Skin Research and Technology 2016; 22: 81–88
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doi: 10.1111/srt.12232

Skin Research and Technology

Young adult gender differences in forearm skin-to-fat tissue dielectric constant values measured at 300 MHz

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Background/Purpose: Skin-to-fat tissue dielectric constant (TDC) values depend on measurement depth and gender. Our goal was to assess male–female differences in TDC values associated with differing skin depths.

Methods: Bilateral forearm TDC measurements were made on young adult male and females with mean ages from 24.7 to 27.3 years. There were four measurement groups distinguished by the TDC measurement depth and include the following numbers of subjects for each gender; 30, 150, 60, and 50 for probe-measurement depths of 0.5, 1.5, 2.5, and 5.0 mm. Data were subsequently compared with values calculated with a simple two-layer model.

Results: For females and males, there was a significant difference in TDC values among depths ($P < 0.001$) with TDC values decreasing with increasing depth. Gender comparisons showed that TDC values of males were significantly ($P < 0.001$) greater than values for females at each depth. Male–female percentage differences ranged from 14.8% to 22.0%. Model calculations suggest that gender differences might be explained by skin thickness differences.

Conclusion: Findings indicate that decisions with regard to skin water content among or between groups based on TDC measurements need to account for gender and are best made when corresponding skin thickness measurements are available. However, changes in TDC values assessed in individual patients and comparisons between corresponding skin areas in affected and non-affected sites are not limited. Thus, assessments of acute treatment effects and assessments of inter-arm or inter-leg TDC differences or ratios within genders are a useful and suitable method to characterize edema and lymphedema features.

Key words: skin dielectric constant – skin water – edema – lymphedema

Accepted for publication 15 May 2015

Investigations of potential gender differences in skin properties have focused on a variety of skin parameters including skin thickness (1), transepidermal water loss (2, 3), mechanical properties (4). pH (5), epidermal thickness (6), sebum (7), and stratum corneum (SC) water content (8, 9). Measurements of SC moisturization based on SC capacitance (3) indicate that neck and forehead water content is greater in young adult males compared with age-matched females. However, SC measurements did not show statistically significant gender differences in forearm SC values when assessed over a wide age range that included groups with average ages of 24.7–66.6 years (3). Similarly in a young group (age 13–35), significantly greater SC water was shown in forehead skin (9), but again not in forearm skin although forehead and forearm SC moisturization did not differ (9). In addition, no significant gender differences in forearm SC water were found in a small group of young subjects (10). In contrast to SC water measurements based on electrical capacitance, skin and skin-to-fat water content have been estimated based on measurements of the skin's tissue dielectric constant (TDC) also known as electrical permittivity (11, 12). TDC measurements in young adults indicated 11–13% greater values in males vs. females at forehead (13) and forearm (13, 14). These reported results were based on the composite water and other constituent content contained within an effective measurement depth of 1.5 mm. Thus for forearm skin, the TDC measurements would have included contributions from SC, epidermis, dermis, and possibly hypodermis depending on skin thickness at the measurement site. In this regard, high frequency ultrasound measurements in young adults (20–40 years) has shown little difference in male–female forearm skin thickness, which has been reported as about 0.9 mm thick (1). Other data indicate a larger forearm skin thickness of about 1.2 mm with males slightly greater than females (15) with the possibility of diurnal variations in which male forearm thickness ranges between about 1.1–1.2 mm and females between about 0.8 and 1.0 mm from morning to evening (16). Taken together, the skin thickness data suggest that the prior TDC measurements to an apparent 1.5 mm depth (13) would have included contributions from SC, epidermis, dermis and also some amount of hypodermis. However, it is not known if shallower or deeper measurement depths would parallel the prior findings that showed greater TDC values among young adult males compared with age-matched females (13). Thus, our goal was to assess potential male–female TDC differences associated with differing skin depths that included measurements using probes rated for depths of 0.5, 1.5, 2.5, and 5.0 mm below the epidermis. Our purpose was to determine the potential gender difference in TDC values when different components of skin were included in the measurement and to provide TDC reference ranges applicable to young adults for these differing forearm tissue depths.

