LYMPHATIC RESEARCH AND BIOLOGY
Volume 00, Number 00, 2018

DOI: 10.1089/lrb.2018.0052

Minimum Detectable Changes Associated with Tissue Dielectric Constant Measurements as Applicable to Assessing Lymphedema Status

Harvey N. Mayrovitz, PhD, Alexander Mikulka, MS, and Don Woody

Abstract

Background: Tissue dielectric constant (TDC) measurements are increasingly being used as a tool to help characterize lymphedema features, detect its presence, and assess treatment related changes. Although the underlying physics of this technology has been well described in the literature, there has been little systematic study of *in vivo* reliability aspects. A central unanswered question is the minimal detectable change (MDC) that, with a given level of confidence, may be ascribed to this technology. Our goal was to address this issue using test-retest measurements from which intraclass correlations coefficients (ICC) and MDC could be estimated.
Methods and Results: Forty volunteers (20 females) aged 19–61 years with body mass indices of 14.7–47 kg/m^2 and body fat percentages of 12.0%–48.9% were evaluated. Two measurers (M1 and M2) used two different TDC measuring devices (multiprobe and compact) to measure TDC in triplicate sequentially and bilaterally at three locations; anterior forearm, hand palmar mid-thenar eminence, and dorsum mid-web. These measurements were made by each measurer twice constituting test-retest values (T1 and T2). From these measurements $ICC_{2,1}$ and MDC at 95% confidence were determined for each site and probe for absolute TDC values and for inter-side ratios. MDC values for absolute TDC ranged from 2 to 9 TDC units, and for inter-side ratios ranged from 5.3% to 8.0% depending on site and probe. $ICC_{2,1}$ values ranged from 0.765 to 0.982.
Conclusions: The MDC values herein documented may be used to provide guidance to aid interpretation of measured TDC changes or differences in a clinical environment.

Keywords: lymphedema measurement, tissue dielectric constant, measurement reliability, minimum detectable change, minimum detectable difference

Introduction

Tissue dielectric constant (TDC) measurements are increasingly being used as a tool to help characterize lymphedema features,[1–4] detect its presence,[5–7] and assess treatment related changes.[8–13] Furthermore, such measurements have shown practicality in a range of pathological conditions[14–22] and have been used to study applied aspects of skin physiology.[23–27] Although the underlying physics and principle of operation of this technology have been well described in the literature,[28–33] there has been surprisingly little systematic study of *in vivo* reliability aspects.[34] Because of its use to assess changes in lymphedema status resulting from various forms of therapy and other conditions the question of measurement reliability becomes increasingly important. A central question in this regard relates to the minimal detectable change (MDC) that, with a given level of confidence, may be ascribed to this technology. Our goal was to address this issue by performing test-retest measurements using two different TDC measuring devices from which intraclass correlations coefficients (ICC) and MDC could be estimated thereby providing a guide to aid interpretation of measured TDC changes or differences in a clinical environment.

Methods

Subjects

A total of 40 adult volunteers (20 females and 20 males) participated in this research study. Subjects were recruited from medical students, faculty, staff, and family through word of mouth resulting in a range of ages (19–61 years), body mass indices (14.7–47 kg/m^2), body fat percentages

College of Medical Sciences, Nova Southeastern University, Ft. Lauderdale, Florida.

(12.0%–48.9%), and total body water percentages (38.0%–62.2%). Respective means and standard deviations (SDs) were 26.3 ± 6.4 years, 26.0 ± 6.1 kg/m^2, 25.5% ± 9.1%, and 54.0% ± 5.9%. After explaining the study to potential participants, and if they agreed to participate, they signed a consent form that was approved by the University institutional review board (IRB), and a time for participation was scheduled. The procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008. To be eligible for participation, potential subjects needed to be at least 18 years of age with no history of arm or hand edema or lymphedema or any current skin condition that might impact the planned measurements. The study was conducted from January through July of 2018 at Nova Southeastern University.

