



Skin Intelligence: Advancing Cutaneous Resilience Through Biological Education, Microbial Symbiosis, and Eco-integrated Approaches

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Abstract

The skin functions as a dynamic organ that integrates biological, microbial, environmental, and neural inputs to maintain resilience. Traditional dermatology has often prioritised treatment of symptoms rather than fostering the underlying mechanisms of cutaneous health. This review introduces the paradigm of ‘educating the skin,’ a proactive approach that emphasises prevention, adaptability, and long-term health through an integrative model. Key elements include barrier function, immune modulation, neural dynamics, microbial symbiosis, and environmental adaptation. Evidence demonstrates the importance of lipid replenishment, circadian regulation, microbiome-targeted therapies, and neuroimmune pathways in enhancing skin integrity and mitigating inflammatory disorders. Environmental challenges such as ultraviolet radiation, pollution, and psychological stress further underscore the need for pre-emptive and barrier-focused strategies. Advances in AI and biotechnology provide opportunities for precision diagnostics, personalised care, and patient empowerment, shifting dermatology towards preventive rather than reactive practice. By integrating biological insights, microbial ecology, neuroendocrine regulation, and environmental adaptation, this framework supports resilient, adaptable skin health. Educating patients about skin biology and daily practices reinforces long-term outcomes. Looking forward, interdisciplinary research and AI-driven tools will refine personalised interventions, paving the way for proactive, sustainable strategies in dermatology. Through this lens, the skin is not merely treated but empowered to thrive in harmony with its environment.

Key Points

1. Chronic skin diseases are influenced by barrier dysfunction, microbiome imbalance, and environmental stressors. Clinicians must understand resilience mechanisms to move beyond symptom-based treatment and promote long-term cutaneous health.

2. This narrative review synthesises evidence on ‘educating the skin’, integrating barrier science, microbial symbiosis, environmental adaptation, and neurocutaneous pathways to provide clinicians with a proactive, preventive framework for dermatological care.

3. Clinicians should adopt proactive strategies, barrier reinforcement, microbiome modulation, stress management, and AI-personalised approaches to strengthen resilience, prevent chronic conditions, and improve patient outcomes in daily dermatological practice.

INTRODUCTION

The skin, as the body’s largest organ, serves as a dynamic interface between internal systems and environmental influences. Beyond its role as a protective barrier, it interacts with microbial ecosystems, immune pathways, and neural networks, while responding to external challenges such as UV radiation and pollution.¹ Despite its complexity, dermatology has traditionally emphasised the treatment of visible symptoms rather than fully addressing the underlying mechanisms that sustain skin health and adaptability. While the biological processes governing skin resilience are still being unravelled, emerging evidence provides actionable insights into strategies that strengthen the skin’s capacity to adapt and thrive.² Recent advancements in skin biology research, microbiome research, environmental science, and neurodermatological studies have laid the foundation for a new framework called ‘educating the skin’.

This paradigm emphasises enhancing the skin’s ability to adapt, repair, and thrive by addressing its biological, microbial, environmental, and neural interactions.^{3,4} It proposes a shift from reactive to proactive treatments, leading the way to comprehensive strategies that foster resilience and long-term health.⁵ The objective of this review is to synthesise current evidence supporting the approach of educating the skin, focusing on key components such as the epidermal barrier, microbial balance, environmental

adaptation, and neural regulation.⁶ By adopting an integrative model, this review combines molecular and clinical insights to provide actionable strategies for implementing this framework. To educate the skin with the aim of preventing conditions and reducing the need for treatment, it is essential to highlight the critical factors that contribute to maintaining healthy skin. This review explores the interconnected roles of skin biology, the microbiome, and environmental stressors, shedding light on their impact on skin resilience. By redefining dermatological care to emphasise prevention and adaptability, educating the skin offers a transformative, holistic approach to advancing the field and improving long-term skin health. While our understanding of the underlying biological mechanisms continues to evolve, this review emphasises the evidence-backed strategies currently available, paving the way for innovative and personalised interventions in dermatology.