Methods

Subjects

Young adult male and female subjects divided into four groups (I, II, III, IV) were evaluated after the research nature of the study was explained to them and they had signed an informed consent that was previously approved by the University Institutional Review Board. Participants were mostly first and second year medical and dental students. For each group, TDC measurements were made at the depths and with the numbers per group as indicated in Table 1. Female–male mean ages ranged from 24.7 to 27.3 years and were not significantly different from each other. Contrastingly, the body mass index of all male groups was greater than females ($P < 0.001$). Prior to participating subjects were advised to not apply any lotion or creams to their forearms on the day of the scheduled procedure. Subjects with any known skin condition affecting the forearm skin, any injury, or open wound on either arm, or any prior arm trauma that might have affected tissue water were excluded from participation.

TDC measurement method and procedure

Tissue dielectric constant measurements were made with the MoistureMeterD (MMD; Delfin Technologies, Kuopio, Finland). The MMD is a device used to measure skin and skin-to-fat TDC at a frequency of 300 MHz by touching the skin's surface with a concentric hand held probe for about 10 s (Fig. 1). There are four different probes with outer diameters that range from 10 mm for a 0.5 mm effective measurement depth to 55 mm for a 5 mm measurement depth. Effective measurement depth is defined as the depth at which the 300 MHz electric field decreases to 1/e of its surface field. In this study TDC values were measured to depths of 0.5, 1.5, 2.5, and 5.0 mm with each subject supine on a padded and insulated examination table with their arms resting with palms up. Measurements were started after they had been supine for a minimum of 5 min and were done in triplicate on both volar forearms 6 cm distal to the antecubital fossa. For each probe, measurements between right and left arm were alternated until three values per arm were

TABLE 1. Group features

	Effective measurement depth							
	Group I (0.5 mm)		Group II (1.5 mm)		Group III (2.5 mm)		Group IV (5.0 mm)	
	Female	Male	Female	Male	Female	Male	Female	Male
N	30	30	150	150	60	60	50	50
AGE (years)	25.0 ± 2.4	25.2 ± 2.3	26.0 ± 3.8	25.9 ± 3.0	25.7 ± 1.6	25.4 ± 2.4	26.0 ± 2.9	26.3 ± 2.5
BMI (kg/m^2)	23.3 ± 4.0	25.3 ± 2.8**	23.1 ± 4.9	25.4 ± 4.0**	22.4 ± 5.1	25.2 ± 3.1**	23.3 ± 3.9	26.1 ± 4.1**

Values are mean ± SD.
**Male body mass index (BMI) greater than females ($P < 0.001$).

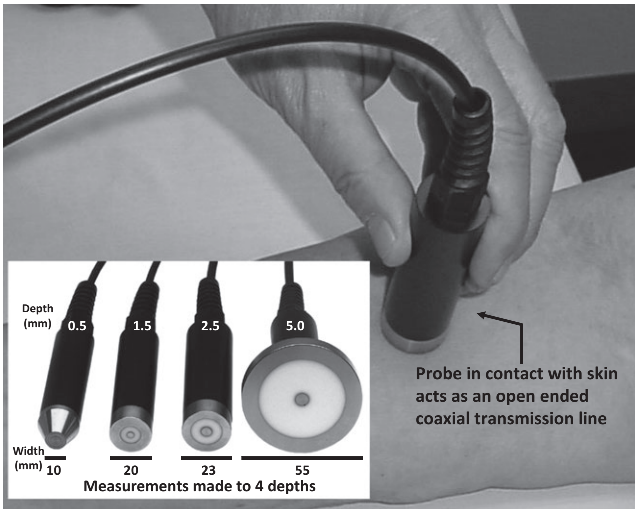


Fig. 1. Measuring tissue dielectric constant (TDC). TDC measured in triplicate bilaterally at each of four effective measurement depths. Touching the skin activates an automatic process and yields a TDC value in less than 10 s. Larger width probes have greater effective measurement depths as shown.

obtained. The average of the three measurements was used to characterize the TDC value of each arm and reported as the average of the two arms. This procedure was done for each of the four effective measurement depths.

