



Measurement of human skin moisture via high-frequency spectroscopy

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Abstract

High-frequency spectroscopy (HFS) is an analytical method that is sensitive to slight changes in the dielectric properties of materials. Since water has high permittivity, HFS can be used to detect changes in water content in materials. In this study, we employed HFS to measure human skin moisture during a water sorption–desorption test. Skin without any treatment showed a resonance peak at approximately 1150 MHz. Furthermore, the peak shifted to lower frequency immediately after the application of water to the skin and gradually returned to its original frequency as time progressed. The resonance frequency obtained via least-squares fitting showed that the applied water remained in the skin after 240 s from the beginning of the measurement. These results illustrated that HFS measurements can monitor the progression of decreasing moisture content in human skin during a water sorption–desorption test.

Keywords High-frequency spectroscopy · Dielectric constant · Skin moisture · Resonance

Introduction

Skin defends the living body from various harmful elements and physicochemical stimulations, and it also regulates the loss and transmission of water. Water content is an important factor in the ability of the skin to maintain its form and function. Thus, knowing skin water content is highly important for understanding skin conditions. Changes to the stratum corneum water content caused by skin diseases [1, 2], aging [3, 4], and different seasons [5, 6] have been reported in a number of studies. In addition, because skin water content is

used to evaluate the effects of skin-related cosmetics, quasi-drugs, and medicines, it is considered to be important information for the development of new cosmetic and medical products [7, 8].

Thus far, various methods for the estimation of skin water content have been proposed, such as a high-frequency conductivity method [9, 10], infrared spectroscopy [11, 12], near-infrared spectroscopy [13, 14], a magnetic resonance imaging method [15], time domain reflectometry [16, 17], confocal Raman spectroscopy, [18, 19] and terahertz attenuated total reflection spectroscopy [20]. These are useful techniques because they can measure the water content of a living body non-invasively and rapidly. However, they face certain issues, e.g., highly complicated processes and expensive devices are necessary for measurements. Therefore, it is important to develop a new technique that is easy, inexpensive, and capable of obtaining accurate results.

We have proposed a new spectroscopic method, high-frequency spectroscopy (HFS), that can detect changes in permittivity via the shift in the resonance frequency of the given sample system [21]. We discovered that the HFS method can sensitively detect dielectric changes caused by state changes of the measured object [22–24]. In addition, it was confirmed that the resonance frequency measurements were not influenced by the presence of an electrolyte in the measured object [25]. Therefore, HFS is a potential method

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for the evaluation of water content in substances, particularly in the case of skin measurement, which is influenced by sweat containing various electrolytes.

In this study, we employed HFS to measure human skin moisture. A new electrode was designed for this purpose, and the analytical techniques for the estimation of skin water content from the high-frequency spectra were discussed.

Experimental

HFS apparatus

Figure 1 shows a schematic of the HFS system. A tracking generator (Model MH680A, Anritsu, Japan) and a spectrum analyzer (Model MS2601B, Anritsu, Japan) were used as a high-frequency oscillator and a detector, respectively. An electrode was inserted in the middle of the coaxial cables connecting the tracking generator and the spectrum analyzer such that it was in parallel with the spectrum analyzer.

Figure 2 shows the structure of the prototype electrode designed for this study. The electrode was composed of a cylindrical component connected to a coaxial cable and a planar component for making contact with the sample (skin). The central, outer peripheral, and planar components of the electrode, which are shaded in the schematic, were composed of aluminum. The other components were composed of Teflon[®]. We utilized this apparatus to detect permittivity changes, i.e., changes in water content in human skin, by monitoring the HFS spectral changes.

Measurements

The water sorption–desorption test reported by Tagami et al. [26] was carried out with slight modifications for this study. The measurement site (flexor aspect of the left forearm, male in his 30 s) was exposed to room air for 20 min to acclimate

