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Skin tissue dielectric constant in women with high body fat content

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Abstract

Background: Skin tissue dielectric constant (TDC) measurements at a frequency of 300 MHz are used to assess skin properties in many conditions. Impacts of patient obesity on these values are unknown, and its quantitative assessment was the goal of this research.

Materials and Methods: Women in a weight loss program (N = 32) had TDC measured on forearm, biceps, neck, jowl, and submental regions along with measurements of total body fat (TBF), water (TBW), intracellular water (ICW), and extracellular water (ECW) via multi-frequency bioimpedance. Group age (mean ± SD) was 40.0 ± 11.6 years (20-70 years) with body mass index (BMI) of 31.8 ± 6.7 Kg/m^2 (23.0-49.9 Kg/m^2). For analysis, subjects were divided into those with BMI < 30 Kg/m^2 (subgroup A, n = 16) vs ≥30 Kg/m^2 (subgroup B, n = 16).

Results: Tissue dielectric constant at forearm and biceps decreased significantly ($P < .001$) with increasing depth from 0.5 to 1.5 to 2.5 mm but TDC values and their inter-side ratios did not differ between subgroups A and B at any measured site. Although correlations between TBW, ECW, and ICW were significant ($P < .001$), there was no dependence of TDC values on any of these parameters.

Conclusions: Previously unknown TDC values for obese persons are provided and based on subgroup analyses suggest that skin TDC values in overweight and obese persons are not confounded by variables such as TBW and TBF. Further, since inter-side ratios and their SD's yielded thresholds for forearm and biceps similar to those established for women with normal BMI, use of these clinical inter-arm TDC ratios now is extended to include a wider BMI range.

KEYWORDS
bioimpedance, extracellular water, intracellular water, lymphedema, obesity, skin permittivity, skin water

1 | INTRODUCTION

Tissue dielectric constant (TDC) measurements at a frequency of 300 MHz are widely used to assess skin tissue properties in a range of conditions including breast cancer treatment related lymphedema,[1-5] lower extremity lymphedema,[6] head and neck cancer-related lymphedema,[7] diabetes,[8,9] and other clinical conditions.[10-15] Because the measurement is influenced by the water content of the tissue being assessed and fat has a low water content, prior work was concerned with possible impacts of body mass index (BMI) and whole-body water or fat percentages on the measured TDC values. Study results[16] indicated a slight impact of these parameters but the findings were based on the evaluation of women with a median BMI of 22.6 Kg/m^2, which is a value currently viewed as within the normal range. Hence, it is unclear if skin TDC values are importantly influenced in women that have higher BMI values, especially the obese category (>30 kg/m^2). The obese category appears to be a significant risk factor for breast cancer and for subsequent lymphedema development[17-20] that is even greater in obese women as compared to those in the overweight category.[21] In other work that has examined the possibility of a skin TDC value dependence on BMI,[22] a minor inverse dependency was detected in young women with an average age of about 26 years. However, since it has been shown that TDC values are dependent on a woman's age[23] and that most women for whom such TDC measurements are clinically useful are older,[1,2,6,24-26] it is important to evaluate and clarify this aspect in other age women. Additionally, all prior assessments of total body water percentages were based on bioimpedance values measured at a single 50 KHz frequency, that by design could not separate intracellular and extracellular water percentages.[16,22] So, it is not known if such water compartment separation between intra- and extracellular water will offer better or worse correlations with measured TDC values. It was thus the specific aim of this research to address the aforementioned issues to determine their potential significance as they relate to middle-to-mature age women having BMI values in the overweight and obese ranges.