SKIN BIOLOGY: BARRIER FUNCTION, IMMUNE MODULATION, AND NEURAL DYNAMICS

The skin’s biological integrity is fundamentally rooted in its barrier function, immune system, neural networks, and circadian rhythms, which work in harmony to maintain homeostasis and protect against external and internal challenges. Circadian rhythms regulate key processes, such as barrier repair, immune cell activity, and hydration, thereby adapting the skin

to daily environmental changes. The skin also produces and metabolises melatonin. This hormone is made by keratinocytes, melanocytes, and fibroblasts. It protects the skin from UV damage, oxidative stress, and inflammation. A recent review confirmed its importance for skin health.⁷ Earlier studies showed that serotonin and N-acetylserotonin are also present in the skin.⁸ Together, they form a local serotonergic–melatoninergic system that supports circadian regulation, repair, and immune balance. Notably, serotonin is also synthesised by simple microorganisms, including many skin-resident species. This further supports the idea that the skin microbiome contributes not only to immune and barrier functions, but also to local neuroendocrine signalling.⁹ In addition, melanocytes also function as sensory and regulatory units within the epidermis. This concept was first proposed in 1993 and has since been supported by in-depth reviews of the pigmentary system's physiological and immunoregulatory functions.^{10,11} Disruptions in these rhythms, caused by ageing or environmental stress, can compromise skin integrity and exacerbate conditions such as dermatitis or psoriasis, highlighting their crucial role in skin health.⁶

The epidermal barrier, composed primarily of lipids such as ceramides, cholesterol, and fatty acids, plays a vital role in preventing transepidermal water loss (TEWL) and protecting against microbial invasion.¹² Research by Elias et al.¹³ has shown that ceramide depletion compromises barrier function, leading to conditions such as atopic dermatitis (AD). In their study of patients with paediatric AD, ceramide-based moisturisers were found to reduce TEWL by 50% within 8 weeks, significantly alleviating inflammation and pruritus. These findings underscore the critical importance of lipid replenishment in maintaining optimal skin barrier function on a daily basis.¹³ These findings were confirmed by Chamlin et al.¹⁴ and Luger et al.,¹⁵ who demonstrated that ceramide-containing formulations not only improve barrier function but also reduce the clinical severity of AD. Their study highlighted the ability of ceramides to enhance stratum corneum integrity, restoring hydration and

reducing inflammatory markers. The long-term benefits of constant ceramide-based interventions were evident in sustained symptom relief and a significant decrease in the need for topical corticosteroids.

Another study emphasised the importance of consistently applying emollients to achieve optimal results, regardless of the formulation used. Regular use of emollients strengthens the skin barrier, reduces TEWL, and minimises flare-ups, reinforcing their critical role in long-term eczema management.¹⁶ Along with these findings, the study by Lefèvre-Utile et al.¹⁷ explores the multifaceted roles of the epidermis in maintaining skin health and integrity. The skin's protective and functional roles are supported by six interconnected barriers. The physical barrier defends against environmental insults, like pathogens and UV radiation, through the structure of the stratum corneum. In contrast, the chemical barrier, maintained by the skin's acidic pH, regulates enzymatic activities and microbiome balance. The microbial barrier supports a protective and diverse microbiota, playing a crucial role in immune modulation and pathogen competition. The immunological barrier, involving Langerhans cells and other immune mediators (innate immunity in the epidermis and the dermis), prevents infections and controls inflammation. The sensory barrier detects mechanical, thermal, and chemical stimuli contributing to homeostasis. In addition to its physical, chemical, and immunological functions, the skin also acts as a neuroendocrine and stress organ.

This concept, first introduced over two decades ago, revolutionised our understanding of the skin's integrative role in homeostasis and adaptation to environmental stressors.¹⁸ Subsequent reviews have further elaborated on how the skin possesses a functional equivalent of the hypothalamic–pituitary–adrenal axis, capable of producing neuropeptides, neurotransmitters, and hormones that influence both local and systemic physiology.¹⁹ This perspective highlights the skin's capacity to respond to stress via neuroendocrine signalling pathways that affect immune modulation, inflammation,

and even pigmentation. Moreover, this neuroendocrine identity positions the skin as both a sensor and effector organ, capable of computing complex environmental inputs to maintain internal equilibrium.²⁰

The sixth component, the endocrine and neuroendocrine barrier, synthesises hormones and neuropeptides that regulate immune responses, repair mechanisms, and stress adaptation. Disruptions in any of these barriers, whether caused by genetic factors, environmental stressors, or disease, can result in various dermatological conditions. These insights underscore the importance of therapeutic strategies aimed at restoring skin barrier functions to improve overall skin health. In addition to these barrier systems, the immune system plays a critical role in maintaining cutaneous homeostasis. Keratinocytes, Langerhans cells, and T cells regulate immune responses by balancing defence mechanisms with tolerance to benign stimuli.