Measurers

TDC measurements (described subsequently) were done by two medical students who before this study had no experience using the TDC measuring devices. Operational procedures were explained by the senior author (H.N.M.), and they had an opportunity to utilize the devices with H.N.M. as a subject with feedback provided regarding technique during a 1-hour training session. Subsequently, the two measurers, denoted as M1 and M2, as part of their experience development made all protocol measurements on five test subjects who would not be part of the main study. The test data were reviewed by H.N.M. for consistency with a primary criterion that at least 80% of all triplicate measurements demonstrated a coefficient of variation of 5% or less. This criterion was achieved by both measurers.

Initial study procedures

Upon entry into a dedicated experimental room, subjects removed their shoes and socks and stood on a body composition scale (Tanita Ironman BC558, Segmental Body Composition Monitor) to measure their weight, body water percentage, total body fat percentage, and individual body compartment fat percentages. Each subject self-reported their age, height, and dominant hand. After this they sat on a padded chair to which an arm rest was attached across the front so that they could comfortably rest their arms. Room temperature and humidity were recorded at the start of measurements. Thereafter the TDC measurement protocol was initiated.

TDC measurement

Two different TDC measuring devices were used, both manufactured by Delfin Technologies (Kuopio, Finland). One was the MoistureMeterD using a 2.5 mm effective depth measuring probe, and the other was the more recently available compact version referred to as the MoistureMeter Compact. TDC measurements were obtained by placing the probe surface perpendicularly on the subject's skin with firm but gentle contact pressure. Measurements were done in triplicate sequentially and bilaterally at three standardized locations: (1) the anterior forearm 5 cm distal to the antecubital fossa, (2) the center of the hand palmar thenar eminence, and (3) the hand dorsum mid-web between the thumb and index finger that was not over bone. The triplicate measurements at each site were done by alternating between sides sequentially, starting with the dominant side. The order of the measurements was hand dorsum to hand palmar to forearm. After placing the probe on the skin, a measurement takes about 5 seconds. Anatomical sites were chosen to be inclusive of sites used related to lymphedema and other TDC-related measurements.[2–6,24,27]

The physics of TDC measurements is well described in the literature.[28,32,33,35] Briefly, a very low intensity 300 MHz signal is transmitted from the probe in contact with the skin and penetrates the skin to varying depths depending on the probe used. Some incident energy is reflected to a processing unit. In the multiprobe device it is a separate unit, and in the compact device it is self-contained. Based on information from the reflected wave the processor calculates the real part of the complex permittivity of the composite tissue being sampled. This value is the TDC that has a value strongly dependent on the relative amount of water in the sampled tissue. The effective penetration depth depends on the probe design and in the present case the multiprobe effective penetration depth was ~2.5 mm, whereas the compact device used has a penetration depth of about 2 mm. Effective penetration depth has been defined as that depth at which the incident energy falls to 37% of its surface value.[29]

Procedure

Two measurers (M1 and M2) and one data recorder participated in the protocol. The procedure was for M1 to do the complete measurement set first using the compact probe with M2 not present in the experimental room. After M1 completed the first measurement set M1 left the room and M2 entered and completed the first measurement set with the compact probe. This process was then repeated with the measurers using the multiprobe. The combined process of measuring with the compact and multiprobe was then repeated so that M1 and M2 both completed two completed measurement sets, the first designated as time 1 (T1) and the second as time 2 (T2). At no time during the measuring process were M1 and M2 in the experimental room at the same time and neither knew of the values obtained by the other. Room temperature and relative humidity of the room were 22.3°C ± 1.0°C and 52.6% ± 4.1%.

Analyses

The MDC is the smallest change or difference that should be interpreted as being real and was calculated at the 95% confidence level using the equation $MDC_{95} = 1.96 \times SEM \times \sqrt{(2)}$.[36] SEM is the standard error of the measurement with $SEM = SD \times \sqrt{(1 - ICC)}$, where SD is the standard deviation of the complete data set for T1 and T2 measurements, and ICC is the intraclass correlation coefficient. For the present design the appropriate generalized ICC is $ICC_{2,1}$ calculated based on a two-way random effects model for absolute agreement as $ICC_{2,1} = (MS_S - MS_E)/[MS_S + (K-1)MS_E + K(MS_T - MS_E)/n]$.[36] In this equation MS_S is the subject mean square, MS_E is error mean square, MS_T is the trials (within) mean square, n is the number of independent measurements, and K is the number of measurers. All statistical analyses were done using SPSS version 16. ICC and MDC values were

determined for the absolute TDC measurements at each site and for each probe and also for the inter-side ratios. Interarm ratios of TDC measurements have been shown to be essentially independent of a person's handedness.[5]