2 | METHODS

2.1 | Subjects

Thirty-two women participated in this research study after having the study explained to them and then signing a University Institutional Review Board (IRB) approved consent form. The age of the entire group (mean ± SD) was 40.0 ± 11.6 years with an age range of 20 to 70 years and an group average body mass index (BMI) of 31.8 ± 6.7 Kg/m^2 with a range of 23.0 to 49.9 Kg/m^2. Participants were volunteers recruited from women who were already enrolled in a local commercial weight loss program. For participation in this study, the women were required to have already been enrolled in the weight loss program. Absolute exclusion criteria for participation were (a) the presence of a current dermatological condition, (b) lacerations or open wounds in the area of intended measurements (forearm, bicep, neck, jowl, submental region), (c) any prior history of trauma to arm or face that may affect tissue water content, and (d) currently pregnant.

2.2 | Measurements

2.2.1 | Total body water and fat

Body composition parameters were determined using the Inbody 570 (Biospace, Inc Seoul, Korea). This device uses impedance measurements made at multi-frequencies (5, 50, 250, and 500 kHz) to determine total body fat (TBF), total body water (TBW), intracellular water (ICW), and extracellular water (ECW) among other body segment parameters. Such measurements have been used in prior studies[27,28] yielding values that compared favorably with those measured using dual-energy X-ray absorptiometry (DXA).[29] In use, the device has electrodes in the handles and also on a platform on which the subject stands and grasps the handles. In this configuration, the skin contacts the electrodes at the anterior and posterior soles of feet as well as the thumb and palm of each hand. Based on the obtained multi-frequency impedance profile, body composition parameters are determined from the device's priority algorithm.

2.2.2 | Tissue dielectric constant

Tissue dielectric constant was measured with the MoistureMeter-D (Delfin Technologies Ltd). The device includes cylindrical probes that are connected to a control unit that shows the TDC value when the probe has been in contact with the skin for about 5 seconds. The physics and principle of operation has been well-described.[30-34] In brief, a 300 MHz signal generated in the control unit is transmitted to tissue via a probe in contact with skin. The probe acts as an open-ended coaxial transmission line. A portion of the incident electromagnetic wave is reflected by an amount 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. The control unit processes reflected wave information to calculate the relative dielectric constant. For reference, the dielectric constant of water is about 76 at a temperature of 32°C. Three different probes were used to achieve effective measurement depths of 0.5, 1.5, and 2.5 mm at two arm sites. Effective measurement depth is defined as the depth at which the 300 MHz excitation field is diminished to 1/e of its value. The dielectric constant or relative permittivity is a dimensionless number equal to the ratio of tissue permittivity to vacuum permittivity. Face and neck measurements were only made to a depth of 1.5 mm only. TDC measurements were done bilaterally except for the submental site. Figure 1 illustrates probe placement at each of the five measured sites. These were as follows: anterior forearm (6 cm distal to the antecubital fossa (A), medial biceps (6 cm superior to the medial epicondyle (B), neck (3 cm lateral to the laryngeal prominences (C), jowl area of the face (1 cm lateral and 2 cm inferior to the right and left oral commissures, (D) and submental region (E). Sites were measured in the order of A through E with bilateral measurements completed prior to moving to the next site. Arm measurements were made first to a depth of 0.5 mm, then 1.5 mm and lastly to 2.5 mm.

2.2.3 | Sequence

Subjects sat in a comfortable chair, and measurement sites were marked with a dot using a surgical pen. After sitting for about five minutes, TDC measurements began as previously described. After completing TDC measurements, subjects removed their shoes and socks and stood on the Inbody 570 for the measurement of weight, TBW, TBF, ICW, and ECW. This measurement took about 30 seconds. This completed the measurement protocol sequence.

