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Assessing Upper and Lower Extremities Via Tissue Dielectric Constant: Suitability of Single Versus Multiple Measurements Averaged

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Abstract

Background: Tissue dielectric constant (TDC) measurements as an index of local tissue water are useful in a range of applications most notably to characterize and assess lymphedema. Once a measuring device is applied to skin and a result is obtained in less than 10 seconds, but multiple sites may be required and use of the standard triplicate measurements may be time prohibitive. Thus, this study's goal was to provide data from which informed judgments could be made as to the impact of making a single measurement to reduce expended clinic time.
Methods and Results: Sixty subjects (30 female) were recruited with an average age (mean ± standard deviation) of 30.6 ± 13.4 years. TDC was measured in triplicate bilaterally at forearm, hand palm, lateral calf, medial calf, and foot dorsum. The agreement in absolute TDC values and interside ratios was evaluated for assessments made using only the first TDC measurement, the average of duplicates and the standard triplicate. Results showed that differences between single and multiple measurement averages were anatomical site dependent with the smallest coefficient of variation (2.19%) at the forearm and the largest at the lateral calf (4.59%).
Conclusions: Results suggest that when clinical time is of major concern, useful TDC data may be obtained in upper limbs using single TDC measurements per anatomical site whereas lower extremity skin assessments should be done using at least duplicate and preferably triplicate measurements. However, as with all such time reliability considerations, clinical judgment should be exercised and aided by the various findings of this study.

Keywords: lymphedema measurement, tissue dielectric constant, local skin water, lymphedema detection, lymphedema diagnosis

Introduction

Tissue dielectric constant (TDC) measurements are one of several methods that are used to characterize various aspects of lymphedema.[1,2] TDC measurements may be used to estimate skin properties, especially changes in skin water content in a variety of situations, including breast cancer-related lymphedema[3–11] and lower extremity lymphedema.[12–14] Most of these studies and other nonlymphedema-related applications of TDC measurements[15–19] have used the average of triplicate measurements at each anatomical site, in part, because the suitability of just a single measurement was not known.

Because of the increasing use of this measurement modality in a variety of situations, most notably with respect to lymphedema detection or characterization[3,6,8–10,12,20–22] and treatment tracking of outcomes,[4,5,10,11,13,14,23,24] it was reasoned that if the relative agreement of single measurements compared to multiple measurements were known, then considerable clinical time could be saved if and when needed. This would be especially true when multiple anatomical sites are required to be measured. Thus, the goal of this research was to provide estimates for the extent of differences in absolute and relative TDC values when TDC measurements are made with one initial measurement per site versus the average of duplicate measurements per site versus the average of the standard triplicate measurements per site.

Materials and Methods

Subjects

A total of 60 subjects, equally divided between female and male, were recruited for participation in this research study. Subjects were recruited from first and second year medical students and from others, including university faculty and

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staff. Participants were evaluated during a single session after the nature of the study was explained and each signed an approved University Institutional Review Board consent form. Recruitment was terminated upon achieving participation of 30 female and 30 male participants. Requirements for study participation were (1) an age of at least 18 years, (2) an absence of a prior history of surgery or substantial trauma to either upper or lower limbs, and (3) an absence of any skin condition that might impact the planned measurements. Absolute exclusionary conditions were (1) the presence of any implanted electronic devices or wires and (2) the presence of any open wounds in any of the limb areas targeted for measurement.

The average age (mean ± standard deviation [SD]) of the entire group ($N = 60$) was 30.6 ± 13.4 years with a range of 18–70 years. Males versus females did not statistically differ with respect to age (30.0 ± 13.2 years vs. 30.6 ± 13.8 years, $p = 0.772$) but had a higher body mass index (26.7 ± 4.1 kg/m^2 vs. 23.5 ± 4.0 kg/m^2, $p = 0.007$).

