

# Spatial variations in forearm skin tissue dielectric constant

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**Background:** Tissue dielectric constant (TDC) values measured at 300 MHz via the open-ended coaxial line reflection method depend on the effective measurement depth and the anatomical site being evaluated. Measurements on the forearm have shown that the TDC values decrease with increasing measurement depth but the spatial variability of the TDC values among forearm anatomical positions is unknown. Our goal was to characterize the extent of such spatial variations.

**Methods:** In 30 healthy seated women ( $27.4 \pm 6.5$  years), TDC was measured on the forearm midline and 1.2 cm medial and lateral to the midline at sites 4, 8 and 12 cm distal to the antecubital crease.

**Results:** The midline and medial TDC values increased progressively from 4 to 8 to 12 cm sites ( $P < 0.001$ ), with the largest spatial gradient along the midline. At a depth of 2.5 mm, the TDC values increased from  $26.3 \pm 2.8$  to  $27.4 \pm 3.4$  to  $28.4 \pm 3.7$ , with a maximum difference of  $8.2 \pm 10.6\%$ . For all sites, the TDC values were significantly ( $P < 0.001$ ) less for increasing depths.

**Conclusion:** The findings reveal increased TDC values along the forearm from proximal to distal, most prominent at the midline and medial positions. Because many skin-related dermatological and biophysical studies utilize the forearm as a test target, such differences may be important to consider because TDC values in part are reflective of local tissue water (LTW). Although the variation in the TDC values among sites was less than 10%, such differences are of importance when evaluating LTW changes using the TDC method in patients with arm lymphedema that is present in variable arm anatomical locations.

**Key words:** skin – dielectric constant – tissue water – edema – lymphedema – arm – spatial variation

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SKIN TISSUE DIELECTRIC CONSTANT (TDC) measurements have been used to estimate local tissue water (LTW) and its changes under a variety of conditions including skin irritation (1), skin irradiation (2), hemodialysis (3), post-cardiac surgery changes (4), weight loss (5), during the menstrual cycle (6) and lymphedema (7, 8). The TDC values in these studies were measured at a frequency of 300 MHz via a coaxial line reflection method (9–13), in which TDC values depend on the tissue water content. Effective measurement depth depends on the size and geometry of the coaxial probe in contact with the skin (11) so that the TDC values obtained reflect the composite tissue to varying measurement depths depending on the probe used. The depth dependence of LTW over a range from 0.5 to 5.0 mm has been investigated in the forearms of individuals with lymphedema (14), and more recently, in non-edematous arms (15). The results of these studies indicate a decrease in LTW with increasing measurement depth. However, as these previous studies utilized a single standardized forearm

site for measurements, the extent of the spatial uniformity of forearm TDC values as reflective of LTW is currently unknown. This information, it is believed, would be useful for a variety of purposes, not the least of which is the fact that forearm skin is a widely used target for skin biophysical measurements (16–25). Thus, the focused goal of this research was to determine and characterize the extent of spatial variations of TDC in normal forearm skin tissue.

## Methods

### Subjects

Thirty female volunteers participated in this study and were evaluated after signing a University Institutional Review Board-approved informed consent. Women were chosen because of the interest in the use of the TDC method for lymphedema assessment. The criteria for entry into the study were as follows: women who were at least 21 years of age, who had self-reported normal upper extremity function with no history

of serious trauma and no upper extremity skin condition. Group age (mean  $\pm$  SD) was  $27.4 \pm 6.5$  years, with a range of 22–48 years. The body mass index (BMI) for the group was  $22.9 \pm 3.4 \text{ kg/m}^2$ , with a range of 17.1–35.8  $\text{kg/m}^2$  and a median of 22.5  $\text{kg/m}^2$ . With respect to the BMI classification, 2 (6.7%) were underweight (BMI  $< 18.5 \text{ kg/m}^2$ ), 22 (73.3%) were in the normal range (BMI 18.5–25  $\text{kg/m}^2$ ), 5 (16.7%) were overweight (BMI 25–29.9  $\text{kg/m}^2$ ) and 1 (3.3%) was classified as obese (BMI  $\geq 30 \text{ kg/m}^2$ ). The right hand was the self-reported dominant hand in 25 subjects (83.3%) and the left hand was dominant in five subjects (16.7%).

