Clin Physiol Funct Imaging (2010) **30**, pp328–332 doi: 10.1111/j.1475-097X.2010.00946.x

Male–female differences in forearm skin tissue dielectric constant

Harvey N. Mayrovitz, Sophia Carson and Michelle Luis

College of Medical Sciences, Nova Southeastern University, Ft. Lauderdale, FL, USA

Correspondence
Harvey N. Mayrovitz, PhD, Professor of Physiology, College of Medical Sciences, Nova Southeastern University, 3200 S. University Drive, Ft. Lauderdale, FL 33328, USA
E-mail: mayrovit@nova.edu

Accepted for publication
Received 30 December 2009;
accepted 26 May 2010

Key words
lymphoedema; oedema; permittivity; skin water; tissue water

Summary

Tissue dielectric constant (TDC) measurements at 300 MHz via the coaxial line reflection method are useful to evaluate local skin tissue water and its change, but virtually all available data relate to measurements on women. Because TDC values in part depend on skin thickness, we hypothesized that differences in male–female skin may be associated with male–female differences in TDC. To test this hypothesis, we compared TDC values in volar forearm skin of 60 young adult volunteers (30 men, 25·0 ± 2·5 years, 30 women, 27·4 ± 6·6 years) in the seated position using a probe with an effective measurement depth of 1·5 mm. Results showed that TDC values (mean ± SD) for men were significantly greater than for women (33·2 ± 4·0 versus 29·4 ± 2·7, $P<0·001$) constituting an overall difference of about 13%. This finding suggests that when TDC measurements are used in research or clinical studies in which both men and women are included in a common study population, it would be prudent to consider this difference in both experimental design and data interpretation. This is especially true if absolute TDC values are of interest in contrast to changes in TDC values on the same subject subsequent to time passage or secondary to an intervention. Despite greater TDC values measured in men, calculations of the impact of a greater male skin thickness indicate that the greater TDC values of men may or may not reflect a greater relative local skin tissue water in men compared to women.

Introduction

Tissue dielectric constant (TDC) measured at a frequency of 300 MHz via the coaxial line reflection method (Stuchly *et al.*, 1981, 1982; Aimoto & Matsumoto, 1996; Alanen *et al.*, 1998a,b) has been used to evaluate local tissue water (LTW) and its change with skin irritation(Miettinen *et al.*, 2006), skin irradiation (Nuutinen *et al.*, 1998), haemodialysis (Nuutinen *et al.*, 2004), postcardiac surgery changes (Petaja *et al.*, 2003), weight loss(Laaksonen *et al.*, 2003), menstrual cycle (Mayrovitz *et al.*, 2007) and lymphoedema (Mayrovitz *et al.*, 2008a,b; Mayrovitz *et al.*, 2009a,b). Although measurements have been taken in various body sites including breast (Nuutinen *et al.*, 1998), leg (Petaja *et al.*, 2003; Mayrovitz, 2009a,b, 2010), thorax and upper arm (Mayrovitz *et al.*, 2008a,b), most studies have targeted the female forearm (Mayrovitz, 2007, 2009a,b, 2010), mainly for its importance in matters related to arm lymphoedema. As a consequence, there is virtually no data available that systematically describes TDC values for men, which by virtue of a possible greater skin thickness in men (Branchet *et al.*, 1990; Gniadecka & Quistorff, 1996; Gniadecka & Jemec, 1998; Chen *et al.*, 2001; Diridollou *et al.*, 2001; Lee & Hwang, 2002; Laurent *et al.*, 2007) may also be associated with male–female differences in skin tissue water as assessed by TDC. Thus, the goal of this research was to test this hypothesis using TDC measurements in normal forearm skin of men and women.