By targeting these immune pathways, DNA repair enzymes have shown promise in reversing damage and restoring skin resilience. Peripheral nerves also contribute to the skin's sensory and regulatory functions, influencing both immunity and barrier dynamics.^{21,22} Takahashi et al.²³ explored how mechanical stress and oxidative damage disrupt nerve signalling, leading to sensory abnormalities and inflammatory skin conditions. Their study demonstrates how disrupted epidermal nerve pruning and prolonged calcium ion signalling contribute to sensory abnormalities, such as chronic itch, in conditions like AD. By identifying aberrant transient receptor potential ankyrin 1 (TRPA1) activity as a key driver of these issues, the research underscores the therapeutic potential of restoring neural pathways to manage sensory dysfunction and improve patient outcomes.²³ Nguyen et al.²⁴ performed a single-nucleus transcriptomic analysis of human dorsal root ganglion neurons, revealing how neural circuits contribute to the sensory and inflammatory pathways involved in skin conditions.²⁴ This research provides

a deeper understanding of how neural mechanisms, such as pain perception and itch, are intricately linked to inflammatory processes. These findings suggest potential therapeutic interventions, including neuromodulating agents that target specific pathways to reduce chronic itch and pain, or the use of neuroprotective peptides to support nerve health and mitigate inflammation. Such approaches could be transformative for conditions like eczema, psoriasis, and chronic pruritus, where neural contributions to symptom persistence are significant. This highlights the interconnectedness of neural health and skin outcomes, suggesting that therapies targeting nerve pathways can provide holistic benefits in conditions involving sensory impairment or chronic itch.

These findings underscore the complex interplay between skin integrity, immune function, and neural health, emphasising that therapies addressing these interconnected systems can provide holistic benefits in preventing inflammatory conditions, sensory disturbances, and maintaining overall skin resilience.

MICROBIOME SYMBIOSIS: A KEYSTONE OF SKIN HEALTH

The skin microbiome is an essential component of its defence system, supporting barrier function, modulating immunity, and preventing pathogen overgrowth.²⁵ Dysbiosis, an imbalance in microbial populations, has been implicated in inflammatory skin conditions such as acne, rosacea, and AD.²⁶ Conversely, a balanced skin microbiome plays a significant role in educating the skin to maintain its natural balance and resilience. Research by Dréno²⁷ demonstrated the efficacy of microbiome-targeted therapies in restoring microbial equilibrium and alleviating symptoms. Recent research highlights the skin microbiome's pivotal role in maintaining cutaneous health by regulating inflammatory processes and microbial stasis.²⁷ Studies on inflammatory acne have revealed that shifts in *Cutibacterium acnes* phylotypes, particularly an overabundance of virulent strains like IA1, contribute to

inflammation and immune activation. The dynamic interplay between *C. acnes* and commensal organisms, such as *Staphylococcus epidermidis*, underscores the importance of microbial diversity in preventing dysbiosis-related conditions. Innovative therapies focusing on restoring microbial equilibrium, including probiotics, postbiotics, and bacteriophage applications, show promise in reducing inflammation and addressing underlying microbial imbalances.^{28,29} Another study by Bae et al.³⁰ highlighted the need for tailored treatments that address microbiome imbalances, which are often linked to acne severity.³⁰ Therapeutic interventions in this context could focus on strategies that enhance the functionality and diversity of the skin's commensal microbiome. Postbiotic creams can support the existing microbial ecosystem, while bacteriophage therapies offer a targeted approach to reducing pathogenic strains, such as *C. acnes*. These interventions aim to restore the balance of microbial phylotypes rather than introducing non-native bacteria, aligning with the skin's natural ecological preferences and its capacity to maintain homeostasis.

These interventions align with a precision-medicine approach, ensuring that treatments are both personalised and effective in restoring the skin's natural microbial balance. These approaches emphasise maintaining the skin's natural microbial ecosystem rather than eradicating bacteria, paving the way for personalised and sustainable microbiome-targeted preventive procedures.³⁰ Similarly, other findings suggest that maintaining a balanced population of *Staphylococcus epidermidis* and *C. acnes* on the skin is crucial for reducing erythema and managing inflammatory skin conditions, highlighting the therapeutic potential of targeting specific bacterial strains.^{31,32} Furthermore, emerging research highlights the role of microbiome modulation in managing rosacea, with treatments targeting bacterial balance showing promise in reducing inflammation and redness. Although evidence is still emerging, some studies suggest that topical applications of probiotics and postbiotics may help support a healthy skin microbiome. While these

approaches show promise as potential non-invasive alternatives to traditional therapies, further research is needed to establish their efficacy and long-term benefits.³³ Recent studies highlight the potential of topical probiotics in managing AD. For instance, Frankel et al.³⁴ conducted a systematic review that evaluated 12 studies and four clinical trials, demonstrating that topical probiotics improved skin barrier function and symptom severity in patients with AD.³⁴ Similarly, Flint et al.³⁵ reported significant reductions in AD severity, as measured by the Severity Scoring of Atopic Dermatitis (SCORAD) index, in RCTs using topical probiotic formulations. These findings underscore the therapeutic potential of microbiome-targeted strategies in dermatology, particularly in addressing inflammatory skin conditions.³⁵ Moreover, research by Liu et al.³⁶ on microbial metabolites such as short-chain fatty acids sheds light on how these by-products influence neural pathways regulating itch and pain.³⁶

By addressing both microbial imbalances and neural dysfunction, dermatologists can offer comprehensive management strategies for conditions like chronic pruritus.