#### TDC measurement device

The MoistureMeter-D (Delfin Technologies Ltd, Kuopio, Finland, <http://www.delfintech.com>) was the device used to measure TDC. It consists of a cylindrical probe connected to a control unit that displays the TDC value when the probe is placed in contact with the skin. The physics and principle of operation has been well described (9, 10, 12, 13, 26). In brief, a 300 MHz signal is generated within the control unit and is transmitted to the tissue via the probe that is contact with the skin. The probe itself acts as an open-ended coaxial transmission line (9, 12). The portion of the incident electromagnetic wave that is reflected depends on the dielectric constant of the tissue, which itself depends on the amount of free and bound water in the tissue volume through which the wave passes. Reflected wave information is processed within a control unit and the relative dielectric constant is displayed. For reference, pure water has a value of about 78.5 and the display-scale range is 1–80. The effective measurement depth depends on the probe di-

mensions, with a larger spacing between the inner and the outer conductors corresponding to greater penetration depths. In the present study, three different probes were used, which had effective measurement depths of 2.5, 1.5 and 0.5 mm (27).

#### Measurement procedures

TDC measurements were started after a subject had been seated for 10 min on a comfortable chair. The chair had an attached padded support upon which the subject rested her arms with her hands positioned palm up to expose the anterior surface of the non-dominant forearm. Before the start of the measurements, nine spots on the non-dominant forearm were marked with a small dot using a surgical pen. These dots served as the center points for subsequent TDC measurements. Using a pre-fabricated template, three reference sites were first marked along the forearm midline at 4, 8 and 12 cm distal to the antecubital crease (Fig. 1). Marks were then made 1.2 cm lateral and 1.2 cm medial from each of the three midline marks. A TDC measurement was obtained by placing a probe in contact with the skin and held in position using gentle pressure. After about 10 s, an audible signal indicated completion of the measurement. Single measurements with each probe were made first along the midline, starting at the 4 cm site and progressing to the 8 and 12 cm distal sites. This sequence was then repeated for medial and then for lateral sites. The measurements were then repeated two more times using the same sequence so that each of the nine sites was measured in triplicate. The time between successive measurements at each site was about 2.5 min. The time to complete triplicate measurements of all sites for both of these probes

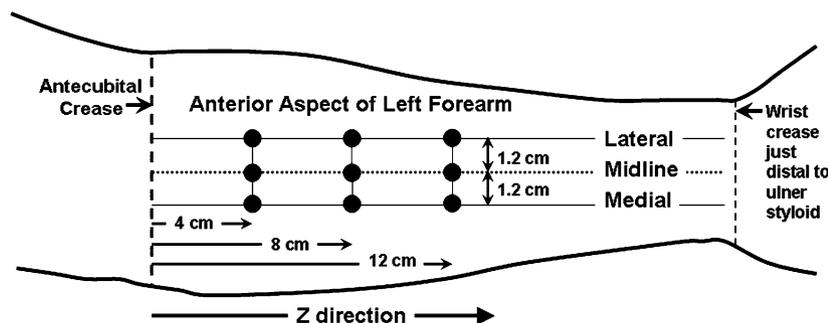


Fig. 1. Forearm Measurement Sites. Each of the nine sites was measured using a measurement sequence that progressed from proximal (4 cm) to distal (12 cm), first along the midline, then medial and lateral. The sequence was repeated three times to yield triplicate measurements. All nine sites were measured with probes to measurement depths of 2.5 and 1.5 mm. Only the midline sites were measured with the probe to a measurement depth of 0.5 mm.

was about 15 min. Triplicate measurements were then made along the midline only (three sites) using a probe with a 0.5 mm measurement depth. For each probe and site, the triplicate measurement average and coefficient of variation (CV) was determined. After completing all the TDC measurements, arm girth (circumference) at each site was measured with a tape measure using a constant tension pull (Gulick-type, Allegro Medical Supplies, Mesa, AZ, <http://www.allegromedical.com>), and skin temperature was measured using an infrared thermometer accurate to 0.1 °C according to specifications (Exergen Model DX501, Watertown, MA, <http://www.exergen.com>).