The dielectric constant is a dimensionless number equal to the ratio of the permittivity of the measured tissue to the permittivity of vacuum. As TDC values mainly depend on tissue water content, TDC values, and their change provide indices of water content and quantitative estimates of water content changes. For reference, the dielectric constant of distilled water at 34°C is 75.2. As measurements are at a frequency of 300 MHz, skin TDC values are sensitive to both free and bound water within the measurement volumes. The inclusion of the bound water component is important since it has been estimated that up to 90% of young adult skin water content is bound (17) although this percentage decreases substantially in photo aged skin (18). Measurements of TDC have been used in basic and clinical research studies in which skin tissue water and its change were of interest at various anatomical sites including face (13, 19), breast (20), forearm (21–23), biceps, axilla and thorax (24), leg and foot (25, 26) and buttocks (27). It has also been used to characterize and track changes related to lymphedema (28–30), changes in post-surgical fluid status (31) and assess skin irradiation effects (20).

In use, the device generates and transmits a very low power 300 MHz signal into a coaxial probe that is in contact with the skin with the probe acting as an open-ended coaxial transmission line (32). Part of the signal is absorbed, mainly by tissue water, and part is reflected back to a control unit, where the complex reflection coefficient is calculated (33, 34) from which the dielectric constant is determined (35, 36). Reflections from the end of this coaxial transmission line depend on the complex permittivity of the tissue which in turn depends on signal frequency and the dielectric constant (the real part of the complex permittivity) and the conductivity of the tissue with which the probe is in contact. At 300 MHz, the contribution of conductivity to the overall value of the permittivity is small and the dielectric constant is mainly determined by water molecules (free and bound). Consequently, the device includes and analyzes only the dielectric constant, that is, directly proportional to tissue water content in a manner close to that predicted by Maxwell mixture theory for low water content, but a slightly less good prediction for high water content tissues (37). In all cases, TDC is strongly dependent on relative water content with TDC values that decrease with water reductions during hemodialysis (38). Further details including validation and repeatability data are described in the literature (26, 38, 39).

Analysis

Differences in forearm TDC values among depths were tested using a one-way ANOVA model for each gender separately with effective measurement depth as a factor. Forearm TDC values obtained for each depth were compared by gender using independent *t*-test with a *P*-value of <0.01 accepted as a statistically significant difference between genders. This significance level was adopted to reduce type II errors that might arise because of using four independent *t*-tests, one for each depth.

Results

TDC depth comparisons

Tissue dielectric constant mean values and their standard deviations for each depth are summarized in Table 2. For both females and males, there was an overall significant difference in TDC values among depths ($P < 0.001$) with a

TABLE 2. Forearm TDC values by effective measurement depth

	Effective measurement depth							
	Group I (0.5 mm)		Group II (1.5 mm)		Group III (2.5 mm)		Group IV (5.0 mm)	
	Female	Male	Female	Male	Female	Male	Female	Male
N	30	30	150	150	60	60	50	50
TDC value	31.3 ± 4.2	38.2 ± 5.0**	30.6 ± 3.4	35.2 ± 4.0**	27.0 ± 4.4	32.7 ± 3.9**	25.3 ± 4.5	30.7 ± 4.4**
% Difference	22.0		13.1		21.1		21.3	

TDC values are mean ± SD. ** indicates male TDC values greater than female TDC values at corresponding measurement depths ($P < 0.001$). TDC values for males and females significantly decrease with increasing depth ($P < 0.001$). Differences in TDC values at the two deepest depths are not significant for females or males. Differences at the two shallowest depths are only significantly different for males ($P = 0.006$).
% Difference is calculated as 100 × (male average − female average)/female average for each depth.

