Received: 20 June 2024 | Accepted: 6 November 2024
DOI: 10.1111/cpf.12916

Clinical Physiology and Functional Imaging

ORIGINAL ARTICLE

Skin tissue dielectric constant: Time of day and skin depth dependence

Harvey N. Mayrovitz

Department of Medical Education, Dr. Kiran C. Patel College of Allopathic Medicine, Nova Southeastern University, Fort Lauderdale, Florida, USA

Correspondence
Harvey N. Mayrovitz, Department of Medical Education, Dr. Kiran C. Patel College of Allopathic Medicine, Nova Southeastern University, 3200 S. University Dr, Ft. Lauderdale, FL 33328, USA.
Email: mayrovit@nova.edu

Abstract

Background: Skin water measurements are used to investigate skin physiology, clinically study dermatological issues, and for conditions like diabetes, oedema, and lymphedema with measurements done at various times of day (TOD). One method used is skin's tissue dielectric constant (TDC), often clinically measured to a single depth of 2.5 mm. This report characterizes intraday variations measured to multiple depths to guide expected TOD and depth dependence.

Materials and Methods: Twelve medical students self-measured TDC on their forearm to depths of 0.5, 1.5, 2.5, and 5.0 mm every 2 h from 08:00 to 24:00 h on 2 consecutive days. All were trained in the procedure.

Results: TDC declined slightly from morning through evening, mostly at 0.5 mm for which TDC was reduced by 4%. TDC values were not related to participants' whole-body fat or water percentages. The TDC decrease was less at 1.5 mm where the reduction was 2.7%. At depths of 2.5 or 5.0 mm, there was no significant decrease in TOD.

Conclusion: Skin TDC shows a minor decreasing trend with an effect greater for shallower depths. In part, the clinical relevance of the findings relates to the confidence level associated with skin water estimates, based on TDC measurements, when measured at different TOD and depths during normal clinic hours. Based on the present data the TOD change is at most 4% and insignificant for measurement depths of 2.5 mm.

KEYWORDS
forearm skin, skin hydration, skin temperature, skin water, TDC, whole body fat, whole body water, young adults

1 | INTRODUCTION

Skin water measurements are used for a variety of purposes ranging from research on aspects of skin physiology (Luebberding et al., 2013), to clinical application to assess dermatological conditions such as atopic dermatitis (Firooz et al., 2007; Knor et al., 2011; Nakai et al., 2015), psoriasis (Darlenski et al., 2021; Lee et al., 2012), ichthyosis (Tomita et al., 2005) and wound healing (Boury-Jamot et al., 2009; Lee et al., 2022; Ousey et al., 2016). In addition, such measurements, often made to a measurement depth of 2.5 mm, are useful to assess localized skin water in other conditions such as diabetes mellitus (Mayrovitz et al., 2013; Mayrovitz, Volosko, et al., 2017; Namgoong et al., 2019) and breast cancer related lymphedema (Mayrovitz, Weingrad, et al., 2009; Mayrovitz et al., 2014; Toro et al., 2024). For many of these assessments the anterior forearm is assessed (Bazin & Fanchon, 2006; Egawa & Tagami, 2008; Mayrovitz, 2023). Such assessments of skin water are made at various times of day (TOD) but there is limited information on the expected intraday variability. This is especially true when one additionally considers the skin depth to which skin water is measured. It is thus of basic and clinical interest to estimate the extent of such variability. Some initial ground-breaking efforts have been made to characterize the temporal variability in skin hydration (Gniadecka, Gniadecki, et al., 1994; Le Fur et al., 2001; Yosipovitch, et al., 1998) as has been recently reviewed (Camilion et al., 2022; Mayrovitz & Berthin, 2021). However, there has been no systematic investigation of the extent of the diurnal variation in skin hydration when measured to varying skin depths. The present report focuses on this issue by assessing local skin hydration via tissue dielectric constant (TDC) measurements obtained every 2 h from 08:00 h to 24:00 h on 2 consecutive days in 12 healthy young adults.

2 | METHODS

2.1 | Subjects

Twelve young healthy adult medical students (seven male) participated in this self-measurement research that was approved by the Nova Southeastern University Institutional Review Board. To be part of the study, subjects needed to agree to be successfully trained in needed measurement methods and be willing and able to do self-measurements at 2-h intervals from 08:00 to 24:00 h on 2 consecutive days of their choice. Exclusions to participation were any skin conditions or open wounds affecting forearm skin which was to be the site of the measurements.