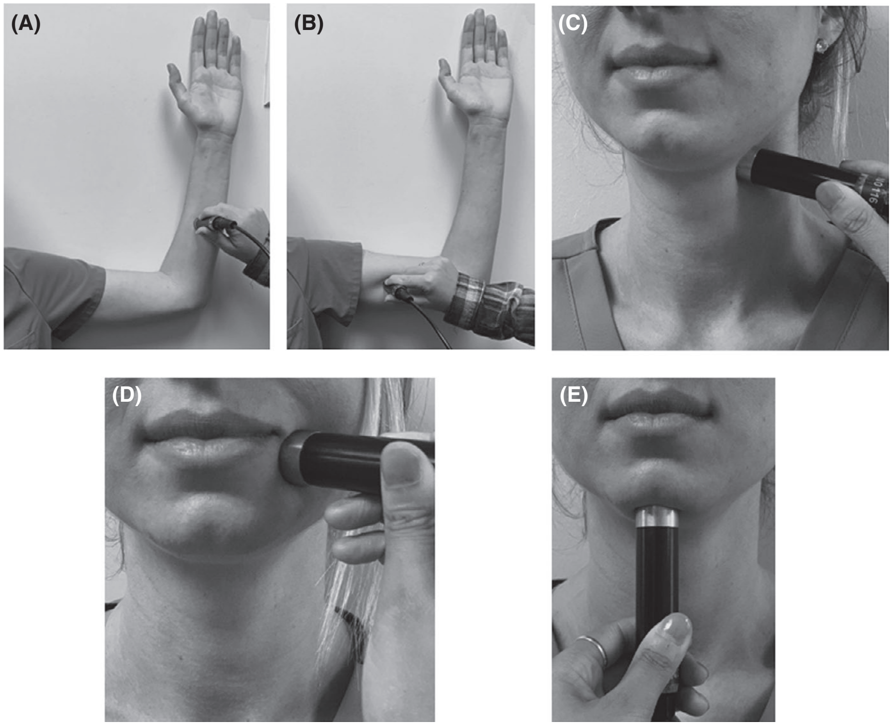

FIGURE 1 TDC measurement sites. Five sites were measured in triplicate; (A) anterior forearm (6 cm distal to the antecubital fossa), (B) medial biceps (6 cm superior to the medial epicondyle), (C) neck (3 cm lateral to the laryngeal prominences), (D) jowl area (1 cm lateral and 2 cm inferior to the right and left oral commissures), (E) submental region (E). Except for (E) all sites were measured bilaterally in the order A through E

2.3 | Analysis

For purposes of subgroup analysis, the full group of women (N = 32) was divided into two subgroups; subgroup A were those women with BMI less than 30 Kg/m^2 and subgroup B consisted of those women with BMI ≥30 Kg/m^2. Conveniently, there were 16 subjects in each of the two subgroups with an overall group median of 30.1 Kg/m^2. Tests for statistical differences between subgroups were based on the non-parametric Mann-Whitney test with a *P*-value < .01 accepted as statistically significant. Differences in TDC values among effective measurement depths for the full group (N = 32) at forearm and hand separately were tested using a general linear measure analysis (GLM) for repeated measures with depths (0.5, 1.5, and 2.5 mm) as the repeated measure. Differences of TDC values and inter-side ratios between subgroups at forearm, biceps, neck, and jowl area were tested for using the Mann-Whitney test with a *P*-value < .01 accepted as statistically significant. Relationships of TDC values at different sites, ECW vs ICW and TBW and parameter values vs subject age were evaluated using regression analysis of the full group and specified via the applicable regression equations.

3 | RESULTS

3.1 | Body composition parameters

Table 1 details a complete portrait of the body composition parameters of the full group of women (N = 32) with a comparison between those women who had BMI values <30 Kg/m^2 (subgroup A, n = 16) vs those women who had BMI values greater than or equal to 30 Kg/m^2 (subgroup B, n = 16). Groups did not statistically differ with respect to age, diastolic blood pressure, or heart rate. Group B tended to have a higher systolic blood pressure and had statistically significant higher values for body fat weight (87.9 ± 13.9 Kg vs 67.7 ± 8.8 kg, *P* < .001) and body fat percentages (46.4 ± 5.4% vs 34.6 ± 6.4%, *P* < .001). Conversely, total body water percentage was significantly less in group B (39.4 ± 3.9% vs 47.9 ± 4.6%, *P* < .001). However, there was no significant difference between subgroups in the ratios of extracellular water (ECW) to either intracellular water (ICW) or total body water (TBW).