Measurement methods

The primary measurement, TDC, was made using a compact hand-held battery-operated device (MoistureMeterD Compact; Delfin Technologies, Kuopio Finland). In use, the probe surface, which is about 20 mm in diameter, is held in contact with the skin and in less than 10 seconds the measurement is completed. Consistency of contact pressure is aided by an integrated pressure sensor and display. The specific device used measures to an approximate effective depth 2–2.5 mm. Effective depth may be defined as the depth, at which the incident electric field falls to 1/*e* of its skin surface value. The measured quantity, TDC, is also called relative permittivity, which is a ratio of tissue permittivity to free space permittivity and is thus a dimensionless quantity. For reference, the dielectric constant of pure distilled water at a temperature of 32°C is about 76.

The compact device internally converts the measured TDC value to a percentage of water, however, for consistency to the literature, all values herein reported are expressed as the unconverted TDC value. The TDC measurement method used by this device has been well described in the literature[25–29] and has been used to assess skin-related properties in a variety of applications, including diabetes,[15,17] skin injury, and ulceration,[30–33] detecting and characterizing lymphedema features[3,6,8–10,12,20–22] and assessing outcomes of lymphedema treatment.[4,5,10,11,13,14,23,24]

In brief, the probe acts as a coaxial transmission line, through which a 300-MHz signal is transmitted. Reflections depend on the tissue's complex permittivity, which in-turn depends on the signal frequency and the TDC (the real part of the complex permittivity). At the frequency used, the contribution of conductivity to permittivity is small, so TDC is mainly determined by water molecules (free and bound). Thus, the device includes and analyzes the dielectric constant that is proportional to tissue water. In addition to the primary TDC measurement, skin temperatures were measured at each site using an infrared thermometer (Exergen, Watertown Main, Model DX501-RS).

Measurement sites and procedure

TDC was measured at five anatomical sites that are representative and have relevance to potential lymphedema development areas in upper or lower limbs. The two upper limb sites were (1) the anterior forearm located 5 cm distal to the antecubital fossa and (2) the hand palmer surface at the approximate midpoint of the thenar eminence. The three lower limb sites were (1) the lateral lower leg (10 cm proximal to the lateral malleolus), (2) the medial lower leg (10 cm proximal to the medial malleolus), and (3) the foot dorsum between the first and second toes. All measurements were done bilaterally and in triplicate at each site with each subject supine. Measurements were not begun until the subject had acclimated in that position for 5 minutes. The measurement order was, forearm to hand to lateral leg to medial leg to foot dorsum. Bilateral measurements were completed before moving to the next target site with the first bilateral measurement on the subject's stated dominant side. The right side was the expressed dominant side in 57 (95%) of subjects. Room temperature and relative humidity over all measurement sessions were 22.0°C ± 1.2°C and 50.0% ± 3.6%, respectively.

Analysis

For purposes of analysis the following definitions were utilized. The first TDC measurement at a site was designated as TDC1. The average of the first and second TDC measurements was designated as TDC12. The average of all three TDC measurements was designated as TDC123. Tests for overall differences in TDC values among anatomical sites were done using a general linear model (GLM; SPSS 16) for repeated measures with TDC123 as the repeated measure. Tests for overall differences among TDC1, TDC12, and TDC123 were done for each site individually using the GLM for repeated measures analysis.

As an additional indicator, the coefficient of variation (CV) of the three sequential TDC measurements at each site for each subject was determined as the SD divided by the mean of the three measurements and expressed as a percentage with CV = 100 SD/mean. The overall CV mean and the overall CV SD were determined using all individually determined CV values.

Results

Absolute TDC values by anatomical site and number of measurements

Results for all 60 subjects (120 upper limbs and 120 lower limbs) are listed (mean ± SD) in Table 1 in descending order of TDC123 values with hand > lateral leg > medial leg > foot dorsum > forearm. The greatest TDC value was recorded at the hand (42.7 ± 8.3 and the least TDC value recorded at the forearm (31.1 ± 4.5). Analysis of differences in TDC123 among sites showed that each site TDC value was statistically different from TDC values at all other sites ($p < 0.001$).

