IFSCC 2025 full paper (IFSCC2025-501)

Breakthrough in skin sensing by monitoring quality of moisture through hydrogen bonding of water molecules

Mariko Egawa [1,*], Koyo Koizumi [1], Go Takehi [1], Naoki Okamoto [1], Makito Suzuki [1], Christopher T. Knight [1], Makiko Goto [1], Yudai Suzuki [2], Feroz Ahmed [2], Yoshiki Taniguchi [2], Miho Yakabe [3], Masato Takeuchi [4], Mika Ishigaki [5], Aiko Nagamatsu [6], Hideaki Kano [7], Toshiaki Hattori [2]

[1] MIRAI Technology Institute, Shiseido Co., Ltd; [2] Department of Applied Physics, Institute of Pure and Applied Sciences, University of Tsukuba; [3] Department of Chemistry, Graduate School of Science, Kyushu University; [4] Department of Applied Chemistry, Graduate School of Engineering, Osaka Metropolitan University; [5] Institute of Agricultural and Life Sciences, Academic Assembly, Shimane University; [6] Space Exploration Innovation Hub Center, Japan Aerospace Exploration Agency; [7] Department of Biosciences and Informatics, Faculty of Science and Technology, Keio University

1. Introduction

The most abundant element in the universe is estimated to be hydrogen, which accounts for approximately 75% of the mass of the universe and 90% of atoms. All life forms on Earth require liquid water for life-supporting activities such as respiration, nutrition, and emissions. Although the properties of water are unique compared with those of other molecular liquids [1,2], the behavior of water molecules is not well understood. In the living body, water serves as a medium for chemical reactions, mediating functions such as skin maintenance, fluid retention, blood circulation, and tactile sensation. Water in the skin is used as an important indicator because it reflects the skin condition. However, even when the skin moisture content is the same, the skin condition and perceived sensation often vary, highlighting a hurdle in discussing moisture solely in terms of quantity.

Water molecules in the body do not always exist freely but are often strongly or weakly bound to other molecules like proteins and lipids. In addition to the water content, the state of water in the skin is an important target for detailed evaluation of the function and physical properties of the skin. For dermatological study, the state of water in the skin has been determined by evaluating free and bound water contents mainly using destructive methods, such as the Karl Fischer method [3], differential scanning calorimetry [4], millimeter wave reflection [5], and nuclear magnetic resonance (NMR) [6]. Spectroscopic studies have unveiled several characteristics of the **hydrogen bond network of water molecules (HB)**: HB at different depths in the stratum corneum (SC) contributes differently

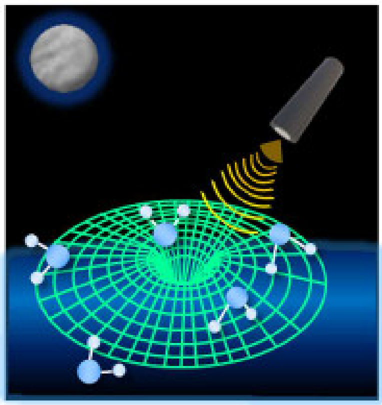

Figure 1. Future contributions of NIR sensing to health science in space and on Earth.

to water diffusion, HB correlates well with the lateral packing order of intercellular lipids and the natural moisturizing factor in the SC [7,8], and HB changes isolated cells from the granular layer [9]. However, the living cell layer of the skin has not been studied in detail.

In the future, space travel is expected to be accessible even to ordinary people. At present, ongoing discussions on the effects of space travel on the human body in the field of medicine are focused on life and death, with limited studies on the skin [10]. However, the behavior of water molecules in the low-gravity environment of outer space is expected to differ significantly from that on Earth, and the effects of this difference on cellular functions, human metabolism, and pharmacological effects remain largely unexplored. The final goal of our research is to elucidate the dynamics of water molecules in the living body, including the skin, and to develop healthcare sensing techniques to monitor water dynamics continuously both on Earth and in space (Figure 1). To this end, the present study aimed to determine changes in HB under low gravity, elucidate the behavior of HB in the skin, and develop a convenient HB-sensing technology based on spectroscopy.

2. Materials and Methods

2.1. Research design

We aimed to **1**) determine whether HB changes under low gravity using near-infrared spectroscopy (NIR) [Exp. 1], **2**) determine whether HB changes during cellular differentiation in living epidermal layers and whether HB is related to skin condition in vivo using Raman spectroscopy [Exp. 2: longitudinal study], **3**) verify changes in HB using Raman, coherent anti-Stokes Raman scattering spectroscopy (CARS), and terahertz time-domain spectroscopy (THz-TDS), in addtion to samples of cultured epidermal cells, dermis, moisturizers [Exp. 3, 4, 5], and **4**) develop a simple in vivo HB-sensing technology using NIR [Exp. 6: cross-sectional study]. Human studies were performed in accordance with the principles of the Declaration of Helsinki and approved by our institution's Ethics Committee (approval numbers: C00226 [Exp. 2], C10218, C10236 [Exp. 4], B10167, B10428 [Exp. 6]). Informed consent was obtained before the measurements.