general trend for TDC values to decrease with increasing depth. The pattern of change is shown in Fig. 2 in which TDC values at 1.5, 2.5, and 5.0 mm are normalized to the value at 0.5 mm and their regression with depth is shown. Regressions with depth are similar for females and males. Comparisons of absolute TDC values among depths (Table 2) showed that for females the shallower depths (0.5 and 1.5 mm) did not significantly differ from each other ($P = 0.980$) nor did the deeper TDC values (2.5 and 5.0 mm) differ from each other ($P = 0.115$). However, TDC values at 2.5 and 5.0 mm were significantly less than TDC values measured at 0.5 and 1.5 mm ($P < 0.001$). For males, the differences between 0.5 and 1.5 mm depths were statistically significant ($P = 0.006$) and both differed significantly ($P < 0.001$) from TDC values at 2.5 and 5.0 mm. TDC values at 2.5 and 5.0 mm did not significantly differ from each other ($P = 0.410$).

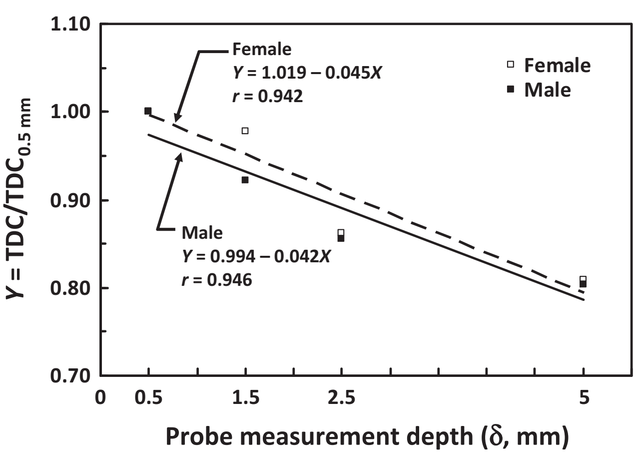


Fig. 2. Tissue dielectric constant (TDC) variation with measurement depth. Data points are mean TDC values for females and males normalized to their respective values at a measurement depth of 0.5 mm ($TDC/TDC_{0.5mm}$). Lines are computed linear regression lines for this ratio vs. effective measurement depth. Regressions are similar for females and males.

TDC gender comparisons

Comparisons of TDC values between genders (Table 2) at each measured depth showed that TDC values of males were significantly ($P < 0.001$) greater than TDC values for females at each depth. Male–female average percentage differences ranged from 14.8% at 1.5 mm depth to 22.0% at 0.5 mm depth.

Discussion

Gender differences

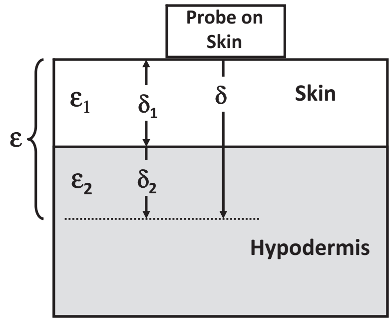
One goal of this study was to determine if previously reported gender differences in forearm skin TDC values measured in young adults only to a depth of 1.5 mm could be generalized with respect to tissue depth when assessed within a much larger subject sample of young adult females and males. To this end, 540 triplicate bilateral forearm TDC measurements were made in this study. The current findings demonstrate that young adult male TDC values are significantly greater than young adult female values at all measured depths from 0.5 to 5.0 mm thus unambiguously establishing this gender-related difference. In comparison with previously determined differences in 11–13% at a depth of 1.5 mm (13, 14) the present much larger sample of subjects yields a similar male–female difference of 13.1%. Based on the current more extensive measurement set, it was also found that the previously reported male–female difference at 1.5 mm depth may represent the least male–female depth-dependent percentage difference. The present results indicate a narrow range of gender differences in the other measured sites ranging from 21.1% to 22%. The explanation for this gender difference is less clear. One possibility is that there is a greater amount of water present within the young male adult skin thereby resulting in a greater value for the measured TDC. However, because the TDC value also depends on the dermis thickness, it may be that the gender difference in TDC values could be explained on the basis of a thinner thickness in females. The viability of this as a possibility is considered subsequently.

