The Occlusion Effects in Capacitive Contact Imaging for *In-vivo* Skin Damage Assessments

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Abstract

OBJECTIVE: The aim of this study is to investigate the occlusion effects in capacitive contact imaging, in order to develop a new quantitative methodology for *in-vivo* skin assessments by using capacitive contact imaging and condenser-TEWL(trans-epidermal water loss) method.

METHODS: Two measurement technologies are used in this study, i.e. capacitive contact imaging and condenser-TEWL method. Three types of skin damages are studies, intensive washes and tape stripping, and sodium lauryl sulfate (SLS) irritation. The test skin sites were choose on the volar forearms of healthy volunteers (aged 25 - 45), the measurements were performed both before and periodically after the damages.

RESULTS: The results show that the time-dependent occlusion curves of capacitive contact imaging can reflect the types of damages, and by analysing the shapes of the curves we can get information about the skin surface water content level and stratum corneum thickness. The results also show that the combination of capacitive contact imaging and condenser-TEWL method gives extra information about the skin damages.

CONCLUSION: We have developed a potential new quantitative methodology for skin damage assessments by using capacitive contact imaging and condenser-TEWL method. The combination of the two technologies can provide useful information for skin damage assessments. We have also developed a mathematical model for analysing the occlusion curves.

Keywords

Skin occlusion, capacitive contact imaging, skin damage assessments, skin hydration, TEWL.

1. Introduction

Skin damage is a very important issue for occupational health as well as environmental threat [1,2]. However, to assess the skin damage is not easy, especially quantitatively. To date, skin damage assessments are largely done through visual assessments, which can be subjective and difficult to quantify. There is a need to develop a new, quantitative, and simple methodology that can quantify the skin damage assessments. We know that water in stratum corneum (SC) plays an important role in skin's cosmetic properties as well as its barrier functions, and SC water concentration and trans-epidermal water loss (TEWL) are two key indexes for skin characterizations [3,4]. In this paper, we present our latest study on the occlusion effects in capacitive contact imaging for *in-vivo* skin damage assessments. Capacitive contact imaging based fingerprint sensors, originally designed for biometric applications, has shown potential for skin hydration imaging, surface analysis, 3D surface profile, skin micro-relief as well as solvent penetration measurements [5-11]. With the capacitive contact imaging, we can measure the skin surface water concentration distribution map. By occluding the skin with capacitive imaging sensor over a period of time, as water dynamically builds up underneath the sensor surface due to the blockage of trans-epidermal water loss, we can also generate time-dependent skin occlusive hydration curves. It is this time-dependent occlusive hydration curves that we are mainly interested in this study. Our previous studies have also shown that skin occlusion measurements can give further information about skin properties [12]. The purpose of this study is to develop a new methodology for skin damage assessments by using skin capacitive contact imaging occlusion measurements, as well as the trans-epidermal water loss (TEWL) measurements.

2. Materials and Methods

2.1 Instruments

The capacitive contact imaging technology developed by the research group [8-11] is based on Fujistu fingerprint sensor (Fujistu Ltd, Japan), which has a matrix of 256 × 300 pixels, with 50 μm spatial resolution per pixel. The fingerprint sensor basically generates capacitance images of the skin surface. In each image, each pixel is represented by an 8 bit grayscale value, 0~255, higher grayscale values mean higher water concentration, and lower grayscale values mean lower water concentration.

The TEWL measurements were performed by using the condenser-TEWL method (AquaFlux, Biox Systems Ltd, UK), which is a condenser based closed-chamber measurement technology [13,14]. Its cylindrical measurement chamber is open at the end placed onto the skin surface, and closed by means of a condenser cooled below the freezing temperature of water at the other end. This design provides a controlled measurement environment, which enhances the repeatability and accuracy of the measurements.