Results

TDC values

Table 1 summarizes absolute TDC values and key ratios for each anatomical site measured by both measurers using the multiprobe 2.5 mm depth probe and the compact probe. Initial comparisons of TDC values measured on dominant and nondominant sides during first and second measurement sets (T1 and T2) showed very similar values with no statistically significant difference ($p > 0.3$) between sides or measurement times. Thus, each value in the table includes data of the combined sides and times for a total of 160 measurements (40 subjects × 2 sides × 2 measurement times). The main findings with respect to measured TDC values are as follows.

(1) For both measurers and for both probes TDC values were significantly different among anatomical sites ($p < 0.001$) with the forearm having the least TDC value and the hand palm showing the greatest TDC value.
(2) TDC values recorded by the compact probe were statistically different from that recorded by the multiprobe probe at all sites and for both measurers. However, the main difference between probes was recorded at the forearm where the compact probe TDC values exceeded the multiprobe by an average of 16.3% for measurer 1 (M1) and by 16.6% for measurer 2 (M2). At the hand sites the difference between probe values was less than 5% at the hand dorsum and less that 2% at hand palm.
(3) There was an overall statistically significant difference ($p < 0.001$) in TDC values measured by M1 and M2 at each site with percentage differences ranging from 2.0% to 4.3% for the multiprobe and 2.2% to 5% for the compact probe.

Intraclass correlation coefficients ($ICC_{2,1}$) and MDC for absolute TDC value

Table 2 summarizes ICC and MDC values for absolute TDC values for each anatomical site measured by both measurers using the multiprobe 2.5 mm depth probe and the compact probe. The main findings with respect to measured TDC values are as follows.

(1) $ICC_{2,1}$ values had a wide range which when averaged between M1 and M2 had a minimum of 0.765 at the hand dorsum when using the multiprobe and a maximum value of 0.982 at the forearm using the compact device. The corresponding largest and least minimum detectable differences are 9 and 2 TDC units, respectively.
(2) For both the multiprobe and the compact probe the least MDC is observed for measurements on the forearm (4 and 2 TDC units, respectively) and

TABLE 1. TISSUE DIELECTRIC CONSTANT VALUES

Site	*Measurer 1 (M1)*				*Measurer 2 (M2)*				*M2/M1*	
	Multiprobe	*Compact*	p	*CP/MP*	*Multiprobe*	*Compact*	p	*CP/MP*	*Multiprobe*	*Compact*
Forearm anterior	27.4 ± 4.3	31.6 ± 3.6	<0.001	1.163 ± 0.103	27.9 ± 4.3	32.2 ± 3.5	<0.001	1.166 ± 0.102	1.020 ± 0.054	1.022 ± 0.026
Hand dorsum	36.4 ± 6.6	37.4 ± 5.1	<0.001	1.041 ± 0.116	37.9 ± 6.9	39.2 ± 5.1	<0.001	1.048 ± 0.113	1.043 ± 0.070	1.050 ± 0.055
Hand palmar	45.8 ± 5.3	45.0 ± 4.3	0.015	0.991 ± 0.103	47.3 ± 5.2	46.5 ± 4.1	0.002	0.989 ± 0.079	1.036 ± 0.066	1.035 ± 0.038

Entries are mean ± SD of combined dominant and nondominant side TDC values measured at times 1 and 2 constituting 160 measurements for each entry. *p*-Values refer to comparisons of multiprobe versus compact probe. Differences in TDC values among and between sites are significant ($p < 0.001$) for probe and measurer. Differences in values between measurers at all sites for each probe are also significant ($p < 0.001$). M2/M1 is the ratio of TDC values measured by measurer 2 (M2) divided by those of measurer 1 (M1). CP/MP is the ratio of compact to multiprobe TDC values.
SD, standard deviation; TDC, tissue dielectric constant.