*Analysis*

An initial test for overall differences in the TDC values among all nine sites was performed using a general linear model (GLM) for repeated measures, with site as the repeated measure and probe (2.5 and 1.5 mm depths) as the between factor. Subsequently, tests for differences in the TDC values longitudinally (z-direction) along the arm midline, medial and lateral positions were performed for each measurement depth using a GLM analysis for repeated measures with position along the arm (z-direction) as the repeated measure. In the analyses, tests for midline longitudinal differences included measurements to depths of 2.5, 1.5 and 0.5 mm. Differences among the circumferential TDC values at each longitudinal site for 2.5 and 1.5 mm measurement depths were tested using a GLM with circumferential position as the repeated measure. Differences in

the TDC values obtained with the different measuring depth probes were tested using a GLM analysis with a probe as the repeated measure and site as the between factor. In all analyses, a *P*-value <0.05 was considered to be significant. To estimate the variability in the triplicate measurements at each site, the CV of the TDC measurement for each site and subject was determined and the average of these over all subjects was determined. All statistics were performed using SPSS version 13.

**Results**

*TDC values*

The results of the GLM analysis test for differences in the TDC values among all the sites showed a highly significant difference (*P*<0.001) among the sites but no significant probe–site interaction (*P* = 0.669). This indicates that the overall differences in the TDC values among the nine sites were not probe dependent. Table 1 summarizes the average values (mean ± SD) for each site for 2.5 and 1.5 mm probe measuring depths along with the CV of the triplicate measurements. The overall average CV for the 2.5 mm probe was 1.38 ± 1.6% (810 measurements), 1.48 ± 1.00% (810 measurements) for the 1.5 mm probe and 1.87 ± 1.52% for the 0.5 mm probe (270 measurements). The CV values did not differ significantly between 2.5 and 1.5 mm measurement depth probes (*P* = 0.4) but both were significantly less than those for the 0.5 mm depth probe (*P* <0.05).

TABLE 1. TDC values among sites for 2.5 and 1.5 mm measurement depths

z (cm)	Measurement depth (mm)					
	2.5 mm			1.5 mm		
	4	8	12	4	8	12
Circumferential position						
Midline	26.3 ± 2.8 <sup>†</sup> [1.5 ± 1.5]	27.4 ± 3.4 <sup>†</sup> [1.2 ± 1.0]	28.4 ± 3.7 <sup>†</sup> [1.3 ± 1.2]	28.5 ± 2.5 [1.5 ± 1.2]	29.4 ± 2.7 [1.1 ± 0.7]	30.1 ± 2.5 [1.4 ± 0.8]
Medial	26.3 ± 3.6 <sup>†</sup> [1.5 ± 1.3]	26.9 ± 3.7 <sup>†</sup> [1.3 ± 0.9]	28.1 ± 4.1 <sup>†</sup> [1.6 ± 1.9]	28.2 ± 2.5 [1.9 ± 1.1]	28.7 ± 2.6* [1.6 ± 1.0]	29.4 ± 2.7* [1.4 ± 1.0]
Lateral	27.9 ± 4.0 <sup>†,*</sup> [1.2 ± 1.0]	28.1 ± 3.1 <sup>†,*</sup> [1.0 ± 0.6]	28.1 ± 3.3 <sup>†</sup> [1.7 ± 1.9]	29.3 ± 2.9* [1.4 ± 0.7]	29.9 ± 2.7 [1.4 ± 1.2]	30.0 ± 2.7 [1.5 ± 1.0]

Entries are average TDC values (mean ± SD) measured on non-dominant forearms of 30 female subjects. Bracketed quantities [ ] are coefficient of variations in percent of triplicate TDC values. Z is the longitudinal distance along the forearm measured from the antecubital crease.

<sup>†</sup>For each site, TDC values measured to a 2.5 mm depth are less than those at corresponding sites measured to a 1.5 mm depth (*P* <0.001). At midline and medial circumferential positions TDC values for both measurement depths progressively increased with increasing Z (*P* <0.001). Lateral position values do not significantly differ with Z for either measurement depth. Differences among circumferential TDC values were variable with the asterisk (\*) denoting values that were significantly different (*P* <0.01) from values at the other two circumferential positions.