2.2 Mathematical Modeling of Skin Occlusion

According to diffusion theory, the skin occlusion can be described by following one dimensional diffusion equation with following initial condition and boundary condition.

$$\begin{cases} D(H)\frac{\partial^2 H}{\partial^2 z} = \frac{\partial H}{\partial t}, & 0 \le z \le L \\ H(z,0) = f(z) \\ H(L,t) = H_1 \\ -D\frac{\partial H}{\partial z}|_{z=0} = 0 \end{cases} \quad (1)$$

where H(z,t) is the skin water content at depth z and time t, L is SC thickness, D(H) is the SC water diffusion coefficient, which is a function of water content H(z,t), f(z) is the initial skin water distribution within SC. In this case, we can assume it is a linear distribution, defined by

$$f(z) = H_0 + \frac{H_1 - H_0}{L} \times z. \qquad (2)$$

where H_0 is the SC surface water concentration, and H_1 is the SC bottom water concentration. In Eq.(1), at the skin surface (z=0), there is zero flux due to occlusion, and at the SC bottom (z=L), we assume there is a constant water concentration H_1. We can solve the Eq.(1) by substituting Eq.(2) into Eq.(1), and the solution can be expressed as,

$$H(z,t) = H_1 + \frac{2}{L}\sum_{n=0}^{\infty}\left(e^{-\frac{D(2n+1)^2\pi^2 t}{4L^2}} \times cos\frac{(2n+1)\pi z}{2L} \times (\frac{2L(-1)^{n+1}H_1}{(2n+1)\pi} + \frac{2L(H_1(2n+1)\pi\cos(n\pi)+2(H_1-H_0)(1+\sin(n\pi)))}{(2n+1)^2\pi^2})\right) \qquad (3)$$

Figure 1 shows results of above solution, the left plot shows the SC water concentration depth profiles at different time during the occlusion, using normalized the depth (z/L, L=20μm) and normalized water concentration (H/H_1, H_1=80% H_0=24%), and right plot shows the time dependent normalized surface water concentration (H/H_1, H_1=80% H_0=24%) levels of three different SC thickness (L=10µm, 20µm, 40µm).

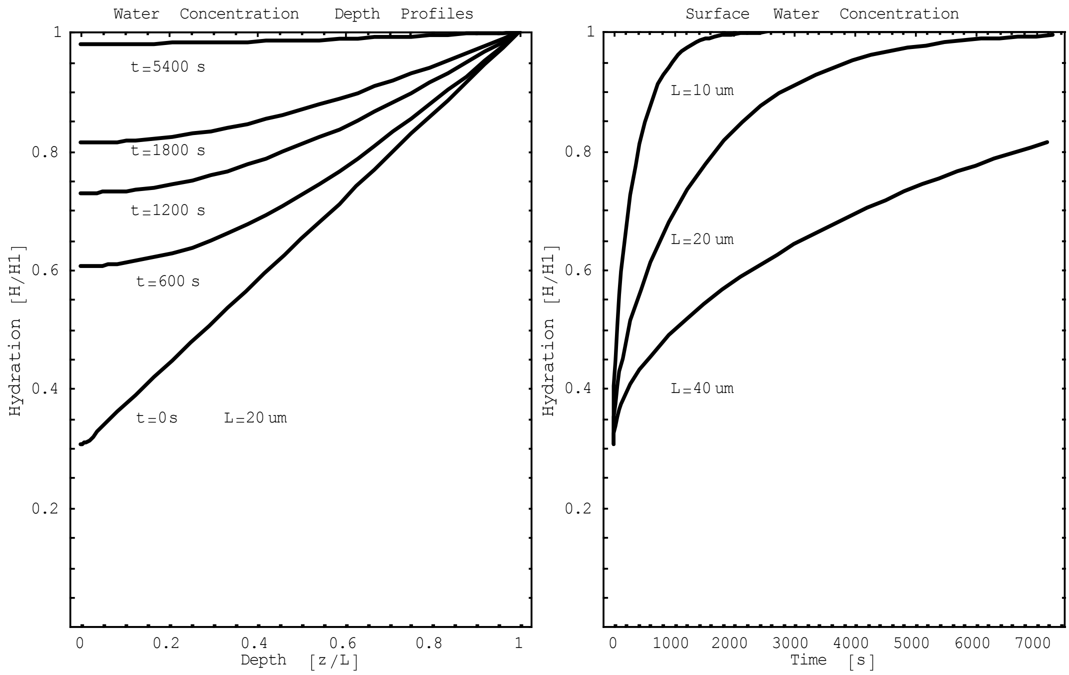


Figure 1 The SC normalized water concentration depth profiles at different time during the occlusion with L=20µm (left), and the time dependent normalized surface water concentration levels of three different SC thickness (right).