Table 2. Reliability Parameters Based on Test-Retest of Absolute Tissue Dielectric Constant Measurements

	Multiprobe			*Compact probe*		
Site	*M1*	*M2*	*Average*	*M1*	*M2*	*Average*
Forearm						
$ICC_{2,1}$	0.861	0.935	0.898	0.983	0.981	0.982
SEM	1.59	1.09	1.34	0.48	0.49	0.49
MDC	4.42	3.03	3.73 (4)	1.32	1.35	1.34 (2)
Hand dorsum						
$ICC_{2,1}$	0.710	0.820	0.765	0.948	0.942	0.945
SEM	3.57	2.82	3.20	1.16	1.24	1.20
MDC	9.91	7.81	8.86 (9)	3.21	3.43	3.32 (4)
Hand palm						
$ICC_{2,1}$	0.892	0.937	0.915	0.944	0.981	0.963
SEM	1.75	1.34	1.55	1.02	0.56	0.79
MDC	4.86	3.71	4.29 (5)	2.83	1.56	2.20 (3)

Average, average of M1 and M2 parameters with value in parentheses of the MDC value rounded up to the next whole number; $ICC_{2,1}$, intraclass correlation coefficients; M1 and M2, measurers 1 and 2; MDC, minimal detectable change; SEM, standard error of measurement.

greatest for measurements on hand dorsum (9 and 4 U, respectively).

(3) For each anatomical site measured the compact probe yielded a smaller MDC value than for the multiprobe.

Intraclass correlation coefficients ($ICC_{2,1}$) and MDC for interarm TDC ratios

Table 3 summarizes ICC and MDC values for dominant to nondominant side TDC ratios for each anatomical site measured by both measurers using the multiprobe 2.5 mm depth probe and the compact probe. The main findings with respect to TDC ratios are as follows.

(1) Average interarm ratios ranged from 0.985–0.986 on the hand palm to 1.000–1.008 on the hand dorsum with all values not differing significantly from a value of one.

(2) For both probes and most anatomical sites the ICC were less compared with corresponding values determined for absolute TDC values (Table 2).

(3) The average MDC for ratios ranged from 0.053 to 0.080 corresponding to MDC% ranging from 5.3% to 8.0% depending on anatomical site and probe used.

Table 3. Reliability Parameters Based on Test-Retest of Tissue Dielectric Constant Ratios

	Multiprobe			*Compact probe*		
Site	*M1*	*M2*	*Average*	*M1*	*M2*	*Average*
Forearm						
$ICC_{2,1}$	0.786	0.750	0.768	0.816	0.894	0.855
SEM	0.025	0.032	0.029	0.019	0.029	0.024
MDC	0.071	0.089	0.080	0.052	0.081	0.067
DOM/NDOM	0.994 (0.055)	0.994 (0.064)	0.994 (0.060)	1.001 (0.056)	0.996 (0.054)	0.999 (0.055)
Threshold			1.254			1.231
Hand dorsum						
$ICC_{2,1}$	0.785	0.838	0.812	0.854	0.613	0.734
SEM	0.025	0.022	0.024	0.031	0.020	0.026
MDC	0.068	0.060	0.064	0.086	0.055	0.071
DOM/NDOM	1.011 (0.053)	1.005 (0.054)	1.008 (0.054)	1.009 (0.053)	0.991 (0.059)	1.000 (0.056)
Threshold			1.234			1.239
Hand palm						
$ICC_{2,1}$	0.816	0.895	0.856	0.931	0.888	0.910
SEM	0.030	0.023	0.027	0.017	0.021	0.019
MDC	0.083	0.063	0.073	0.047	0.059	0.053
DOM/NDOM	0.979 (0.070)	0.990 (0.070)	0.985 (0.070)	0.984 (0.065)	0.989 (0.064)	0.986 (0.065)
Threshold			1.273			1.234

Parameters based on dominant to nondominant side ratios.

Average, average of M1 and M2 parameters; DOM/NDOM, dominant to nondominant side TDC ratio ± (SD); Threshold is defined as the mean ratio +3 SD + MSD for a given site and probe.