3.2 | Tissue dielectric constant parameters

Table 2 details the average TDC values measured at each site and depth for the entire group and also compared between subgroups A and B. TDC values obtained for these subgroups were very similar for all parameters with none being statistically different between subgroups. In contrast to the similarity between BMI subgroups at each site and depth, there was a significant decrease in TDC values with increasing measurement depth observed at the medial forearm (*P* < .001) and the medial biceps (*P* < .01). However, when considering inter-side TDC ratios (dominant/non-dominant) as shown in Table 3, these ratios were similar for each subgroup and did not statistically differ at any site or depth.

3.3 | Correlation of TDC values among sites

Tissue dielectric constant values measured to the same depth at different sites tended to be correlated with each other. This is illustrated in Figure 2 that shows the correlation between TDC values

TABLE 1 Subject data

	BMI < 30 Kg/m^2	BMI ≥ 30 Kg/m^2	*P*-value	All subjects
N	16	16		32
Age (years)	37.4 ± 11.3	42.6 ± 11.6	.361	40.0 ± 11.6
Systolic BP (mm Hg)	118.9 ± 13.0	133.6 ± 19.4	.035	126.3 ± 17.9
Diastolic BP (mm Hg)	80.6 ± 10.7	82.4 ± 13.7	.401	81.5 ± 12.1
Heart Rate (bpm)	73.1 ± 10.1	70.6 ± 18.5	.769	71.9 ± 14.7
Weight (Kg)	67.7 ± 8.8	87.9 ± 13.9	<.001	77.8 ± 15.4
BMI (Kg/m^2)	26.4 ± 2.5	37.2 ± 4.9	<.001	31.8 ± 6.7
TBW (%)	47.9 ± 4.6	39.4 ± 3.9	<.001	43.6 ± 6.0
ICW (Kg)	20.1 ± 2.0	21.4 ± 3.0	.054	20.8 ± 2.6
ECW (Kg)	12.1 ± 1.2	13.0 ± 1.8	.036	12.5 ± 1.6
ECW/ICW	0.598 ± 0.016	0.605 ± 0.020	.402	0.602 ± 0.018
ECW/TBW	0.374 ± 0.006	0.377 ± 0.007	.381	0.376 ± 0.007
TBF (%)	34.6 ± 6.4	46.4 ± 5.4	<.001	71.4 ± 26.4
TBF (Kg)	23.7 ± 6.8	41.2 ± 9.5	<.001	32.5 ± 12.0

Note: Entries are mean ± SD. *P*-values are from Mann-Whitney non-parametric tests.
Abbreviations: BMI, body mass index; ECW, extracellular water; ICW, intracellular water; TBF%, total body fat as percentage of body weight; TBF, total body fat; TBW%, total body water as percentage of body weight; TBW, total body water.

measured to a depth of 1.5 mm at the medial forearm vs values measured to the same depth on the neck and TDC values measured to a depth of 2.5 mm at medial forearm vs medial biceps. The correlation coefficient (*r*) between TDC values at forearm and bicep is .780 and between forearm and neck is .650.

3.4 | Correlation among body composition parameters

Extracellular water (ECW)-intracellular water (ICW) relationships and ECW-total body water (TBW) relationships for the full group

TABLE 2 Tissue dielectric constant (TDC) data

	BMI < 30 Kg/m^2	BMI ≥ 30 Kg/m^2	*P*-value	All subjects
N	16	16		32
Forearm (medial)				
0.5 mm depth	31.8 ± 4.2	31.7 ± 4.5	.897	31.8 ± 4.3**
1.5 mm depth	29.2 ± 2.4	29.8 ± 3.4	.780	29.5 ± 2.9**
2.5 mm depth	24.5 ± 2.0	24.5 ± 3.1	.926	24.5 ± 2.6**
Biceps (medial)				
0.5 mm depth	27.6 ± 4.8	27.9 ± 3.6	.956	27.8 ± 4.1*
1.5 mm depth	26.7 ± 2.2	26.8 ± 3.3	.838	26.8 ± 2.7*
2.5 mm depth	21.7 ± 1.8	21.8 ± 2.6	1.000	21.8 ± 2.2**
Neck				
1.5 mm depth	31.2 ± 2.8	30.6 ± 3.3	.381	30.9 ± 3.0
Jowls				
1.5 mm depth	34.9 ± 3.6	33.3 ± 4.9	.515	34.1 ± 4.3
Submental area				
1.5 mm depth	32.6 ± 2.9	31.5 ± 3.7	0.160	32.1 ± 3.3