ENVIRONMENTAL INTERACTIONS: MITIGATING EXTERNAL STRESSORS

Environmental stressors, including UV radiation, pollution, stress, and climate variability, significantly influence skin health and resilience. Chronic exposure to these factors disrupts cellular homeostasis, accelerates oxidative damage, and weakens the skin's barrier.³⁷ Another study highlighted the detrimental effects of urban pollution, showing that it increases oxidative stress markers and compromises barrier function.³⁸ Choi and Kang³⁹ demonstrated that skin barrier function is influenced by both intrinsic factors (such as genetics, age, and hydration levels) and extrinsic factors (such as climate, skincare products, and irritants). Their research emphasises the importance of maintaining the acidic pH of AD and senile xerosis. Their findings underline how disruptions in stratum

corneum acidity caused by environmental or biological factors can lead to skin barrier dysfunction and increased susceptibility to infections and inflammatory conditions.³⁹ Similarly, another study conducted by Soares et al.⁴⁰ explores the bilateral relationship between psychological stress and inflammatory skin diseases such as psoriasis, AD, and acne. It highlights how stress exacerbates skin inflammation through neuroimmune pathways, while chronic skin conditions can, in turn, increase psychological distress, creating a cycle that impacts overall health and quality of life.⁴⁰ They highlight that stress triggers a cascade of neuroimmunological responses, such as the activation of the hypothalamic–pituitary–adrenal axis and the release of pro-inflammatory cytokines, which can impair the skin barrier, worsen inflammation, and delay healing processes. Furthermore, they discuss the bilateral nature of this relationship, where inflammatory skin diseases can themselves lead to increased psychological stress, creating a vicious cycle. Their review also underscores the importance of integrative approaches that combine dermatological and psychological therapies, including mindfulness, cognitive behavioural therapy, and stress management techniques, to effectively manage these conditions.⁴⁰ By examining these ways, Lefèvre-Utile et al.¹⁷ highlight how external factors such as UV radiation, pollution, temperature changes, and pathogens can compromise the physical integrity of the barrier, disrupt its chemical pH balance, and alter the skin's microbiota, leading to dysbiosis. These stressors also impact the immunological barrier by triggering inflammatory responses and impairing the skin's sensory function, which can exacerbate conditions like eczema, psoriasis, and premature ageing. By understanding the mechanisms through which environmental stressors affect these five functional aspects, the review underscores the need for barrier-targeted therapies and preventative strategies to mitigate their impact and maintain skin health.¹⁶ Similarly, the work by Nomura⁴¹ on the cellular effects of UV exposure revealed its role in inducing inflammation and barrier degradation. Photoprotective strategies, including broad-

spectrum sunscreens and antioxidant serums, are essential for mitigating these impacts.⁴¹ Environmental stressors affect not only cellular homeostasis but also the neurodermatological mechanisms that respond to environmental challenges.

UV radiation, particularly UVB, plays a dual role in skin physiology, acting both as a stressor and as a modulator of local and systemic homeostasis. While excessive exposure can lead to DNA damage, inflammation, and carcinogenesis, controlled UV exposure activates essential phototransduction pathways that regulate immune, endocrine, and neural responses. Notably, UVB stimulates cutaneous production of vitamin D3 and its metabolites, including lumisterol and tachysterol, which contribute to immune regulation and systemic calcium homeostasis. Recent research highlights a broader framework termed photo-neuro-immuno-endocrinology, which describes how UV radiation influences not only the skin but also neuroendocrine pathways affecting the brain and immune system.⁴² In addition, UVB exposure induces the production of secosteroids such as vitamin D, lumisterol, and tachysterol. These molecules, particularly via cytochrome P450 (CYP)11A1-derived metabolic pathways, contribute not only to local skin homeostasis but may also have systemic regulatory effects.⁴³ Research by Takahashi²³ showed that oxidative stress, as a part of environmental stressors, alters nerve conduction, leading to sensory dysfunction. In the same way, this finding suggests that inhibiting TRPA1 activity could serve as a therapeutic strategy for managing chronic itch and sensory dysfunction associated with conditions like AD, thus broadening the insight in terms of preventive measures.²³