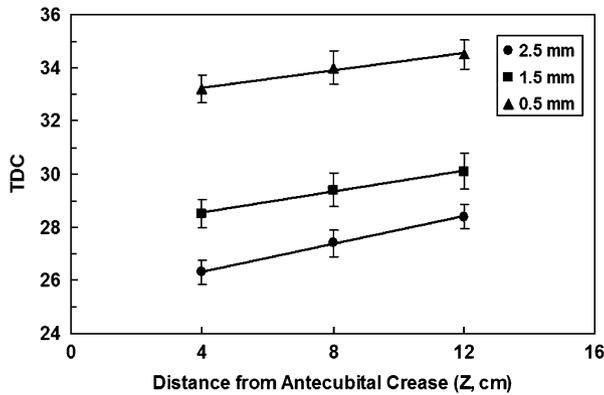


Fig. 2. Midline tissue dielectric constant (TDC) values vs. longitudinal position along the forearm. Data points are the mean TDC values of 30 subjects measured to depths of 2.5, 1.5 and 0.5 mm. Bars are  $\pm 1$  SEM. Solid lines show linear regression lines with equations and parameters as shown for each of the measurement depths. The TDC values for each measurement depth differed significantly ( $P < 0.001$ ) from all the others. For a given measurement depth, the TDC values at each longitudinal site differed from all others ( $P < 0.001$ ).

#### TDC longitudinal variations

The results of tests for differences in the TDC values longitudinally along the arm (z-direction) showed that the TDC values along the midline and medial positions increased progressively from the 4 to the 8 cm to the 12 cm sites ( $P < 0.001$ ), with the TDC values at these sites all significantly different from each other ( $P < 0.001$ ). This pattern is illustrated for the midline measurements in Fig. 2. The TDC values along the midline to a measurement depth of 0.5 mm were greater ( $P < 0.001$ ) than the values obtained for either the 1.5 or the 2.5 mm depth, being  $33.2 \pm 2.8$ ,  $34.0 \pm 3.3$  and  $34.5 \pm 2.9$  for 4, 8 and 12 cm longitudinal sites, respectively. The slopes of the regression lines in Fig. 2 reflect the average increase in TDC with the z-direction and indicate that the spatial rate of increase is the greatest for the deepest measurement depth (2.5 mm) and the least for the most shallow measurement depth (0.5 mm). Average percentage increases in the midline TDC values between 4 and 12 cm sites were calculated to be  $8.2 \pm 10.6\%$ ,  $5.7 \pm 6.8\%$  and  $4.0 \pm 7.0\%$  for 2.5, 1.5 and 0.5 mm depths, respectively. Average percentage increases in the medial TDC values were  $6.9 \pm 8.6\%$  and  $4.3 \pm 7.1\%$  for 2.5 and 1.5 mm depths, respectively. In contrast, the TDC values measured at the lateral position of the forearm at the three different longitudinal sites were insignificantly different from each other ( $P = 0.223$ ), with the average percentage changes between the proximal and most distal

sites being  $1.2 \pm 7.3\%$  and  $2.4 \pm 5.6\%$  for measurement depths of 2.5 and 1.5 mm, respectively.

#### TDC circumferential variations

Comparisons of circumferential values at each site along the arm did not reveal a consistent pattern of differences among positions. The maximum difference among the three circumferential positions was the greatest at the 4 cm site for the 2.5 mm depth measurement, with an average difference among circumferential positions at any longitudinal site being 1.6 TDC units (Table 1), corresponding to a 5.7% difference between the highest and the lowest values. All other maximum circumferential differences were less than or equal to 1.2 U, corresponding to maximum percentage differences ranging from 1.0 to 4.2%. Statistical differences among the circumferential values at some longitudinal positions could be demonstrated (Table 1).