Note: Entries are mean ± SD of averaged TDC values measured on dominant and non-dominant sides. At each site, TDC values were measured in triplicate and averaged. *P*-values are from Mann-Whitney non-parametric tests. There was no significant difference at any site or depth in any measured TDC value between women with lower vs higher BMI values. Contrastingly, TDC values measured at forearm and biceps differed by depth with TDC values at each depth statistically different for each other.
*$P < .01$.
**$P < .001$.

TABLE 3 TDC inter-side ratios (dominant/non-dominant)

	BMI < 30 Kg/m^2	BMI ≥ 30 Kg/m^2	*P*-value	All Subjects
N	16	16		32
Forearm (medial)				
0.5 mm depth	1.003 ± 0.043	1.010 ± 0.056	.926	1.006 ± 0.049
1.5 mm depth	0.986 ± 0.069	1.014 ± 0.103	.270	1.000 ± 0.087
2.5 mm depth	1.020 ± 0.071	1.018 ± 0.084	.669	1.019 ± 0.077
Biceps (medial)				
0.5 mm depth	0.980 ± 0.084	0.973 ± 0.070	.838	0.976 ± 0.076
1.5 mm depth	0.985 ± 0.054	1.006 ± 0.067	.381	0.996 ± 0.061
2.5 mm depth	1.002 ± 0.045	0.997 ± 0.081	.926	0.999 ± 0.064
Neck				
1.5 mm depth	0.983 ± 0.081	0.977 ± 0.049	.642	0.980 ± 0.066
Jowls				
1.5 mm depth	1.007 ± 0.093	0.987 ± 0.146	.094	0.997 ± 0.121

Note: Entries are mean ± SD for inter-side TDC ratios (dominant/non-dominant). *P*-values are from Mann-Whitney non-parametric tests. There was no significant difference at any site or depth in any TDC ratio between women with lower vs higher BMI values. TDC ratios measured at forearm and biceps did not differ significantly by depth nor did ratios significantly statistically differ by anatomic site.

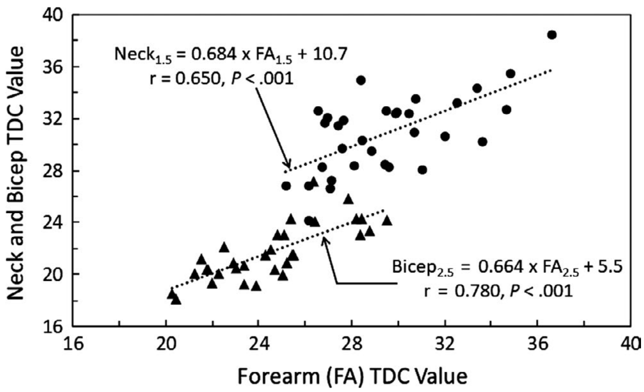

FIGURE 2 Correlation of TDC values among sites. TDC values measured to a depth of 1.5 mm (circles) at neck vs those measured at forearm (FA) and TDC values measure to a depth of 2.5 mm (triangles) at forearm and biceps along with their linear regression lines and associated equations