EDUCATING THE SKIN: A HOLISTIC AND PERSONALISED FRAMEWORK

Educating the skin involves a holistic approach that addresses its biological and environmental components, fostering long-term skin health and resilience. Advances in diagnostic technologies, such as AI-

driven analyses, enable the identification of unique patient needs, allowing for more personalised and effective care.⁴⁴ AI tools are increasingly used in both clinical and consumer skincare. For example, deep learning algorithms can analyse high-resolution skin images to detect early signs of ageing, pigmentation, or inflammation. Computer vision and convolutional neural networks are applied to evaluate texture, tone, and pore structure in real time. Mobile-based AI applications, such as SkinVision® (SkinVision, Amsterdam, the Netherlands), or DermAI™ (Proscia, Philadelphia, Pennsylvania, USA), help track skin changes and suggest product routines. In dermatology clinics, AI-driven platforms integrate skin imaging, microbiome profiling, and patient-reported outcomes to generate tailored treatment plans. These technologies support more precise, proactive, and data-informed skin management strategies.⁴⁵

Nicolau and Kendall demonstrated the utility of combining skin condition assessments with microbiome profiles and neural sensitivities to tailor treatment strategies, showing how these insights can guide precise, individualised interventions.⁴⁶ These studies illustrate the transformative potential of personalised interventions. Biotechnology further supports this framework by developing innovative tools for skin health. The study by Usui et al.⁴⁷ investigates the role of transient receptor potential vanilloid 1 (TRPV1)-positive sensory nerves and neuropeptides in the epidermal barrier. Their findings suggest that activation of these sensory nerves and the release of neuropeptides are crucial for promoting skin barrier recovery and reducing inflammation after barrier disruption.⁴⁷ Combining these neural therapies with microbiome-focused treatments provides a comprehensive approach for complex dermatological conditions. This integrated framework emphasises prevention over reactive treatments, empowering dermatologists and patients to focus on maintaining skin health and addressing issues before they become chronic.

PRE-EMPTIVE MEASURES ACROSS DERMATOLOGY

With advancements in dermatological science and personalised medicine, it is now possible to delve deeper into a patient's skin biology, analysing individual gene expression profiles and identifying vulnerabilities influenced by genetic predisposition. These insights, coupled with a detailed understanding of potential environmental stressors such as UV radiation, pollution, or lifestyle-related oxidative damage, allow dermatologists to predict the skin's susceptibility to various conditions, including inflammatory disorders, neuropathic pain, and premature ageing. By incorporating this knowledge into care strategies, dermatology can transition from a reactive to a proactive discipline. The concept of 'educating the skin' as a preventive measure is built on this foundation. By focusing on early risk assessment and targeted interventions, we can take initial steps toward bolstering the skin's resilience and potentially delaying the onset of chronic or multifactorial conditions. While the ability to fully predict and pre-empt such issues remains a future goal, emerging research on genetic markers and skin profiling shows promise. For instance, understanding tendencies towards impaired barrier function or heightened inflammation could, in the future, guide the introduction of ceramide-enriched therapies and immune-modulating treatments tailored to individual needs. Similarly, by analysing DNA markers linked to microbial imbalances or heightened sensory nerve responses, clinicians can tailor microbiome-supportive and neuroprotective interventions, reducing the risk of conditions such as rosacea or chronic pruritus. This predictive approach not only safeguards against the development of debilitating skin conditions but also enhances overall skin health and quality of life. By integrating data on skin biology, environmental exposures, and patient-specific vulnerabilities, dermatologists can design personalised regimens that reinforce the skin's natural defences. This comprehensive strategy supports the idea that educating the skin is not only a therapeutic tool but also a cornerstone of preventive

dermatological care, ensuring long-term adaptation and functionality in a rapidly changing environment.

PATIENT EMPOWERMENT AND EDUCATION

Patient empowerment and education play a crucial role in the success of the 'educating the skin' approach, particularly as it shifts dermatology from a reactive, treatment-focused discipline to one that emphasises prevention and long-term skin health.^{48–50} By educating patients about the underlying mechanisms that contribute to their skin conditions, including the importance of maintaining a healthy skin barrier, managing the skin microbiome, and adapting to environmental factors, patients can become more active participants in their care.⁵¹ A key component of patient empowerment is providing individuals with the tools and knowledge they need to make informed decisions about their skincare routines.⁵² This could involve educating patients on how to select the appropriate skincare products, such as emollients, moisturisers, and sunscreens that support their skin's natural barrier function. It also involves teaching patients how to recognise early signs of skin imbalance or irritation, enabling them to take proactive measures before symptoms escalate into more serious conditions.⁵³ Moreover, patient education about lifestyle factors such as diet, stress management, and sleep hygiene can enhance the skin's ability to adapt and repair itself.⁵⁴ For example, patients could be educated about the benefits of anti-inflammatory diets or mindfulness practices to reduce the impact of stress on their skin.⁵⁵ Additionally, understanding the influence of environmental factors, such as pollution and UV radiation, could help patients make informed choices about how to protect their skin on a daily basis. Empowering patients also involves ensuring that they understand the importance of consistent skincare practices. Educating patients about the significance of daily routines and how they directly contribute to skin health can encourage adherence to long-term preventive measures.⁵⁶ As patients gain more knowledge, they may