#### Forearm girth and skin temperatures

As would perhaps be expected, forearm girth at the three longitudinal TDC measurement sites decreased significantly ( $P < 0.001$ ) from the most proximal to the most distal site, being  $21.9 \pm 1.5$ ,  $20.9 \pm 2.2$  and  $17.7 \pm 1.3$  cm, respectively. The TDC values at a given longitudinal site (4, 8 or 12 cm) showed no correlation with girth at that site for any of the circumferential positions (midline, medial or lateral). Skin temperatures ( $^{\circ}\text{C}$ ) showed an overall difference among the nine measured sites ( $P < 0.001$ ) attributable to a slightly lower skin temperature for the midline ( $30.7 \pm 1.4$ ) compared with the medial ( $31.6 \pm 1.3$ ) or lateral ( $31.3 \pm 1.4$ ) positions. For a given circumferential position, there was no significant difference in skin temperatures along the arm.

## Discussion

The ability to assess LTW easily, reliably and non-invasively within skin and subcutis offers a potentially powerful research tool to investigate a variety of physiologically and clinically related conditions in which changes in skin tissue water and properties are of interest. The TDC method has shown such potential in a number of areas (1, 2, 4–6). In addition, TDC measurements have been shown to be useful to assess LTW in both healthy and lymphedematous arms (8, 15, 28) but all such previous forearm data were obtained at a

single standardized site. Because edematous changes in lymphedema and other conditions can occur at any forearm location, there is a need for reference information as to the expected anatomical variability of these measurements within normal forearm tissue. Thus, the goal of this study was to characterize the extent to which TDC measurements varied among forearm anatomical sites.

#### *Methods' considerations*

With the TDC method, a probe in contact with the skin measures a TDC that depends on the electrical properties of all tissues within the effective measurement depth, which has been defined as the depth at which the induced electric field declines to  $1/e$  of its surface value (3). For the three different-sized probes used in the present study, this depth includes the epidermis and the upper dermis (0.5 mm probe), the skin including the epidermis and most or all of the dermis (1.5 mm probe) or skin and subcutaneous fat (2.5 mm probe). Thus, all measurements include the low water content stratum corneum, the relatively high water content epidermis and dermis and for the 2.5 mm probe also a substantial amount of the relatively low water content subcutaneous fat. Thus, the TDC values obtained reflect to varying degrees the differing tissues and water contents within the measurement volume. Quantitative aspects of this dependence have been described previously based on analysis of a two-layer model composed of an upper skin layer and a lower fat layer (11, 29). The data reported here are based on probe-specific calibration factors that were pre-programmed by the manufacturer within the device's processing unit that take into account differing field penetrations of the different probe geometries used.

#### *Extent of anatomical variability in TDC values*

Statistically significant differences in the TDC values were found among the values obtained along the arm (longitudinal) for midline and medial positions but not for lateral positions. For midline and medial positions, there was a progressive increase in the TDC values from the most proximal site to the most distal site, with percentage increases dependent on the measurement depth. The greatest percentage difference was associated with measurements to a depth of 2.5 mm, which, along the midline, was 8.2% and least (4.0%) to a measurement depth of 0.5 mm.

This pattern of variation might in part be explained if the relative amount of lower water content subcutaneous fat included in the measurement volume was less in the more distal sites. A search of the literature was unable to reveal data describing spatial variations in relative thickness along the arm, and so, the above is speculative. However, the TDC values were also increased as measured to a depth of 0.5 mm, which, for reported values of forearm skin thickness of 0.75–1.1 mm (30–34), would include only skin. Thus, the present data support the notion that there is a slightly greater amount of relative skin tissue water in the distal as compared with the proximal forearm midline and medial sites. The reason for the absence of a detected longitudinal increase in the TDC values as measured along the lateral position of the forearm at either measurement depth (2.5 and 1.5 mm) is unclear. It may be related to the fact that the lateral position TDC values for both measurement depths at the most proximal site (4 cm) were significantly greater than for either the midline or the medial position (Table 1). Future investigative effort to study this aspect appears to be warranted.

In summary, the combined findings demonstrate an increase in the TDC values along the forearm from proximal to distal sites most prominent at midline and medial positions and also demonstrate differences among circumferential positions more prominent at proximal than distal sites. Because many skin-related dermatological and biophysical studies utilize the forearm as a test target, such differences may be important to consider in experiment design and data interpretation as the TDC values at least in part are reflective of the LTW. In addition, although the variation in the mean TDC values among the measured sites is less than 10%, such differences may be of importance when evaluating LTW changes using the TDC method in patients with arm lymphedema that is present in variable arm anatomical locations.

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