2.2 | Measurements

TDC was measured to effective depths of 0.5, 1.5, 2.5 and 5.0 mm using the MoistureMeter multiprobe system (Delfin Technologies). This device consists of multiple probes of different diameters as illustrated in Figure 1 that are one-by-one connected to a control box that generates a 300 MHz signal and functions as an open-ended coaxial transmission line (Alanen et al., 1998b; Gabriel et al., 1996; Grant et al., 1988; Stuchly et al., 1982), to determine TDC that largely depends on water content within the measurement volume (Alanen et al., 1998a; Alanen et al., 1999). The method has been validated (Nuutinen et al., 2004), and shown to be reliable (De Vrieze et al., 2020; Jönsson et al., 2020; Mayrovitz et al., 2019). Measurements are done by touching skin with one of the probes for a few seconds as illustrated in Figure 2. Based on the relationship between the transmitted and reflected part of the 300 MHz signal, software within the control box processes the data and yields the TDC value that is displayed on the unit. In addition, each participant's whole-body fat and water percentages (FAT% and H_2O% respectively) were measured using bioimpedance at 50 KHz (InnerScan Body Composition Monitor, Tanita model BC558; The Competitive Edge). Body composition measurements were made after the subject removed their footwear and stood on a scale for about 10 s while gripping a handle-electrodes. Weight, FAT%, and H_2O% were measured as previously described that is determined by a device priority algorithm (Mayrovitz, Grammenos, et al., 2017). Skin temperature (TSK) at the site of TDC measurements was measured using an infrared noncontact device (Model DX501-RS; Exergen) with a stated repeatability of ±0.1°C. Room temperature (TRM) and relative humidity (RH) were also measured (Fluke Model 971, with a stated accuracy of ±0.1°C for TRM and ±2.5% for RH.

FIGURE 1 TDC measurement system. Four probes were used to measure to effective depths of 0.5, 1.5, 2.5 and 5.0 mm as labelled. Each acts as an open ended coaxial transmission line. The larger diameter allows for deeper penetration of the 300 MHz signal generated by the control box. The physicl diameter of the probes from smallest to largest in mm is 55, 22, 15 and 10. Upon contact with the skin the measurement process starts and the TDC value is displayed on the readout. TDC, tissue dielectric constant.

FIGURE 2 Self-measuring TDC on volar forearm. The measurement using the probe for a 0.5 mm depth is illustrated. Each depth is measured in triplicate and the average used to characterize the sites TDC value at that depth. TDC, tissue dielectric constant.

2.3 | Initial procedures

Before starting self-measurements, each potential participant was trained and evaluated in the proper use of each skin measuring device by the author during a dedicated training session. During that session, but following their training, each participant performed a series of measurements that replicated what they would do during their self-measurement protocol. This sequence of measurements was observed for proper technique and corrected if needed, and a second sequence was carried out. No participant required any further corrections. After this training and validation session the total body weight, FAT%, and H_2O% were measured as described in the methods section.

2.4 | Self-measuring procedure

The self-measurer performed their measurements on 2 consecutive days, usually the weekend when they were to be at home for the entire day. The skin of the nondominant forearm was measured while the self-measurer was seated, and the arm rested on a suitable support surface. No lotions creams or other substances were permitted to be applied to the forearm on measurement days. The measurement site was the volar forearm 5 cm distal to the antecubital fossa. It was marked with a small dot using a surgical pen. TDC was measured in triplicate at this site with each of the probes, first to a depth of 0.5 mm, followed to depths of 1.5, 2.5, and 5.0 mm. After the TDC measurements, TSK was measured at the same site and then TRM and RH were recorded. This sequence was repeated every 2 h starting at 08:00 h and continuing to and including 24:00 h constituting nine sequential measurement cycles over 16 h. During the entire sequence, the measurer's activities were confined to normal ones that consisted mostly of studying, watching TV, listening to music, and at times eating and drinking noncaffeinated beverages. No vigorous activity was permitted nor was washing of the forearm permitted. The entire procedure was replicated the next day.

2.5 | Analysis

The triplicate TDC values at each of the nine daily measurement times were averaged to yield one TDC value per measurement time for each of the four measurement depths. Overall, this yielded 36 TDC values per participant per day. These values were tested for normality via the Shapiro–Wilk test at each measurement time. These tests indicated that normality could not be assumed for any time or for either of the 2 days. Thus, statistics were based on nonparametric tests. To test for potential differences in TDC values among the nine measurement times, the nonparametric Friedman test was used. TDC values at each time and each depth were compared between day1 and day2 values using the nonparametric Mann–Whitney test. All statistical tests were done using SPSS, version 16. To evaluate if body habitus parameters (BMI, FAT%, H_2O%) impacted TDC values, the per person time average TDC value (TDC_{AVG}) was determined as the average TDC value over all nine measured times for both days and the correlation among the parameters determined.

3 | RESULTS

3.1 | Subject characteristics

Table 1 summarizes the main demographic features of the group. Male and female participants had similar ages that ranged from 23 to 30 years with a mean ± SD of 25.1 ± 2.1 years for the entire group ($N = 12$). Males compared with females had a greater height ($p = 0.003$) but there was no statistical difference in weight ($p = 0.106$), body mass index ($p = 0.343$), body water percentage ($p = 0.530$) or fat percentage ($p = 0.530$). It was notable that 75% of the participants were within a normal BMI classification. For all but one participant their nondominant hand was the left hand.

3.2 | Temperature and humidity variation among time-of-day

Figure 3 shows the pattern of variation among time-of-day as measured at 2-h increments as averaged between day1 and day2. Tests

TABLE 1 Demographic comparisons by gender.