feel more confident in managing their skin conditions, reducing their reliance on medications and invasive treatments. Overall, patient empowerment and education are fundamental to successfully implementing the 'educating the skin' framework. When patients understand the science behind their skin's health, they are more likely to take ownership of their well-being, ultimately leading to improved outcomes and quality of life. Through continued education and support, dermatologists can foster a partnership with patients that promotes self-care, prevention, and long-term resilience.⁵⁷

CHALLENGES AND FUTURE DIRECTIONS

The concept of educating the skin would necessitate further research to validate its long-term efficacy and refine its implementation.⁵⁸ Longitudinal studies are crucial for exploring the complex interactions between microbiome metabolites, neural pathways, and environmental stressors, which will uncover new preventive targets for skin health.⁵⁸ These studies should focus on the dynamic relationship between these factors and their collective impact on the skin's resilience and immune response. Interdisciplinary collaborations between dermatologists, neurologists, microbiologists, and environmental scientists will be essential for advancing this integrated framework. By combining expertise from these fields, more effective strategies can be developed to address the root causes of skin conditions, rather than merely treating symptoms. Additionally, partnerships with biotechnology companies will be instrumental in accelerating the development of innovative products that harness these diverse insights. With the increasing use of AI and deep learning, the potential for personalised skincare solutions will be significantly enhanced. AI-driven tools, such as biosensors that monitor real-time changes in skin conditions, can provide valuable data that inform more precise and targeted treatments. These technologies could allow for adaptive, on-demand therapies that respond to the skin's immediate needs, improving both short-term

and long-term outcomes. By integrating AI with the expertise of dermatologists and other specialists, the future of skincare can become more proactive, personalised, and data-driven, ensuring accessibility to cutting-edge treatments while improving patient care and skin health.

CONCLUSION

The concept of 'educating the skin' offers a groundbreaking, proactive framework for dermatology, integrating the fundamental pillars of skin health: biological mechanisms, microbial symbiosis, environmental adaptation, and neural function. By shifting the focus from reactive symptom management to prevention, adaptability, and resilience, this paradigm has the potential to transform dermatological care. Current evidence underscores the importance of addressing skin health at multiple levels, from fortifying the epidermal barrier and balancing the microbiome to mitigating environmental stressors and enhancing neural interactions.

The integration of advanced technologies and scientific insights into skin biology is essential for realising the full potential of this approach. The role of AI is pivotal, enabling precise analysis of inter-individual variability and supporting the personalisation of interventions. By identifying genetic, environmental, and microbial factors that contribute to chronic skin conditions, AI tools can facilitate targeted strategies, ensuring interventions are tailored to the unique needs of each patient. Looking forward, advancements in AI and personalised medicine will continue to propel this approach, fostering interdisciplinary collaboration between dermatologists, researchers, and technologists. By connecting these elements, educating the skin not only strengthens resilience but also redefines the standard of care, emphasising prevention, patient-centred strategies, and long-term well-being. This innovative framework has the potential to elevate dermatological outcomes and improve quality of life, making it a cornerstone for the future of dermatology. Through this lens, the skin is no longer just treated; it is empowered to thrive in harmony with its environment.

