promotes hair growth through IGF-1 induction in dermal papilla cells.
Kim *et al.*[51]	Mitomycin C after RF ablation for trichiasis	0.02% mitomycin C improves success rate of RF ablation in regrowing eyelashes for trichiasis patients. No complications noted.	Suggests potential benefit of mitomycin C in enhancing eyelash regrowth post RF ablation.
Sadick and Shaoul[56]	Aurora Syneron Medical technology for photoepilation	Novel IPL-RF technology achieves 75% hair clearance at 18 months. Chromophore-independent RF compensates for reduced optical energy. Safe and effective.	Aurora Syneron Medical technology demonstrates prolonged photoepilator effects, safe for all skin types.
Verner and Lotti[52]	HairLux device for Androgenetic Alopecia	HairLux device, based on fractional RF, shows increased hair density (31.6%) and hair shaft thickness (18%) after ten treatments.	HairLux device suggests efficacy in treating Androgenetic Alopecia.
Pablo *et al.*[53]	CRET for female pattern hair loss	CRET sessions result in significant hair redensification (10–15%). *In vitro* electrostimulation enhances DPC proliferation.	CRET shows promise for treating Female Pattern Hair Loss by inducing hair redensification and DPC proliferation.
Yu *et al.*[54]	FRM and 5% topical minoxidil for male pattern hair loss	Combined FRM and minoxidil significantly increased mean hair count and thickness in male pattern hair loss. Higher improvement compared to monotherapy.	Suggests FRM and minoxidil combination as an effective and safe treatment for male pattern hair loss.
Kim *et al.*[57]	RF-induced thermal damage to hair follicles	27.12-MHz RF causes significant thermal damage to bulge and bulb/dermal papilla. Potential risk to hair follicle epithelial stem cells.	Raises concerns about potential risks associated with RF-induced hair removal.

IPL: Intense pulsed light, IGF-1: Insulin-like growth factor-1, RF: Radiofrequency, CRET: Capacitive-resistive electrothermal therapy, FRM: Fractional RF microneedling, DPC: Dermal papilla cells

particularly during periods of oxygen deficiency, suggesting potential benefits for addressing hair loss. A nanoemulsion based on perfluorooctyl bromide is highlighted as a tool for sustainable oxygen supply, promoting hDPC growth and gene expression.

PHYSIOLOGICAL EFFECTS OF OXYGEN

Oxygen therapy showcases various physiological effects with potential benefits for hair care. Oxygen is known to enhance cellular metabolism and accelerate healing processes. It exerts anti-inflammatory effects by inhibiting fibroblast apoptosis, decreasing tumor necrosis factor-alpha expression, and inhibiting prostaglandin synthesis. In addition, oxygen promotes neoangiogenesis by releasing vascular endothelial growth factors and other factors. Its antibacterial effect is attributed to the release of reactive oxygen species, which can degrade cellular membranes and eliminate pathogenic microorganisms.

TOPICAL OXYGEN THERAPY FOR HAIR LOSS

Bennardo *et al.*[58] explored the use of topical oxygen therapy as an adjuvant treatment for hair loss, evaluating its efficacy in delivering 5% Mx and a phytotherapeutic agent through an oxygen dispenser. Results demonstrated the usefulness of topical oxygen therapy in treating conditions such as AGA and telogen effluvium. The study suggests its potential as an adjuvant therapy, emphasizing the need for further research in larger study groups.

HYPERBARIC OXYGEN THERAPY (HBOT) IN HAIR TRANSPLANTATION

Fan *et al.*[59] conducted a study assessing the clinical efficacy of HBOT as an adjuvant treatment for hair transplantation surgery. The results indicated a significant decrease in itching and folliculitis in the HBOT group, along with a lower post-operative shedding rate. Although the survival rate at 9 months showed no significant difference, early post-operative satisfaction was notably higher in the HBOT group. The study provides evidence for the potential of HBOT in minimizing postsurgical follicle shedding and reducing associated discomfort, making it a promising adjuvant therapy in hair transplantation surgery.