The results show that different SC thicknesses have different times to reach steady state, for a SC with 20µm thickness, which is typical SC thickness in volar forearm, it is about 30 minutes to reach 80% of H_1 and about 2 hours to reach the steady state, i.e. 100% of H_1.

2.3 Experimental Procedures

In this paper, skin sites on volar forearms of healthy volunteers, aged 25 - 45, were chosen for the measurements. The skin test sites were deliberately damaged by intensive washes, tape stripping and sodium lauryl sulfate (SLS) irritation. Intensive washing used room temperature running water and washing-up liquid, rubbing the site gently for 3 minutes with a finger. Tape stripping was performed 20 times per site by the use of standard stripping tape. SLS irritation was achieved by applying 2% SLS solution (w/w) on skin. Capacitive contact imaging measurements and TEWL measurements were performed both before and after the skin was damaged. The skin occlusion measurements using capacitive contact imaging to occlude the skin test sites for a period of one minute, during which skin capacitance images were recorded continuously. The average grayscale values of the images were then calculated at different times during occlusion. Since grayscale values are proportional to SC hydration [8,11], the plots of grayscale value against time, can be interpreted as SC hydration against time.

All the measurements were performed under normal ambient laboratory conditions, of 20-21°C, and 40-50% RH. The volar forearm skin sites used were initially wiped clean with ETOH/H2O (95/5) solution. The volunteers were then acclimatized in the laboratory for 20 minutes prior to the experiments.