	Female	Male	Combined
N	5	7	12
Age (years)	25.0 ± 3.0	25.1 ± 1.7	25.1 ± 2.1
Height (cm)	159.5 ± 8.3	179.6 ± 4.1[a]	171.2 ± 11.7
Weight (kg)	63.7 ± 24.2	82.7 ± 12.5	74.8 ± 19.4
BMI (kg/m^2)	25.3 ± 8.9	26.0 ± 3.9	25.7 ± 5.9
Fat%	25.2 ± 20.2	19.5 ± 6.2	21.9 ± 13.1
H_2O%	43.5 ± 26.3	56.8 ± 4.8	51.2 ± 17.3
BMI classification			
%Underweight (BMI < 18.5 kg/m^2)	0	0	0
%Normal weight (BMI 18.5–24.9 kg/m^2)	80	71.4	75.0
%Overweight (BMI 25.0–30.0 kg/m^2)	0	28.6	16.7
%Obese (BMI > 30 kg/m^2)	20	15	8.3
Race/Ethnicity			
%White/Caucasian	100	57.1	75
%Hispanic	0	42.9	25

Note: *$p < 0.01$. Variable entries are the mean ± SD or percentages. Race/Ethnicity was based on self-report of participants. Note that the only statistical difference between sexes was in their height.

[a]Indicates significantly different between male and female at $p < 0.01$ using the nonparametric Mann–Whitney test.

for significant differences among times using the nonparametric Friedman test failed to detect a significant difference in room temperature (TRM), skin temperature (TSK) or room relative humidity (RH) over the 16-h measurement interval. However, for RH there was a slight decreasing trend in relative humidity from morning to evening ($r = -0.724$, $p = 0.028$). The trends for TSK ($r = +0.571$) and TRM ($r = 0.673$) were not statistically significant ($p = 0.143$ and $p = 0.054$ respectively). Averaging values over the nine measurement times yielded an overall average ± SD for TRM_{AVG}, TSK_{AVG} and RH_{AVG} of 22.3 ± 1.8°C, 31.9 ± 1.6°C, and 56.0 ± 6.9%, respectively.

3.3 | Day1 versus Day2 TDC comparisons

TDC values at each time and depth were compared between day1 and day2 values using the nonparametric Mann–Whitney test. The results showed no significant difference between day1 and day2 values at corresponding times and measurement depths. The average percentage differences between day1 and day2 overall times for each time and depth are summarized in Table 2. The percentage difference in TDC at the same times between days was calculated as the day1–day2 difference divided by the average of day1 and day2 values. The percentage difference in TDC between day1 and day2 ranges from a low of 3.08 ± 1.34% at the 1.5 mm depth to 6.92 ± 4.30% at the 5.0 mm depth. However, there is no statistically significant difference in these percentages among depths.

3.4 | TDC by measurement depth

Figure 4 shows the TDC averages of day1 and day2 as a function of measurement depth. These averages are calculated based on all 216 measurements at each depth (9 TOD × 2 days × 12 subject). Results show that TDC values are greatest at a measurement depth of 0.5 mm, reduced at a depth of 1.5 mm and further reduced at depths of 2.5- and 5.0-mm. Progressive values at 0.5, 1.5, 2.5 and 5.0 mm along with their SD are respectively: 40.6 ± 8.0, 35.5 ± 3.6, 30.5 ± 6.7 and 29.7 ± 7.7.

3.5 | TDC by time-of-day

TDC values for each measurement depth are shown in Figure 5 as a function of TOD. The TDC values are the average of those obtained on day1 and day2 at corresponding times. There is an overall pattern characteristic of a decrease in TDC from morning to night that depends on the measurement depth. The sharpest decline is for the shallowest measurement depth (0.5 mm) in which there is a statistically significant decline ($r = 0.889$, $p = 0.001$). Also, there is a decrease in TDC from 08:00 to 24:00 at a depth of 1.5 mm ($r = 0.827$, $p = 0.006$) and to a lesser extent at a depth of 2.5 mm ($r = 0.672$, $p = 0.047$), with a nonsignificant trend at a measurement depth of 5.0 mm ($r = 0.476$, $p = 0.195$).

3.6 | TDC dependence on body habitus parameters

There was no correlation between TDC_{AVG} at any measurement depth and either BMI, FAT% or H_2O% values.

4 | DISCUSSION

Evidence consistent with a reduction in skin water from morning to afternoon was reported based on skin ultrasound measurement changes in skin thickness (Tsukahara et al., 2001). In that study of 40 young adults (20 male), skin thickness was measured twice, once in the morning between 08:30 and 10:30 and again between 15:30 and 17:00. Skin thickness of the forearm was reported to decrease in both groups and this change was attributed to a diurnal redistribution of water. Skin thickness was also measured on face areas which showed a similar finding but an opposite one when measured on the lower extremities. Other work on a group of 23 elderly (ages 75–100) nursing home residents also reported a diurnal change in forearm skin thickness that might be attributed to redistribution of fluid from