Discussion

A main goal of this study was to provide useful estimates of the MDC that could be reliably taken to represent a real difference or change when measuring TDC. This undertaking was triggered by the fact that TDC measurements have been widely used and are increasingly being used in a variety of research and clinical studies but until now there has not been a systematic determination of the associated MDC. Without such clarification interpretation of findings is unnecessarily hindered.

The anatomical sites chosen for these measurements and assessments were those that are often used in the evaluation of upper limb edema or lymphedema. So that strictly speaking it is to these sites (forearm and hand) that the MDC estimates apply. Furthermore, because the test subjects were specifically chosen to be free of lymphedema for this reliability study, the extent to which the determined estimates directly apply to persons with lymphedema is unspecified. However, they importantly serve as a lower bound on expected MDC values.

In making these assessments two different TDC measuring devices were utilized. One was a multiprobe device capable of accommodating different probes that measure to differing tissue depths. The other was a compact device that is contained in single handheld device that measures to a single tissue depth. These devices, which are made by the same manufacturer, differed in construction and the depth to which they measured. The multiprobe measured to an effective depth of about 2.5 mm as specified by the manufacturer, whereas the compact probe measured to a depth of about 2 mm as previously determined.[37] These two probes are the ones that are most widely reported in use within the literature.

The fact that absolute TDC values recorded at the forearm were greater when measured using the compact probe was confirmed through the present measurements, with the compact yielding a value of about 4.2 TDC units higher at the forearm. This difference is likely since measuring deeper will include more low-water content subcutaneous fat to be included in the measured volume. The effect would be a lower TDC reading for the 2.5 mm probe.

However for the forearm this difference is about 16.5%, whereas a prior study reported a difference of about 5.6%.[37] There are several possibilities that may account for this difference. In the prior report the percentage difference was based on the mean difference divided by the average of the values determined by the two probes. In the present study the divisor in the calculation was the value of the 2.5 mm depth. This was used to determine the percentage that the compact exceeded the multiprobe. If percentage difference between the two measurements was determined for the present study a value of 14.2% would be calculated. Another factor that may account for the difference relates to the absolute value determined using the multiprobe. In the present study absolute TDC values measured with the compact probe (31.9 ± 3.5) on the 40 subjects (half female and half male) were similar to that previously reported (31.1 ± 2.6) measured on 64 subjects, also half female and half male. However, the multiprobe TDC values measured in the present study were less than previously measured (27.6 ± 4.3 vs. 29.4 ± 2.7). Such a difference might account for some of the discrepancies and would occur if the current subjects had a greater fraction of hypodermal fat within the measurement volume of the multiprobe. Since this was not measured this plausible reason must for now remain speculative.

Contrastingly, average TDC values at the hand differed by less than 1.0 TDC unit. The smaller probe-related difference might reflect structural differences inherent among anatomical sites. However, despite differences in absolute values measured between probes at the forearm, interarm ratios computed as dominant/nondominant side TDC values proved to be remarkably similar at all sites (Table 2). This suggests that use of either probe would yield comparable results when assessments of interarm ratios were the parameter of interest.

The MDC values summarized in Tables 2 and 3 provide the main reliability outcome of the present study. Because some research and clinical applications may utilize absolute TDC differences while others may use inter-side ratios, MDC is needed separately for each application. The results for the absolute value analysis demonstrate that MDCs are dependent on the anatomical site being evaluated and on the probe being used. For all sites measured, the compact probe had the least MDC value that ranged from 2 TDC units at the forearm to 4 TDC units at the hand dorsum.

At each site the multiprobe demonstrated a greater MDC value that ranged from 4 TDC units at the forearm to 9 TDC units at the hand dorsum. The explanation for the difference in MDC values between these two probes is speculative but probably involves at least two factors. The standard compact device has an included pressor sensor, not present in the multiprobe device, which might allow for a more uniform application pressure which in turn may have yielded a greater intraclass correlation coefficient value. In addition, because the compact probe measures to a lesser depth than the multiprobe, minor differences in contact pressure during the measurement might have less effect on the measured TDC value. This follows since a lesser depth measurement probe includes proportionately more of the homogeneous high-water content dermal region as opposed to possibly including different proportions of dermis and low-water content hypodermis as would be the case for the deeper measurement probe.

