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Repairing a Compromised Skin Barrier in Dermatitis: Leveraging the Skin's Ability to Heal Itself

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Abstract

Skin barrier defects play a major role in many dermatoses including irritant and allergic contact dermatitis, atopic dermatitis, dry skin, aged skin, xerosis, rosacea, acne and more. Skin barrier repair technology has heretofore focused on physiologic skin lipid replacement and skin protection without addressing the myriad other areas of compromise such as an elevated pH, balance of the microbiome, inflammation, succeptibility to infection, aberrant calcium gradients and the proclivity for contact sensitization. By changing the paradigm from physiologic skin lipid supplementation to that of supplementing the epidermis with lipids that have recently been found to be particularly deficient from the disrupted skin barrier, and by simultaneously addressing the many facets of vulnerability, the skin barrier can be effectively repaired. This model of advanced skin barrier repair wherein physiologic deficiencies are supplemented and/or augmented may be an effective method for restoring the ability of xerotic and dermatitic skin to heal itself.

Keywords: Skin barrier repair; Ceramide; Phytosphingosine; Cholesterol ester; 18-β Glycyrrhetinic acid; Niacinamide; pH; Calcium chelation; Silicone; Paraffin

Abbreviations: ACD: Allergic Contact Dermatitis; AD: Atopic Dermatitis; AHAs: Alpha Hydroxy Acids; GLU: Gluconolactone; ICD: Irritant Contact Dermatitis; PPAR: Peroxisome Proliferator Activated Receptor; TEWL: Transepidermal Water Loss

Introduction

A compromised skin barrier plays a major role in many dermatoses including irritant and allergic contact dermatitis, atopic dermatitis, dry skin, aged skin, xerosis, rosacea, and acne [1–5]. Many of these conditions share common defects in the skin barrier and an association with inflammation [4,6]. The knowledge we have regarding specific lipid deficiencies, pH aberration, inflammation, irregular calcium gradients, and susceptibility to contact sensitization can be leveraged to address many aspects of the disrupted skin barrier. By addressing these major points of vulnerability the skin's inherent ability to heal itself can be optimized for skin barrier repair.

Dermatitis is a term that includes irritant and allergic contact dermatitis, atopic dermatitis and many other conditions that are explained by skin barrier disruption and dysfunction. An association with inflammation and, in many cases, exacerbation from chemical irritants and allergens is common (Figure 1). We will discuss the commonalities of skin barrier compromise in dermatitis and other forms of skin barrier disruption. We will discuss the role that skin barrier dysfunction plays in these conditions, how to leverage the strengths of the skin's barrier repair pathways to stimulate skin barrier repair, and the optimal features of skin barrier repair products.

ACD and ICD are associated with skin barrier defects that may be a result of exogenous (the nature of an irritant or allergen, exposure concentration, duration, chronicity, and other mechanical factors) and endogenous factors [7]. In atopic dermatitis, there are several known inherent skin barrier defects including specific lipid deficiencies and fillagrin null mutations [8–10]. Though the specific etiology of ACD, ICD and AD may be variable, all three conditions have similar deficiencies that drive the disease state. All three conditions are initiated as a result of skin barrier defects that lead to the activation of inflammatory mediators such as IL-1 and TNFα [5,11,12]. These pro-inflammatory mediators set into motion inflammatory cascades in an effort to induce reparative processes and restore skin barrier function [13]. Unfortunately, the role of inflammation may overshoot the skin barrier repair mechanisms and result in dry, scaly, inflamed, and irritated skin.

For protection, the skin utilizes the following types of barriers: physical, biochemical, redox, and immune [4]. The epidermis makes up the physical barrier that is the first line of defense, mostly attributed to the protective effects of the stratum corneum which includes the lipid bilayer, the acid mantle (one contributor to the acidic pH of the epidermis), a calcium gradient which influences desquamation and cellular turnover and differentiation of the epidermis, and the many aspects of the cutaneous immune system [14]. The epidermis is able to provide protection from solids, liquids, and gases in addition to warding off attacks from viruses, bacteria, fungi, and other microbes [15].