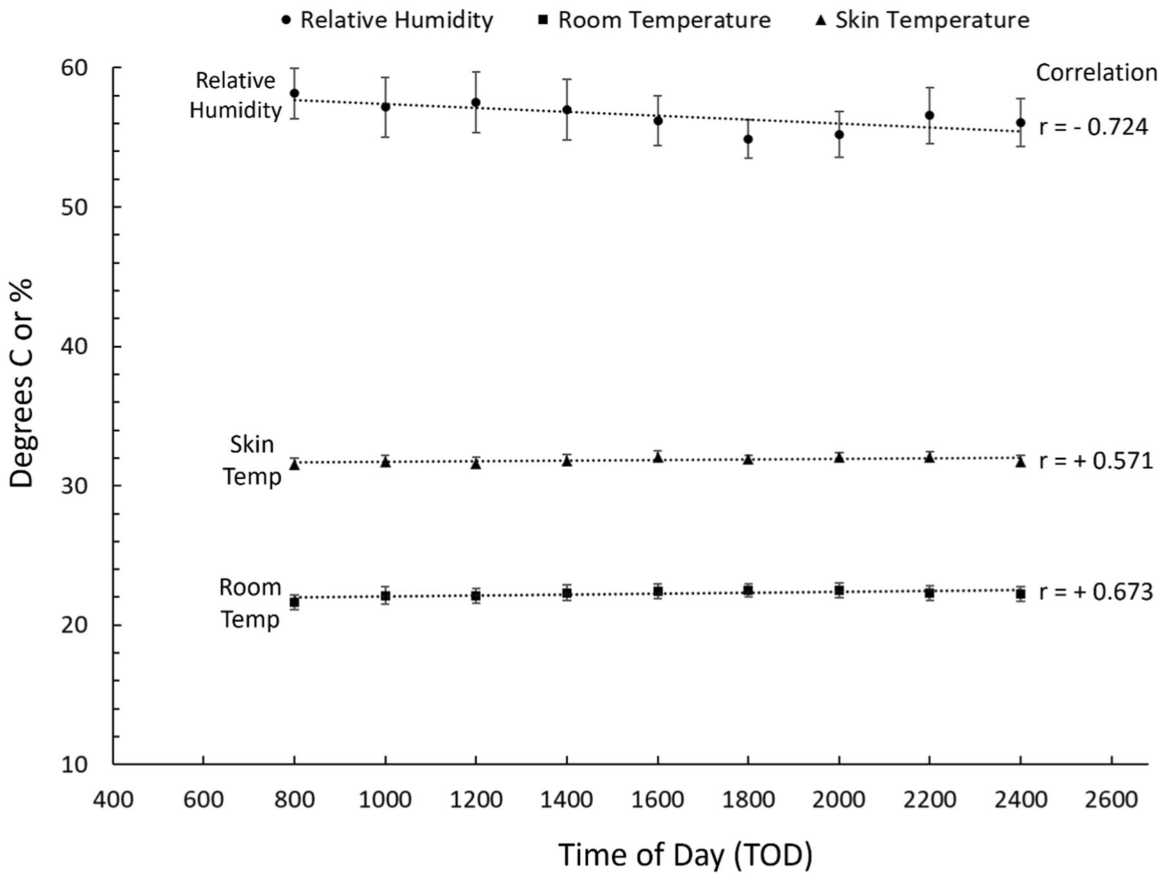

FIGURE 3 Temperature and humidity conditions. Data points are the mean and standard error of the mean (SEM) for room relative humidity (RH), room temperature (TRM) and skin temperature (TSK) at the forearm measurement site averaged over day1 and day2. Dashed lines indicate the linear regression trend of the group mean values ($N = 12$). No significant difference in any parameter among times was detected as determined by the Friedman test. The negative trend for RH from morning to night is minor but statistically significant ($p = 0.028$). The apparent positive trends for TRM and TSK are not statistically significant ($p > 0.05$).

TABLE 2 Interday TDC values and percentage differences.

	Measurement depth (mm)			
	0.5	1.5	2.5	5.0
TDC Day1	40.7 ± 7.5	35.6 ± 3.4	30.8 ± 6.5	29.9 ± 7.9
TDC Day2	40.4 ± 7.6	35.4 ± 3.7	30.1 ± 6.2	29.6 ± 7.6
Percent difference	3.77 ± 4.89	3.08 ± 1.34	3.47 ± 2.69	6.92 ± 4.30

Note: TDC values in this table are determined as the average of all measured times for each measurement depth ± SD. The percentage difference is calculated as day1–day2 values divided by the average of day1 and day2 ± SD. The differences in TDC between days at corresponding depths is not statistically different. The percentage differences among measurement depths are also not statistically different. TDC values among depths on both days are significantly different based on the Friedman test ($p < 0.001$).

Abbreviation: TDC, tissue dielectric constant.

morning to evening in the aged skin (Gniadecka, Gniadecki, et al., 1994). One study used ultrasound low echogenicity patterns as an index of skin water and also reported patterns consistent with diurnal changes in 22 young adults but not in 22 elderly persons (Gniadecka, Serup, et al., 1994). In these studies, skin water content was not actually measured. In a small study of 12 females skin water was self-measured from TDC measurements to a single depth of about 2.0 mm on a single day every hour between 08:00 and 20:00 (Camilion et al., 2022). In that study, both facial and forearm skin water decreased from morning to evening whereas lower extremity skin water increased due to gravity. The present results extend these prior findings with respect to intraday and interday forearm skin water changes based on direct TDC measurements and by including the potential impact of skin measurement depth as a contributing factor.