Tests for differences among TDC1, TDC12, and TDC123 for each anatomical site showed a statistically significant difference only at hand and forearm that was attributable to the statistical difference ($p < 0.01$) between TDC1 and TD3 at these two sites. However, despite the statistical difference at the two sites, overall differences between TDC1, TDC12, and TDC123 were less than 1% at all sites, and there was no statistical difference between TDC12 and TDC123 at any site. The least CV of the triplicate TDC values was 2.19% ± 1.96% at the forearm and the largest, 4.59% ± 3.2%, at the lateral leg. Skin temperature at the foot dorsum (30.1°C ± 1.9°C) was the least of all sites and was significantly ($p < 0.001$) less than at all other

Table 1. Tissue Dielectric Constant Values by Anatomical Site

	TSK (°C)	*TDC1*	*TDC12*	*TDC123*	*CV (%)*
Hand palm	31.8 ± 1.9	42.4 ± 8.2	42.6 ± 8.3	42.7 ± 8.3*	2.64 ± 1.62
Lateral leg	32.1 ± 1.0	39.9 ± 6.8	40.0 ± 6.7	40.1 ± 6.7	4.59 ± 3.20
Medial leg	31.4 ± 1.1	34.1 ± 5.2	34.2 ± 5.3	34.4 ± 5.3	4.16 ± 3.79
Foot dorsum	30.1 ± 1.9	31.3 ± 5.3	31.5 ± 5.2	31.5 ± 5.3	3.22 ± 3.14
Forearm	32.5 ± 1.1	30.9 ± 4.5	31.0 ± 4.5	31.1 ± 4.5*	2.19 ± 1.96

Table entries are mean ± SD of values for 60 subjects (120 limbs) for single TDC measurements (TDC1), average of duplicate measurements (TDC12), and average of triplicate measurements (TDC123). TDC data are listed in descending order of TDC123 values. All TDC values differed among sites ($p < 0.001$) with values at each site significantly different for each other ($p < 0.01$). A statistical difference ($*p < 0.01$) between TD123 and TDC1 was found only at hand and forearm. Overall differences between TDC1, TDC12, and TDC123 were less than 1% at all sites. There was no statistical difference between TDC12 and TDC123 at any site. TSK is skin temperature. TDC1 is based on first TDC measurements, TDC12 is based on the average of the first and second TDC measurements and TDC123 is based on the average of all three TDC measurements at each anatomical site. Skin temperature at the foot dorsum was significantly ($p < 0.001$) less than at all other sites. CV (%) is the overall CV of triplicate TDC measurements.

CV, coefficient of variation; SD, standard deviation; TDC, tissue dielectric constant; TSK, skin temperature.

sites, whereas the highest skin temperature was at the forearm (32.5°C ± 1.1°C).

Dominant-to-nondominant side TDC ratios by anatomical site and number of measurements

Results for dominant/nondominant side TDC ratios for the 60 subjects are listed in Table 2. There was no statistically significant difference in TDC *ratios* among sites ($p = 0.547$) for TDC1, TDC12, or TDC123 despite differences in *absolute* TDC values among sites already described (Table 1). Values of TDC123 ratios ranged from 1.012 ± 0.092 at forearm to 1.051 ± 0.133 at the medial leg site. Furthermore, at each of the five anatomical sites, the TDC ratios as determined by TDC1, TDC12, or TDC123 did not statistically differ from each other, judged by p values ranging from 0.905 at forearm to 0.118 at the medial leg site.

Gender comparisons and threshold ratios

Table 3 summarizes TDC123 absolute values and side-to-side TDC123 ratios for females and males. At all anatomical sites, absolute TDC values for males tended to be greater than for females, but statistically significant differences were demonstrated only for hand ($p < 0.05$) and forearm ($p < 0.001$). Contrastingly, interside TDC123 ratios were not statistically different between genders at any anatomical site. For females and males separately, a threshold ratio is calculated for each anatomical site based on the mean + 2.5 SD. For this threshold, a greater value would normally occur in about 0.6% of cases.