In conclusion, oxygen therapy, whether through topical applications or more advanced techniques like HBOT, holds promise in cosmetic and hair care procedures. The physiological effects of oxygen on cellular processes and its potential benefits for promoting hair growth make it an area of interest for further research and development in the field of dermatology and esthetics.

IPL

IPL is a popular non-invasive method for hair reduction and removal, offering versatile and effective solutions for various skin conditions. Light-based technology for hair removal uses selective photothermolysis to target melanin in hair shafts.

A polychromatic IPL device operates in the wavelength range of 400–1200 nm. It is non-coherent, meaning it has a disorganized array through space, and its photobiological reactions are not dependent on the coherence of lasers. The light is non-collimated, diverging randomly in all directions from the upper lamp while progressing. The device has a large spot size, resulting in less scatter and a slower decay of fluence. Notably, a handheld, low-fluence, and home-use IPL device has received FDA approval for the treatment of unwanted facial hair.[60]

Studies have explored the efficacy and safety of IPL devices, targeting different aspects of hair growth and reduction.[61] A study by Dawood *et al.*[62] explored the efficacy of an IPL home-use device in women with unwanted facial hair, revealing a substantial average hair reduction of 70.9% after five sessions, with 40% of subjects showing excellent responses. El-Domyati *et al.*[63] delved into the changes in hair follicles in post-IPL, highlighting a decrease in hair count and terminal anagen follicle percentage, suggesting the mechanism involves telogenesis and miniaturization. In a murine model, Jiang *et al.*[64] demonstrated that low-fluence IPL promotes hair growth by inducing an earlier transition from telogen to anagen phase and prolonging the anagen phase duration, suggesting its potential as a therapeutic treatment for hair regrowth.

However, challenges arise from the variability of IPL outcomes, as illustrated by a retrospective chart review conducted by Willey *et al.*[65] Among 543 patients undergoing laser/IPL photo epilation, 10.49% exhibited increased hair growth, primarily in Alexandrite and IPL devices, with onset occurring between the third and tenth treatments in 71.2% of cases. This emphasizes the need for understanding patient demographics and treatment parameters. On the other hand, El Bedewi[66] underlined the safety and efficacy of non-coherent IPL for hair removal, with an 80% reduction observed in 210 patients with skin type III-V.

Li *et al.*[67] underscored IPL's two-decade history of successful cosmetic applications and anticipated broader clinical use with improved IPL devices and combined treatments. Furthermore, Hattersley *et al.*[68] provided insights into AEs related to home-use IPL devices, revealing skin pain, thermal burn, and erythema as common AEs. This marks a significant contribution to the understanding of IPL safety through post-marketing surveillance.

Table 6 provides a comprehensive summary of key studies, ranging from home-use IPL devices to low-fluence IPL irradiation in mice, shedding light on the diverse applications and outcomes associated with IPL technology in the realm of dermatology and cosmetic treatments.

HIGH-INTENSITY FOCUSSED ULTRASOUND

Ultrasonography has emerged as a promising diagnostic tool in various medical fields, with high-frequency ultrasonography (HF-USG) gaining recognition in dermatological practice, particularly in aesthetic dermatology. This review delves into recent studies exploring the application of ultrasonography in trichology, shedding light on its potential as a non-invasive method for diagnosing and evaluating hair-related conditions.

The study by Mikiel *et al.*[69] presents an insightful comparison between trichoscopy and HF-USG in a group of healthy adults. The results indicate that HF-USG can serve as a valuable complement to non-invasive diagnostic procedures, revealing hyperechogenic entrance echoes and well-defined hypoechoic follicular structures. Notably, HF-USG exhibited a higher resolution and broader visualization of follicular structures compared to trichoscopy, showcasing its potential to enhance scalp evaluation.

In the realm of AGA treatment, the integration of ultrasound and drug delivery systems has shown promising results. Liao *et al.*[70] developed a biomedical approach utilizing ultrasound contrast agent albumin-shelled microbubbles (MBs) to enhance transdermal delivery of Mx. This innovative approach, involving chitosan oligosaccharide lactate and Mx, not only accelerated drug diffusion but also promoted hair growth while minimizing treatment duration. Further research by Liao *et al.*[71] expanded on this concept, demonstrating that dual-frequency ultrasound-mediated MB cavitation significantly enhanced Mx delivery and hair growth efficacy both *in vitro* and *in vivo*, showcasing the potential for improved treatment outcomes.