Points of Vulnerability

A disrupted skin barrier has many points of vulnerability including excessive water loss, slow/deficient lipid production, an imbalance in content and ratio of skin lipids, a dry skin barrier, an elevation of pH, susceptibility to infection and inflammation, and susceptibility to contact sensitization [16–19]. There have been many approaches to induce and enhance skin barrier repair in chronic dermatitis. Some products have focus on skin barrier protection or physiologic skin lipid replacement or inflammation. To effectively heal the skin barrier, trans-epidermal water loss (TEWL) must be minimized and the skin must be protected

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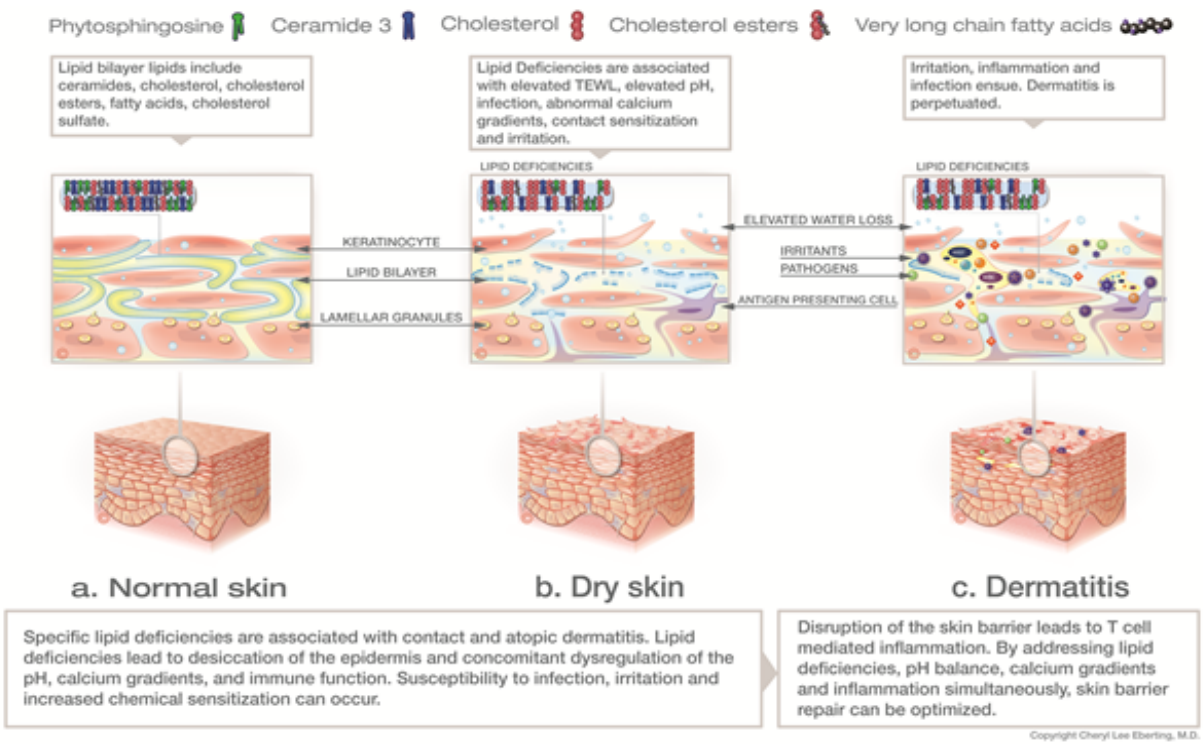

Figure 1: The epidermal barrier plays an important role in many dermatoses. Copyright of Cheryl Lee Eberting, M.D.

from further contact with irritants, allergens, and infectious organisms [20]. Ideally, the skin pH would be optimized to encourage natural ceramide production and to discourage the growth of pathogens while encouraging the growth of a healthy microbiome [21,22]. Modulation of the disrupted calcium gradient may restore appropriate levels of desquamation [23]. Inflammation must also be minimized while all sensitizers, irritants and proinflammatory mediators should be avoided [24]. By addressing all of these points of vulnerability simultaneously, the skin's ability to itself may be optimized.

Skin Barrier Heal

Current medical and scientific literature provides insight to the characteristics, features, and classes of ingredients able to address the aforementioned vulnerabilities of the disrupted epidermis in chronic dermatitis.