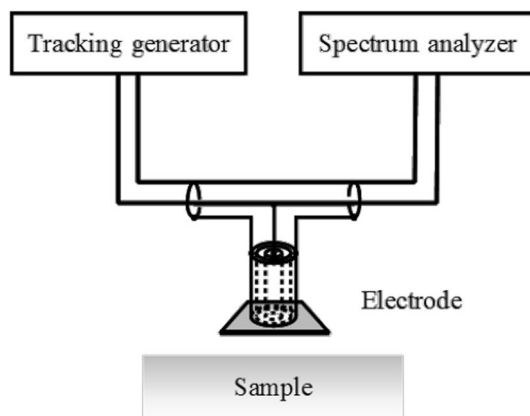


Fig. 1 Schematic of the HFS experimental system

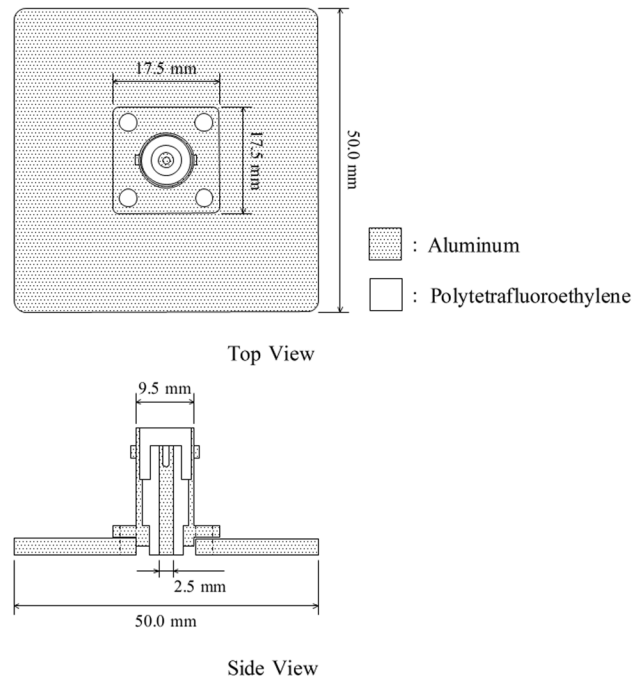


Fig. 2 Schematic of the experimental electrode

it to the measurement conditions. A piece of filter paper (1.5 cm × 1.5 cm) impregnated with ultra-pure water (Wako Pure Chemical Industries, Ltd., Japan, LC/MS grade) was placed on the site for 15 s to allow the skin to absorb the water. The filter paper was then removed, and the measurement was initiated immediately after wiping off any residual water from the skin. The measurements were repeated at an interval of 40 s for a total of 240 s and were performed over the range from 0 to 2000 MHz at ambient conditions (27 ± 1 °C, relative humidity $28 \pm 5\%$).

In addition to HFS measurements, electrical measurements using a skin surface hygrometer (SKICON-200EX, IBS, Japan), which is commonly used for measuring skin moisture, were performed under the same conditions and compared with the obtained HFS results.

Results and discussion

The results of the water sorption–desorption test using the skin surface hygrometer are shown in Fig. 3. The electric conductance increased markedly immediately after the application of water to the skin, then decreased rapidly within 40 s. Since no changes in the measured values were observed after 80 s, it was suggested that a majority of the absorbed water disappeared within this time range.

Figure 4 shows a comparison of the HFS spectra obtained over the course of the water sorption–desorption test. The observed resonance frequencies in the spectra

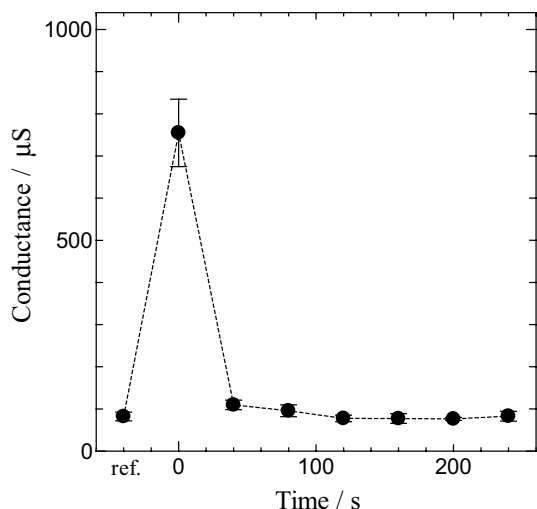


Fig. 3 Electric conductance of the stratum corneum during the water sorption–desorption test. Plotted marks and vertical lines indicate the means ($n=5$) and standard errors, respectively

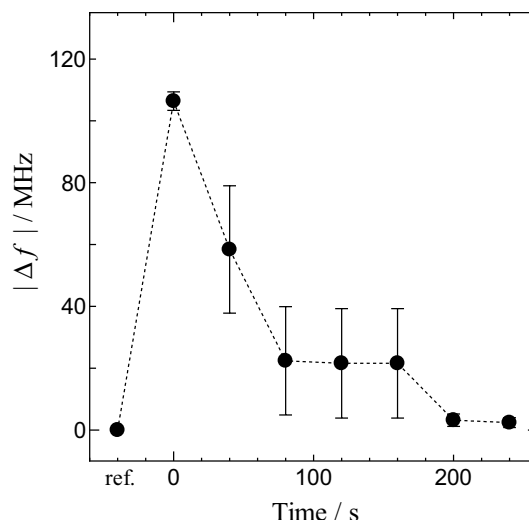


Fig. 5 Peak frequency shifts during the water sorption–desorption test of the stratum corneum. Plotted marks and vertical lines indicate the means ($n=5$) and standard errors, respectively

