The effect of mechanical forces (vibration or external compression) on the dermal water content of the upper dermis and epidermis, assessed by high frequency ultrasound

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An ultrasound scanner, is used to detect changes in water content of the upper dermis. This has previously been found to vary with age and to show diurnal variation. Furthermore, oedema due to venous disease can be shown, using this technique, to respond to elevation. In this study, the water content of the upper dermis and epidermis of the leg in 16 subjects is increased following vibration for 10 minutes using a passive exercise system. A study of pressure applied to the skin of the heel for 10 minutes in 14 volunteers also showed an increase in water content of epidermis and dermis in young persons, but less so in the elderly. It is postulated that the anatomical structure of the vascular bed of the upper dermis predisposes to transudation when pressure to the skin is applied, thereby maintaining the resilience of the skin in the young, but less so in the elderly.

Keywords: ultrasound, water content of skin, pressure and vibration effects

Introduction

Gniadecka¹ summarises studies on cutaneous water distribution and structure in the upper dermis. They had detected a sub-epidermal low echogenic band in human skin, which was interpreted as a site of increased water content. They demonstrated that the band’s width varied during the day, and that there was inter-individual variability and diurnal changes. They have emphasised that skin water comprises 70% of the cutaneous mass, it is easily exchangeable, and therefore plays an important role in fluid homeostasis in the body. Water is essential for the well-being of the skin, and it is well established that the resilience, elasticity and protective role of the skin depends on its moisturisation. Gniadecka¹ found that skin ageing affects the water content, and made a distinction between photo-ageing – in which water may accumulate in the upper dermis and chronologically aged skin in which it may be depleted in the lower dermis. In persons with chronic venous insufficiency, dermal oedema increases, and studies by Hu et al.² have shown that this can be reduced by elevation. It is proposed that the water distribution is mostly in the upper dermis in venous disorders, uniformly distributed in lymphoedema, and predominantly in the lower dermis in cardiac insufficiency. In a study of different compression forces on dermal oedema, an increased echogenicity – reduced water content – was observed throughout the entire dermis.

Many years ago, Ryan³ observed that focal compression of the skin by indenting the skin with a steel probe shifted water from the upper dermis, but this effect depended on the anatomy of the vasculature – and, in later studies, probably also on the distribution of the lymphatics. Because the structure of the upper dermal vasculature includes tangentially orientated capillary loops projecting into the papilla of the dermis and surrounded by epidermis, compression on the surface can sometimes impede outflow leading to congestion and increased oedema in the upper dermis. In aged skin, the number of capillary loops is much reduced and compression of the epidermis has no such effect. It is
hypothesised that pressure at the surface of the skin could be harmful if it were to remove fluid and increase the rigidity of the epidermis. Certain areas are constantly or intermittently compressed, such as the heel of the foot. In the elderly, this is a site for pressure sores.

It is well established that clearance of fluid from the skin depends on the lymphatics, and these in their turn depend on movement of the skin, which shifts the fluid into the lymphatics and empties the lymphatics in a one-way direction towards the lymph node consequent on the lymphatic valves' distribution. Thought has been given to studies which might separate off the effects of compression on the lymphatics from those on blood supply, or might give further information on the effects of compression on the skin. It was hypothesised that the skin movement within compression bandages might be influenced by the muscle pump compressing the skin from within. Another system which might have the same effect is the use of multi-directional vibrations, such as provided by a passive exercise system used to promote blood supply (Leg Ulcer Cyclopod; Niagara Manufacturing Ltd). It is conceivable that solid structures like bone may be moved within the sleeve of the skin in the lower limb, leading to compression of the dermis during the course of vibration. It is an old observation that light pressure on the surface of the skin results in dilution of the vessels on release (reviewed by Ryan). It has also been observed that vibration causes a rise of skin temperature, presumably due to an increase in blood supply.

In the following study, measurement of the water content of the upper dermis and the epidermis has been studied using short periods of vibration at the same time as measuring blood flow with a scanning laser Doppler. A second study examined the fluid content of the upper dermis and epidermis in the skin of the heel after standing on a solid object - a bronze disc.