Depth differences

In addition to identifying significant gender differences in TDC values and the range of those differences, the present findings also demonstrate a significant monotonic decrease in TDC values with increasing depth that is present for both genders. The interpretation of this TDC depth pattern relates to the tissue types included in the TDC measurements at different effective measurement depths. All measurements include the SC and the epidermis, but depending upon measurement depth there are other included components. For a 0.5 mm depth, it is mainly the upper dermis; for a 1.5 mm depth, it is the dermis and a hypodermal component; for a 2.5 mm depth, it is the dermis and a moderate amount of hypodermis; and for a 5.0 mm depth, it is the dermis and a substantial amount of hypodermis with its associated low water content fat. These qualitative statements can be placed on a more quantitative basis using a simplified conceptual approach in which the tissue measurement volume is viewed as being comprised of two layers, one being the skin including SC, epidermis and dermis with combined skin depth δ, and the other part being the subcutaneous tissue including fat as schematized in Fig. 3. The goal is to determine if a simplified model can provide a plausible explanation that is consistent with the measured TDC depth dependence and the male–female differences in TD values.

Conceptual model

In the conceptual model (Fig. 3) the skin-to-fat is simply viewed as composed of two layers with the first layer skin (epidermis + dermis) and the other the hypodermis with skin and hypodermis dielectric constants at 300 MHz



$$\varepsilon = \frac{\varepsilon_1 (1 + \delta_2/\delta_1)}{[1 + (\delta_2/\delta_1)(\varepsilon_1/\varepsilon_2)]}$$

Fig. 3. Conceptual model to assess skin and hypodermis effects on measured TDC. The parameter ε represents the tissue dielectric constant measured by probes of various effective measurement depths (δ) in terms of the dielectric constants ε_1 and ε_2 for skin and hypodermis, respectively. The parameter δ_1 is the skin (epidermis + dermis) thickness (different for males and females) and δ_2 is the effective penetration depth into the hypodermis measured from the skin-hypodermis margin.

being ε_1 and ε_2, respectively. The parameter δ_1 represents skin thickness and δ represents an effective measurement depth from which the transmitted signal is reflected such that the composite measured TDC value (ε in the figure) would yield the average measured TDC values of Table 2. For the two-layer series model, the composite ε is then calculable using the equation shown in the figure, which depends on ε_1, ε_2, δ_1, and δ_2 in which δ_2 is equal to $\delta - \delta_1$. For purposes of analysis, skin thickness is set at 1.2 mm for males and 1.0 mm for females which are consistent with average values summarized in the literature (13). The question that the model seeks to answer is whether the gender differences in skin thickness can alone account for the measured differences in average TDC values. To address this, the skin water percentage of both genders is assumed the same at a value of 73.4% with the remaining being 26.6% protein. This skin water percentage is consistent with prior dermal measurements (17, 18, 40). The value for ε for this combination has been measured at 25°C at 300 MHz for hemoglobin (41) yielding a composite value of 57.8. Since measurements on forearm skin are at an average skin temperature of about 34°C, the corresponding *in vivo* value would by extrapolation be 56.4. This value that is assigned to skin as ε_1, is slightly less than the value of 49.8 reported for dry skin (42, 43). Contrastingly,