2.2. Instruments

NIR [11,12,13] and Raman [11,14] measurements targeted the intramolcular vibrations of the HB, while THz measurements [15] targeted the intermolecular vibrations of the HB (Figure 2). NIR spectra were obtained in the range of 1450–2450 nm using a NIR spectrometer (PAL one, trinamiX, Ludwigshafen, Germany) equipped with a 256 pixel PbS line array detector. Raman spectra were acquired using backscattering type confocal Raman (Model 3510 SCA/ gen2-SCA, RiverD International, Rotterdam, Netherlands) and forwardscattering type confocal Raman (RAMANTouch, Bruker, Billerica, MA, USA) spectrometers. CARS images (50×50 μm; 101×101 pixels) were acquired in the wavenumber range of 600–3700 cm^{-1} using an in-house CARS microscope [16]. THz spectra were acquired using an in-house THz-TDS spectrometer [15], and spectral information were obtained through Fourier transformation of temporal waveforms of THz pulses.

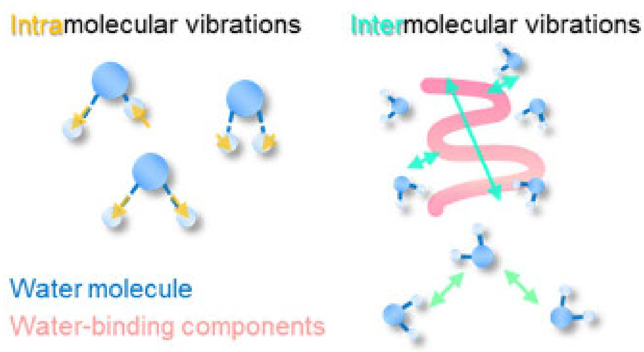

Figure 2. Targets of spectroscopic measurements of the hydrogen bond network of water molecules (HB).

2.3. Experiments

2.3.1. NIR spectroscopy of HB under low gravity on a 3D-Clinostat [Exp. 1]

The low-gravity environment of the Earth's orbit was reproduced using a 3D-clinostat (PMS-VIII, Japan Aerospace Exploration Agency, Tokyo, Japan) capable of achieving less than 0.1G in approximately 15 min (horizontal (x) axis: 6 rpm, vertical (y) axis: 6 rpm). Synthetic zeolite (F-9, X-type, Na, 100 mesh-pass powder, Tosoh Corp., Yamaguchi, Japan), mesoporous silica (SBA-15, <150 μm particle size, Sigma–Aldrich, Burlington, MA, USA), and distilled water (DW) were placed in a special container, which was fixed to the NIR spectrometer secured to the 3D-clinostat. Changes in HB under low gravity and 1G were monitored over 60 min.

2.3.2. In vivo Raman spectroscopy of HB of viable epidermal layer of human skin [Exp. 2]

Raman spectra of the cheek of 27 healthy Asian participants (13 female and 14 male, 22–53 years old) were obtained in the range of 2500–4000 cm^{-1} at depth intervals of 2 μm from the skin surface over the four seasons in an air-conditioned environment. The water content of the skin was also obtained using a Corneometer (CM825; C+K Electronic, Cologne, Germany) before Raman measurements. Participants washed the measurement areas with commercially available cleansing oil and solid soap 1 h prior to the measurement.

2.3.3. In vitro Raman spectroscopy of HB of cultured epidermal cells [Exp. 3]

Normal human epidermal keratinocytes (NHEK) (P3, Kurabo Ind., Osaka, Japan) were suspended in fresh low-Ca medium (phenol red-free Humedeia-KG2 with 60 μM of Ca^{2+}) and seeded in 35 mm Φ14 quartz bottom dish to 100% confluency. The medium was replaced with fresh high-Ca medium (1.5 mM of Ca^{2+}) on day 0 and replaced with fresh high-Ca medium every 2–3 days. Raman and CARS spectra were acquired during keratinocyte differentiation.

2.3.4. Ex vivo THz-TDS of HB of human skin tissue [Exp. 4]

Four samples of skin from the abdomen (57-, 64-, and 70-year-old Caucasian females) were supplied by Biopredic International (Rennes, France). Frozen sections (100 μm thick) were created, and the slide glasses were numbered. Slices corresponding to the dermis were used for THz-TDS measurements.

2.3.5. In vitro Raman and THz-TDS of HB of moisturizer [Exp. 5]

Aqueous solutions of 0–1.0 wt% hyaluronic acid (FUJIFILM Wako Pure Chemical Co., Osaka, Japan) and 0–10 wt% glycerol (FUJIFILM Wako Pure Chemical Co.) were prepared for Raman and THz-TDS measurements.

2.3.6. In vivo simplified NIR sensing of HB [Exp. 6]

NIR spectra of cotton containing water were acquired during a heating cycle to confirm whether NIR could evaluate changes in the HB. In vivo NIR and Raman spectra of the left volar forearm skin of 30 healthy Asian participants (female and male, 37–64 years old) were obtained to verify whether one-shot NIR spectroscopy was equivalent to Raman spectroscopy in detecting the HB.