Single versus duplicate versus Triplicate-based TDC interside ratios

The relative agreements in dominant-to-nondominant interarm TDC ratios, as dependent on whether these ratios are formed using single bilateral measurements, duplicate averages, or triplicate averages, are summarized in Table 4. An arbitrary threshold of 5% was considered as a reasonable figure of merit for comparison purposes. The best agreement is found for forearm measurements, in which TDC1 and TDC123 ratios agree for 96.7% of measurements and duplicate measurements (TDC12) agrees with TDC123 measured ratios for 98.4% of measurements. The least good agreement between single TDC measurement determined ratios versus triplicate TDC measurement determined ratios was on the lateral leg, in which agreement was 75.8% of measurements.

Discussion

TDC measurements as an index of local tissue water and other skin features have shown utility in a range of applications most notably to characterize and assess lymphedema.[3–5,8,10,11,20,23,34–36] Although individual TDC measurements usually take less than 10 seconds once the

Table 2. Dominant-to-Nondominant Side Tissue Dielectric Constant Ratios by Anatomical Site

	TDC ratios (dominant/nondominant sides)			
	TDC1	*TDC12*	*TDC123*	p
Hand palm	1.028 ± 0.121	1.026 ± 0.119	1.014 ± 0.091	0.634
Lateral leg	1.003 ± 0.160	1.011 ± 0.162	1.019 ± 0.162	0.547
Medial leg	1.041 ± 0.150	1.045 ± 0.137	1.051 ± 0.133	0.118
Foot dorsum	1.027 ± 0.120	1.028 ± 0.108	1.029 ± 0.108	0.478
Forearm	1.007 ± 0.095	1.007 ± 0.094	1.012 ± 0.092	0.905

Table entries are mean ± SD for TDC dominant/nondominant side ratios for 60 subjects with sites listed in the same order as in Table 1. TDC1 is based on first TDC measurements, TDC12 is based on the average of the first and second TDC measurements, and TDC123 is based on the average of all three TDC measurements. The p-value is that determined from analysis of variance with TDC1, TDC12, and TDC123 as repeated measures. There was no overall statistical difference among these ratios at any site. There was also no statistically significant overall difference in TDC ratios among sites ($p = 0.547$).

Table 3. Gender Comparisons of TDC123 Absolute and Interside Ratios

	Female			*Male*		
Site	*TDC123*	*TDC123_RATIO*	*Threshold*	*TDC123*	*TDC123_RATIO*	*Threshold*
Hand palm	40.8 ± 8.4	1.018 ± 0.113	1.30	44.3 ± 7.8*	1.028 ± 0.111	1.30
Lateral leg	39.1 ± 7.0	1.026 ± 0.150	1.40	40.5 ± 6.5	1.008 ± 0.171	1.45
Medial leg	33.2 ± 5.1	1.015 ± 0.087	1.25	35.0 ± 5.5	1.086 ± 0.165	1.50
Foot dorsum	31.2 ± 5.1	1.027 ± 0.123	1.35	32.0 ± 5.2	1.024 ± 0.092	1.26
Forearm	29.5 ± 3.1	1.009 ± 0.083	1.23	32.9 ± 4.8**	1.021 ± 0.097	1.27

Table TDC entries are mean ± SD with TDC123, the average of triplicate measurements at each anatomical site. TDC123_RATIO is the dominant-to-nondominant interside ratio. Threshold values represent the TDC123 interside ratio mean value +2.5 SD. *$p < 0.05$ compared to female, **$p < 0.001$ compared to female. Absolute TDC values tend to be greater in males, but ratios are similar in males and females.

device is applied to the skin, there is additional time associated with data recording, recycling of the device for the next measurement, and the proper placement of the next measurement. Taken together and depending on the skill and training of the person measuring, the overall time per triplicate measurement is about one minute. The focus on the time for triplicate measurements is because triplicate measurements have emerged as a de facto standard in the literature being thought of as a reasonable average for a given anatomical site at a given instant of time. In terms of utilizing TDC either to detect incipient lymphedema or to track its course, multiple measurement sites may be required since the sites of the earliest initial changes are not known a priori.