Lipid Replacement

Close examination has revealed that much of the barrier protection from the epidermis comes from stratum corneum lipids. The lipids are arranged in a highly organized structure with controlled ratios. When these ratios or structure are interrupted or unbalanced, barrier function is compromised which gives microbes and allergens unencumbered entrance to the deeper layers of the skin where inflammatory pathways are triggered [15,25].

Current therapeutic options include products which address skin barrier repair by supplementing the skin with lipids in physiologic ratios, while other products have employed behentrimonium methosulfate, a cationic surfactant quaternary ammonium salt, as part of a dynamic lipid delivery system [20,26]. Several specific lipid deficiencies have been elucidated in many forms of chronic dermatitis. Phytosphingosine-containing ceramides such as ceramide 3 [27–29], and possibly phytosphingosine itself are deficient in conditions such as dry skin, aged skin, and in atopic skin. In fact, as dryness levels of the skin increase, so does the degree of phytosphingosine-containing ceramide deficiency [27,30,31]. Marked deficiency in ceramide 3 (N-Acyl phytosphingosine) has also been well-documented in atopic skin and correlated to increased TEWL [32].

Cholesterol esters are deficient relative to cholesterol in xerotic skin [33] and in SDS-induced dry skin (Figure 2). The overall sterol content is preserved, but the ratio of cholesterol to cholesterol esters is increased with an excess relative concentration of cholesterol [27,33]. When SDS-induced dry skin treated with 1% cholesterol base was compared to 1% cholesterol ester base, the cholesterol ester treated skin showed improved conductance values while the cholesterol-treated skin did not [34]. Atopic skin has also been shown to have abnormally elevated levels of cholesterol [32]. Cholesterol esters are esterified to short, medium, long, and very long chain fatty acids. Based on these studies of chronic dermatitis conditions where the cholesterol:cholesterol ester ratio has been shown to be elevated as compared to normal skin, it may be optimal to supplement the skin with cholesterol esters rather than with cholesterol as has traditionally been done by many physiologic skin lipid replacement products. Indeed, it may not be necessary and may possibly be less efficacious, to supplement, xerotic, atopic, and SDS-induced dry skin with unesterified cholesterol, because the cholesterol:cholesterol ester ratios in these conditions have been shown to be abnormally elevated. (Figures 2-5) Of note however, cholesterol itself was shown to aid barrier recovery in a tape stripping model in aged skin, but not in young skin [35]. The aged skin in this study was not controlled for ingestion of cholesterol lowering medications. Of note, a disease of unknown etiology in aged skin, Grover's disease, is

Figure 2: Irritant "Lip-licker's Dermatitis" Before and eight hours after a single application of a preservative-free ointment that contains skin barrier lipids, isostearyl isostearate, petrolatum, paraffin wax and 18-β glycyrrhetinic acid. Photos copyright of Cheryl Lee Eberting, M.D.

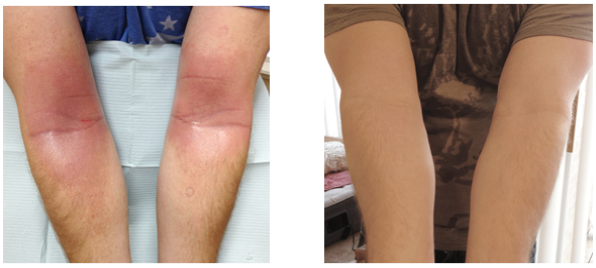

Figure 3: Atopic and allergic contact dermatitis due to lanolin. R. arm was treated with 0.1% Triamcinolone ointment and L. arm was treated with a preservative-free ointment that contains skin barrier lipids, isostearyl isostearate, petrolatum, paraffin wax and 18-β glycyrrhetinic acid. Photos copyright of Cheryl Lee Eberting, M.D.

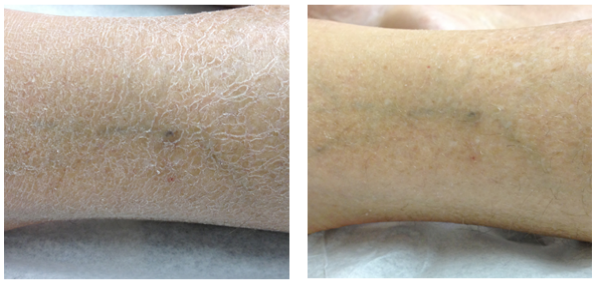

Figure 4: Severe Xerosis before and 30 seconds after application of a preservative-free ointment that contains skin barrier lipids, isostearyl isostearate, petrolatum, paraffin wax 18-β glycyrrhetinic acid. Photos copyright of Cheryl Lee Eberting, M.D.

frequently benefited from cholesterol ester-containing skin barrier repair products. Author's experience, CLE (Figure 6).