2.4. Data analysis

Spectra were analyzed using Python (ver. 3.8.3, Python Software Foundation, Wilmington, DE, USA), RStudio (ver. 27771613, RStudio PBC, Boston, MA, USA), Pirouette (ver. 5.0, Infometrix, Bothell, WA, USA), and Iogr Pro (ver. 9.05, WaveMetrics, Lake Oswego, OR, USA). Statistical analysis was performed using JMP16.0.0 (512247, SAS Institute, Cary, NC, USA). Values of $p < 0.05$ were considered statistically significant. Regarding Exp.1, paired t-tests were conducted, and *p*-values were corrected using the Bonferroni's method at the significance level α of 0.05.

3. Results

3.1. HB changes in a low-gravity environment

We measured changes in the HB in a low-gravity environment, which was simulated using a 3D-clinostat (Figure 3a). *W/S ratio_ng* was calculated from NIR spectra (Figure 3b) in ranges of 1844–1922 nm and 1922–2144 nm after linear baseline correction at 1844 and 2144 nm.

$$W/S\ ratio\_ng = \text{Weakly-bound water}_{1844\text{–}1922} / \text{Strongly-bound water}_{1922\text{–}2144} \quad (1)$$

W/S ratio_ng changed in the low-gravity environment of approximately 0.1G, and the change differed depending on the spatial environment of the water molecules (Figure 3c,d).

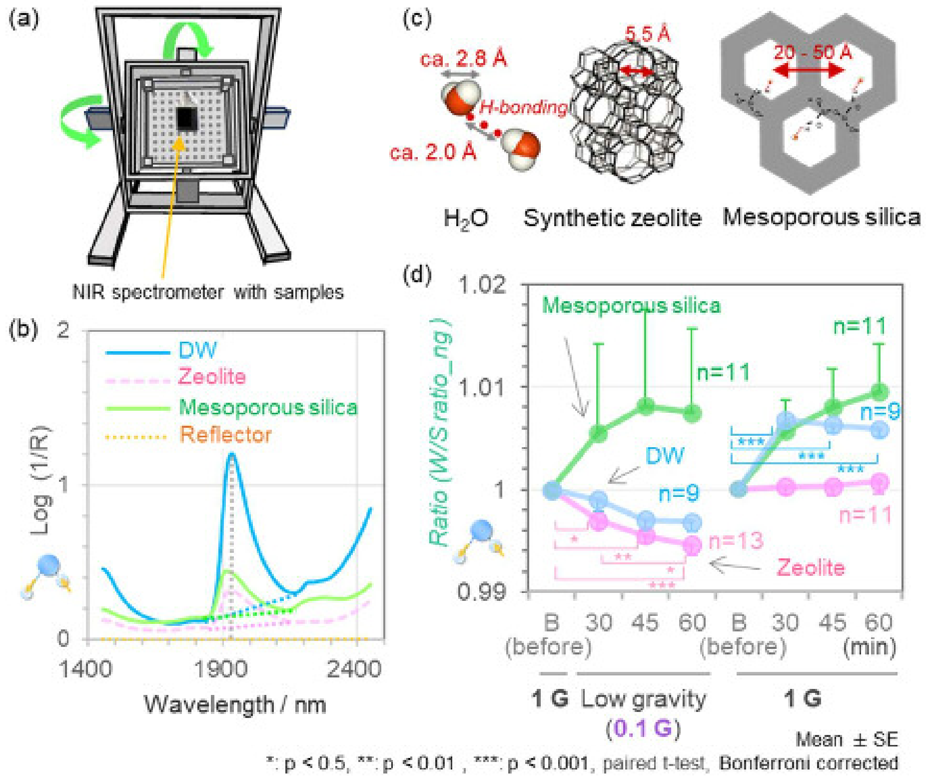

Figure 3. Changes in the ratio of weakly- to strongly-bound water (*W/S ratio_ng*) under low gravity: (a) Schematic diagram of 3D clinostat used to reproduce a low-gravity environment on Earth; (b) NIR spectra of each sample under low gravity; (c) Molecular size of H_2O and pore size of mesoporous materials; (d) Changes in *W/S ratio_ng* under low gravity.

3.2. HB increases during differentiation in the epidermal viable cell layer

To evaluate changes in the HB of the viable cell layer of the epidermis in vivo, the ratio of weakly-bound water to strongly-bound water (*W/S*) was calculated from Raman spectra in the ranges of 3370–3550 cm^{-1} and 3100–3230 cm^{-1} after linear baseline correction using a straight line connecting 2510 and 3800 cm^{-1}.

$$W/S = \text{Weakly-bound water}_{3370\text{–}3550} / \text{Strongly-bound water}_{3100\text{–}3230} \quad (2)$$

Total water (*TW*) was calculated as the relative water content per protein.

$$TW = (\text{Weakly-bound water}_{3370\text{–}3550} + \text{Strongly-bound water}_{3100\text{–}3230}) / \text{Protein}_{2910\text{–}2965} \quad (3)$$

W/S increased from the deeper to upper part of the viable epidermal layer and dropped sharply from this layer to the SC (Figure 4a). *W/S* and *TW* showed a similar trend with depth in the SC but the opposite trend in the viable cell layer. Normally, HB increases as the water content increases. However, this trend was not observed in the viable epidermal layer. The water band was also deconvoluted using four Gaussian functions at peak positions of 3277, 3330, 3458, and 3604 cm^{-1} (Figure 4b) to compare the area under the curve (equations 2).