The main findings of the present study indicate the presence of a slight decline in TDC from morning through evening that was most prevalent when measured to a skin depth of 0.5 mm. The overall percentage reduction in TDC from 08:00 through 24:00 h was determined to be 4%. However, when considering the likely clinical times when such measurements would be made (08:00 to 16:00) the calculated reduction was about 3.5%. The TDC values were not significantly related to the participants BMI or whole-body fat or water percentages. The decreasing TDC with increasing time-of-day was less important when TDC was measured to a depth of 1.5 mm where

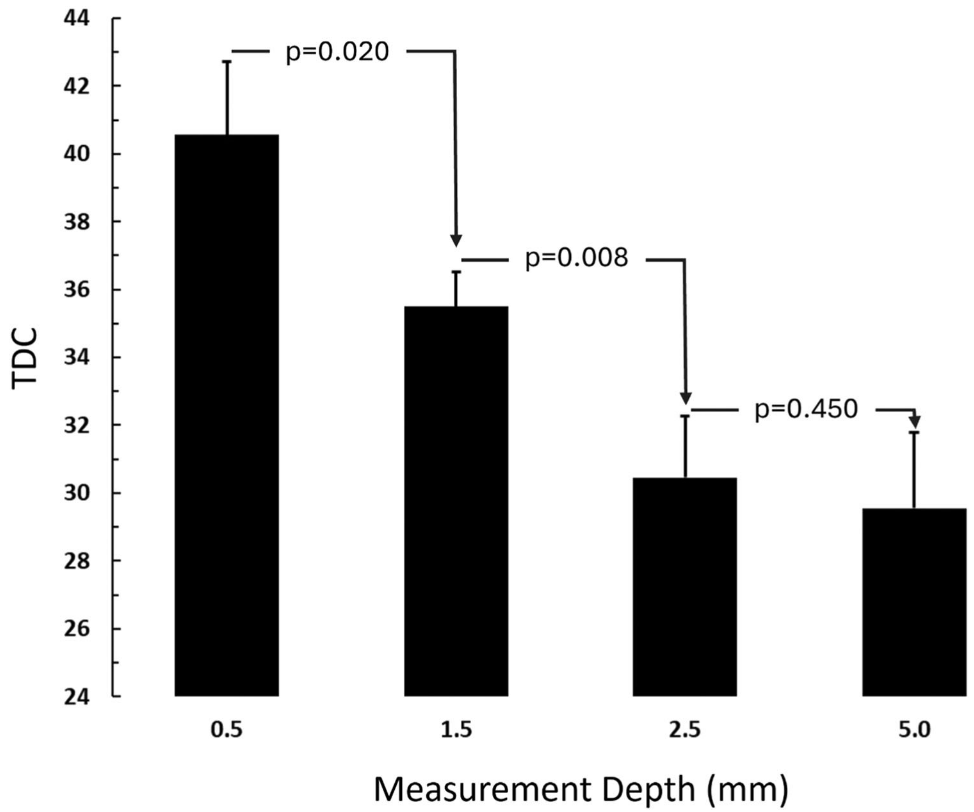

FIGURE 4 TDC as a function of measurement depth. Bars represent mean values of TDC averaged over all measurement times for both days. Error bars are standard error of the mean. Except for differences between 2.5 and 5.0 mm all other progressive differences were statistically significant as noted by the *p* values. TDC, tissue dielectric constant.

the percentage reduction from 08:00 to 24:00 h was 2.7%. For measurements made to a depth of 2.5 or 5.0 mm there was a minor trend that was not statistically significant.

A possible explanation of this time-of-day depth dependent pattern is that shallower measurements are more impacted by transepidermal water loss (TEWL). Consistent with this concept would be data that has shown a diurnal pattern (Iwanaszko et al., 2024; Shahidullah et al., 1969; Yosipovitch et al., 2004). However, independent of the possible causes, the present findings, based on measurements in combined males and females, indicate that measurements made to depths of 2.5 mm or greater are mostly free of time-of-day issues and those that may be made to either 0.5 or 1.5 mm depths are subject to only small variations attributable to time-of-day. Thus, the present findings document the amount of variation to be expected which should help in estimating the potential importance of small differences if measured at a different time of the day.

In addition to the nature of the temporal variations in TDC values, the present results show a clear difference in absolute values obtained for TDC at different measurement depths at all measured times. These are characterized by greater values at the shallower depths of 0.5 and 1.5 mm and lower TDC values when measured to a depth of 2.5 and 5.0 mm. This pattern of differences is consistent with those previously reported for both healthy and compromised persons when measured on the volar forearm (Mayrovitz, Davey, et al., 2009; Mayrovitz, Mahtani, et al., 2017). An explanation that has been advanced is that the depth-related differences are due to the inclusion of greater amounts of low water content fat with increasing depth of the measurements. The present findings also indicate that day-to-day values of TDC at the measured depths are similar, with the most commonly used measurement depth of 2.5 mm differing from day1 to day2 by less than 3.5% in this healthy young adult group.

4.1 | Study limitations

One limitation of the present study is the fact that the data obtained is based on self-measurements done by multiple persons. Although each participant was trained and certified in the measurement and protocol process by the author, this does not guarantee that, when not observed, errors may occur. However, the consistency of the data among all participants, that was carefully reviewed, suggests that any deviations would have been small and limited in overall effect considering the reasonable number of individual participants.