In contrast to probe-dependent MDC differences associated with absolute TDC values, probe differences in MDC were less clear as applied to interarm TDC ratios (Table 3). The compact probe average MDC was less than for the multiprobe at forearm and hand palmar but greater at the hand dorsum. Overall the MDC value for interarm TDC ratios ranged from 0.053 to 0.080. These MDC values may be used for lymphedema assessments in two separate ways. When comparing a prior measured interarm ratio to a measurement taken later or after treatment, a change in ratio needs to be greater than the MDC values specified in Table 3 to be considered a possibly real change. For example, if a presurgery interarm ratio (at-risk/contralateral) of 1.065 was measured at the forearm, using the multiprobe, then anything less than a subsequently measured ratio less than $1.065 + 0.080$ or 1.145 should not be considered as a real change at the 95% confidence level. If the compact probe were being used, its smaller MDC leads to a threshold of $1.065 + 0.067 = 1.132$. Similar calculations could be done for other anatomical sites of interest.

MDC values determined for interarm ratios may also help specify threshold ratios to detect lymphedema. Such thresholds have been calculated as those values that exceed normal

reference ratio averages by at least 3 SDs. For forearm these range between 1.26[2,4] and 1.29[38] and for hand dorsum are 1.23 for a 2 SD threshold or 1.32 for a 3 SD threshold.[6] Threshold values based on the present more limited data set and calculated using the 3 SD threshold using site-dependent and probe-dependent MSD values added ranged between about 1.23 and 1.27, values similar to those previously reported.

Acknowledgments

The authors thank the many study participants without whom this research could not have come to fruition.

Author Disclosure Statement

No competing financial interests exist.