Materials and Methods

Skin ultrasonography

Images of the skin were obtained by Dermascan C Ver. 3, a 20 MHz ultrasound scanner (Cortex Technology, Hadsund, Denmark). The instrument has been described previously. The instrument consists of three main parts: the two-dimensional scanning B probe, the visualisation and analysis system, and the data storage system. The probe is housed in a water-bath, and sealed at the point of contact with an ultra-thin plastic diaphragm. A minimum amount of coupling gel, recommended by the manufacturers as not influencing hydration, was used on the surface of the skin. The ultrasonic wave penetrating the skin is partially reflected at the boundaries between adjacent structures, and echoes of various amplitudes are generated. The average amplitude of the echoes in a defined area of the image is designated 'echogenicity'. With computer-assisted image analysis systems, it is possible to quantify the amplitude of single echoes and thus to objectively measure echogenicity. The density of the tissue determines the velocity of longitudinal waves in a tissue. The intensity of the reflected echoes is evaluated by the microprocessor, and visualised as a coloured two-dimensional image (estimates supplied by the manufacturers). The velocity of the ultrasound in the skin is approximately 1580 m/s. However, in the stratum corneum the velocity is higher and will probably approach the velocity of ultrasound in the nail plate, 2459 m/s. Therefore we have adjusted the estimates of depth to this higher velocity of ultrasound in the stratum corneum. The Dermascan C Ver. 3 can reach a depth of signal penetration of about 7 mm. This means that the zone of main interest, the epidermis and dermis, is covered. The gain/compensation curve was adjusted in the horizontal position to 30 dB for the images of the thick ridged skin. For the images of the thin skin, we used the conventional gain/compensation curve of 22 dB. Care was taken to maintain the probe perpendicular to the skin surface during scanning and to minimise the pressure of the transducer on the skin surface to ensure a satisfactory scan. The echographic images were saved on hard disk and analysed with image analysis software (GIPPS, Cortex Technology). In this system the amplitudes of echoes of single image elements (pixels) are assigned to a numerical scale (0-255). The low echogenic range extends from 0 to 30 being proportional to the degree of skin oedema but it is not a direct estimate of water content.

Design of the study

Sixteen subjects (age range 27-68, 10 males and 6 females) were recruited from colleagues in a Department of Dermatology. Ethical permission was obtained for the use of the vibration and ultrasound measurement (COREC C00.176). The subjects were asked to stand while the skin of the calf was measured at a distance of 12 cm from the floor to standardise the point of measurement. They were then asked to lie in a horizontal position for a rest period of 20 minutes. Following this, the right leg was examined by ultrasound and the left leg by a laser Doppler scanning device while still lying in the horizontal position. Following this total period of rest amounting to 30 min, the skin of the legs was vibrated using the Vibro-Pulse Leg Ulcer Cyclopod, a device that complies with the latest harmonised European standards. The device was switched to a constant speed cycloid massage action in which the solid tissues are moved by low amplitude multi-directional arc forces, which constantly vary in direction and intensity and whose frequency is variable between 1200 and 3600 per minute.

For the studies on the heel, 25 feet of 14 healthy volunteers (ages 21-67, median 38, 8 women and 6 men) were studied. The skin under the calcaneus was chosen.
The subjects walked into the unit and the first image was made after 10 minutes' rest in the supine position. Pressure was then applied for a period of 10 minutes by standing on a flat bronze disc measuring 3½ cm in diameter by 1 cm in thickness. Pressure images were repeated following 15 min in a supine position while making small movements with the feet to promote clearance of fluid by venous drainage and lymph vessels. The data are presented for two different age groups: Group 1 20–40 years old, mean age 27, and Group 2 41–70, mean age 58. The temperature of the room was maintained in the 21°C–23°C range.

Results

Statistical analysis

The data are presented as mean ± SD. To test the differences between the values at baseline and after pressure the Wilcoxon signed rank test was used. The Mann–Whitney U test was used to test a difference between the mean values of the different age groups. P<0.05 was chosen as the level of significance. The Microsoft Excel Analysis Toolpack (GreyMatter International, Inc, Cambridge, UK) and SPSS 8.0 were used for all calculations.

In the ultrasound images, the epidermis can be clearly distinguished from the dermis, but the definition of the epidermal border requires some interpretation on the sole of the foot .

Results following vibration for 10 min

Laser Doppler studies revealed a consistent increase in blood supply (P=0.0033, table 1). Ultrasound showed a trend for the water content of the upper dermis and epidermis to increase (P=0.0593, table 2).

