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INVESTIGATIVE REPORT

Mechanical Properties and Barrier Function of Healthy Human Skin

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The aim of this study was to investigate the relationship between the mechanical properties and the epidermal barrier function of the skin *in vivo*. A suction cup device commonly used for measurement of skin mechanics was used to provide a defined stress to the skin using the ventral forearm in 16 healthy volunteers. The integrity of the barrier function was assessed by trans-epidermal water loss and skin capacitance. In the first part of the study, changes in barrier function were measured following the application of standardized strain to the skin barrier. In the second part of the study changes in skin mechanics were assessed following standardized barrier removal. The Wilcoxon signed rank test and Spearman's rank correlation were used for statistical analysis. Significant increases were established in trans-epidermal water loss ($p < 0.01$) with concomitant significant decreases in capacitance ($p < 0.05$) following 400 mbar and 600 mbar of suction, suggesting that the mechanical integrity of the skin barrier was disrupted. A significant increase in distensibility ($p < 0.05$) and hysteresis ($p < 0.01$) was found following stripping, relating the role of the skin barrier to the overall mechanical properties of the skin. This study showed that the water permeability of the epidermis was significantly affected by the application of mechanical stress to the skin and vice versa, the mechanical properties of the skin were altered when the barrier was compromised. These observations suggest that the mechanical strength of the skin barrier may play a role in the development of, for example, friction dermatitis and other skin diseases affected by mechanical stress. *Key words: mechanical properties of skin; skin barrier; non-invasive methods.*

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The skin must allow repeated reversible extensions and compressions with the general movement of the individual while simultaneously acting as an impermeable barrier in order to maintain the homeostasis of the organism. On a macroscopic level the presence of creases and wrinkles in the skin provides a means of absorbing linear forces by changing them into angular forces. The actual mechanical properties of the skin, however, reside mainly in the collagen and elastic fibres of the dermis, whereas the barrier is confined to the uppermost layer of the epidermis, the stratum corneum (1–3).

It may be speculated that the intimate connection between the dermis and the epidermis will necessarily cause a mutual interaction of the functions in question, i.e. extension will result in alterations of the permeability, and a deterioration of the barrier will affect the plasticity of the skin (4–6).

In the present study we sought to establish and evaluate the interaction between the two main functions of the skin: the mechanical properties and the barrier function.

MATERIALS AND METHODS

Sixteen healthy volunteers (5 men and 11 women, age range 31–58 years) participated in the study. None had any history of previous or current diseases confined to the skin, nor had the skin been treated in any way for approximately 2–3 h prior to the examination.

The Dermaflex® (Cortex Technology, Hadsund, Denmark) (7, 8), a suction cup device designed to measure the mechanical properties of the skin, and used previously to assess, for example, the effects of moisturizers (9, 10) was used in this study. It generates a vacuum on the surface of the skin ranging from 100 to 600 mbar and it operates in cycles of suction periods; each cycle lasting 4 s, six cycles equals the completion of one test. The Dermaflex® records three parameters: distensibility, elasticity and hysteresis.

Distensibility is defined as the elevation resulting from a given force applied on the skin, and is expressed in millimetres.

Elasticity, or the relative elastic retraction, describes the ability of the tissue to regain its initial shape after deformation, and is expressed in percentage.

Hysteresis defines the absolute extensibility of the skin resulting from repeated stretches of the same area, and is expressed in millimetres.

The Dermalab TEWL probe® (Cortex Technology, Hadsund, Denmark) (11) was used to measure the permeability of the skin, registered as the trans-epidermal water loss (TEWL). A high TEWL values reflect a reduction in the quality of the barrier with a subsequent high permeability. TEWL is expressed in $g/m^2 \times h$.

The Corneometer CM420®PC (12) was used to measure the level of hydration in the epidermis. The Corneometer® registers the water content by creating an electric field in the epidermis. Capacitance reflects the amount of water confined mainly to the stratum corneum. Hydration is expressed in arbitrary units.