In addition, *W/S* in a monolayer of NHEK cells was calculated from spontaneous Raman spectra after linear baseline correction at 2500 and 3800 cm^{-1}. The average and standard deviation of *W/S* for 20 cells are shown in Figure 5. *W/S* also increased during differentiation in cultured epidermal cells. The HB measured using CARS during the differentiation of epidermal cells revealed that the region of weakly-bound water increased on day 4 compared to day 1 (Figure 6), which agreed with the results of spontaneous Raman spectroscopy (Figure 5).

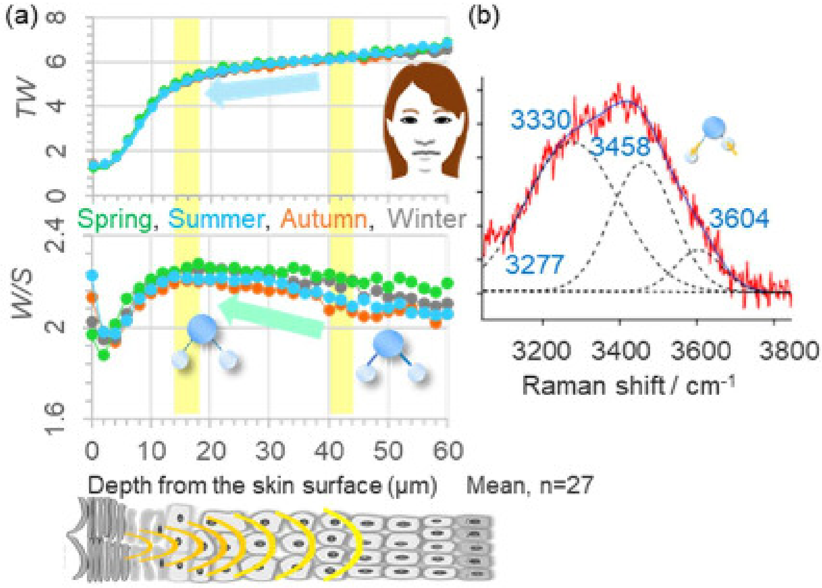

Figure 4. Changes in the hydrogen bond network of water molecules (HB) in the epidermal living cell layer of the cheek: (a) Ratio of weakly- to strongly-bound water (*W/S*); (b) Total water content (*TW*); (c) Deconvolution of the water band using four Gaussian functions.

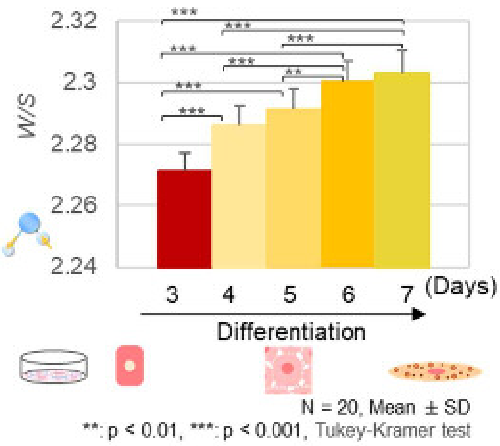

Figure 5. Changes in the ratio of weakly- to strongly-bound water (*W/S*) during keratinocyte differentiation.

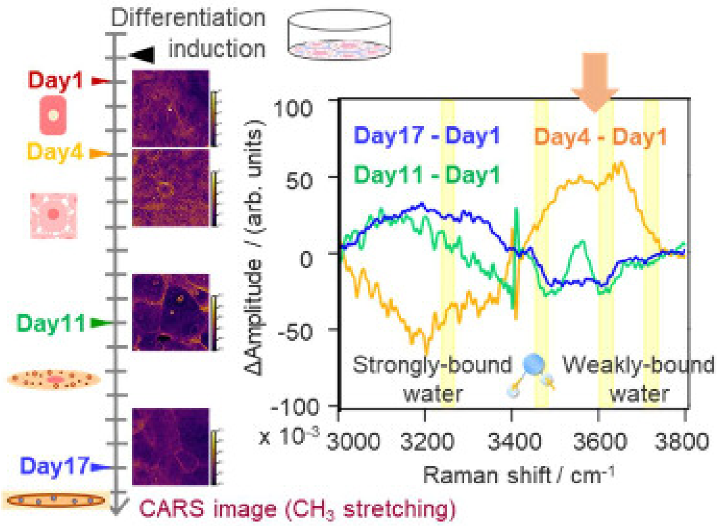

Figure 6. Changes in the hydrogen bond network of water molecules (HB) during keratinocyte differentiation. Difference Raman spectra of water bands from CARS.

3.3. Changes in HB in the viable cell layer in vivo correlate with skin conditions

Because *W/S* increased during differentiation in the viable cell layer both in vivo and in vitro, we calculated *ΔW/S* as an index of *W/S* change via differentiation in vivo using the mean of *W/S* at depths of 14–18 µm and 40–44 µm.