Fatty acid deficiency also contributes to a disrupted skin barrier. Long chain fatty acids like palmitic (C16) and stearic acids (C18) are known to be deficient in atopic skin [36], but more recent studies have shown a particular deficiency in the very long chain fatty acids cerotic (C26) montanic, (C28), and melissic (C30) acids [37]. Very long chain fatty acids are naturally occuring in candelilla wax. Candelilla wax is accessible, affordable, and has only one reported case of contact sensitization [38].

Inflammation

The use of molecules with inherent anti-inflammatory qualities has been shown to be effective in many forms of skin barrier disruption [39]. Glucocorticoids are most commonly prescribed for this purpose, but non-glucocorticoid molecules also show anti-inflammatory qualities [40]. An over the counter petrolatum and lanolin-based product that employs bisabolol as an anti-inflammatory agent has shown comparable efficacy to a prescription medical device cream [41]. Increasing numbers of contact sensitization to this product are being reported in patients who are using it to treat dermatitis. Those who are sensitized to bisabolol should be counseled to avoid any bisabolol-containing products [42–44].

18β-Glycyrrhetinic acid exhibits corticosteroid-like anti-inflammatory, anti-allergic activity, and many other benefits in contact dermatitis. In vitro, glycyrrhetic acid is known to inhibit Δ4β-reductase, an enzyme that competitively inactivates steroid hormones, and 11β-hydroxysteroid dehydrogenase, an enzyme that deactivates cortisol [45]. Inhibiting the metabolism of naturally occurring cortisol enhances the body's natural anti-inflammatory capacity by potentiating the activity of endogenous (and possibly even exogenously applied) corticosteroids. When used in formulation by it or with a glucocorticoid, glycyrrhetinic acid may augment and extend the effectiveness of glucocorticoids, allowing the use of less-potent glucocorticoids and/or a shorter course of treatment. This could limit overall glucocorticoid exposure and associated side effects. When a metabolic precursor to 18β-glycyrrhetinic acid was given intraperitoneally, it suppressed contact dermatitis in mice with higher efficacy than prednisolone. When administered orally, it was ineffective [46]; possibly highlighting the necessity to deliver the active molecule directly to the area of contact dermatitis. This same molecule is bactericidal to MRSA and has anti-candidal effects [47,48], a beneficial characteristic when treating disrupted skin that particularly is susceptible to these organisms. This molecule has skin brightening and lightening effects [49] and thus may have additional benefits for dermatitis associated with

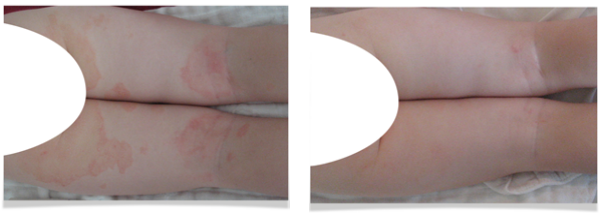

Figure 5: Atopic Dermatitis before and after ten days twice daily application of a hypoallergenic skin barrier repair cream that contains skin barrier lipids, isostearyl isostearate, petrolatum, niacinamide, gluconolactone, 18-β glycyrrhetinic acid, gluconolactone and EDTA. Photos copyright of Cheryl Lee Eberting, M.D.

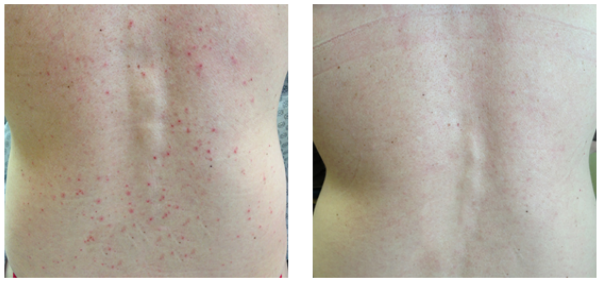

Figure 6: Grover's Disease before and after ten days of twice daily application of a preservative-free ointment that contains skin barrier lipids, isostearyl isostearate, petrolatum, paraffin wax and 18-β glycyrrhetinic acid. Photos copyright of Cheryl Lee Eberting, M.D.