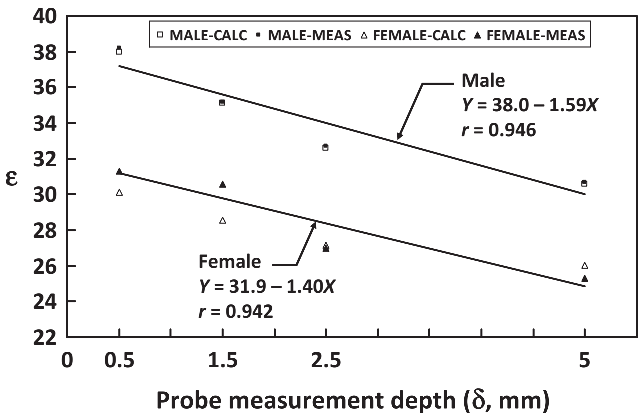


Fig. 4. Measured vs. calculated TDC values for young males and females. The calculated TDC values (ε) for the composite model of Fig. 4 (open symbols) are shown vs. the measured values of Table 2 (closed symbols). The regression lines and equations correspond to the measured data for males and females.

dielectric constant values for fat are low and range from 5.67 to 11.7 (42). For purposes of the present model, ε_2 of the hypodermal layer was calculated on the basis of an assumed hypodermis uniform mixture of 87% fat with a dielectric constant of 5.67% and 13% water with a dielectric constant of 75.2 at 34°C to yield a value for ε_2 of 14.8. For purposes of calculation, the value of δ_2 that minimized the (measured-calculated) difference for males was determined for each of probes used. The values determined for males were used unchanged for females. Thus, difference in ε between genders in this model would only be due to differences in skin depth. The results of these ε calculations are shown in Fig. 4 along with the measured mean values. Although based on a relatively simplified model, the fact that gender differences in measured TDC values at all depths can be explained on the basis of differences in skin thickness implies that conclusions with regard to skin water content among or between groups can only be made when corresponding skin thickness measurements are available. However, changes in TDC values assessed in individual subjects or patients and comparisons between corresponding skin areas in affected and non-affected sites are not limited in this way. Thus, assessments of acute treatment effects and assessments of inter-arm or inter-leg TDC differences or ratios within genders, as has previously been done (21, 22, 27–30, 44, 45), remains a useful and suitable method to characterize edema and lymphedema features.

Summary

Young adult male forearm TDC values are shown to be significantly greater than young adult female values at all probe-measurement depths with values for both genders decreasing with increasing depth. Simple model calculations indicate that these TDC differences may not uniquely reflect skin water differences between groups due to potential confounding effects of skin thickness differences.

References

1. Diridollou S, Black D, Lagarde JM, Gall Y, Berson M, Vabre V, Patat F, Vaillant L. Sex- and site-dependent variations in the thickness and mechanical properties of human skin in vivo. Int J Cosmet Sci 2000; 22: 421–435.
2. Chilcott RP, Farrar R. Biophysical measurements of human forearm skin in vivo: effects of site, gender, chirality and time. Skin Res Technol 2000; 6: 64–69.
3. Luebberding S, Krueger N, Kerscher M. Skin physiology in men and women: in vivo evaluation of 300 people including TEWL, SC hydration, sebum content and skin surface pH. Int J Cosmet Sci 2013; 35: 477–483.
4. Luebberding S, Krueger N, Kerscher M. Mechanical properties of human skin in vivo: a comparative evaluation in 300 men and women. Skin Res Technol 2014; 20: 127–135.
5. Ehlers C, Ivens UI, Moller ML, Senderovitz T, Serup J. Females have lower skin surface pH than men. A study on the surface of gender, forearm site variation, right/left difference and time of the day on the skin surface pH. Skin Res Technol 2001; 7: 90–94.
6. Sandby-Moller J, Poulsen T, Wulf HC. Epidermal thickness at different body sites: relationship to age, gender, pigmentation, blood content, skin type and smoking habits. Acta Derm Venereol 2003; 83: 410–413.
7. Kim BY, Choi JW, Park KC, Youn SW. Sebum, acne, skin elasticity, and gender difference - which is the major influencing factor for facial pores? Skin Res Technol 2013; 19: e45–e53.
8. Liu Z, Song S, Luo W, Elias PM, Man MQ. Sun-induced changes of stratum corneum hydration vary with age and gender in a normal Chinese population. Skin Res Technol 2012; 18: 22–28.
9. Man MQ, Xin SJ, Song SP, Cho SY, Zhang XJ, Tu CX, Feingold KR, Elias PM. Variation of skin surface pH, sebum content and stratum corneum hydration with age and gender in a large Chinese population. Skin Pharmacol Physiol 2009; 22: 190–199.
10. Cua AB, Wilhelm KP, Maibach HI. Frictional properties of human skin: relation to age, sex and anatomical region, stratum corneum