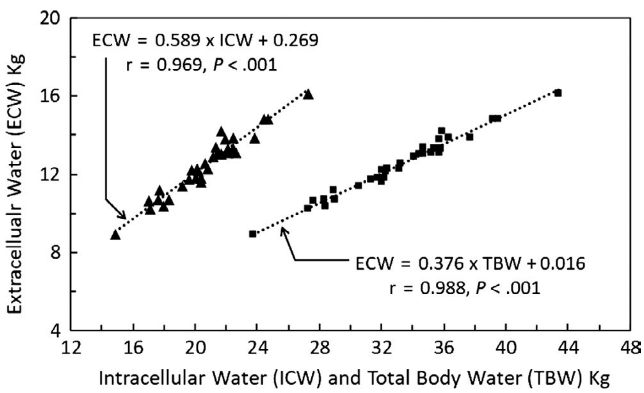

FIGURE 3 Correlation between body water components. Extracellular water (ECW)-intracellular water (ICW) relationship (triangles) ECW-total body water (TBW) relationship (squares) for the full group (N = 32)

(N = 32) are detailed in Figure 3. Results demonstrate the wide range of these values that characterize the present study group and also show the highly significant correlations between these parameters.

3.5 | Age dependencies of water and TDC values

Results showed the presence of a slight but statistically significant increase in the ratio of extracellular water (ECW) to total body water (TBW) with increasing subject age as presented in Figure 4A. Contrastingly, despite this variation there was essentially no change in absolute TDC values measured at any site with age as illustrated in Figure 4B of TDC measurements made to a depth of 1.5 mm on the medial forearm ($FA_{1.5}$).

4 | DISCUSSION

A main goal of the present study was to quantitatively characterize skin TDC values in mostly overweight and obese women and to determine the extent to which TDC values were related to intra- and extravascular water. As a class, skin properties of women with BMI values and total body fat percentages as herein studied have received only moderate systematic evaluation. Early workers had indicated that in chronically obese persons, skin collagen and thickness were not altered[35] and that elastic properties of skin did not correlate with degree of obesity.[36] Others have indicated obesity-linked changes in skin collagen, subcutaneous fat and other skin changes[37] with reduced transepidermal water loss rates (TEWL) as compared with normal weight subjects.[38] Alterations in skin microcirculation of obese persons have also been reported,[39,40] and obesity has been linked to several skin dermatoses and conditions.[41-43] Weight loss

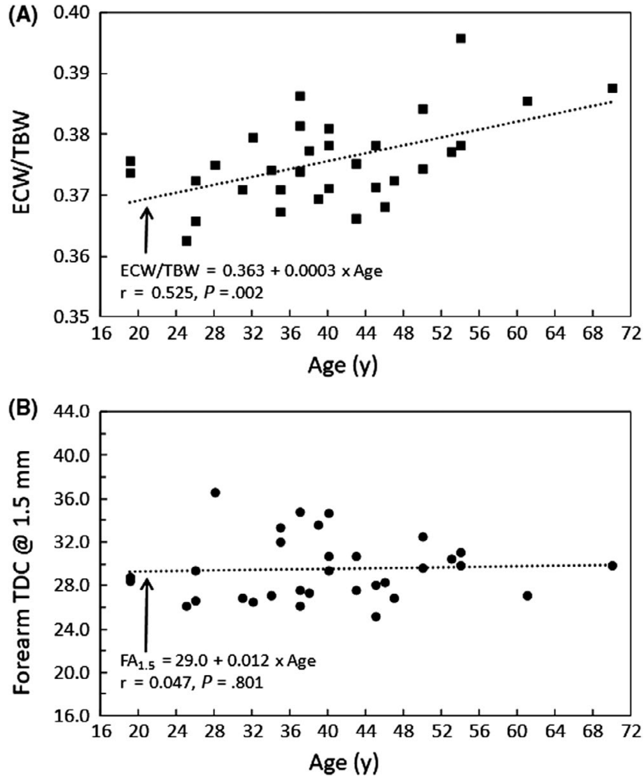

FIGURE 4 Age relationships. Part A shows the presence of a slight but statistically significant increase in the ratio of extracellular water (ECW) to total body water (TBW) with increasing age. Part B shows that despite this variation there is essentially no change in absolute TDC values measured on the forearm to a depth of 1.5 mm ($FA_{1.5}$)

has been reported to reverse some aspects of obesity-linked dermal changes.[44] The present findings extend our understanding of the impact of obesity and overweight on skin properties as assessed via TDC measurements.