post-inflammatory hyperpigmentation in light and darker-skinned individuals [49]. This molecule also has photoprotective benefits. After UV exposure, it reduced ROS, NF-KB, cytochrome c, and caspase 3 levels and inhibited hyaluronidase, possibly by inhibition of MMP1 activation by modulating NF-KB signaling [50]. Feeding mice with this molecule prior to UVB radiation caused delays in tumor appearance, multiplicity, and size [51]. This molecule also offers protection from UVB radiation damage in humans [52].

Niacinamide, a B vitamin and possible Peroxisome Proliferator-Activated Receptor (PPAR) ligand, has been shown to up regulate fillagrin and involucrin synthesis [53]. It has been proven effective in the treatment of many forms of a disrupted skin barrier [54-56]. Niacinamide also suppresses antigen-induced lymphocytic transformation, an added benefit that may minimize rates of contact sensitization. Niacinamide also inhibits 3'-5' cyclic AMP phosphodiesterase, and blocks the inflammatory actions of iodides [57]. Niacinamide increases the thickness of the epidermis [58] while inducing de novo ceramide production through up-regulated expression of serine palmitoyltransferase, the rate-limiting enzyme in sphingolipid synthesis [59]. Ceramides are effective in blocking the reduction, and even stimulating the synthesis, of collagen after UV irradiation [60]. Niacinamide shows improved facial wrinkle appearance and tolerability compared to tretinoin [61]. Additionally, a niacinamide-containing moisturizer applied with tretinoin therapy enhanced the response to tretinoin, improved the stratum corneum, and decreased tretinoin-associated side-effects [62]. Niacinamide is well tolerated by the skin and provided significant improvements versus control in fine lines/wrinkles, hyperpigmentation spots, texture, red blotchiness, elasticity, and skin yellowing versus an oil in water moisturizer control [63,64]. Both niacinamide and 18-β glycyrrhetinic acid are optimal anti-inflammatory molecules for optimizing repair of the compromised skin barrier.

pH Modulation

The pH of the epidermis becomes abnormally elevated in the setting of dermatitis, infection, or from contact with alkaline substances such as soap, bleach, solvents and even tap water [65]. The optimal pH of the skin is between 4.6 and 5.6 which is ideal for ceramide production. The skin lipid-producing enzymes β-glucocerebrosidase and acid sphingomyelinase both have optimal levels of activity within this pH range [21,22]. When the skin is overly alkaline, both serine protease-mediated inactivation and metabolism of the **β**-glucocerebrosidase and acid sphingomyelinase enzymes take place. Ceramide and lipid production slows or comes to a halt [66]. The disrupted and alkaline skin barrier is unable to support a healthy microbiome. Staphylococcus aureus, Candida, and Propionibacterium acnes all grow more effectively in an alkaline environment. Natural skin flora also become compromised at an elevated pH [67,68]. This shift in the microbiome of the skin may lead to a cycle of increased alkalinity, infection, and a disrupted epidermal barrier. Additionally, as the pH reaches and exceeds 5.7, there is inhibition of lamellar body secretion and corneo-desmosome-constituent proteins can be degraded [66].

Acidification and even hyper-acidification of the epidermis has been shown to decrease TEWL [69]. In fact, a common technique for acidifying topical skin care formulations is the addition of acidic salts, such as citric or lactic acids. These acids are uncommon sensitizers, but are prone to crystallization, which can result in irritation of the skin. Alpha Hydroxyacids (AHAs) are also used to modulate the pH of the skin and to enhance stratum corneum desquamation and improve skin appearance. Unfortunately, AHAs result in sunburn cell formation and increase the risk of skin cancer. The FDA now requires a sun-burn warning on products containing AHAs [70]. A natural polyhydroxy acid, Gluconolactone (GLU) is a free radical scavenger and is a superior TEWL inhibitor when compared to several other acids [69,71]. Additionally, GLU is known to enhance stratum corneum desquamation, improve skin appearance, prevent skin irritation, and is protective against UV radiation-induced elastin promoter activation [71]. GLU treatment does not result in a significant increase in sunburn cells. UV absorption of GLU is low, so the UV protective effect must be due to other mechanisms, such as its ability to function as a chelating agent and free radical scavenger [71]. Additionally, GLU does not crystalize and become an irritant to the skin as easily as citric and lactic acid, making it an optimal epidermal acidifier (CLE, unpublished author observation).