hydration and transepidermal water loss. Br J Dermatol 1990; 123: 473–479.
11. Athey TW, Stuchly MA, Stuchly SS. Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial line: part I. IEEE Trans MTT. 1982; 30: 82–86.
12. Stuchly MA, Athey TW, Samaras GM, Taylor GE. Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial line: part II - experimental results. IEEE Trans MTT. 1982; 30: 87–92.
13. Mayrovitz HN, Bernal M, Carson S. Gender differences in facial skin dielectric constant measured at 300 MHz. Skin Res Technol 2012; 18: 504–510.
14. Mayrovitz HN, Carson S, Luis M. Male-female differences in forearm skin tissue dielectric constant. Clin Physiol Funct Imaging 2010; 30: 328–332.
15. Shuster S, Black MM, McVitie E. The influence of age and sex on skin thickness, skin collagen and density. Br J Dermatol 1975; 93: 639–643.
16. Tsukahara K, Takema Y, Moriwaki S, Fujimura T, Imokawa G. Dermal fluid translocation is an important determinant of the diurnal variation in human skin thickness. Br J Dermatol 2001; 145: 590–596.
17. Gniadecka M, Faurskov Nielsen O, Christensen DH, Wulf HC. Structure of water, proteins, and lipids in intact human skin, hair, and nail. J Invest Dermatol. 1998; 110: 393–398.
18. Gniadecka M, Nielsen OF, Wessel S, Heidenheim M, Christensen DH, Wulf HC. Water and protein structure in photoaged and chronically aged skin. J Invest Dermatol. 1998; 111: 1129–1133.
19. Mayrovitz HN, Bernal M, Brlit F, Desfor R. Biophysical measures of skin tissue water: variations within and among anatomical sites and correlations between measures. Skin Res Technol 2013; 19: 47–54.
20. Nuutinen J, Lahtinen T, Turunen M, Alanen E, Tenhunen M, Usenius T, Kolle R. A dielectric method for measuring early and late reactions in irradiated human skin. Radiother Oncol 1998; 47: 249–254.
21. Mayrovitz HN, Guo X, Salmon M, Uhde M. Forearm skin tissue dielectric constant measured at 300 MHz: effect of changes in skin vascular volume and blood flow. Clin Physiol Funct Imaging 2013; 33: 55–61.
22. Mayrovitz HN, Davey S, Shapiro E. Local tissue water changes assessed by tissue dielectric constant: single measurements versus averaging of multiple measurements. Lymphology. 2008; 41: 186–188.
23. Mayrovitz HN, Brown-Cross D, Washington Z. Skin tissue water and laser Doppler blood flow during a menstrual cycle. Clin Physiol Funct Imaging 2007; 27: 54–59.
24. Mayrovitz HN, Davey S, Shapiro E. Local tissue water assessed by tissue dielectric constant: anatomical site and depth dependence in women prior to breast cancer treatment-related surgery. Clin Physiol Funct Imaging 2008; 28: 337–342.
25. Mayrovitz HN, McClymont A, Pandya N. Skin tissue water assessed via tissue dielectric constant measurements in persons with and without diabetes mellitus. Diabetes Technol Ther. 2013; 15: 60–65.
26. Jensen MR, Birkballe S, Nørregaard S, Karlsmark T. Validity and interobserver agreement of lower extremity local tissue water measurements in healthy women using tissue dielectric constant. Clin Physiol Funct Imaging 2012; 32: 317–322.
27. Harrow JH, Mayrovitz HN. Subepidermal moisture surrounding pressure ulcers in persons with a spinal cord injury: a pilot study. J Spinal Cord Med 2014; 37: 719–728.