$\Delta W/S = 1^{st}$ range $(W/S_{14\text{–}18})$ – 2^{nd} range $(W/S_{40\text{–}44})$ (4)

We found that the variation in the data at depths greater than 48 μm was largely owing to factors such as the attenuation of laser intensity, and thus we selected the 2nd range. *ΔW/S* showed a seasonal change, which was similar to the change determined using the corneometer. Then, data from the corneometer were divided into two groups, high and low values, and comparison of the two groups revealed that the high group had a significantly higher *ΔW/S* (Figure 7a). Moreover, the high and low values from the corneometer were not biased toward any particular season, and they reflected differences between individuals (Figure 7b), enabling the development of a novel patent-pending algorithm based on changes in HB under healthy skin conditions.

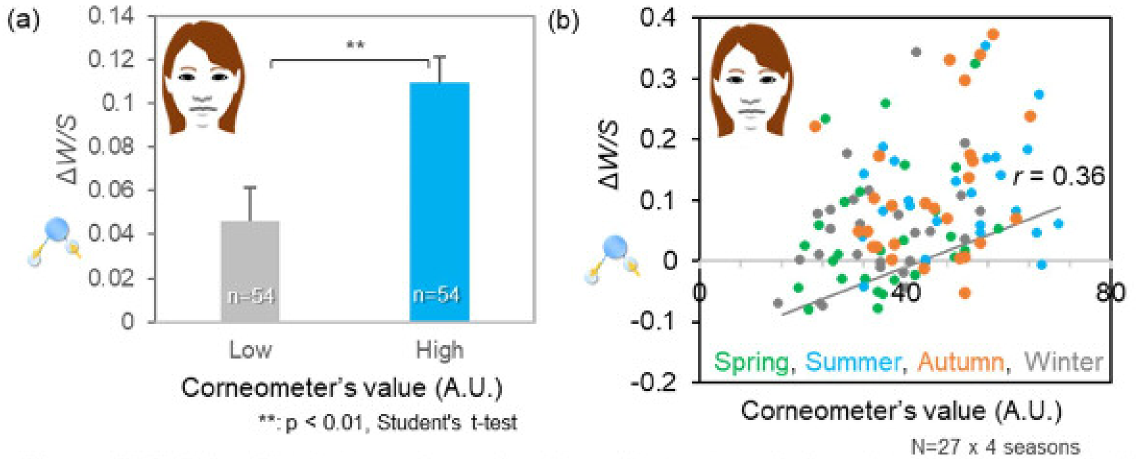

Figure 7. Relationship between the ratio of weakly- to strongly-bound water (*W/S*) and skin condition in vivo: (a) Difference in *W/S* at 14–18 μm and *W/S* at 40–44 μm (Δ*W/S*) between the high and low values from the corneometer; (b) Correlation plot of Δ*W/S ratio* and values from the corneometer color-coded by season.

3.4. Verification of changes in HB using multiple spectroscopic methods and samples

Changes in HB were verified through THz-TDS of moisturizers and the dermis (Figure 8a). The number of weakly-bound water molecules in the aqueous solution of hyaluronic acid increased in a concentration-dependent manner (Figure 8b). Moreover, the amount of weakly-bound water in the dermis was greater than that of DW, and this increase was also concentration dependent (Figure 8c).

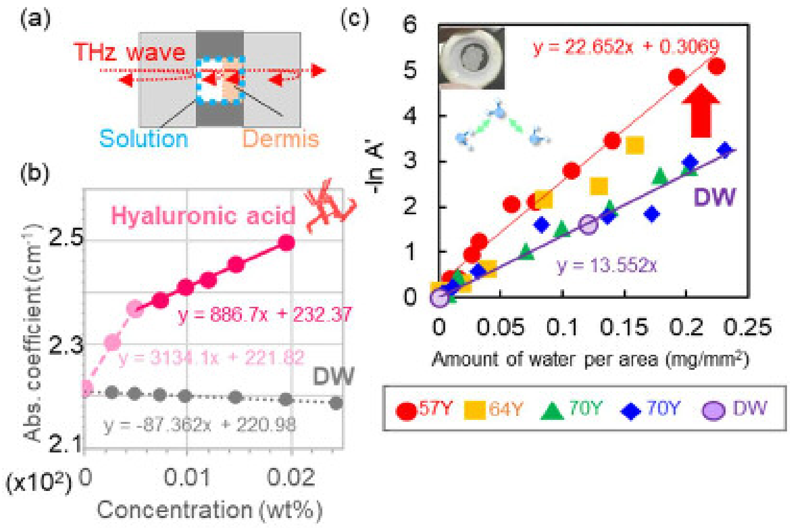

Figure 8. Changes in the hydrogen bond network of water molecules (HB) in moisturizers and the dermis using THz-TDS: (a) Schematic diagram of sample holder; (b) Amount of weakly-bound water versus concentration of hyaluronic acid measured at 1.0 THz; (c) Amount of weakly-bound water in the dermis.