A further advancement in the field relates to the direct assessment of the relationship between skin TDC values and the separate whole-body water compartments of intracellular water (ICW) and extracellular water (ECW). Because skin TDC is largely dependent on skin water,[33] the expectation was that TDC values would correlate with total body water percentage (TBW). Further, since TDC assessments are made at 300 MHz, it was anticipated that both ICW and ECW components would be included in the measured TDC value and thus TDC would separately correlate with each. The results showed that although ECW was highly correlated with both TBW and ICW, neither of these were correlated with TDC values measured at any depth. The practical implications of this finding suggest that when skin TDC is measured in overweight or obese individuals, the values measured are unlikely to be dependent on confounded variables such as total body water. However, for now we can offer no satisfactory explanation as to why such TDC values would not be more influenced by total, intracellular or extracellular water.

An additional new finding relates to the skin TDC facial and neck measurements. Although there are limited data in the literature on facial skin TDC values, there is sufficient data to compare the present high BMI and fat mass group with measurements in women who had either normal range BMI values or similar BMI values as measured in the jowl area. The average jowl TDC value of the present group (34.1 ± 4.3) is close to the value of 37.5 ± 4.8 reported[45] for a similar depth in a group of 32 women of a slightly older age (56.4 ± 7.6 years) with an average BMI (29.0 ± 6.4 Kg/m^2) close to that of the present studied group (31.8 ± 6.7 Kg/m^2). Further, jowl TDC values (36.8 ± 6.2) reported in a group of 35 younger women[46] who had normal BMI values (22.8 ± 4.1 Kg/m^2) were also similar to those measured in the high BMI group included in the present study. From this limited but consistent data, it can be tentatively concluded that BMI and body fat effects as they relate to these TDC measurements do not have a major impact.

In contrast to prior TDC measurements made on the jowl or other facial areas, there has been only one report of neck measurements. This anatomic area is of clinical interest because it is a site of lymphedema development in head and neck cancer[47,48] which has proved difficult to quantitatively assess. Measurements of TDC of neck skin to a depth of 2.5 mm in 20 patients with lymphedema show an elevation as compared to 20 in a health control group (48.2 ± 6.6 vs 28.4 ± 6.5, $P < .001$) suggesting such measurements may be useful in this condition.[49] The present data for the 32 women evaluated extend potential normal reference values available for such further work with TDC values herein obtained (30.9 ± 3.0) being similar but slightly less than reported previously. This small difference might be explained by the difference in effective measurement depth used, being 1.5 mm in the present study vs 2.5 mm in the above referenced study.[49]

A further expansion of the knowledge base on skin TDC values as they may relate to lymphedema secondary to head and neck cancer treatment and other conditions is the set of submental skin TDC measurements. To the authors' knowledge, there have been no prior reports of TDC values in this anatomic region. The reference values herein provided may serve as an initial estimate of the expected mean and variance for further studies aimed at assessing the utility of these submental skin TDC values as a quantitative measure for tracking head and neck cancer-related lymphedema.

A final comparison may be made with respect to the presently determined inter-side skin TDC ratios in the studied group. Previous studies have used inter-side TDC ratios and their associated standard deviations obtained in non-lymphedematous women to establish threshold ratios above which would suggest the presence of early developing breast cancer-related lymphedema. The present findings demonstrate no significant difference in such ratios for women who were obese vs those overweight (subgroup B vs subgroup A). Further, the ratios and their associated SD's would yield thresholds for forearm and biceps inter-arm ratios that are similar to those established for women of normal range BMI values.[3] This finding thus extends the usage of such inter-arm TDC ratios to include women of a wide range of BMI's.

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