Concurrent Validity of Upper-Extremity Volume Estimates: Comparison of Calculated Volume Derived From Girth Measurements and Water Displacement Volume

Background and Purpose. The volume of all limbs can be determined by water displacement methods or calculations derived from girth measurements. The purpose of this study was to determine the concurrent validity of calculated volume and water displacement volume measurements. **Subjects.** Both upper extremities of 14 women with lymphedema were measured. **Methods.** Volumetric measurements were taken with a volumeter, and circumferential measurements were taken with a tape measure. Calculated volume was determined by summing segment volumes derived from the truncated cone formula. Pearson product moment correlations, paired *t* tests, and linear regression tests were used to assess relative association and absolute differences between calculated and actual volumes. **Results.** The correlation coefficient for calculated volume versus upper extremity minus fingers (UE-F) water displacement volume was .99. Paired *t* tests showed differences between calculated volume and UE-F water displacement volume ($t=-3.88$, mean difference$=-95.62$ mL), and the linear regression slope was 0.83 with an intercept of 255.28 mL. **Discussion and Conclusion.** Calculated volume measurements were highly associated with measurements based on water displacement; therefore, clinicians should feel confident in using either calculated volume or water displacement volume. The differences, however, indicated that the measures were not interchangeable. Thus, clinicians should not mix or substitute measurement methods with a single patient or in a single study. [Karges JR, Mark BE, Stikeleather SJ, Worrell TW. Concurrent validity of upper-extremity volume estimates: comparison of calculated volume derived from girth measurements and water displacement volume. *Phys Ther.* 2003;83:134–145.]

Key Words: *Circumference measurement, Limb volume, Lymphedema, Volumeter.*

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One type of edema managed by physical therapists is postmastectomy lymphedema. Tunkel and Lachmann[1] reported that the incidence of postmastectomy lymphedema is unknown. Other authors, however, have reported that the incidence of postmastectomy lymphedema ranges from 3% to 36%,[2] from 5.5% to 80%,[3] from 6% to 30%,[4] from 6.7% to 62.5%,[5,6] and from 11% to 46%.[7] The varying incidence rates were related to the surgical procedure, postsurgical treatment, and other risk factors such as obesity.[1–7] Petrek and Heelan[4] contended that of the 2 million people worldwide who have been treated successfully for breast carcinoma, about 15% to 20% are currently living with posttreatment lymphedema.

Two primary methods of measuring edema and lymphedema are water displacement volumetric measurements and girth measurements. Water displacement is used to measure limb volume and is based on Archimedes' Principle, which states that the water volume displaced is equal to the volume of the object immersed in the water.[8] Volumeter-obtained measurements of the water displaced by an edematous limb have been shown to be reproducible, with an error of less than 1%.[8–11]

Kaulesar Sukul and colleagues[12] calibrated the water tank prior to their volumetric studies by using an object with a standard volume of 1,240 mL and measuring the spillwater 10 times. The greatest difference among mea-

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All authors provided concept/research design and consultation (including review of manuscript before submission). Ms Karges provided writing, project management, fund procurement, institutional liaisons, and clerical support. Ms Mark provided data collection, and Ms Karges and Dr Worrell provided data analysis. Ms Mark provided subjects, and Ms Karges and Ms Mark provided facilities/equipment. The authors thank Clyde Killian, PT, PhD, for his dedication, enthusiasm, and expertise in the statistical analysis and revisions of the manuscript.

This study was approved by the Committee on Research Involving Human Participants at the University of Indianapolis.