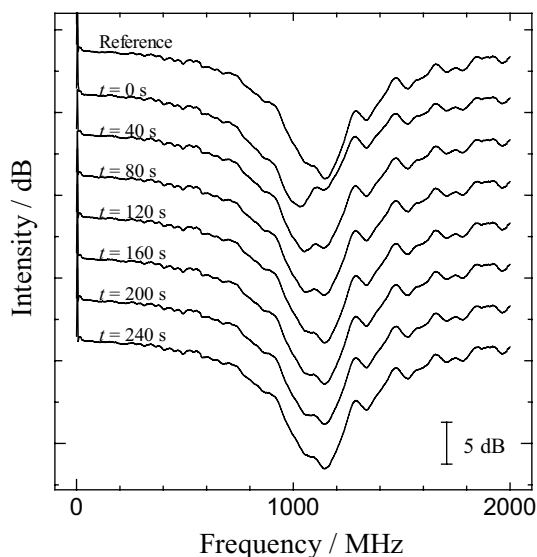


Fig. 4 Change in the high-frequency spectra during the water sorption–desorption test

shifted to a lower frequency immediately after the application of water, then gradually returned to the original frequency as time elapsed. These results indicated that HFS was able to detect small changes in skin water content, which manifested as changes in the resonance frequency. Therefore, we determined the resonance frequencies of the measured spectra and plotted them against the elapsed time of the water sorption–desorption test, and the results are shown in Fig. 5. The vertical axis represents the absolute value of the difference between the resonance frequencies

obtained before and after the water sorption–desorption test, which is expressed as follows:

$$|\Delta f| = |f_t - f_{\text{ref.}}|, \tag{1}$$

where $f_{\text{ref.}}$ and f_t are the resonance frequencies measured before and t seconds after the test began, respectively. As shown in Fig. 5, the measured change in resonance frequency was high, even after 40 s, and continued to clearly decrease until 80 s. This suggested that the HFS measurements of absorbed water in the skin surface penetrated deeper than the skin surface hygrometer, and that the absorbed water may have remained in the skin for a long time. Thus, the HFS measurement results were examined more closely.

Figure 6 shows the difference spectra obtained by subtracting the pre-test spectrum from each test spectrum. Negative peaks appeared in the low-frequency range, whereas positive peaks appeared in the high-frequency range. These data clearly indicated that there were no rapid changes in the measurements shown in Figs. 3 and 5, and that the spectral intensities decreased smoothly over time. These spectral HFS features suggested that the technique probes further into the skin than the skin surface hygrometer, which is a standard method for measuring surface skin components such as the stratum corneum. In addition, considerable measurement variation was observed in the results shown in Fig. 5. These variations were thought to arise from difficulties in obtaining the correct resonance frequencies, since the spectral peaks, as shown in Fig. 4, were split into two peaks from a periodic voltage change (parasitic oscillation caused by the electric length of the coaxial cable). Since the parasitic oscillation in the original spectrum was removed via the difference

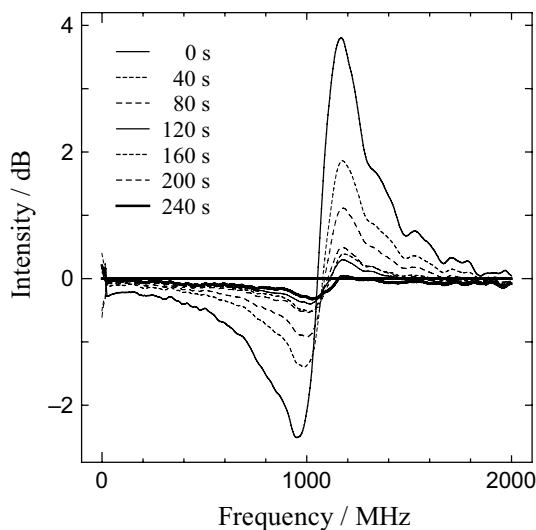


Fig. 6 Changes in the difference spectra during the water sorption-desorption test