In addition, the application of ultrasound in the early detection of Hidradenitis Suppurativa (HS) marks a

Table 6: Comprehensive summary of key studies on IPL device in trichology.

Study	Participants	Intervention	Results/Findings	Citation
IPL for hair reduction in women	45 females with Fitzpatrick skin phototype	IPL home-use device	An average hair reduction of 70.9% after five sessions. The technique was effective and safe for women.	Dawood *et al.*[62]
Changes in hair follicles after IPL hair reduction	21 volunteers	IPL hair reduction	Six sessions led to decreased hair count, HS diameter, terminal anagen follicle percentage, PCNA, and Ki67, while increased terminal telogen and total vellus follicles with vellus-like type and P53 expression. Hair reduction occurs due to telogenesis, miniaturization, decreased hair follicle proliferation, and increased DNA damage.	El-Domyati *et al.*[63]
Low-fluence IPL on hair growth in mice	C57BL/6 mice	Low-fluence IPL	IPL promotes hair growth by initiating the anagen phase, prolonging its duration, and up-regulating WNT3A and β-catenin protein levels, suggesting low-fluence IPL irradiation as a potential treatment for hair regrowth.	Jiang *et al.*[64]
Laser and IPL photo-epilation in Basque country Spain	543 Fitzpatrick skin types II, III, IV	Laser and/or IPL photo-epilation	Hair growth increased in 10.49% of patients, with thicker and darker areas. No reduction in 44 patients, while 78.08% experienced a decrease. Growth onset occurred between treatments.	Willey *et al.*[65]
PEFs for Hair Follicle Stimulation	Sprague–Dawley rats	PEF	PEF stimulates hair follicles in a rat model, causing dense patches of hair and increasing anagen follicles by 5.05-fold in a single treatment, with voltage being the most influential parameter.	Khan *et al.*[14]
Non-coherent IPL for Permanent Hair Removal	210 patients with skin type III-V	Non-coherent IPL	a significant 80% reduction, offering a safer and more effective hair removal option compared to popular laser systems like ruby, alexandrite, diode, and Nd: YAG lasers.	El Bedewi[66]

IPL: Intense pulsed light, HS: Hair shaft, PCNA: Proliferating cell nuclear antigen, DNA: Deoxyribonucleic acid, PCOS: Poly cystic ovary syndrome, HOMA-IR: Homeostasis model assessment for insulin resistance, FAI: Free androgen index, PEF: Pulsed electrical field, WNT3A: Wingless-related integration site 3A, Nd: YAG: Neodymium-doped yttrium aluminum garnet

significant advancement. In a cross-sectional study conducted by Wortsman *et al.*,[72] abnormalities in hair follicles were revealed using 70-MHz ultrasound among patients with HS. The ultrasound identified signs such as a connecting band between adjacent hair follicles (known as the bridge sign), a fragment of the hair shaft protruding through a dilated hair follicle (referred to as the sword sign), and the presence of retained cylindrical keratin fragments in the dermis. These findings were correlated with disease severity, underscoring the diagnostic utility of ultrasound in the early detection of HS signs and aiding treatment decisions.

The reviewed studies collectively highlight the promising role of ultrasonography in trichology. From enhancing diagnostic capabilities to improving drug delivery systems for hair-related conditions, ultrasound technologies present exciting possibilities for the future of trichological diagnostics and treatments. As research continues to explore and refine these techniques, ultrasonography may become an indispensable tool in the hands of trichologists, offering precise and non-invasive insights into various hair and scalp conditions.

CONCLUSION

To the best of our knowledge, this is the first review study to discuss a diverse range of advancements in non-invasive techniques in the field of both diagnostic and therapeutic trichology. As technology continues to evolve, further research is essential to refine protocols, establish long-term efficacy, and overcome logistical challenges for widespread adoption. These advancements collectively contribute to a comprehensive understanding of non-invasive interventions in trichology.

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