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surements was 10 mL. Boland and Adams[13] reported that water displacement volumetrics could detect a change of 10 mL (<1%) in inert objects with a fixed volume. Thus, volumetric measurements have been considered to be the "gold standard" for measuring limb volume.[12–15]

Despite the documented reliability of volumetric measurements, there are disadvantages to the use of water displacement measurements in the practice setting. These disadvantages are related to set-up and use of the volumeter,[14,16] transport, design, and certain patient conditions.[12,16] Volumeters that are big enough for arms and legs have the capacity to hold several liters of water, take several minutes to fill and empty, and are difficult to move once full of water. To measure the volume, the water must be poured into a graduated cylinder, which most commonly does not have a capacity greater than 1,000 mL. More than one graduated cylinder often are needed to measure the volume of a nonedematous arm. Due to the size of the volumeter, the collection container, and the graduated cylinder, it is difficult to transport the equipment between locations. The design of most volumeters is also problematic because the outflow spout is located below the top of the volumeter, making it impossible to measure an entire limb. Additionally, the use of water displacement volumetric measures is unsuitable for patients with skin ulcers[16] and for patients in the immediate postoperative period.[12]

Girth measurements are one alternative to water displacement volumetrics. Girth measurements are simple, efficient, and, in our view, clinically useful.[7,14,16] By taking measurements at fixed points on an edematous limb (eg, every 4 cm), it is easy to see where the changes in girth are occurring with intervention. In comparison, water displacement measurements characterize the volume as a single value, making it difficult to identify the locations of changes in limb size. Girth measurements can be used by themselves to record changes in limb size over time, or a "calculated volume" can be generated from the girth measurements by use of a mathematical formula.

Calculated Volume

Two basic formulas (cylinder[14,17–19] and truncated cone [frustum][20–22]) are used to calculate volume based on girth measurements. The limb is divided into sections, with each section representing a cylinder or cone. The final volume is determined by adding the volumes of the sections together. Sitzia[23] compared the cylinder and frustum formulas and stated that the frustum formula was intrinsically the most accurate, which is easy to visualize because most extremities are shaped like a cone rather than like a cylinder. The results of the study by Sitzia indicated that the cylinder formula consistently "underestimates quantity of percentage excess volume . . . by an average 1.5%"[23(p16)] when compared with the frustum formula.

The interval between measurements for the calculated volume formula varied most consistently between 10 cm and 4 cm.[14,18,19,21,22] Boris and colleagues[22] used 10-cm segments with the truncated cone formula, as did Casley-Smith.[21] Bunce and associates[17] also used 10-cm segments, but they preferred the cylinder formula. Mortimer,[14] Charge,[18] and Rose et al[19] all used 4-cm increments with the cylinder formula. Sitzia[23] compared the cone and frustum formulas, but only mentioned specific height intervals of 4 cm when referring to the cylinder formula. Rinehart-Ayres[6] reported that there was little consistency among clinicians on the use of landmarks and the distance between measurements, making it difficult to compare outcomes among clinics or research studies.

Latchford and Casley-Smith[24] compared different height intervals with the truncated cone formula. They used 10-cm intervals, 1.5-in intervals (the interval of space used when measuring for Jobst compression garments*), and 2 measurements only (wrist and top of the arm 9 in proximal to the elbow).[24] Correlations were found (>.99, type of correlation not specified) between the 10-cm and 1.5-in methods. Latchford and Casley-Smith concluded that the 10-cm and 1.5-in height intervals gave comparable results, and they stated that the 10-cm intervals were sufficient for routine measurements of the limb unless there were grossly localized bulges. They also concluded that it was not appropriate to use just 2 circumference measures for a whole limb.[24]

Girth Measurements

Whitney et al[25] examined the reliability of lower-extremity girth measurements within and between raters. Intraclass correlation coefficients (ICCs [2,1]) ranged from .91 to 1.00, except for one site. An analysis was completed to compare the first measurements from each day, and the results showed ICCs ranging from .81 to .98, with the exception of .69 at the 14-cm site for one rater. Results indicated that the measurements in this study were reliable between sessions on the same day and on different days, which is useful because many physical therapists take only one measurement per site.[25]

Water Displacement

DeVore and Hamilton[8] and Engler and Sweat[9] found water displacement volumetrics to have an "error of method"[9] of less than 1% when measuring the volume of hands[8] and upper extremities[9] in subjects without edema. Waylett-Rendall and Seibly[11] measured hand

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volume in subjects with edematous and nonedematous hands. Results indicated that the volume was accurate within 1.0% in nonedematous and edematous hands if successive measurements were taken by the same examiner.[11] Boland and Adams[13] reported that water displacement volumetrics could be used to detect a change of 10 mL (<1%) in bottles containing a fixed volume of water. They also reported that water displacement volumetrics could be used to reliably measure forearm and hand volumes (ICC [2,1]=.99), and they demonstrated that between 40% and 50% of the within-session and between-session pairs were different by less than 10 mL.