Another limitation is the number of participants and their demographics. The present findings apply specifically to the young adult healthy population herein studied and potential generalizations to either older populations or persons with conditions such as arm

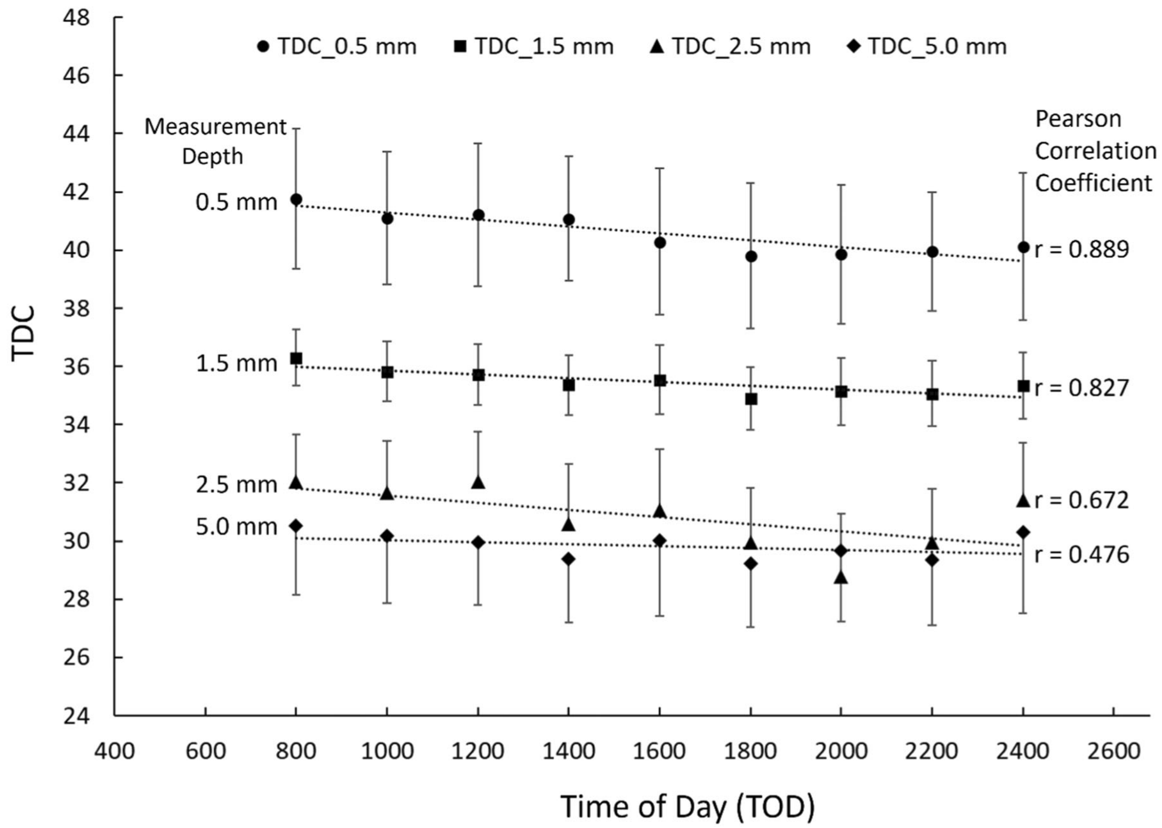

FIGURE 5 TDC by time of day for each measurement depth. Data points are tissue dielectric constant (TDC) averages for each time point averaged between day1 and day2 for effective measurement depths of 0.5, 1.5, 2.5- and 5.0-mm. Error bars are the standard error of the mean (SEM). The r values are the Pearson correlation coefficients. The trend for TDC to decrease from morning to evening becomes less with increasing measurement depth.

oedema or lymphedema would require further verification. However, the results call attention to the possible depth dependency of skin hydration and the magnitude of impact on these values attributable to time-of-day.

5 | CONCLUSION

Skin tissue water assessed by TDC values shows minor intraday variations, with TDC values tending to decrease from morning to evening with a pattern that is greater for shallower depths than for measurements at deeper depths. The explanation for this pattern is not provided by the present data. However, it is suggested that a greater TEWL influence may be experienced at the more surface tissues thereby explaining the decrease with TOD. In part, the clinical relevance of the findings relates to the confidence level associated with skin water estimates, based on TDC measurements, when measured at different TOD during normal clinic hours, which based on the present data is expected to be less than about 4%.

ACKNOWLEDGEMENTS

The author wishes to thank the participants for their dedication to this research without which this study would not be successful.

CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

The data supporting this study's findings are not publicly available because they were not included in the original consent forms. The anonymized data are available from the corresponding author upon request.

ORCID

Harvey N. Mayrovitz http://orcid.org/0000-0003-2690-7922

REFERENCES

Alanen, E., Lahtinen, T. & Nuutinen, J. (1998a) Measurement of dielectric properties of subcutaneous fat with open-ended coaxial sensors. *Physics in Medicine and Biology*, 43, 475–485.

Alanen, E., Lahtinen, T. & Nuutinen, J. (1998b) Variational formulation of open-ended coaxial line in contact with layered biological medium. *IEEE Transactions on Biomedical Engineering*, 45, 1241–1248.

Alanen, E., Lahtinen, T. & Nuutinen, J. (1999) Penetration of electromagnetic fields of an open-ended coaxial probe between 1 MHz and 1 GHz in dielectric skin measurements. *Physics in Medicine and Biology*, 44, N169–N176.