Results following standing on a bronze disc

In the study of standing on a bronze disc, it was noted that subjects had a low amount of water in their skin at the beginning of the examination, which increased during the period of rest. The number of LEPs (low echogenic pixels, representing water content) increased from 0.7 ± 0.9 at baseline to 8.1 ± 6.6 after standing on the weight, an increase of 7.5% (P=0.01) (figure 1). During the recovery time the number of LEPs in the epidermis decreased but did not completely return to baseline values after 15 min. There was a significant increase in the water content of the epidermis itself in the age group of 20–40 years. In the age group 41–70 years the % LEP within the epidermis itself was very small at baseline and it did not increase significantly after pressure. The difference in response of the epidermis between the two age groups is significant (P<0.01).

In the estimates of thickness of the epidermis and the upper part of the dermis to a depth of 1.5 mm, the increase in number of LEPs after applying pressure was significant for both age groups. In young subjects the number of LEPs increased 14%, from 6.6 ± 4.7 to 20.6 ± 11.2 (P=0.01). In the group of 41–70 years the number of LEPs increased 5.4%, from 4.4 ± 3.6 to 9.8 ± 6.3 (P=0.03). The estimates between the two age groups were also significant (P=0.03). The increase in water content is larger if you measure the epidermis as well as the upper part of the dermis because a large amount of LEPs are present in the subepidermal low echogenic layer. During the 15 minutes of recovery the amount of LEPs decreased in both age groups but still remains higher than at baseline.

Furthermore there was a significant difference in the epidermal thickness at baseline between the two age groups (P<0.01). The group of 20-40 years had a...
Figure 1. Echographic images of the legs pre- and post-vibration. This is usually expressed as a colour scale (density): white> yellow>red>green>blue>black, and after vibration there was more of the green/blue spectrum in the epidermis and upper dermis. a: pre-vibration of a 36-year-old male volunteer. b: post-vibration of the same subject. c: pre-vibration of a 67-year-old female volunteer. d: post-vibration of the same subject.

thickness of 1.1 ± 0.1 mm, the group of 41-70 years had a thickness of 0.8 ± 0.1 mm. After applying pressure the epidermal thickness increased significantly in young people to 1.2 ± 0.1 mm (P<0.01). In the older age group it did not change significantly.

Discussion
As previously noted, the water content of the skin and especially of the upper dermis varies during the day and is responsive to manipulation. In this study, the effects of vibration - commonly used in the management of a number of disease processes - the increase in blood flow following vibration was confirmed. It was expected that stimulus of lymphatic function would reduce the amount of water in the skin, and it was initially a surprise to find an increase in the upper dermis. The later study on standing similarly showed an increase in the younger age group.

We have interpreted our results as indicating an increase in water content. However, there are unresolved technical problems in the interpretation of upper dermal LEPs when the overlying epidermis is of varying thickness and shape.

The mechanism underlying the reaction of the skin to pressure is probably an obstruction of subpapillary venous and lymphatic outflow without an obstruction of the capillary inflow in the papilla. This is followed by reactive hyperaemia after releasing the pressure. This was at one time the basis of a skin test for reactive hyperaemia. It was the observation of the capillaries of the upper dermis using in vivo microscopy that led to the interpretation of dilatation as a consequence of the redistribution of water due to the mechanical stress of light compression forces on the surface of the skin. When such forces are confined to an area of less than 2 mm², tissue fluid is dispersed from the upper dermis. When the force is to an area of 1 cm² or more, tissue fluid is squeezed out of the deep dermis and may accumulate in the upper dermis. The venous and lymphatic systems in the skin are horizontal to the skin surface and will therefore be obstructed during pressure. The capillary system in the skin is organised in capillary loops and they will not be obstructed during pressure on the skin. This causes the formation of extravascular fluid.
during a period of pressure. The skin needs this water to enhance its resilience and its resistance to external injury, but it is also a system which makes its best use of the lymphatic system's location in the upper dermis for the removal of excess fluid in the skin.

Acknowledgement
This study on vibration was supported by Vibro-Pulse Ltd, 88A High Street, Shoreham-by-Sea, West Sussex, BN43 5DB; e-mail vibropulse@aol.com

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References
12 Carrier EB. Studies on the physiology of capillaries. V. The reaction of the human skin capillaries to drugs and other stimuli. American Journal of Physiology 1922; 61: 528–549.

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