The study was divided into two sections using different randomly chosen areas on the ventral aspect of the left forearm. (*i*) The volunteer was instructed to rest for 5–10 min prior to the examination in order to minimize sweat secretion during the TEWL measurements. An area 3×3 cm on the ventral aspect of the left forearm was marked and TEWL and hydration were recorded. The skin was subsequently stretched with a pressure

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of 100 mbar for 6 consecutive cycles of suction periods, each period lasting 4 s, whereupon TEWL and hydration were recorded again. Another 3×3 cm area was marked and TEWL plus hydration were read. The area was subsequently stretched, this time, a pressure of 200 mbar was applied to the skin. TEWL and hydration were registered by the end of the test. The same procedure was repeated twice on different areas using 400 and 600 mbar of suction, respectively. (*ii*) An area 3×3 cm was marked, TEWL was read, and the mechanical parameters were registered using 600 mbar of suction. With the aim of compromising the barrier, a layer of the stratum corneum was removed using the stripping method. Strips of adhesive tape (Scotch Book tape) were placed on the marked area and subsequently removed in a brisk, single continuous motion. The first strip was removed wrist-to-elbow, the second in the opposite direction, and so on. TEWL was read regularly during the stripping procedure. The procedure was terminated when TEWL reached a value approximately 6 times the initial recording, whereupon the mechanical parameters were registered using 600 mbar of suction (avoiding the area used for the initial measurement). On an adjacent site we registered the mechanical parameters twice as control in order to adjust possible changes in data due to artefacts.

The study was conducted in accordance with the ethical guidelines of the Helsinki II accord, and all participants provided informed consent.

Statistics

The Wilcoxon signed rank test and Spearman's rank correlation were used for statistical analysis. The chosen level of significance was $p < 0.05$.

RESULTS

The results are given in Tables I and II and Figs 1 and 2. No significant changes were found in either TEWL or capacitance following 100 mbar or 200 mbar of suction. Significant increases were established in TEWL ($p < 0.01$) with concomitant significant decreases in the capacitance ($p < 0.05$) following 400 mbar and 600 mbar of suction.

A significant increase in distensibility was found following stripping ($p < 0.05$). Elasticity decreased after stripping, but the tendency was not significant. Hysteresis was the parameter showing the most profound alteration following stripping ($p < 0.01$).

No correlations were found between TEWL and the corresponding mechanical characteristics before or after stripping.

Table II. Characteristics of the mechanical parameters of Dermaflex. Changes in distensibility, elasticity and hysteresis resulting from the removal of layers of the stratum corneum by the stripping method (n = 16). Values are given as mean and 95% confidence interval

	Before stripping	After stripping
Distensibility (mm)	1.70 (1.43–1.97)	1.95 (1.79–2.11)*
Elasticity (%)	62.07 (55.09–69.05)	56.64 (50.57–62.71)
Hysteresis (mm)	0.13 (0.11–0.15)	0.56 (0.33–0.79)**

*$p < 0.05$, **$p < 0.01$.

DISCUSSION

Water permeability of the epidermis was significantly affected by the application of mechanical stress to the skin and vice versa, the mechanical properties of the skin were altered when compromising the barrier.

In accordance with other studies, TEWL and skin capacitance were chosen to describe the integrity of the skin barrier (13–15). An intact barrier function is generally reflected by low TEWL values and high capacitance, whereas barrier disruptions cause increases in TEWL and decreases in capacitance. Following the measured mechanical stress due to the application of multiaxial distension using the Dermaflex, significant increases in TEWL and similar significant decreases in capacitance were seen when more than 400 mbar of suction was applied. This suggests that the mechanical integrity of the barrier function was compromised. It is not likely to be the result of increased skin hydration caused by the migration of fluid from the deeper structures of the skin due to the applied vacuum by the Dermaflex® on the surface of the skin, as any such changes would be registered as an increase in capacitance. In contrast, a reduction in skin capacitance was seen. High levels of TEWL with concomitant low levels of capacitance is an observation in several studies of atopic dermatitis (9, 16, 17). Since this skin disease is characterized by a dry and cracked epidermis, severely affecting the barrier function of the skin, we suggest that similar alterations, though to a lesser extent, have occurred as a result of deformation of the skin in the present study, i.e. barrier damage has occurred.

No changes were found in either TEWL or capacitance following 100 mbar and 200 mbar of suction.