Bazin, R. & Fanchon, C. (2006) Equivalence of face and volar forearm for the testing of moisturizing and firming effect of cosmetics in hydration and biomechanical studies. *International Journal of Cosmetic Science*, 28, 453–461.

Boury-Jamot, M., Daraspe, J., Bonte, F., Perrier, E., Schnebert, S. & Dumas, M.et al. (2009) Skin aquaporins: function in hydration, wound healing, and skin epidermis homeostasis. In: Beitz, E. (Ed.) *Handbook of experimental pharmacology*, 190. Berlin, Heidelberg: Springer, pp. 205–217.

Camilion, J.V., Khanna, S., Anasseri, S., Laney, C. & Mayrovitz, H.N. (2022) Physiological, pathological, and circadian factors impacting skin hydration. *Cureus*, 14, e27666.

Darlenski, R., Bogdanov, I., Kacheva, M., Zheleva, D., Demerdjieva, Z., Hristakieva, E. et al. (2021) Disease severity, patient-reported outcomes and skin hydration improve during balneotherapy with hydrocarbonate- and sulphur-rich water of psoriasis. *Journal of the European Academy of Dermatology and Venereology*, 35, e196–e198.

Egawa, M. & Tagami, H. (2008) Comparison of the depth profiles of water and water-binding substances in the stratum corneum determined in vivo by Raman spectroscopy between the cheek and volar forearm skin: effects of age, seasonal changes and artificial forced hydration. *British Journal of Dermatology*, 158, 251–260.

Firooz, A., Gorouhi, F., Davari, P., Atarod, M., Hekmat, S., Rashighi-Firoozabadi, M. et al. (2007) Comparison of hydration, sebum and pH values in clinically normal skin of patients with atopic dermatitis and healthy controls. *Clinical and Experimental Dermatology*, 32, 321–322.

Le Fur, I., Reinberg, A., Lopez, S., Morizot, F., Mechkouri, M. & Tschachler, E. (2001) Analysis of circadian and ultradian rhythms of skin surface properties of face and forearm of healthy women. *Journal of Investigative Dermatology*, 117, 718–724.

Gabriel, S., Lau, R.W. & Gabriel, C. (1996) The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Physics in Medicine and Biology*, 41, 2251–2269.

Gniadecka, M., Gniadecki, R., Serup, J. & Søndergaard, J. (1994) Ultrasound structure and digital image analysis of the subepidermal low echogenic band in aged human skin: diurnal changes and interindividual variability. *Journal of Investigative Dermatology*, 102, 362–365.

Gniadecka, M., Serup, J. & Sondergaard, J. (1994) Age-related diurnal changes of dermal oedema: evaluation by high-frequency ultrasound. *British Journal of Dermatology*, 131, 849–855.

Grant, J.P., Clarke, R.N., Symm, G.T. & Spyrou, N.M. (1988) In vivo dielectric properties of human skin from 50 MHz to 2.0 GHz. *Physics in Medicine and Biology*, 33, 607–612.

Iwanaszko, M., Waldeck, N., Anafi, R., Paller, A.S., Zee, P.C. & Fishbein, A.B. (2024) Circadian rhythms in skin barrier function in atopic dermatitis: a pilot study. *Journal of Biological Rhythms*, 39, 208–214.

Jönsson, C., Bjurberg, M., Brogårdh, C. & Johansson, K. (2020) Test–retest reliability of volume and local tissue water measurements in lower limbs of healthy women and men. *Lymphatic Research and Biology*, 18, 261–269.

Knor, T., Meholjić-Fetahović, A. & Mehmedagić, A. (2011) Stratum corneum hydration and skin surface pH in patients with atopic dermatitis. *Acta Dermatovenerologica Croatica*, 19, 242–247.

Lee, T.Y., Yoon, I.J., Han, S.K., Namgoong, S., Jeong, S.H., Kim, D.W. et al. (2022) Skin hydration level cutoff value to predict wound healing potential in diabetic foot ulcers. *Diabetes Research and Clinical Practice*, 193, 110122.

Lee, Y., Je, Y.J., Lee, S.S., Li, Z.J., Choi, D.K., Kwon, Y.B. et al. (2012) Changes in transepidermal water loss and skin hydration according to expression of aquaporin-3 in psoriasis. *Annals of Dermatology*, 24, 168–174.

Luebberding, S., Krueger, N. & Kerscher, M. (2013) Skin physiology in men and women: in vivo evaluation of 300 people including TEWL, SC hydration, sebum content and skin surface pH. *International Journal of Cosmetic Science*, 35, 477–483.

Mayrovitz, H.N. (2023) Transepidermal water loss and stratum corneum hydration in forearm versus hand palm. *Skin Research and Technology*, 29, e13218.

Mayrovitz, H.N. & Berthin, T. (2021) Assessing potential circadian, diurnal, and ultradian variations in skin biophysical properties. *Cureus*, 13, e17665.

Mayrovitz, H.N., Davey, S. & Shapiro, E. (2009) Suitability of single tissue dielectric constant measurements to assess local tissue water in normal and lymphedematous skin. *Clinical Physiology and Functional Imaging*, 29, 123–127.