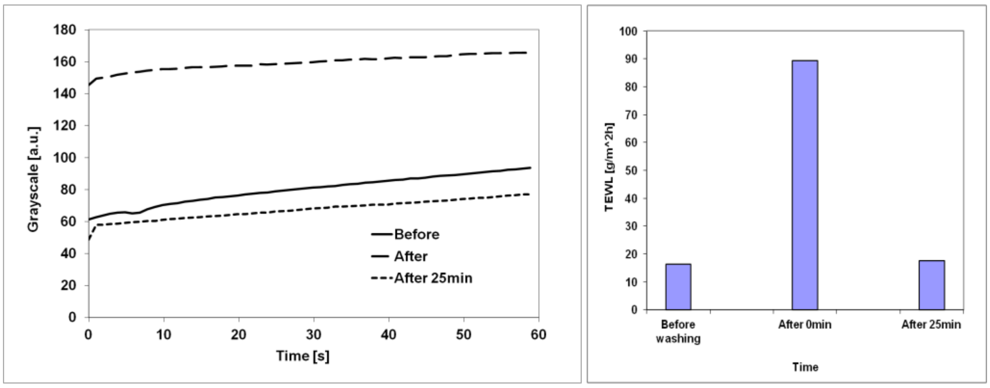
3 Results and Discussions

3.1 The Occlusion Curves

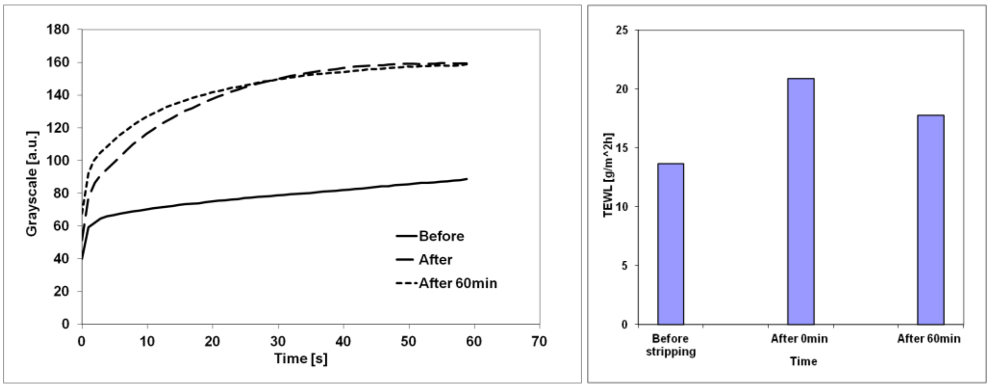
Figure 2 shows capacitive contact imaging occlusion curves and corresponding TEWL results of intensive wash, tape stripping and SLS irritation measurements. The intensive washes produced small changes in the shapes of the contact imaging occlusion curves. The general higher grayscale values of the occlusion curve immediately after the washes indicate general higher SC hydration levels, which may be caused by two factors, namely (i) superficial absorption of the water used in the washes, and (ii) the removal of superficial SC cells during washing. After 25 minutes recovery time, the average grayscale values were found to have returned to near-normal level. However, there is an undershoot, which suggests a dehydration after the intensive washes, possibly due to the removal of some superficial SC cells and the resultant loss of some SC barrier function. The TEWL results follow a similar trend, and also confirmed the undershoot.

In tape stripping, the time dependent contact imaging occlusion curves show a significant difference in shape (i.e. more curvature) between normal skin and damaged skin. This curvature change reflects the SC structure change due to tape stripping. Even after 60 minutes, the contact imaging occlusion curves were found to be still significantly different from those of normal skin, indicating that SC was still damaged. The TEWL values, however, has started returning to its normal value after 60 minutes, indicating that although SC is still damaged, it starts to recover.

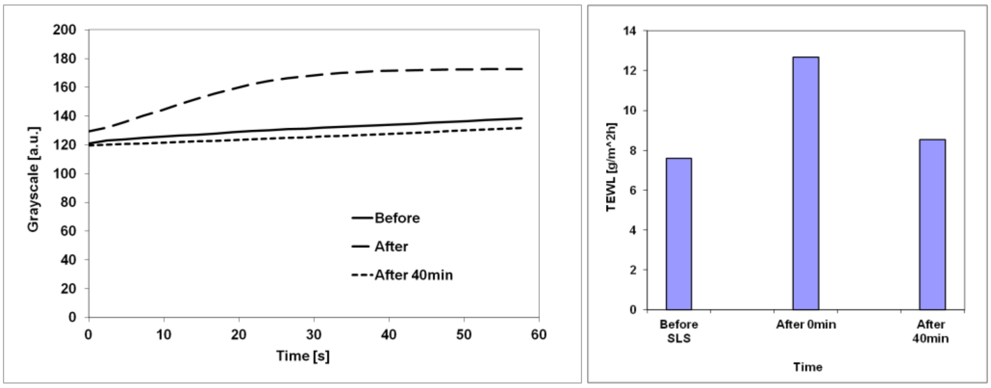
In SLS irritation, both the contact imaging occlusion curve and TEWL value changed after irritation, but largely recovered after 40 minutes. It is interesting to point out that the three types of skin damages produce three distinctive occlusion curves, which indicates that, according to our theoretical modeling, the SC surface hydration and SC structure are quite different under the different types of skin damages. This suggests that the shapes of capacitive contact imaging occlusion curves can provide extra information about skin damages. The results also show that TEWL results can reflect the skin damages, but can not differentiate the damages. Therefore, the combination of capacitive contact imaging occlusion measurements and TEWL measurements can provide more detailed, comprehension information about skin damages.