Figure 9a shows the Raman spectra of aqueous solutions of hyaluronic acid and glycerol at different concentrations and the wavenumbers for calculating *W/S*. *W/S* slightly increased as the concentration of hyaluronic acid increased but was unaffected by the concentration of glycerol (Figure 9b).

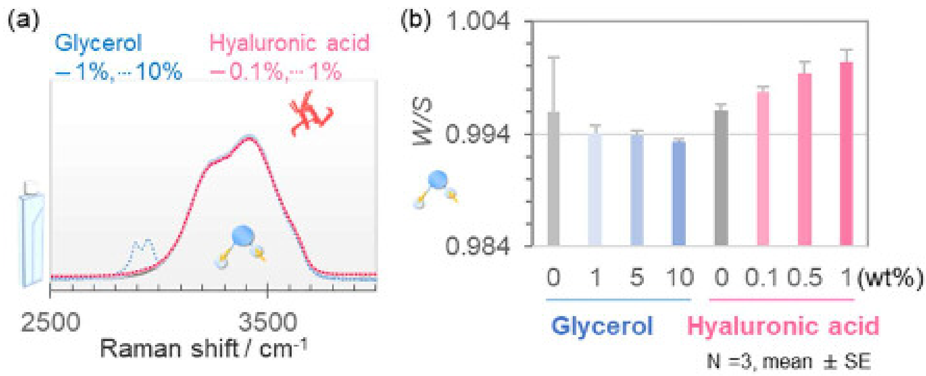

Figure 9. Changes in the hydrogen bond network of water molecules (HB) in moisturizers using Raman spectroscopy: (a) Raman spectra of moisturizers; (b) Dependence of *W/S* on the concentration of moisturizers.

3.5. One-shot NIR sensing of HB in humans

We determined the possibility of in vivo one-shot NIR sensing of HB using the water band at 1900 nm. *W/S ratio_n* was calculated from NIR spectra in the regions of 1818–1922 nm and 1922–2242 nm after linear baseline correction at 1818 and 2242 nm.

$$W/S\ ratio\_n = \text{Weakly-bound water}_{1818–1922} / \text{Strongly-bound water}_{1922–2242} \quad (5)$$

First, we confirmed that *W/S ratio_n* increased as the temperature increased, and it decreased when the heater was turned off. Then, we investigated whether one-shot NIR sensing could be used as an alternative to Raman spectroscopy to measure *ΔW/S*. Considering the depth of Raman measurements in usual human tests and the depth of NIR measurements by Monte Carlo simulations [17], *ΔW/S* was calculated using the alternative 2nd range (Figure 10a).

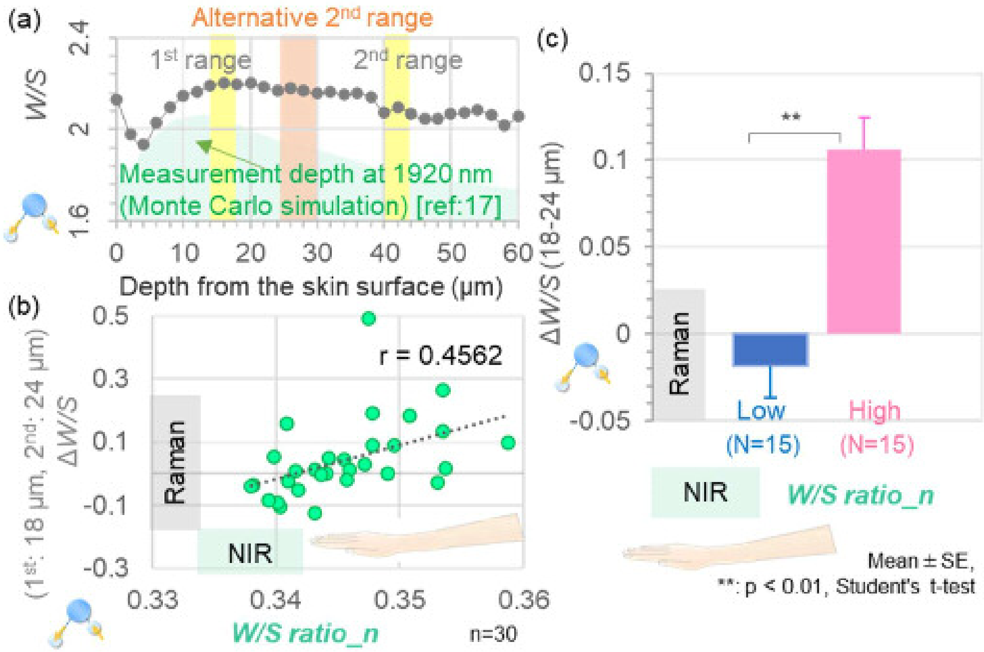

Figure 10. Relationship between HB measured using NIR and HB measured using Raman spectroscopy: (a) Calculation of Δ*W/S* using the alternative 2nd range; (b) Correlation between Δ*W/S* at the forearm from Raman measurements and *W/S ratio_n* at the forearm from NIR measurements; (c) Comparison between ΔW/S ratio and *W/S ratio_n* in the two groups.