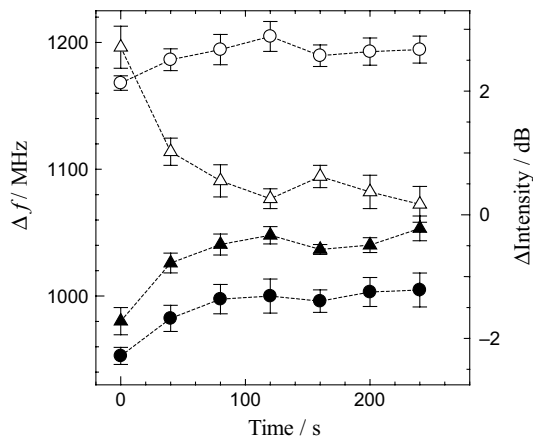


Fig. 7 Analysis results of the peaks obtained from difference spectra. Marks and vertical lines represent the means ($n=5$) and standard errors, respectively. Symbol: \circ , frequency of the high-frequency peak; \bullet , frequency of the low-frequency peak; Δ , intensity of the high-frequency peak; \blacktriangle , intensity of the low-frequency peak

spectrum calculations, the difference spectra shown in Fig. 6 displayed a smooth change. Since the low-frequency peak in the difference spectrum nearly corresponded to the resonance frequency observed in the original spectrum, it can be used as an indicator of skin water content. Moreover, since the intensities of difference spectra decreased smoothly with time, they were also a potential index of skin water content in addition to the resonance frequency. Therefore, we further analyzed the dependency of the peak frequency and intensity of the difference spectra with respect to time.

Figure 7 shows the time course of the peak frequency and intensity of the difference spectra. The frequency and intensity of the low-frequency peak changed smoothly with

time. In contrast, for the high-frequency peak, although the intensity showed a smooth decreasing curve, the frequency remained at almost a constant value. This can be explained as follows. The location of the high-frequency peak did not shift because it strongly depended on the resonance frequency of the reference spectrum. On the other hand, because the intensity change is proportional to the degree of spectral overlap, it displayed a similar trend to the shift in the low-frequency peak. These results showed that changes in skin water content could be measured by tracking the low-frequency peak location in the difference spectra. However, this analytical method faces the issue of measurement precision, which was markedly reduced by noise as time progressed after the beginning of the water sorption-desorption test. This is because the spectrum obtained before the test was used as a reference, and thus the peak intensity weakened as the skin water content decreased and approached the quantity present before the test. Moreover, since this method cannot determine the skin resonance frequency before the test, it is difficult to determine by how much the water content increased or the time required to return to the pre-test value. Therefore, a more accurate analytical method for measuring the skin water content was developed by analyzing the spectra in more detail. Specifically, a part of the data near the peak that was not affected by the parasitic oscillation was extracted from the original spectrum and fitted with the least-squares method, since it was assumed that the correct resonance frequency could not be determined due to the parasitic oscillation influencing the original spectra.

Figure 8 shows an example of the least-squares analysis of the high-frequency spectrum. Fitting was performed with a quadratic function using a part of the data from the original spectrum, which is indicated by a bold line in the figure. Consequently, the resonance frequency obtained by the analysis was slightly lower than the value read directly from the original spectrum. The spectrum in Fig. 8 is from before the water sorption-desorption test began, and the equation of a curve for the least-squares analysis is as follows:

$$I(f) = 505.9 - 8.461 \times 10^{-1}f + 3.775 \times 10^{-4}f^2, \quad (2)$$

where f and $I(f)$ are the frequency and the corresponding intensity, respectively. The resonance frequency is given by the local minimum derived from this function. As a result, the calculated value ($f_C = 1121$ MHz) was lower than the directly obtained value ($f_D = 1144$ MHz).

A similar analysis was applied to the high-frequency spectra obtained at each elapsed time point after the test began, and the f_C values were compared with their corresponding f_D values. The results are listed in Table 1. The f_D values remained nearly constant from 80 s and beyond, whereas the f_C values changed continuously until 120 s.

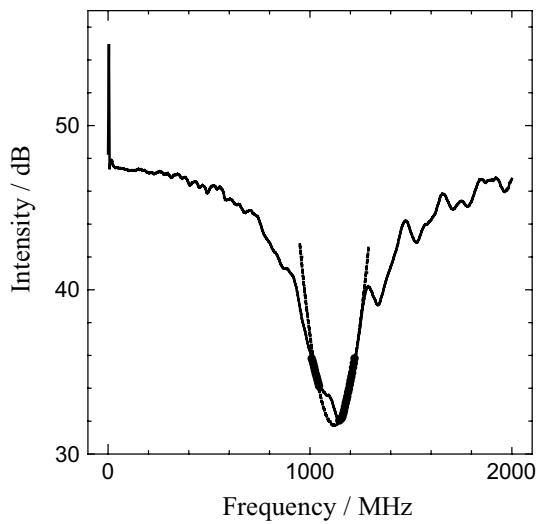


Fig. 8 An example of the least-squares analysis of a high-frequency spectrum. The dark marks and the dotted line show the data for the fitting with quadratic function and a curve fitted with the least-squares method, respectively