Skin Barrier Protection

Effective transepidermal water loss inhibition

TEWL measurements can be used as a marker for skin barrier integrity. Improvements in TEWL have been tied to improvements in SCORAD scores in atopic dermatitis and are considered a marker for stratum corneum integrity and hydration [20]. In addition to the TEWL lowering benefits of sphingolipid and cholesterol ester fractions, TEWL inhibitors like petrolatum, dimethicone and other lipid fractions are commonly used as skin protectants. Petrolatum is considered to be the gold standard TEWL inhibitor [72]. In an effort to explore possible alternatives to petrolatum, the author subjectively tested countless plant-based petrolatum substitutes and was unable to find one that matched the characteristics of petrolatum including: hypoallergenicity, hydration, taste, viscosity, melting temperature, and non-desiccating effects on palmar and lip skin (as these areas tend to become most-easily irritated/tight when they are desiccated). Petrolatum is a complex semi-solid combination of paraffin wax, microcrystalline wax and white mineral oil. Paraffin wax is even more impermeable to water than petrolatum and when combined with petrolatum, is also an extremely efficient TEWL inhibitor.

Dimethicone, a man-made polymer of the naturally occurring element silica or silicon, is a very common skin protectant. Silicon is naturally present in very small amounts in the human body and may be associated with bone health [73]. Silicone and dimethicone are manufactured by polymerizing silicon with carbon, hydrogen and oxygen. The human body does not have the ability to metabolize these polymers and in fact, when human monocytes were incubated on dimethicone, they secreted variable levels of IL-1 beta, IL-6 and TNF-alpha [24]. Furthermore, dimethicone has the potential to cause an inflammatory reaction when implanted [74]. When five different silicone materials were tested for skin sensitization potential, the murine local lymph node assay showed weak to moderate skin sensitization potential for four of the five materials. Sensitization via cutaneous contact or via injection or implantation is increasingly reported in the literature. Reactions include allergic contact dermatitis, granuloma formation, systemic sclerosis, and a psoriasiform eruption, among others [75-78]. Rates of sensitization to silicone and silicone polymers are increasing in both topical and implanted exposures [79-81].

While it is technically difficult to objectively study a skin protectant's ability to prevent penetration of allergens, irritants, and microbes into the skin, there are three objective measures that may be used to determine a product's or ingredient's effectiveness in these areas: 1) if a product or molecule has superior hydrophobicity; 2) lower water solubility; and 3) a higher melting point than another, it may be more

difficult to wash off and therefore more efficient at preventing contact with irritants, allergens and pathogens. Solvent permeability and penetration characteristics are also to be considered.

Hydrophobicity

Hydrophobicity is the measure of a product or ingredient's degree of repellency from a mass of water. Hydrophobic molecules are non-polar and prefer other neutral molecules. The hydrophobicity of a skin barrier product or ingredient can be objectively measured by determining the contact angle, or the angle measured through the liquid where a liquid/vapor interface meets a solid surface, of a drop of water applied to the product in question. The contact angle is also directly correlated with a molecule's ability to adhere to a surface. While there are many variables that can alter the contact angle of a molecule, hydrophobicity can be subjectively measured by observing how easily water will bead and roll off of the skin. A product that is very hydrophobic will have a high contact angle, causing water to bead more efficiently [82]. The higher the contact angle, the more hydrophobic and adherent to the skin the molecule is. The largest contact angles measured between water and a smooth surface are with paraffin. Paraffin is a mixture of saturated aliphatic hydrocarbons and is considered to be the most hydrophobic water-repelling agent [83]. By comparison, to reach this range of hydrophobicity, dimethicone must be applied to a smooth surface such as glass and then must be baked on [84]. The contact angle of paraffin is between 106 and 112 degrees and is dependent on the texture of the surface and the purity of the paraffin [83]. Paraffin is composed of non-polar alkane chains that, like the methyl groups in silicone fluid, have hydrophobic properties. They interact very weakly with water molecules so water stays in a drop and does not wet the paraffin wax.