Mayrovitz, H.N., Grammenos, A., Corbitt, K. & Bartos, S. (2017) Age-related changes in male forearm skin-to-fat tissue dielectric constant at 300 MHz. *Clinical Physiology and Functional Imaging*, 37, 198–204.

Mayrovitz, H.N., Mahtani, S.A., Pitts, E. & Michaelos, L. (2017) Race-related differences in tissue dielectric constant measured non-invasively at 300 MHz in male and female skin at multiple sites and depths. *Skin Research and Technology*, 23, 471–478.

Mayrovitz, H.N., McClymont, A. & Pandya, N. (2013) Skin tissue water assessed via tissue dielectric constant measurements in persons with and without diabetes mellitus. *Diabetes Technology & Therapeutics*, 15, 60–65.

Mayrovitz, H.N., Mikulka, A. & Woody, D. (2019) Minimum detectable changes associated with tissue dielectric constant measurements as applicable to assessing lymphedema status. *Lymphatic Research and Biology*, 17, 322–328.

Mayrovitz, H.N., Volosko, I., Sarkar, B. & Pandya, N. (2017) Arm, leg, and foot skin water in persons with diabetes mellitus (DM) in relation to HbA1c assessed by tissue dielectric constant (TDC) technology measured at 300 MHz. *Journal of Diabetes Science and Technology*, 11, 584–589.

Mayrovitz, H.N., Weingrad, D.N. & Davey, S. (2009) Local tissue water in at-risk and contralateral forearms of women with and without breast cancer treatment-related lymphedema. *Lymphatic Research and Biology*, 7, 153–158.

Mayrovitz, H.N., Weingrad, D.N. & Davey, S. (2014) Tissue dielectric constant (TDC) measurements as a means of characterizing localized tissue water in arms of women with and without breast cancer treatment related lymphedema. *Lymphology*, 47, 142–150.

Nakai, K., Yoneda, K., Murakami, Y., Koura, A., Maeda, R., Tamai, A. et al. (2015) Effects of topical N-acetylcysteine on skin hydration/transepidermal water loss in healthy volunteers and atopic dermatitis patients. *Annals of Dermatology*, 27, 450–451.

Namgoong, S., Yang, J.P., Han, S.K., Lee, Y.N. & Dhong, E.S. (2019) Influence of peripheral neuropathy and microangiopathy on skin hydration in the feet of patients with diabetes mellitus. *Wounds*, 31, 173–178.

Nuutinen, J., Ikäheimo, R. & Lahtinen, T. (2004) Validation of a new dielectric device to assess changes of tissue water in skin and subcutaneous fat. *Physiological Measurement*, 25, 447–454.

Ousey, K., Cutting, K.F., Rogers, A.A. & Rippon, M.G. (2016) The importance of hydration in wound healing: reinvigorating the clinical perspective. *Journal of Wound Care*, 25(122), 122–130.

Shahidullah, M., Raffle, E.J., Frain-Bell, W. & Rimmer, A.R. (1969) Diurnal variation in transepidermal water loss. *British Journal of Dermatology*, 81, 866–867.

Stuchly, M.A., Athey, T.W., Samaras, G.M. & Taylor, G.E. (1982) Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial line: part II - experimental results. *IEEE Transactions on Microwave Theory and Techniques*, 30, 87–92.

Tomita, Y., Akiyama, M. & Shimizu, H. (2005) Stratum corneum hydration and flexibility are useful parameters to indicate clinical severity of congenital ichthyosis. *Experimental Dermatology*, 14, 619–624.

Toro, C., Markarian, B. & Mayrovitz, H.N. (2024) Breast cancer-related lymphedema assessed via tissue dielectric constant measurements. *Cureus*, 16, e59261.

Tsukahara, K., Takema, Y., Moriwaki, S., Fujimura, T. & Imokawa, G. (2001) Dermal fluid translocation is an important determinant of the diurnal variation in human skin thickness. *British Journal of Dermatology*, 145, 590–596.

De Vrieze, T., Gebruers, N., Nevelsteen, I., De Groef, A., Tjalma, W.A.A., Thomis, S. et al. (2020) Reliability of the MoistureMeterD compact device and the pitting test to evaluate local tissue water in subjects with breast cancer-related lymphedema. *Lymphatic Research and Biology*, 18, 116–128.

Yosipovitch, G., Sackett-Lundeen, L., Goon, A., Yiong Huak, C., Leok Goh, C. & Haus, E. (2004) Circadian and ultradian (12 h) variations of skin blood flow and barrier function in non-irritated and irritated skin-effect of topical corticosteroids. *Journal of Investigative Dermatology*, 122, 824–829.

Yosipovitch, G., Xiong, G.L., Haus, E., Sackett-Lundeen, L., Ashkenazi, I. & Maibach, H.I. (1998) Time-dependent variations of the skin barrier function in humans: transepidermal water loss, stratum corneum hydration, skin surface pH, and skin temperature. *Journal of Investigative Dermatology*, 110, 20–23.

How to cite this article: Mayrovitz, H. N. (2024) Skin tissue dielectric constant: time of day and skin depth dependence. *Clinical Physiology and Functional Imaging*, 1–9. https://doi.org/10.1111/cpf.12916