(a)

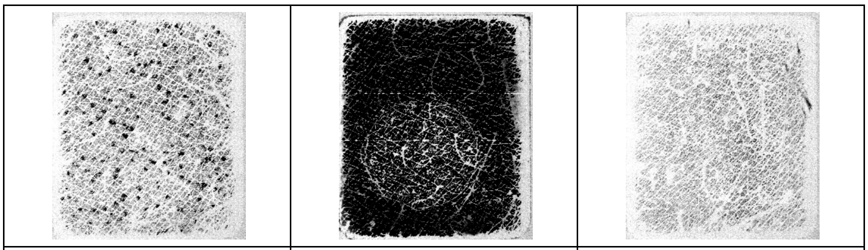


(b)



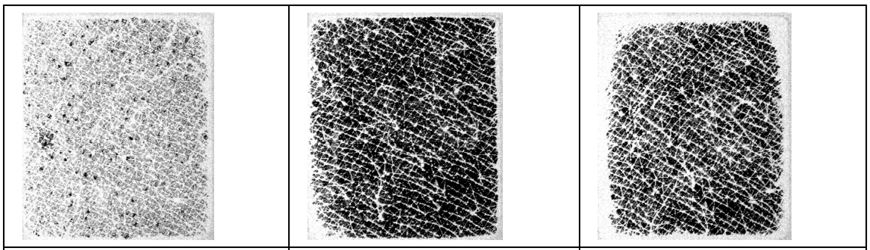
(c)

Figure 2. Skin capacitive contact imaging occlusion curves and corresponding TEWL results of intensive washing (a); tape stripping (b); and SLS irritation (c).



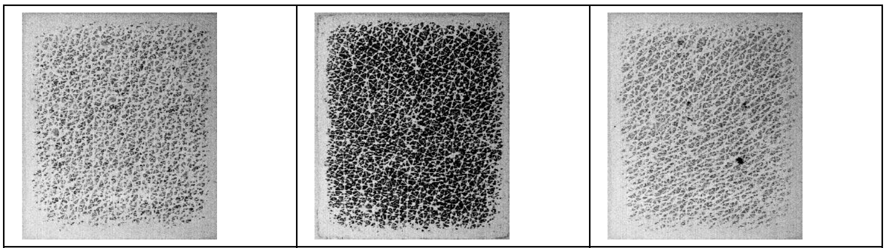
Before washing	After (0 min)	After (25min)

(a)



Before stripping	After (0 min)	After (60min)

(b)



Before SLS	After (0 min)	After (40min)

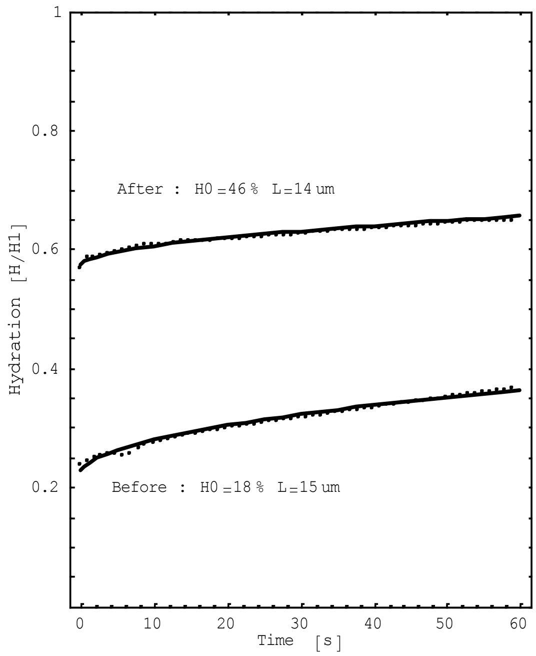
(c)

Figure 3 Skin capacitive contact images of intensive washes (a); tape stripping (b); and SLS irritation (c).

