In-vivo Stratum Corneum Thickness and Water Diffusion Coefficient Measurements Using Opto-Thermal Radiometry and Condenser-Chamber TEWL Method

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Introduction

Stratum corneum (SC) is the outmost skin layer, which plays a key role in skin barrier function as well as in skin cosmetic properties. For trans-dermal drug delivery, the two key parameters are SC water diffusion coefficient and SC thickness. In this paper, we present our latest study on stratum corneum thickness and its water dependent diffusion coefficient measurements by using opto-thermal transient emission radiometry (OTTER) [1,2] and condenser-chamber TEWL (trans-epidermal water loss) method [3,4] technologies. With OTTER, we can measure the SC surface water concentration, and underneath water distribution gradient [5-7]. Condenser-chamber TEWL method based on Nilsson's diffusion gradient measurement principle is a new closed-chamber water vapour flux measurement technology [8], which can be used to accurately measure the SC TEWL. The combination of OTTER and condenser-chamber TEWL method, provides unique information on the stratum corneum thickness, stratum corneum water diffusion coefficient, and the relationship between water diffusion coefficient and water concentration.

Theory

Stratum corenum is dry outside and wet inside, and therefore exists a water concentration gradient, see Figure 1. This water concentration gradient will cause water diffuse from the deeper part of SC to the SC surface, and hence form a water diffusion flux , according Fick's first law [1]

$$J_{TEWL} = -D\frac{\partial H(z,t)}{\partial z} \quad (1)$$

where H(z,t) is SC water concentration at position z, and time t in kg/m^3 , D is SC water diffusion coefficient in m^2/s.

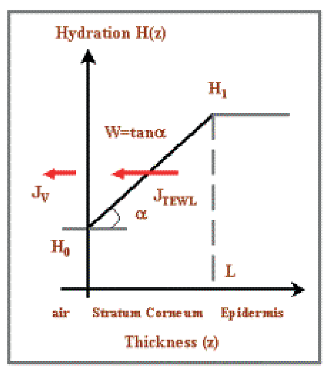

Figure 1. A simplified linear water concentration distribution model for *in-vivo* human statum corneum.

When the water arrives the SC surface, it will evaporate and form a water vapour density flux J_v. Apparently, the value of J_v depends on SC surface water concentration, SC surface temperature, SC water holding capability and external environments such as ambient temperature, ambient relative humidity (RH) and air movements. J_v is what we can measure with various of TEWL measurement devices, and J_{TEWL} is the real TEWL that we want to know. J_v and J_{TEWL} are two independent processes, and generally J_v dos not equal J_{TEWL}. To be more specific,

$$J_{TEWL} - J_V = \int \frac{\partial H(z,t)}{\partial t} dz \quad (2)$$

That is, the difference between J_{TEWL} and J_v, equals the net increase of overall SC water concentration per unit time. At the steady state, when SC has reached equilibrium with the external environment, we have , i.e.

$$J_V = J_{TEWL} = -D\frac{\partial H(z,t)}{\partial z} \quad (3)$$

hence

$$D = -\frac{\partial H(z,t)}{\partial z} \Big/ J_V \quad (4)$$

With OTTER we can measure the average $\frac{\partial H(z,t)}{\partial z}$ of top 10μm of SC, and with condenser-chamber TEWL method we can measure J_v, together with Eq.(4), we can calculate the water diffusion coefficient of SC.

Our previous study [1] shows that, according to diffusion law, the water concentration depth profile within SC depends on SC water diffusion coefficient . The water concentration depth profile within SC will be a straight line profile if water diffusion coefficient D is a constant; a convex distribution profile (e.g. negative second derivative) if D is proportional to water concentration; and a concave distribution profile (e.g. positive second derivative) if D is inversely proportional to water concentration. For in-vivo human SC, it is more realistic that D is proportional to water concentration [1-3], if we assume a linearly relationship, i.e.

$$D(H) = D_0 + A \times H \quad (5)$$

where D_0 is the water diffusion coefficient at 0% of water, and A is a scaling parameter. Then the water diffusion problem within stratum corneum can be described by following equation,

$$\begin{cases} \frac{\partial}{\partial z}\left(D(H)\frac{\partial H}{\partial z}\right) = \frac{\partial H}{\partial t} \\ H(0,t) = H_0 \\ H(L,t) = H_1 \\ H(z,0) = f(z) \end{cases} \quad (6)$$

where H_0 is SC surface water concentration, H_1 is the water concentration as deep epidermis, L is SC thickness, f(z) is a function the describe the initial water concentration distribution within SC. At the steady state, where $\frac{\partial H}{\partial t} = 0$, solution of the above equation, which will not depend on f(z), can be expressed as,

$$\begin{cases} H(z,t) = \frac{-D_0 + \sqrt{D_0^2 + 2 \cdot A \cdot C_1(C_2 + z)}}{A} \\ C_1 = \frac{-A \cdot H_0^2 - 2 \cdot H_0 \cdot D_0 + H_1^2 \cdot A + 2 \cdot H_1 \cdot D_0}{2 \cdot L} \\ C_2 = \frac{H_0 \cdot L \cdot (A \cdot H_0 + 2 \cdot D_0)}{-A \cdot H_0^2 - 2 \cdot H_0 \cdot D_0 + H_1^2 \cdot A + 2 \cdot H_1 \cdot D_0} \end{cases} \quad (7)$$