Melting point

The melting points of skin protectant molecules may be another indicator of their persistence on the skin after washing and effectiveness. The melting point of paraffin wax ranges from 47°C up to 65°C depending on which grade of wax is used [85]. The melting point of dimethicone is generally below 50°C (depending on which polymer is used) [86].

Water solubility

Water solubility is an objective variable that can be used to assess the effectiveness of a skin protectant. The water solubility of an ingredient is an important indicator of its ability to protect the skin from water, allergens and irritants. The water solubility of dimethicone is 33-77 g/l, while paraffin wax is insoluble in water [87].

In addition to petrolatum, paraffin wax, and dimethicone, many lipid-based TEWL inhibitors have also been investigated. These lipids include glyceryl monoisostearate, isopropyl isostearate, isostearyl isostearate, cetyl alcohol, potassium cetyl phosphate, cetyl behenate and behenic acid [88,89]. Isostearyl Isostearate has been proven to be the most effective lipid-based TEWL inhibitor in these studies [88].

Calcium chelation

Forslin et al. were able to use a scanning nuclear microprobe to map calcium distribution in cross sections of normal, atopic, and psoriatic skin. In normal skin, calcium localizes to the uppermost granular layer of the epidermis as well as to the basal and spinous layers. Forslind et al. found that psoriatic and dry atopic skin had an epidermal calcium gradient higher than normal skin [90]. Calcium is a necessary part of the apoptotic process, and increased intracellular calcium may induce the activation of endonuclease, transglutaminase, and morphological changes [90]. Lee et. al., showed that removal of extracellular calcium stimulates both lamellar body secretion and lipid synthesis, while also blunting those responses when extracellular calcium concentration was raised for hairless mice [91]. Calcium also seems to impair corneodesmin hydrolysis with incomplete desquamation at alkaline pH and without the presence of EDTA [23]. The final step appears to be inhibited by calcium, resulting in incomplete desquamation and residual intercorneocyte cohesion in cases of skin barrier disruption. The skin's naturally occurring chelating agent is unknown, but calcium chelation in a lower pH environment and in the presence of EDTA allows this step to proceed [92]. Therefore, weak calcium chelation may benefit a disrupted skin barrier by improving desquamation. Gluconolactone and EDTA are both mild chelating agents that can safely be used in skin barrier repair formulations to help optimize desquamation.

Susceptibility to contact sensitization

Those with fillagrin null mutations have been found to have increased rates of ACD particularly to lanolin and p-tert-butylphenol-formaldehyde resin [93]. Research regarding the relevance of ACD in atopic dermatitis is emerging [17,94,95]. Those with atopic dermatitis are more likely to develop contact sensitization to certain chemicals relative to non-atopics. Formaldehyde-releasers [18], cocamidopropylbetaine [96] nickel, cobalt, chromium [16], Kathon CG, fragrance, neomycin [97], and propolis (from beeswax but found in cough syrup, pills, cosmetics, and vitamins) are advisably avoided in atopic dermatitis in the setting of contact dermatitis as atopics are possibly more likely to develop contact dermatitis [96].

Discussion

Techniques that optimize skin barrier repair include skin lipid replacement, pH modulation/optimization, the use of anti-inflammatory molecules, the use of mild calcium chelation, and the overt avoidance of known skin irritants and allergens in formulation. The effectiveness of a skin barrier repair and protectant product may also be determined by its ability to adhere to the skin and its ability to prevent the contact of water, irritants, allergens, and solvents from coming in contact with the skin. These qualities may be a function of a product's hydrophobicity, melting point, and water solubility.

Conclusion

A healthy skin barrier protects from pathogens, allergens, toxins, and irritants. When the skin's leading physical barrier, the stratum corneum, is damaged as a result of disease or acute destruction, the deeper layers of the epidermis and dermis are vulnerable to further irritation and sensitization. Finding ways to protect the skin and repair its natural barrier qualities is a major goal in reducing the incidence of chronic dermatitis. Utilizing the large amount of existing and recent data on different chemicals' interaction with the stratum corneum and the skin barrier to create novel products based on evidence-based medicine is essential to improving treatment outcomes. Further research and investigation into the skin's barrier function and our ability to enhance its protective qualities is paramount to the future treatment of these patients.

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