Figure 10b shows the correlation between *ΔW/S* at the forearm from Raman measurements (1st range–alternative 2nd range) and *W/S ratio_n* at the forearm from NIR measurements. The correlation coefficient r was 0.4562, enabling further development of the novel patent-pending algorithm based on *ΔW/S* for simple one-shot NIR sensing. The data were divided into two groups, high and low *W/S ratios_n*, and comparison of the two groups revealed that values of *ΔW/S were* signficantly different from Raman spectra-derived values (Figure 10c).

4. Discussion

We have approached healthcare sensing in the living environments of Earth and beyond by considering not only the skin itself but also the skin as a mirror of overall physical condition. We selected the bonding state of water molecules as the sensing target because on Earth, various activities use water as a solvent (e.g., enzymatic reactions), and hydrogen bonds, which are weak bonds, are easily affected by the environment surrounding water molecules. Furthermore, HB within the body is not uniform. For example, water molecules may exist in pores surrounded by solid substances such as zeolite or mesoporous silica, in a liquid state like DW, or in a state bound to other components such as proteins or lipids in body fluids or pores. The variations are numerous.

In Experiment 1, we investigated whether the hydrogen bonds in water molecules are affected by changes in gravity, and found that the effects of gravity on HB vary depending on the environment of water molecules, i.e., how many water molecules are in the space, how close they are to other molecules. Furthermore, the varying effects of the environment of water molecules indicate that in biological systems such as the skin or internal organs, the direction of change in response to gravity may be heterogeneous, depending on the morphology of each organ or cell. All living organisms on Earth have evolved to adapt to conditions of near 1G, and thus the long-term effects of gravity on complex biological systems and the skin in space remain unpredictable. However, because these effects are related to weak hydrogen bonds, evolutionary adaptations may occur.

In Experiments 2 and 3, we investigated the significance of HB in the skin, both in vivo and in vitro. The results showed that *W/S* increased during differentiation in the epidermal living cell layer, indicating an increase in the weaker binding water molecules. A previous report [13] indicated that the higher the activity in fish embryos, the greater the amount of water in a weak bonding state, suggesting a relationship between HB and the activity of biochemical reactions involving enzymes in living organisms.

In Experiments 4 and 5, we examined the significance of HB in the skin. The results revealed that *W/S* increased during differentiation, even in cultured cells, *W/S* in the presence of hyaluronic acid was greater than that of DW, and the dermis contained more water molecules in a weaker bond state than DW. In general, as the concentration of a component increases, the relative amount of water decreases in turn, and the amount of weakly-bound water decreases [15]. However, our results revealed that some moisturizing agents such as hyaluronic acid and the dermis induced the opposite change in weakly-bound water, providing insight into the fundamental mechanism of moisturizing components in the skin and their contribution to the physical properties of the skin.

Finally, in Experiment 6, we demonstrated one-shot sensing of HB in the skin using NIR as a simple spectroscopic method that can be used by the general public both on the ground and in space. Although NIR sensing did not exhibit the research-level discrimination of high-precision methods, a certain degree of accuracy would be sufficient for applications such as setting living conditions on Earth or for use in space where activities are limited owing to the distance from the ground. NIR bands shift in response to hydrogen bond formation, and thus NIR spectroscopy can be used to investigate HB and molecular bonding states non-invasively. Although NIR spectroscopy may be replaced by other high-precision methods for research purposes, it is very effective in situations requiring simple methods, such as space exploration [18].

In dermatology and cosmetic science, researchers have studied the maturation of the SC. Thinking broadly, water is so ubiquitous as a solvent for life on Earth that we may not fully appreciate the subtle changes in its behavior and their potential impact on living organisms. Although the SC is the final target of cosmetics, beneath it lie multiple layers of epidermal cells, the dermis, and blood vessels that deliver nutrients, all connected through water. Furthermore, individual characteristics of the skin, connected to the body's tissues, may allow us to detect the individuality of a body by sensing the HB of the skin.

The world is actively promoting space development for life beyond Earth, and the day when ordinary citizens can stay in space is gradually approaching. New habitable areas developed in the future (e.g., the moon) are expected to affect the HB of our skin and body in a different manner from Earth owing to differences in gravity. It is a well-known fact that gravity is the weakest of the four fundamental interactions (strong force, electromagnetic force, weak force, and gravity) [19], yet all life on Earth is bound by gravity. Although the Experiment 1 was conducted in a simulated low-gravity environment experienced during spaceflight, the results suggest that the effects of low gravity on HB may occur under Earth's varying gravitational conditions. Our experimental results showed that even a reduction in gravity from 1G to approximately 0.1G (Figure 11a) and variation in skin conditions (Figure 11b) caused a change of 10^{-2} in absorbance. The same simulated low-gravity environment also affects plant growth [20]. If changes in gravity can alter plants, then it is only logical that these changes will also affect the human body. The effects of gravity are not limited to space.