References

1. Mayrovitz HN. Assessing local tissue edema in postmastectomy lymphedema. Lymphology 2007; 40:87–94.
2. Mayrovitz HN, Weingrad DN, Davey S. Local tissue water in at-risk and contralateral forearms of women with and without breast cancer treatment-related lymphedema. Lymphat Res Biol 2009; 7:153–158.
3. 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 related lymphedema. Lymphology 2014; 47:142–150.
4. Mayrovitz HN, Weingrad DN, Lopez L. Patterns of temporal changes in tissue dielectric constant as indices of localized skin water changes in women treated for breast cancer: A pilot study. Lymphat Res Biol 2015; 13: 20–32.
5. Mayrovitz HN, Fasen M, Spagna P, Wong J. Role of handedness on forearm skin tissue dielectric constant (TDC) in relation to detection of early-stage breast cancer-related lymphedema. Clin Physiol Funct Imaging 2018; 38: 670–675.
6. Mayrovitz HN, Arzanova E, Somarriba S, Eisa S. Reference values for assessing localized hand lymphedema using interhand tissue dielectric constant ratios. Lymphat Res Biol 2018; 16:442–445.
7. Birkballe S, Jensen MR, Noerregaard S, Gottrup F, Karlsmark T. Can tissue dielectric constant measurement aid in differentiating lymphoedema from lipoedema in women with swollen legs? Br J Dermatol 2014; 170:96–102.
8. Tugral A, Viren T, Bakar Y. Tissue dielectric constant and circumference measurement in the follow-up of treatment-related changes in lower-limb lymphedema. Int Angiol 2018; 37:26–31.
9. Pigott A, Nixon J, Fleming J, Porceddu S. Head and neck lymphedema management: Evaluation of a therapy program. Head Neck 2018; 40:1131–1137.
10. Fife CE, Davey S, Maus EA, Guilliod R, Mayrovitz HN. A randomized controlled trial comparing two types of pneumatic compression for breast cancer-related lymphedema treatment in the home. Support Care Cancer 2012; 20:3279–3286.
11. 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.
12. Mayrovitz HN. Assessing lymphedema by tissue indentation force and local tissue water. Lymphology 2009; 42: 88–98.
13. Mayrovitz HN, Davey S, Shapiro E. Localized tissue water changes accompanying one manual lymphatic drainage (MLD) therapy session assessed by changes in tissue dielectric constant inpatients with lower extremity lymphedema. Lymphology 2008; 41:87–92.
14. Mayrovitz HN, Gildenberg SR, Spagna P, Killpack L, Altman DA. Characterizing the tissue dielectric constant of skin basal cell cancer lesions. Skin Res Technol 2018; 24: 686–691.
15. Toyooka KT, Niwa H, Hashiba E, Hirota K. Can tissue dielectric constant measurements assess circulating blood volume changes in patients undergoing haemodialysis? Clin Physiol Funct Imaging 2017; 38:497–501.
16. Mayrovitz HN, Volosko I, Sarkar B, Pandya N. 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. J Diabetes Sci Technol 2017; 11:584–589.
17. Bates-Jensen BM, McCreath HE, Patlan A. Subepidermal moisture detection of pressure induced tissue damage on the trunk: The pressure ulcer detection study outcomes. Wound Repair Regen 2017; 25:502–511.
18. Bates-Jensen BM, McCreath HE, Nakagami G, Patlan A. Subepidermal moisture detection of heel pressure injury: The pressure ulcer detection study outcomes. Int Wound J 2018; 15:297–309.
19. 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.
20. Miettinen M, Monkkonen J, Lahtinen MR, Nuutinen J, Lahtinen T. Measurement of oedema in irritant-exposed skin by a dielectric technique. Skin Res Technol 2006; 12: 235–240.
21. 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.
22. Nuutinen J, Lahtinen T, Turunen M, et al. A dielectric method for measuring early and late reactions in irradiated human skin. Radiother Oncol 1998; 47:249–254.
23. Mayrovitz HN, Mahtani SA, Pitts E, Michaelos L. Race-related differences in tissue dielectric constant measured noninvasively at 300 MHz in male and female skin at multiple sites and depths. Skin Res Technol 2017; 23:471–478.
24. Mayrovitz HN, Grammenos A, Corbitt K, Bartos S. Age-related changes in male forearm skin-to-fat tissue dielectric constant at 300 MHz. Clin Physiol Funct Imaging 2017; 37: 198–204.
25. Mayrovitz HN, Corbitt K, Grammenos A, Abello A, Mammino J. Skin indentation firmness and tissue dielectric constant assessed in face, neck, and arm skin of young healthy women. Skin Res Technol 2017; 23:112–120.
26. Mayrovitz HN, Singh A, Akolkar S. Age-related differences in tissue dielectric constant values of female forearm skin measured noninvasively at 300 MHz. Skin Res Technol 2016; 22:189–195.
27. Mayrovitz HN, Grammenos A, Corbitt K, Bartos S. Young adult gender differences in forearm skin-to-fat tissue dielectric constant values measured at 300 MHz. Skin Res Technol 2016; 22:81–88.

28. 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.
29. Alanen E, Lahtinen T, Nuutinen J. Penetration of electromagnetic fields of an open-ended coaxial probe between 1 MHz and 1 GHz in dielectric skin measurements. Phys Med Biol 1999; 44:N169–N176.
30. 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.
31. 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.
32. Grant JP, Clarke RN, Symm GT, Spyrou NM. In vivo dielectric properties of human skin from 50 MHz to 2.0 GHz. Phys Med Biol 1988; 33:607–612.
33. 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 Microw Theory Techn 1982; 30: 87–92.
34. Jensen MR, Birkballe S, Norregaard 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.
35. 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.
36. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005; 19:231–240.
37. Mayrovitz HN, Weingrad DN, Brlit F, Lopez LB, Desfor R. Tissue dielectric constant (TDC) as an index of localized arm skin water: Differences between measuring probes and genders. Lymphology 2015; 48:15–23.
38. Mayrovitz HN, Weingrad DN, Lopez L. Assessing localized skin-to-fat water in arms of women with breast cancer via tissue dielectric constant measurements in pre- and post-surgery patients. Ann Surg Oncol 2015; 22:1483–1489.

Address correspondence to:
Harvey N. Mayrovitz, PhD
College of Medical Sciences
Nova Southeastern University
3200 South University Drive
Ft. Lauderdale, FL 3328

E-mail: mayrovit@nova.edu