References

1. Eyerich S et al. Cutaneous barriers and skin immunity: differentiating a connected network. *Trends Immunol.* 2018;39(4):315-27.
2. Cope H et al. Transcriptomics analysis reveals molecular alterations underpinning spaceflight dermatology. *Commun Med.* 2024;4(1):1-18.
3. Inchingolo AD et al. The integumentary system and its microbiota between health and disease. *J Biol Regul Homeost Agents.* 2021;35(2 Suppl_1):303-21.
4. Ongoro G et al. Skin inclusion: addressing deficits in medical education to promote diversity in dermatological diagnosis and treatment. *Clin Cosmet Investig Dermatol.* 2023;16:3481-5.
5. Agostini L et al. A management perspective on resilience in healthcare: a framework and avenues for future research. *BMC Health Serv Res.* 2023;23:774.
6. Salazar A, von Hagen J. Circadian oscillations in skin and their interconnection with the cycle of life. *Int J Mol Sci.* 2023;24(6):5635.
7. Slominski AT et al. Melatonin and the skin: current progress and perspectives for human health. *J Invest Dermatol.* 2025;145(6):1345-60.e2.
8. Slominski RM et al. Neuro-immuno-endocrinology of the skin: how environment regulates body homeostasis. *Nat Rev Endocrinol.* 2025;21(8):495-509.
9. Slominski AT et al. Melatonin, mitochondria, and the skin. *Cell Mol Life Sci.* 2017;74(21):3913-25.
10. Slominski A et al. Melanocytes as "sensory" and regulatory cells in the epidermis. *J Theor Biol.* 1993;164(1):103-20.
11. Guo L et al. Recent advances and progress on melanin: from source to application. *Int J Mol Sci.* 2023;24(5):4360.
12. Baker P et al. Skin barrier function: the interplay of physical, chemical, and immunologic properties. *Cells.* 2023;12(23):2745.
13. Elias PM. Optimizing emollient therapy for skin barrier repair in atopic dermatitis. *Ann Allergy Asthma Immunol.* 2022;128(5):505-11.
14. Chamlin SL et al. Ceramide-dominant, barrier-repair lipids improve childhood atopic dermatitis. *Arch Dermatol.* 2001;137(8):1110-2.
15. Luger T et al. Atopic dermatitis: role of the skin barrier, environment, microbiome, and therapeutic agents. *J Dermatol Sci.* 2021;102(3):142-57.
16. Ridd MJ et al. Effectiveness and safety of lotion, cream, gel, and ointment emollients for childhood eczema: a pragmatic, randomised, phase 4, superiority trial. *Lancet Child Adolesc Health.* 2022;6(8):522-32.
17. Lefèvre-Utile A et al. Five functional aspects of the epidermal barrier. *Int J Mol Sci.* 2021;22(21):11676.
18. Slominski A, Wortsman J. Neuroendocrinology of the skin. *Endocr Rev.* 2000;21(5):457-87.
19. Slominski AT et al. Neuroendocrine signaling in the skin with a special focus on the epidermal neuropeptides.