Based on current knowledge, a reasonable minimum protocol would be to routinely assess five bilateral sites preoperatively and repeat at a patient's subsequent visits. One set of five standardized sites that might be used for breast cancer-related tracking would include hand (dorsum or palmer), medial forearm, medial upper arm, lateral thorax, and upper back. At a minimum, the measurements alone would take 10 minutes for such an assessment.

Beyond time reduction as a factor, there is the issue as to whether the assessments are used at all. Experience has shown that if a routine additional procedure becomes ''too time consuming,'' it is simply not done. In the case of applying the best standards of care for detecting potential lymphedema at an early stage, this would be unfortunate. Thus, the goal of present study was to provide data from which informed judgments could be made as to the impact of making fewer measurements and thereby reduce expended clinic time for such measurements.

The composite data herein reported, clearly indicate that the impact of reducing the number of measurements depends on the anatomical site being evaluated, at least for the group of healthy subjects herein studied. The forearm is revealed as the site most amenable to utilizing a single measurement in that 96.7% of measurements are within ±5% of those determined using triplicate measurements (Table 4). This would be consistent with the fact that the forearm site demonstrated the lowest overall CV (2.19%) in the triplicate TDC measurements as shown in Table 1. In addition, for the forearm, the interside threshold ratios (mean ±2.5 SD) that would be determined using TDC1 or TDC123 are the same at 1.24. This interarm (dominant-to-nondominant TDC ratio) is similar to ratios (1.25–1.26) previously reported.[8,10]

Contrastingly, TDC measurements at the lateral leg site using only first TDC measurements was within ±5% of the triplicate averages only 75.8% of the time. This finding would also be consistent with the fact that TDC measurements at this site had the largest CV (4.59%). Despite this discrepancy, the interarm threshold ratios using either measurement strategy were similar (1.40–1.42). Agreements between single and triplicate absolute TDC measures of the other measured sites lie between the forearm and lateral leg site, with hand values being close to those obtained on the forearm and all lower extremity sites demonstrating less agreement between single and triplicate measurements. In all cases, using duplicate measurements did somewhat improve the relative agreements with respect to triplicate measures.

In conclusion, the overall composite findings suggest that when clinical time is a major concern, useful TDC data may be obtained in upper limbs using single TDC measurements

Table 4. Deviations of Single- and Duplicate-Based Tissue Dielectric Constant Ratios from Triplicate-Determined Ratios

	TDC1 vs. TDC123			*TDC12 vs. TDC123*		
Deviation%	*<5%*	*>5%*	*Within ±5%*	*<5%*	*>5%*	*Within ±5%*
Hand palm	3.3	4.2	92.5	2.5	2.5	95
Lateral leg	11.7	12.5	75.8	6.7	12.5	80.8
Medial leg	8.3	8.3	83.4	5.8	12.5	81.7
Foot dorsum	8.0	9.2	82.8	0.8	6.7	92.5
Forearm	2.5	0.8	96.7	0.8	0.80	98.4

TDC1, TDC12 and TDC123 are absolute TDC values based on single, duplicate, and triplicate measurements, respectively. Entries are percent of cases for which interside TDC ratios deviate from that determined from the triplicate measurements considering cases that are <5%, >5%, or within ±5% of the triplicate average. Data indicate a strong dependence of the extent of agreement on the anatomical site, at which the measurements are made.

per anatomical site, whereas assessments of lower extremity skin should be based on at least duplicate and preferably triplicate measurements. However, as with all such time reliability considerations, clinical judgment should be exercised and aided by the various findings of this study.

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Author Disclosure Statement

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