28. Mayrovitz HN, Weingrad DN, Lopez L. Patterns of temporal changes in tissue dielectric constant (TDC) as indices of localized skin water changes in women treated for breast cancer: a pilot study. Lymphat Res Biol. 2015; 13: 20–32.
29. Mayrovitz HN, Weingrad DN, Davey S. Tissue dielectric constant (TDC) measurements as a means of characterizing localized tissue water in arms of women with and without breast cancer treatment releated lymphedema. Lymphology. 2014; 47: 142–150.
30. Mayrovitz HN, Davey S. Changes in tissue water and indentation resistance of lymphedematous limbs accompanying low level laser therapy (LLLT) of fibrotic skin. Lymphology. 2011; 44: 168–177.
31. Petaja L, Nuutinen J, Uusaro A, Lahtinen T, Ruokonen E. Dielectric constant of skin and subcutaneous fat to assess fluid changes after cardiac surgery. Physiol Meas 2003; 24: 383–390.
32. Stuchly MA, Athey TW, Stuchly SS, Samaras GM, Taylor G. Dielectric properties of animal tissues in vivo at frequencies 10 MHz–1 GHz. Bioelectromagnetics. 1981; 2: 93–103.
33. Aimoto A, Matsumoto T. Noninvasive method for measuring the electrical properties of deep tissues using an open-ended coaxial probe. Med Eng Phys 1996; 18: 641–646.
34. Lahtinen T, Nuutinen J, Alanen E. Dielectric properties of the skin. Phys Med Biol 1997; 42: 1471–1472.
35. Alanen E, Lahtinen T, Nuutinen J. Measurement of dielectric properties of subcutaneous fat with open-ended coaxial sensors. Phys Med Biol 1998; 43: 475–485.
36. Alanen E, Lahtinen T, Nuutinen J. Variational formulation of open-ended coaxial line in contact with layered biological medium. IEEE Trans Biomed Eng 1998; 45: 1241–1248.
37. Smith SR, Foster KR. Dielectric properties of low-water-content tissues. Phys Med Biol 1985; 30: 965–973.
38. Nuutinen J, Ikaheimo R, Lahtinen T. Validation of a new dielectric device to assess changes of tissue water in skin and subcutaneous fat. Physiol Meas 2004; 25: 447–454.
39. Mayrovitz HN. Assessing free and bound water in skin at 300 MHz using tissue dielectric measurements with the moisturemeterD. In: Greene AK, Brorson H and Slavin SA, eds. Lymphedema: presentation, diagnosis, and treatment, Chapter 13, ISBN 978-3-319-14492-4. New York, NY: Springer; 2015; 133–148.
40. Diridollou S, de Rigal J, Querleux B, Leroy F, Holloway Barbosa V. Comparative study of the hydration of the stratum corneum between four ethnic groups: influence of age. Int J Dermatol 2007; 46 (Suppl 1): 11–14.
41. Pennock BE, Schwan HP. Further observations on the electrical properties of hemoglobin-bound water. J Phys Chem 1969; 73: 2600–2610.
42. Gabriel S, Lau RW, Gabriel C. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. Phys Med Biol 1996; 41: 2251–2269.
43. Gabriel S, Lau RW, Gabriel C. The dielectric properties of biological tissues: III. Parametric

models for the dielectric spectrum of tissues. Phys Med Biol 1996; 41: 2271–2293.
44. Mayrovitz HN. Assessing lymphedema by tissue indentation force and local tissue water. Lymphology 2009; 42: 88–98.
45. Mayrovitz HN. Assessing local tissue edema in postmastectomy lymphedema. Lymphology 2007; 40: 87–94.

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