Methods

Subjects

Sixty young adult volunteer subjects participated in this study (30 men and 30 women) that were evaluated after signing a University Institutional Review Board approved informed consent. Requirements for participation were that subjects be at least 21 years of age and have self-reported normal upper extremity function with no history of serious trauma and no self-reported or visual evidence of any abnormal arm skin condition at the time of evaluation. As summarized in Table 1, height, weight, body mass index (BMI) and forearm girth were

Table 1 Subjects.

	Men (*N* = 30)	Women (*N* = 30)
Age (years)	25·0 ± 2·5	27·4 ± 6·6
Height (m)	1·75 ± 0·10*	1·65 ± 0·07
Weight (Kg)	79·6 ± 18·5*	61·9 ± 10·8
BMI (Kg m^{-2})	26·0 ± 5·7*	22·8 ± 3·3
Girth (cm)	25·5 ± 2·6*	20·9 ± 2·2
Right hand dominant	27/30 (90%)	27/30 (90%)

BMI, body mass index.
Entries are mean ± SD. Girth is forearm circumference at site of tissue dielectric constant measurement.
*Significantly greater for men than women ($P<0·01$).

significantly greater for men than for women ($P<0·01$). Male versus female group ages were insignificantly different (25·0 ± 2·5 versus 27·4 ± 6·6 years).

Tissue dielectric constant measurement device

The device used to measure TDC was the MoistureMeter-D (D3N014; Delfin Technologies Ltd, Kuopio, Finland). 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 have been well described (Stuchly *et al.*, 1981, 1982; Aimoto & Matsumoto, 1996; Alanen *et al.*, 1998a,b; Alanen *et al.*, 1999). In brief, a 300-MHz signal is generated within the control unit and is transmitted to the tissue via the probe that is in contact with the skin. The probe acts as an open-ended coaxial transmission line (Stuchly *et al.*, 1982; Aimoto & Matsumoto, 1996). A portion of the incident electromagnetic wave is reflected that 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 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 dimensions, with larger spacing between inner and outer conductors corresponding to greater penetration depths. In this study, a probe with an effective measurement depth of 1·5 mm was used. This probe has an outside diameter of 20 mm with 3-mm spacing between the inner and outer concentric conductors.

Tissue dielectric constant measurement procedure

All measurements were taken with subjects seated and started after a 10-min acclimation rest interval. TDC measurements were taken on the non-dominant volar forearm at a standardized site along the forearm midline located 8 cm distal to the antecubital crease. This site was marked with dot to serve as a reference centre point for probe placement. A single measurement was obtained by placing the 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. Second and then third measurements were made at the same site with 60 s between the start of each measurement yielding triplicate sequential measurements at each site. After TDC measurements, arm girth (circumference) at the measurement site was determined using a tape measure pulled to constant tension using a Gulick-type tape measure (Allegro Medical Supplies, Mesa, AZ, USA).

Analysis

Differences in TDC values between male and female arms were tested using a general linear model (GLM) for repeated measures with the three sequential TDC values as the repeated measure and gender as the between groups factor. A P-value $<0·05$ was *a priori* set as the threshold level for a significant statistical difference between groups. Subsequently, to test for possible impacts of BMI and arm girth, each was included in the GLM analysis as a covariate.

Results

Results of the GLM analysis showed that TDC values measured on volar forearm skin of men were significantly greater than for women (Table 2) being about 13% greater in men than in women (33·2 ± 4·0 versus 29·4 ± 2·7, $P<0·001$). Follow-up analyses that used BMI or arm girth as covariates in the GLM analysis did not change this primary result with male TDC values remaining significantly greater than female values with significance levels of $P<0·001$ with BMI as a covariate and $P<0·01$ with arm girth as a covariate. An ancillary finding relates to the uniformity of sequentially measured triplicate values at the same skin site. Analysis of the coefficient of variation (CV) indicates good measurement repeatability with an overall CV across all subject of 1·5 ± 1·0% with an average difference between any single measurement and the triplicate average being <1%.