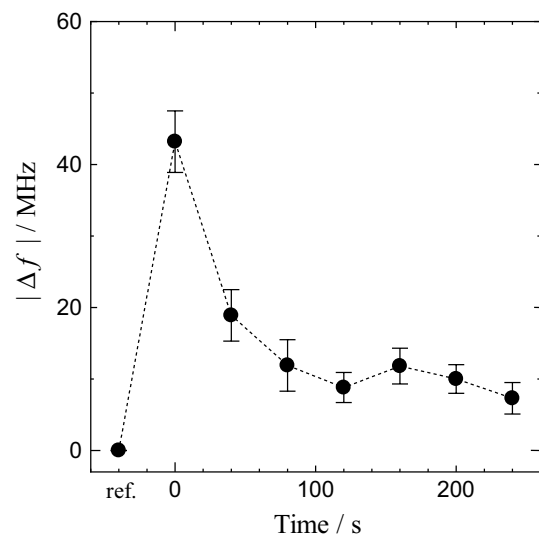


Fig. 9 Least-squares analysis frequencies during the water sorption–desorption test. Plotted marks and vertical lines indicate the means ($n=5$) and standard errors, respectively

Table 1 Comparison of measured and calculated resonance frequencies

Time/s	Frequency/MHz		$ \Delta f /\text{MHz}$	
	Spectrum ^a	Calculation ^b	Spectrum ^a	Calculation ^b
Reference	1144	1121	0	0
0	1032	1064	112	57
40	1052	1089	92	32
80	1140	1100	4	21
120	1144	1113	0	8
160	1140	1111	4	10
200	1140	1109	4	12
240	1144	1115	0	6

^aThe direct reading method

^bThe frequency estimation method using least-squares fitting

The HFS measurements were repeated multiple times, and the results were analyzed in the same manner. Then the obtained f_C values were employed in Eq. (1) in place of f_{ref} and f_i to calculate $|\Delta f|$. The plots of $|\Delta f|$ versus elapsed time are shown in Fig. 9. The $|\Delta f|$ values obtained from the least-squares analysis gradually decreased for 120 s. Furthermore,

$|\Delta f|$ did not return to 0 MHz, even after 120 s, suggesting that the skin water content remained higher than that before the test began. Since the skin surface hygrometer measurements were strongly influenced by moisture on the skin surface [26, 27], the measured values decreased within a short period as the moisture on the skin surface evaporated. In contrast, because HFS measurements can detect not only the water on the surface of the skin but also the water absorbed within the skin, a decreasing $|\Delta f|$, that is, a decreasing water content, was observed for a longer period than the skin surface hygrometer measurement was able to indicate.

The results of the water sorption–desorption test using HFS were analyzed via several different approaches: direct reading of the spectra (Fig. 5), difference spectra (Fig. 7), and a least-squares method (Fig. 9). Each of these analytical methods is outlined in Table 2. Any of these HFS analytical methods can be used to detect a gradual decrease in skin moisture that could not be observed with the skin surface hygrometer. Therefore, it was concluded that HFS can be used as a new evaluation method for human skin moisture, unlike conventional methods such as the skin surface hygrometer.

Table 2 Summary of analytical methods for the high-frequency spectral measurements of skin moisture

Analytical method	Advantage	Disadvantage
Direct reading of the original spectra	A simple and easy method	Considerable variation in measured values can arise from the influence of parasitic oscillations
Peak frequency tracking using difference spectra	A simple and easy method The frequency change (Δf frequency) obtained from the difference spectra is roughly proportional to the Δf frequency of the original spectra	Analyzed values are susceptible to noise as water content in the skin returns to its original state Pre-test skin resonance ($f_{ref.}$) cannot be determined
Peak intensity tracking using difference spectra	A simple and easy method Change in peak intensity is roughly proportional to peak frequency shift $\Delta I=0$ can be considered as the pre-test skin state	Changes in intensities in the original spectra affect the analyzed values Theoretical development of the peak intensity is required because the conventional principle, i.e., that the peak frequency shift reflects the change in permittivity, cannot be applied to understand the behavior of analyzed values
Frequency estimation using least-squares fitting	Pre-test resonance frequency ($f_{ref.}$) of the skin can be determined Based on the measurement principle, changes in permittivity depending on skin water content can be related to peak shifts	Somewhat complicated analytical procedure Final calculated value is an estimated frequency

Data availability All data generated or analysed during this study are included in this published article.

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