- Am J Physiol Cell Physiol. 2022;323(6):C1757-76.
20. Slominski AT et al. Sensing the environment: regulation of local and global homeostasis by the skin's neuroendocrine system. *Adv Anat Embryol Cell Biol.* 2012;212:v,vii,1-115.
 21. Kupper TS, Fuhlbrigge RC. Immune surveillance in the skin: mechanisms and clinical consequences. *Nat Rev Immunol.* 2004;4(3):211.
 22. Zhou L et al. The roles of skin langerhans cells in immune tolerance and cancer immunity. *Vaccines (Basel).* 2022;10(9):1380.
 23. Takahashi S et al. Homeostatic pruning and activity of epidermal nerves are dysregulated in barrier-impaired skin during chronic itch development. *Sci Rep.* 2019;9(1):8625.
 24. Nguyen MQ et al. Single-nucleus transcriptomic analysis of human dorsal root ganglion neurons. *eLife.* 2021;10:e71752.
 25. Theodorou IM et al. Cosmeceuticals: a review of clinical studies claiming to contain specific, well-characterized strains of probiotics or postbiotics. *Nutrients.* 2024;16(15):2526.
 26. Haykal D et al. Dermatological health in the light of skin microbiome evolution. *J Cosmet Dermatol.* 2024;23(12):3836-46.
 27. Dréno B et al. Microbiome in healthy skin, update for dermatologists. *J Eur Acad Dermatol Venereol.* 2016;30(12):2038-47.
 28. Dréno B et al. The skin microbiome: a new actor in inflammatory acne. *Am J Clin Dermatol.* 2020;21(Suppl 1):18-24.
 29. Bowe W et al. Acne vulgaris, probiotics and the gut-brain-skin axis: from anecdote to translational medicine. *Benef Microbes.* 2014;5(2):185-99.
 30. Bae IH et al. A comprehensive review of the acne grading scale in 2023. *Ann Dermatol.* 2024;36(2):65-73.
 31. Landemaine L et al. Staphylococcus epidermidis isolates from atopic or healthy skin have opposite effect on skin cells: potential implication of the AHR pathway modulation. *Front Immunol.* 2023;14:1098160.
 32. Brown MM, Horswill AR. Staphylococcus epidermidis-skin friend or foe? *PLoS Pathog.* 2020;16(11):e1009026.
 33. Grinnell M et al. Probiotics in acne and rosacea: a systematic review. *J Am Acad Dermatol.* 2019;81(4):AB258.
 34. Frankel D, Lio P. The role of topical probiotics for atopic dermatitis: a systematic review. *J Integr Dermatol.* 2023;DOI:10.64550/joid.cfqv4r95.
 35. Flint E et al. Topical probiotics decrease the severity of atopic dermatitis in children and adults: a meta-analysis of double-blind, randomized, placebo-controlled trials. *Cureus.* 2024;16(9):e70001.
 36. Liu XF et al. Regulation of short-chain fatty acids in the immune system. *Front Immunol.* 2023;14:1186892.
 37. Kortekaas Krohn I et al. The influence of lifestyle and environmental factors on host resilience through a homeostatic skin microbiota: an EAACI Task Force Report. *Allergy.* 2024;79(12):3269-84.
 38. Belzer A, Parker ER. Climate change, skin health, and dermatologic disease: a guide for the dermatologist. *Am J Clin Dermatol.* 2023;24(4):577-93.
 39. Choi EH, Kang H. Importance of stratum corneum acidification to restore skin barrier function in eczematous diseases. *Ann Dermatol.* 2024;36(1):1-8.
 40. Biazus Soares G et al. The mind-skin connection: a narrative review exploring the link between inflammatory skin diseases and psychological stress. *J Eur Acad Dermatol Venereol.* 2024;38(5):821-34.
 41. Nomura T, Kabashima K. Advances in atopic dermatitis in 2019-2020: endotypes from skin barrier, ethnicity, properties of antigen, cytokine profiles, microbiome, and engagement of immune cells. *J Allergy Clin Immunol.* 2021;148(6):1451-62.
 42. Slominski RM et al. Photo-neuro-immuno-endocrinology: how the ultraviolet radiation regulates the body, brain, and immune system. *Proc Natl Acad Sci U S A.* 2024;121(14):e2308374121.
 43. Slominski AT et al. Biological Effects of CYP11A1-derived vitamin D and lumisterol metabolites in the skin. *J Invest Dermatol.* 2024;144(10):2145-61.
 44. Haykal D et al. What happens when simulations get real and cosmetic dermatology goes virtual? *J Cosmet Dermatol.* 2023;22(10):2682-4.
 45. Haykal D. Emerging and pioneering AI technologies in aesthetic dermatology: sketching a path toward personalized, predictive, and proactive care. *Cosmetics.* 2024;11(6):206.
 46. Nicolaou A, Kendall AC. Current insights into skin lipids and their roles in cutaneous health and disease. *Curr Opin Clin Nutr Metab Care.* 2023;26(2):83-90.
 47. Usui K et al. TRPV1-positive sensory nerves and neuropeptides are involved in epidermal barrier repair after tape stripping in mice. *J Allergy Clin Immunol.* 2024;153(3):868-73.e4.
 48. Bhattad PB, Pacifico L. Empowering patients: promoting patient education and health literacy. *Cureus.* 2022;14(7):e27336.
 49. Zirwas MJ, Holder JL. Patient education strategies in dermatology: part 1: benefits and challenges. *J Clin Aesthet Dermatol.* 2009;2(12):24-7.
 50. de Bes J et al. "Patient education in chronic skin diseases: a systematic review," Database of abstracts of reviews of effects (DARE): quality-assessed reviews. [Internet] (2011) The University of York. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK81420/>. Last accessed: 18 November 2024.
 51. Swaney MH, Kalan LR. Living in your skin: microbes, molecules, and mechanisms. *Infect Immun.* 2021;89(4):e00695-20.
 52. Vainauskienė V, Vaitkienė R. Enablers of patient knowledge empowerment for self-management of chronic disease: an integrative review. *Int J Environ Res Public Health.* 2021;18(5):2247.
 53. Barnes TM et al. Vehicles for drug delivery and cosmetic moisturizers: review and comparison. *Pharmaceutics.* 2021;13(12):2012.
 54. Lippman D et al. Foundations of lifestyle medicine and its evolution. *Mayo Clin Proc Innov Qual Outcomes.* 2024;8(1):97-111.
 55. Cowan S et al. Inflaming public interest: a qualitative study of adult learners' perceptions on nutrition and inflammation. *Nutrients.* 2020;12(2):345.
 56. Arlinghaus KR, Johnston CA. The importance of creating habits and routine. *Am J Lifestyle Med.* 2018;13(2):142-4.
 57. Haykal D et al. The art of a successful cosmetic consultation in 2023. *J Eur Acad Dermatol Venereol.* 2023;37(9):e1166-7.
 58. Price K et al. Education and process change to improve skin health in a residential aged care facility. *Int Wound J.* 2017;14(6):1140-7.