Table I. *Trans-epidermal water loss (TEWL) and capacitance prior and after the application of mechanical stress to the skin, using 100–600 mbar of suction (n = 16), Values are given as mean and 95% confidence interval*

	100 (mbar)	200 (mbar)	400 (mbar)	600 (mbar)
TEWL				
Before suction	14.94 (13.99–15.89)	14.69 (13.39–15.99)	13.99 (12.98–15.00)	14.11 (13.06–15.16)
After suction	15.70 (14.21–17.19)	15.28 (13.98–16.58)	14.59 (13.74–15.44)**	15.58 (14.56–16.60)**
Capacitance				
Before suction	34.38 (29.47–39.29)	31.44 (27.88–35.00)	32.44 (28.54–36.34)	32.63 (28.78–36.48)
After suction	33.38 (29.27–37.49)	31.13 (28.28–33.98)	31.00 (27.12–34.88)*	31.06 (27.80–34.32)*

*$p < 0.05$, **$p < 0.01$.

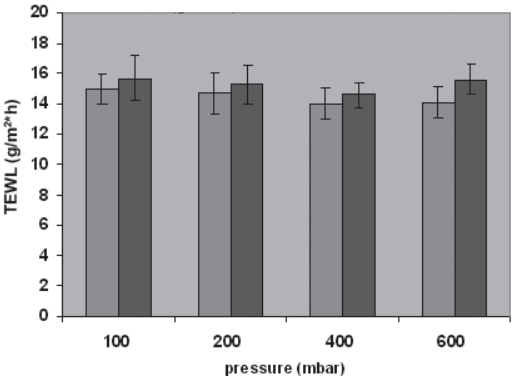

Fig. 1. Mean value of trans-epidermal water loss (TEWL) before (■) and after (■) suction with 95% confidence interval indicated. The figure illustrates the permeability of the skin, measured as the TEWL, prior and after applying mechanical stress to the skin (n = 16).

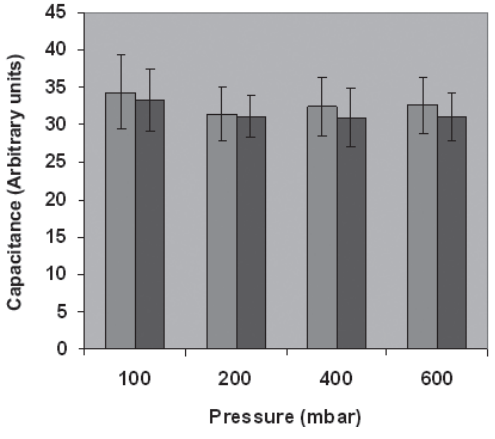

Fig. 2. Mean values of capacitance before (■) and after (■) suction with confidence intervals indicated. The figure illustrates the changes in capacitance resulting from deformation of the skin at four different levels of suction (n = 16).

This indicates that the barrier of the skin can uphold its integrity and withstand distension to a critical point, whereupon the permeability changes significantly. It also suggests that the application of the suction probe did not affect the barrier in itself. The data indicates that mechanical integrity of the stratum corneum *in vivo* has a breaking threshold of somewhere between 200 and 400 mbar (20,000–40,000 N/m^2 or 0.204–0.408 kg/cm^2) in healthy normal individuals. The increase in the permeability resulting from stretching the skin may be speculated to be due to disorganization of the stratum corneum when all slack is taken up and tensile forces are converted into actual deformation.

Since the present study primarily sought to establish a possible connection and interdependence between barrier and mechanics, we allowed a considerable variation between the suction pressures. For further evaluation and quantification between the two parameters in question, additional studies are necessary.

When the barrier is compromised by tape stripping this also leads to significant alterations in the mechanical characteristics of the skin. The increase in distensibility and hysteresis reflects values that closely mimic the mechanical properties of the dermis (1, 18). Similar changes have been observed when hydrating the stratum corneum. This observation is also in accordance with previous studies establishing hysteresis as a possible parameter to changes in the skin barrier (19–21).

The epidermis, in particular the stratum corneum is, compared with the dermis, a rigid and stiff structure. Subsequently, removal of the stratum corneum will cause mechanical recordings that reflect a greater extensibility of the skin. Skin thickness is known to influence the mechanical properties, but the absolute thinning of the overall skin thickness by tape stripping the stratum corneum is minimal and unlikely to be an independent factor.

The interdependence between the mechanical properties of the skin and the barrier function is of relevance not only to our understanding of physiology of the skin, but also potentially to a number of diseases. In particular, it may be relevant to our understanding of the development of mechanically induced dermatitis and the effects of moisturizers, as it offers a new dynamic and measurable parameter describing relevant aspects of skin physiology.

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