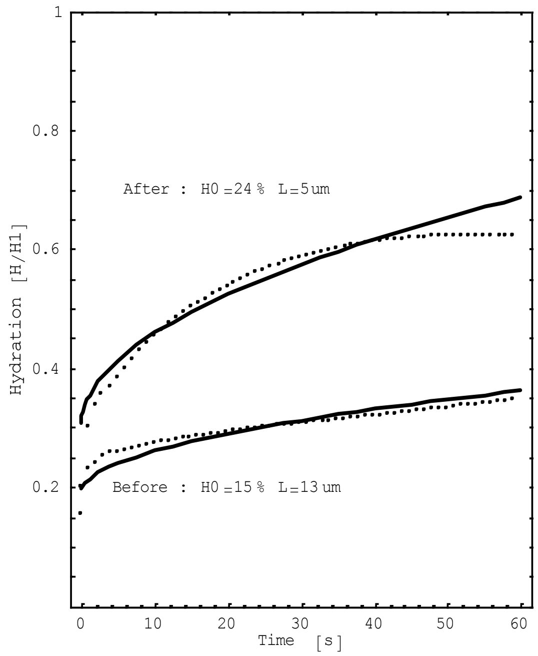
Figure 3 shows corresponding capacitive contact images of intensive wash, tape stripping and SLS irritation measurements. The skin images are generally getting darker after damage, which indicates higher water content in SC. In both intensive washes and SLS irritation, the lighter recovery skin images indicate there is a drying effect after the damage. The lighter areas in the images immediately after the intensive washing are imprints from the TEWL measurement head.

3.2 Comparison of Theoretical and Experimental Results

If we assume the maximum grayscale representing 100% water content, and zero grayscale represent 0% water content, then we can compare the theoretical results using Eq.(3) with above experimental results, see Figure 4. The comparison results show that the intensive washing has significantly increased the SC surface water content, but only slightly reduced the SC thickness, whilst the 20 tape stripping only slightly increase the SC surface water content, but significantly reduced the SC thickness. It is worth mentioning that the reduced SC thickness in theoretical modeling data after SLS irritation is more likely to reflect the changes of water distribution in SC, rather than the changes of SC structure. Overall, the theoretical data matches better with normal skin data, the significant mismatch of theoretical data and the data after 20 tape stripping, indicate that tape stripping has significantly changed the structure of the SC.



(a)



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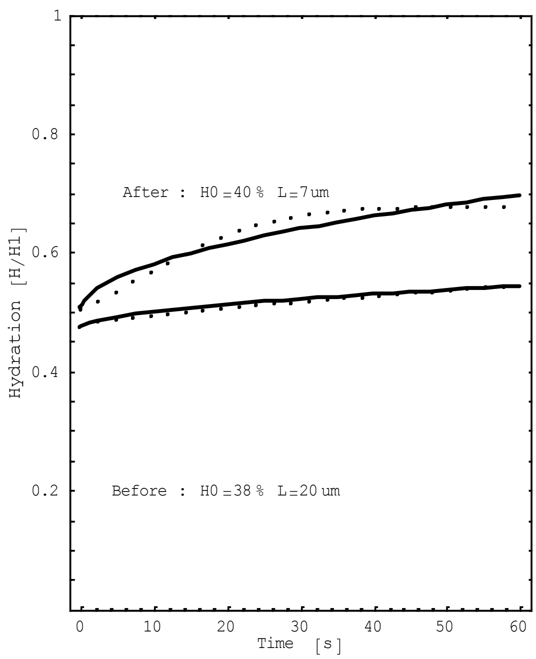

(c)

Figure 4 The comparison of theoretical results and experimental results, the intensive washing (a), the tape stripping (b), and SLS irritation (c).

Clearly, whence the capacitive contact imaging is calibrated, we will be able to get the SC surface content and SC thickness values by analysing the experimental results using mathematical model described in Eq.(3).

4 Conclusions and Future Works

We have studied the occlusion effect in capacitive contact imaging for skin damage assessments. The results show that the shapes of the capacitive contacting imaging occlusion curves can be related to skin conditions, and different types of skin damages have different shapes of occlusion curves. The TEWL measurements can reflect the skin damages but can not differentiate different types of damages. Therefore, the combination of skin occlusions using capacitive contact imaging and TEWL measurements can provide useful, complementary information about skin damage, and have potential as a new methodology for *in-vivo* skin damage assessments. We have also developed a mathematical model for the skin occlusion, the comparison of theoretical data and experimental data shows that the intensive washes changes more of the SC surface water content, and the tape stripping changes more of the SC thickness. The future work will be comparing the capacitive contact imaging and TEWL measurements with other skin assessment technologies, and to calibrate the capacitive contact imaging results, in order to quantify the skin damage.

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