With OTTER, we can measure both surface water concentration H_0 and the average water concentration gradient ($W = \frac{\partial H(z,t)}{\partial z}$) of top 10μm of SC. Fit H_0 and W with Eq.(7), and assume that H_1 is known (for example, 80% of water), then we work out the SC thickness L.

Results and Discussions

All the measurements are performed under normal ambient laboratory conditions, i.e. 21°C, and 40% relative humidity (RH), and all the volunteers are acclimatized in the laboratory for 20 minutes prior to the measurements. The skin sites used for the measurements are untreated, but were wiped clean with ETOH/H_2O (95/5) solution.

Different Skin Sites

Nine skin sites, namely finger back, finger front, palm, hand, volar forearm low, volar forearm high, neck, cheek, and forehead, were studied among four healthy volunteers aged 20-40 years old, both male and female.

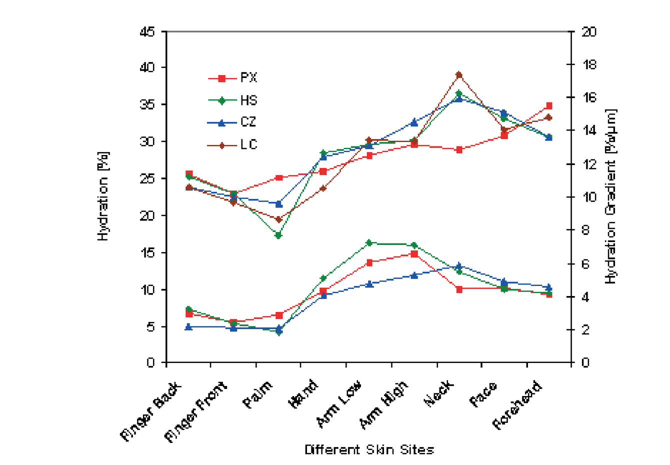

Figure 2. SC surface water concentration and water concentration gradient of four different volunteers at nine different skin sites.

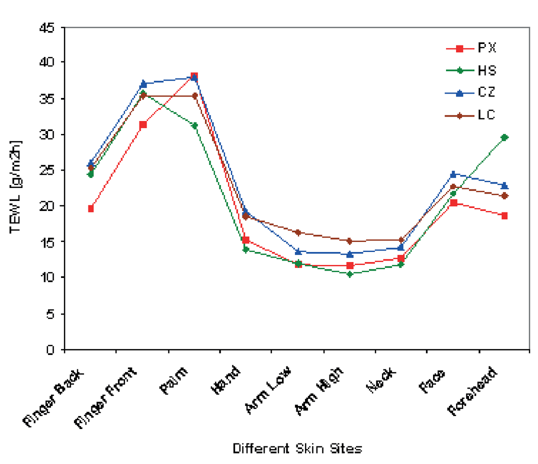

Figure 3. SC TEWL values of four different volunteers at nine different skin sites.

Figure 2 shows the SC surface water concentration and its underneath water concentration gradients of the different skin sites measured by using OTTER. Figure 3 shows the TEWL measurement results of the different skin sites measured by using condenser-chamber TEWL method. Of the nine skin sites, neck and face have the highest hydration level, volar forearm has the highest hydration gradient and palm and finger front have the highest TEWL values.

Perform the least-squares fitting on the data in Figure 2, using Eq(7), we can calculate the stratum corneum thickness at the different skin sites. Figure 4 shows some of the least-squares fitting curves and Figure 5 shows the SC thickness results of the different skin sites. Finger front and palm sites have the thickest SC whilst volar forearm and neck have the thinnest SC.

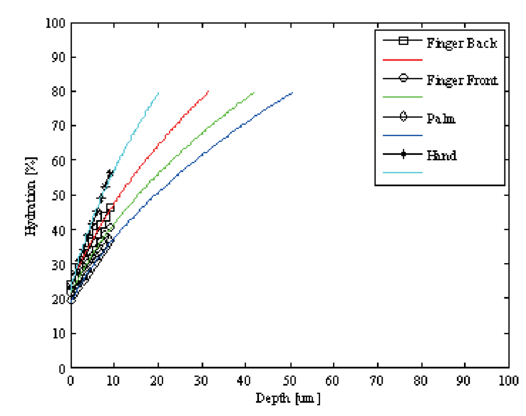

Figure 4. Some least-squares fittings curves of different skin sites.