Discussion

An easily used non-invasive method to assess LTW within skin and subcutis offers a useful research tool to investigate physiologically and clinically related conditions in which changes in tissue water are of interest. The TDC method has shown such potential in a several applications (Nuutinen *et al.*, 1998; Laaksonen *et al.*, 2003; Petaja *et al.*, 2003; Miettinen *et al.*, 2006; Mayrovitz, 2007, 2009a,b, 2010; Mayrovitz *et al.*, 2007, 2008a,b; Mayrovitz *et al.*, 2009a,b), but for the most part data has only systematically been obtained on women. Recently (Mayrovitz *et al.*, 2008a,b, 2009a,b), it was shown that TDC values as measured on the forearm of women depend on the depth to which the excitation field penetrates with lower values obtained at deeper penetration. Additional investigations (Mayrovitz, 2009a,b, 2010) indicated that for deeper measurement depths (2·5 and 5·0 mm), TDC values were less for

Table 2 TDC Comparisons.

Group	TDC_1	TDC_2	TDC_3	TDC_{AVG}
Men (N = 30)	33·0 ± 3·9*	33·3 ± 3·9*	33·3 ± 4·2*	33·2 ± 4·0*
Women (N = 30)	29·4 ± 2·6	29·5 ± 2·7	29·2 ± 2·7	29·4 ± 2·7

TDC, tissue dielectric constant.
Entries are Mean ± SD for 1st, 2nd and 3rd sequential TDC measurements and their average. TDC_1, TDC_2 and TDC_3 were insignificantly different from each other or from the average (TDC_{AVG}) of the triplicate measurements.
*All differences between men and women were highly significant ($P<0{\cdot}001$).

subjects with a greater BMI. Contrastingly, at more shallow measurement depths (0·5 and 1·5 mm), there was no dependence on BMI, but for these measurement depths TDC values were found to increase with increasing subject age. Because skin thickness (epidermis + dermis) of the forearm is in the range of 0·8–1·2 mm (Branchet *et al.*, 1990; Gniadecka & Jemec, 1998; Chen *et al.*, 2001; Diridollou *et al.*, 2001; Lee & Hwang, 2002) with men having greater thickness than women (Lee & Hwang, 2002), this study was undertaken to investigate whether there were associated male–female differences in skin TDC. The use of male and female subjects of similar age helped minimize possible age-dependent factors. The non-dominant forearm was chosen for study, because it was felt that its features would be more uniform among subjects than the dominant arm as to possible confounding effects attributable to variability in muscle development and within gender forearm girth.

Male–female tissue dielectric constant differences

The main result of this study showed that TDC values obtained on forearm skin of the young adult population investigated were about 13% greater for men than women. This fact alone suggests that when TDC measurements are used in research or clinical studies in which both men and women are included in a common study population, this difference may represent an important consideration in both experiment design and data interpretation. This would be especially true if it were absolute TDC values that were of interest rather than changes in TDC values on the same subject subsequent to time passage or secondary to an intervention.

Although TDC values depend on tissue water content (Nuutinen *et al.*, 2004) and the TDC values herein found were greater in men than women, it is important to note that the present data should not be interpreted as clearly indicating that water content of male forearm skin is greater than women. Reasons for the ambiguity are related to measurement considerations and to considerations of male–female differences in skin thickness. Male forearm skin is thicker than female skin (Lee & Hwang, 2002), and thus more subcutaneous fat may be included in the TDC measurement volume for women.