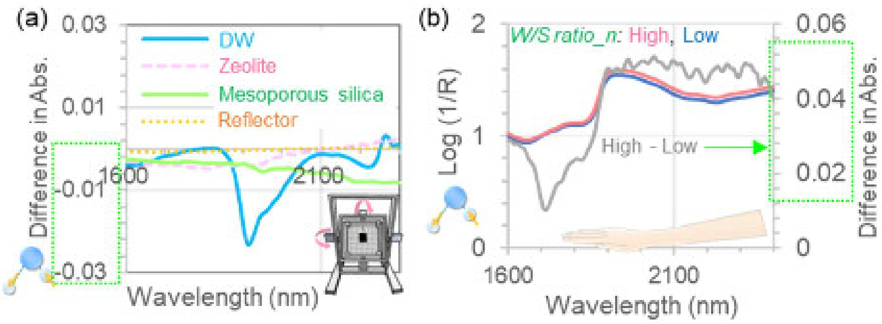

Figure 11. Extent of HB change in living environments: (a) Changes in NIR spectra between 1G and 0.1G; (b) Changes in NIR spectra depending on skin condition.

On Earth, gravity varies by approximately 1 Gal (1G = 9.8 m/s² = 980 Gal) depending on location [21]. In our daily lives, we experience variations in gravity due to factors such as changes in atmospheric pressure, air travel, differences in altitude, and tidal movements. How do changes in gravity affect the HB, a medium for chemical reactions? This study provides a platform for future research on water science, which will be vital not only

Figure 12. Potential directions for future research.

for understanding the behavior of water molecules but also for supporting human activities beyond Earth (Figure 12).

5. Conclusion

We have demonstrated, for the first time, the relationship between the HB of the epidermal viable cell layer and skin condition in vivo. Because the HB plays an essential role in the activity of enzymes in major biochemical processes, our findings may unlock steps toward achieving optimal skin conditions from the perspective of microchemical reaction activity. Furthermore, we discovered the possibility of simple NIR sensing for customer use. We also showed that HB changed under low gravity, and these changes differed depending on the space surrounding water molecules. The effect of gravity on water, which makes up a large proportion of the ingredients in skin and cosmetics, is likely to be relevant to life in space and the use of cosmetics in the near future.

References

[1] Eisenberg, D., Kauzmann, W. The structure and properties of water, Oxford Classic Texts in *Physical Sciences* (Oxford, 2005; online edn, Oxford Academic, 2007).
[2] Debenedetti, P.G. *J Phys: Condens Matter* **15**(45), R1669(2003).
[3] Dubinskaya, V.A. et al. *Bull Exp Biol Med* **144**(3), 294–297(2007).
[4] Tang, R. et al. *Skin Res Technol* **23**(4), 573–580(2017).
[5] Alekseev, S.I., Ziskin, M.C.H. *Bioelectromagnetics* **28**(5), 331–339(2007).
[6] Zhang, Y. et al. *Food Hydrocoll* **91**, 136–142(2019).
[7] Choe, C., Lademann, J., Darvin, M. *Analyst* **141**(22), 6329–6337(2016).
[8] Boireau-Adamezyk, E., Baillet-Guffroy, A., Stamatas, G.N. *J Invest Dermatol* **134**(7), 2046–2019(2014).
[9] Shiraga, K., Ogawa, Y., Kikuchi, S. et al. *Molecules* **27**(9), 2886(2022).
[10] Farkas, Á., Farkas, G. *Skin Pharmacol Physiol* **34**(5), 239-245(2021).
[11] Egawa, M. Application of Raman and Near-infrared Spectroscopies to Skin Science, in *Encyclopedia of Analytical Chemisty* (John Wiley & Sons, Ltd., 2025).
[12] Egawa, M. et al. *Appl Spectrosc* **60**(1), 24–28(2006).
[13] Ishigaki, M. et al. *Anal Chem* **92**(12), 8133–8141(2020).
[14] Caspers, P.J. et al. *J Invest Dermatol* **116**(3), 434–442(2001).
[15] Aoki, K., Shiraki, K., Hattori, T. *Phys Chem Chem Phys* **18**, 15060–15069(2016).
[16] Okuno, M. et al. *Angew Chem Int Ed* **49**(38), 6773–6777(2010).
[17] Arimoto, H., Egawa, M., Yamada, Y. *Skin Res Tec* **11**(1), 27–35(2005).
[18] Abe, M. et al. *Science* **312**(5778),1334–1338(2006).
[19] https://science.nasa.gov/universe/overview/forces/
[20] Totsline, N., Kniel, K.E., Sabagyanam, C. et al. *Sci Rep* **14**, 898(2024).
[21] http://dagik.org/dow/Dagik_Earth_folder/land/Dagik_Geoid_GravityAnomaly/index.html

Author contribution

M. E. supervised and designed the project and wrote the manuscript. Experimental data acquisition and analysis: Exp. 1 by M. E., K. K., G. T., N. O., M. T., M. I., and A. N.; Exp. 2 by M. E. and K. K.; Exp. 3 by M. S., M. Y., M. E., and H. N.; Exp. 4 by Y. S., M. E., and T. H.; Exp. 5 by F. A., Y. T., M. E., and T. H.; Exp. 6 by M. E., K. K., G. T., and N. O. All authors interpreted the results and approved the final version of the manuscript.