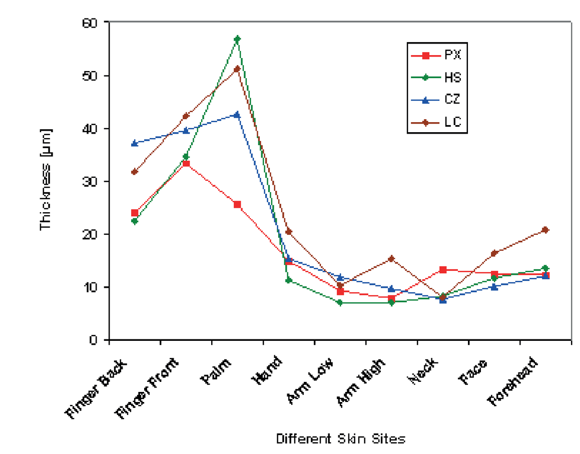

Figure 5. SC thickness of four different volunteers at nine different skin sites.

Combine the results in Figures 2 and 4, using Eq(4), we can also calculate the water diffusion coefficients of the nine different skin sites (Figure 6). The water diffusion coefficient of different skin can be very different, the skin sites of finger front and palm can be 6-9 times higher than that of volar forearm and neck sites.

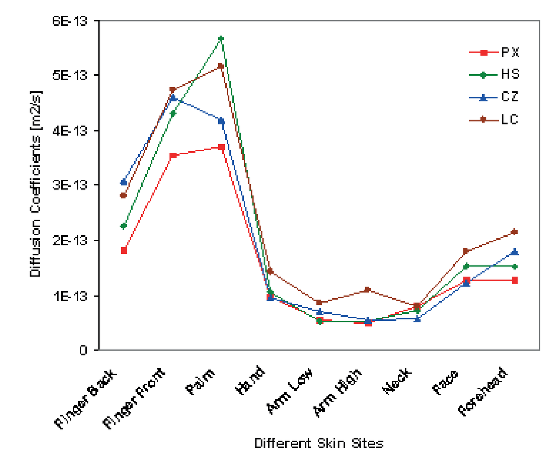

Figure 6. SC water diffusion coefficients of four different volunteers at nine different skin sites.

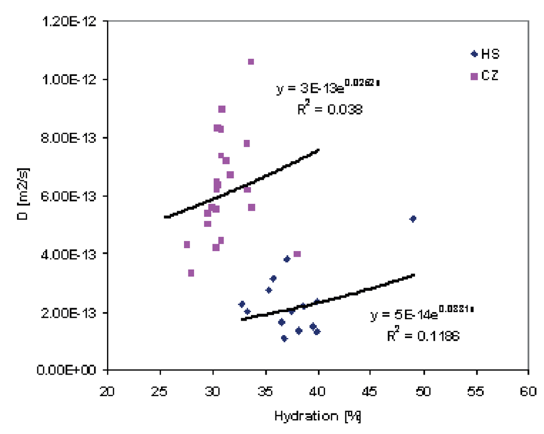

Figure 7. SC water diffusion coefficient at different water concentration level during the recovery of immersive hydration.

Stratum Corneum Immersive Hydration

In order to study the water dependency of the SC water diffusion coefficient, we performed skin immersive hydration measurements, in which two volunteers first soaked their left index finger in room temperature water for 20 minutes, then left it recovery under laboratory ambient environment for 30 minutes. The measurements were performed both before the soaking and periodically afterwards. Both SC hydration results and TEWL results increased after the immersive hydration, then gradually return to their normal values. Combine the SC hydration results and TEWL results, using Eq(2), we can also calculate the SC water diffusion coefficient at different recovery time, and hence different water concentration level, Figure 7 shows the results. The results show that SC water diffusion coefficient is proportional to SC hydration level, but not in a simple linear relationship. The SC water diffusion coefficients of different volunteers are apparently different. This different water dependency of the SC water diffusion coefficients is likely a reflection of the different SC water holding capabilities or barrier functions of different volunteers.

Conclusions

The results of the studies show that the combination of opto-thermal measurements and condenser-chamber TEWL measurements, can provide a new information for our skin studies. With OTTER, we can measure water concentration at the surface as well as its underneath water concentration gradient within stratum corneum. With a suitable diffusion model, we can also work out the stratum corneum thickness. With condenser-chamber TEWL method we can measure the TEWL values, combine the OTTER results and TEWL results, we can get the SC water diffusion coefficient and its water dependency relationship. The SC water diffusion coefficient's water dependency relationship is different for different people and for different skin sites, which is likely a reflection of different SC water holding capabilities as well as its barrier functions.

Acknowledgement

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