Methods considerations

With the current method, a probe in contact with the skin measures a tissue dielectric constant that depends on the electrical properties of all tissues within the effective measurement depth that has been defined as the depth at which the induced electric field falls to 1/e of its surface value (Nuutinen *et al.*, 2004). For the probe used in this study, this effective measuring depth is about 1·5 mm and includes skin (epidermis + dermis) and some subcutaneous fat. The thinner the skin the more is the relative amount of subcutaneous fat that would be included in the measurement. Further, the relative water content of these components is not uniform. Stratum corneum and fat have relatively low water content in comparison with the dermis, but even within the epidermis and dermis, water distribution is not uniform. Within the epidermis, the gradual transition from below the corneum to basal cell layers is accompanied by a water content that increases from about 20% to about 70% (Warner *et al.*, 1988). Within the dermis, superficial papillary and deep reticular regions also differ in their water content (Richard *et al.*, 1991, 1993) with an average dermal water fraction of about 70% in contrast to about 10% in subcutaneous fat (Foster & Schwan, 1989). Thus, TDC values obtained with the present method reflect to varying degrees differing water contents within the measurement volume.

Skin thickness considerations

The extent to which gender-related skin thickness differences could have affected the TDC values in this study can be estimated using the formula (Lahtinen *et al.*, 1997; Alanen *et al.*, 1998a,b) derived for a two-layer model composed of an upper skin layer and lower fat layer. Accordingly, the TDC value was shown to be expressible in terms of skin and fat dielectric constants (ϵ_s and ϵ_f), skin (epidermis and dermis) depth δ and probe-specific calibration factors q as $TDC = (\epsilon_s - \epsilon_f)(1 - e^{-q\delta}) + \epsilon_f$. Although the main focus of this study was on the totally measured TDC value as reflective of all measured tissue components, the aforementioned relationship can be used to estimate the extent to which gender differences in estimated skin thickness may affect the measured TDC value by considering representative parameter values reported in the literature. Forearm skin values for δ are reported as 1·17 mm for men and 0·87 mm for women (Lee & Hwang, 2002). Representative dielectric constant values for forearm skin (ϵ_s) and fat (ϵ_f) are reported as about 50 and 6, respectively (Gabriel *et al.*, 1996a,b). If it is assumed that for the same water content ϵ_s and ϵ_f are equal for men and women, then the effect of differences in δ can be estimated using the aforementioned representative values together with the probe-specific calibration factor ($q = 0{\cdot}82$) provided by the device's manufacturer. Using this approach, the calculated TDC values for male and female groups are respectively 33·7 and 29·0. These calculated values are sufficiently close to the male–female values herein measured (33·2 and 29·4) to indicate that the measured male–female TDC differences could as easily be explained on the basis of male–female differences in skin thickness as with male–female differences in tissue water content. To distinguish between these possibilities would require comeasured values of TDC and skin thickness, which was not part of the present protocol.

Because the present findings are based on TDC values obtained to an approximate measurement depth of 1·5 mm, it is unknown whether similar male–female differences would be obtained for more shallow or for deeper measurement depths. If the male–female difference herein measured is due mainly or exclusively to the smaller skin thickness of women, then the prediction is that such differences would be much reduced or eliminated for measurement depths that only include the epidermis and dermis. Contrastingly, if the measured differences are mainly because of differences in skin tissue water, then for the same shallow measurements, the prediction is that the male–female differences would remain greater although perhaps not of the same magnitude as herein measured. Future additional investigative efforts to further study, this aspect would appear warranted.

References

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.

Alanen E, Lahtinen T, Nuutinen J. Measurement of dielectric properties of subcutaneous fat with open-ended coaxial sensors. *Phys Med Biol* (1998a); **43**: 475–485.

Alanen E, Lahtinen T, Nuutinen J. Variational formulation of open-ended coaxial line in contact with layered biological medium. *IEEE Trans Biomed Eng* (1998b); **45**: 1241–1248.

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.

Branchet MC, Boisnic S, Frances C, Robert AM. Skin thickness changes in normal aging skin. *Gerontology* (1990); **36**: 28–35.

Chen L, Dyson M, Rymer J, Bolton PA, Young SR. The use of high-frequency diagnostic ultrasound to investigate the effect of hormone replacement therapy on skin thickness. *Skin Res Technol* (2001); **7**: 95–97.

Diridollou S, Vabre V, Berson M, Vaillant L, Black D, Lagarde JM, Gregoire JM, Gall Y, Patat F. Skin ageing: changes of physical properties of human skin in vivo. *Int J Cosmet Sci* (2001); **23**: 353–362.

Foster KR, Schwan HP. Dielectric properties of tissues and biological materials: a critical review. *Crit Rev Biomed Eng* (1989); **17**: 25–104.

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* (1996a); **41**: 2251–2269.

Gabriel S, Lau RW, Gabriel C. The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. *Phys Med Biol* (1996b); **41**: 2271–2293.

Gniadecka M, Jemec GB. Quantitative evaluation of chronological ageing and photoageing in vivo: studies on skin echogenicity and thickness. *Br J Dermatol* (1998); **139**: 815–821.

Gniadecka M, Quistorff B. Assessment of dermal water by high-frequency ultrasound: comparative studies with nuclear magnetic resonance. *Br J Dermatol* (1996); **135**: 218–224.

Laaksonen DE, Nuutinen J, Lahtinen T, Rissanen A, Niskanen LK. Changes in abdominal subcutaneous fat water content with rapid weight loss and long-term weight maintenance in abdominally obese men and women. *Int J Obes Relat Metab Disord* (2003); **27**: 677–683.

Lahtinen T, Nuutinen J, Alanen E. Dielectric properties of the skin. *Phys Med Biol* (1997); **42**: 1471–1472.

Laurent A, Mistretta F, Bottigioli D, Dahel K, Goujon C, Nicolas JF, Hennino A, Laurent PE. Echographic measurement of skin thickness in adults by high frequency ultrasound to assess the appropriate microneedle length for intradermal delivery of vaccines. *Vaccine* (2007); **25**: 6423–6430.

Lee Y, Hwang K. Skin thickness of Korean adults. *Surg Radiol Anat* (2002); **24**: 183–189.

Mayrovitz HN. Assessing local tissue edema in postmastectomy lymphedema. *Lymphology* (2007); **40**: 87–94.

Mayrovitz HN. Assessing lymphedema by tissue indentation force and local tissue water. *Lymphology* (2009a); **42**: 88–98.

Mayrovitz HN. The standard of care for lymphedema: current concepts and physiological considerations. *Lymphat Res Biol* (2009b); **7**: 101–108.

Mayrovitz HN. Local tissue water assessed by measuring forearm skin dielectric constant: dependence on measurement depth, age and body mass index. *Skin Res Technol* (2010); **16**: 16–22.

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.

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* (2008a); **28**: 337–342.

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* (2008b); **41**: 87–92.

Mayrovitz HN, Davey S, Shapiro E. Suitability of single tissue dielectric constant measurements to assess local tissue water in normal and lymphedematous skin. *Clin Physiol Funct Imaging* (2009a); **29**: 123–127.

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* (2009b); **7**: 153–158.

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.

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.

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.

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.

Richard S, Querleux B, Bittoun J, Idy-Peretti I, Jolivet O, Cermakova E, Leveque JL. In vivo proton relaxation times analysis of the skin layers by magnetic resonance imaging. *J Invest Dermatol* (1991); **97**: 120–125.

Richard S, Querleux B, Bittoun J, Jolivet O, Idy-Peretti I, de Lacharriere O, Leveque JL. Characterization of the skin in vivo by high resolution magnetic resonance imaging: water behavior and age-related effects. *J Invest Dermatol* (1993); **100**: 705–709.

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.

Stuchly MA, Athey TW, Samaras GM, Taylor G. Measurement of radio frequency permittivity of biological tissues with an open-ended coaxial line: Part II - Experimental Results. *IEEE Trans Microw Theory Tech* (1982); **30**: 87–92.

Warner RR, Myers MC, Taylor DA. Electron probe analysis of human skin: determination of the water concentration profile. *J Invest Dermatol* (1988); **90**: 218–224.