Swedborg[10] found that upper-extremity volume in women without edema was ±0.5% of the mean each day, with the total volume of the upper extremities ranging from 1,500 to 2,525 cm^3. Measurements of the subjects' upper extremities were taken 3 times within 5 minutes on 3 consecutive days. Van Velze et al[26] measured each hand 3 times to determine a mean volume, and the results indicated an intermeasurement variation between 3 and 5 mL. They concluded that because there was so little variability between the first and subsequent measures, measurements would only have to be taken once.

Comparison of Calculated Volume Derived From Girth Measurements and Water Displacement Volume

Pani et al[16] compared water displacement volume with calculated volume in the leg. The whole foot was included in the calculated volume, and the measurements went to a point on the leg that was 30 cm from the level of the ground. Results showed correlations between the 2 methods of measuring volume, with $r=.61$ for nonedematous limbs and $r=.80$ for edematous limbs.[16] The regression equations for the nonedematous limbs and edematous limbs showed slopes of 1.51 and 1.45 and intercepts of −659.23 mL and −664.88 mL, respectively.[16]

Stranden[27] compared calculated volume (truncated cone method) with water displacement volume in people with leg edema following femoropopliteal bypass grafting. His calculated volume was for the leg minus the foot, while his water displacement volume included the whole leg. His results showed a correlation coefficient of .98 (type of correlation not specified) and a regression line with a slope of 1.13 and an intercept of −1.4 mL. He reported that there was a slight overestimation of edema using the calculated volume method, with an increase in leg volume of greater than 11%. Stranden stated, however, that the calculated volume method was satisfactory for clinical use.

Kaulesar Sukul et al[12] compared water displacement volume with calculated volume from the cylinder method and the truncated cone method in measuring the leg minus the foot volume. They measured between the ankle and knee starting 3 cm below the medial gap of the knee joint and ending just above the medial malleolus. Their "leg volume" from water displacement was the volume of the leg minus the volume of the ankle and foot. Results indicated that the Pearson correlation coefficient was .99 for the cylinder method, with the linear regression line having a slope of 1.03 and an intercept of −32.13 mL. Results from the truncated cone method indicated a Pearson correlation coefficient of .93, with the linear regression line having a slope of 0.86 and an intercept of −201.6 mL. Kaulesar Sukul et al reported that only the cylinder method was interchangeable with the water displacement model. In contrast, Sitzia[23] reported that use of the cylinder formula led to underestimating the volume when compared with the truncated cone (frustum) formula. However, he did not make a comparison of the calculated volume with the water displacement volume.

Sander and associates[28] conducted a study comparing water displacement with 4 geometric formulas for calculated volume of the hand (cylinder, frustum, rectangular solid, and trapezoidal solid). They also compared upper extremity minus hand water displacement volume with 2 geometric formulas for upper extremity minus hand calculated volume using the cylinder and frustum formulas with 3 interval lengths (3-, 6-, and 9-cm segments). Pearson product moment correlations between water displacement and the geometric formulas for hand volume ranged from .81 to .91, and Pearson product moment correlations between water displacement and geometric formulas for the upper extremity minus the hand volume ranged from .97 to .98. The limits of agreement ranged from 18% to 24% of the mean hand volume and from 16% to 19% of the mean upper extremity minus hand volume. Their results indicated that, although the water displacement and geometric measurements were correlated, the measures were not interchangeable due to the large limits of agreement. Sander and associates recommended using the frustum formula for calculated hand volume, and they calculated upper extremity minus hand volume because the frustum formula had the smallest standard error of measurement (SEM) compared with the other geometric formulas.

In summary, researchers who compared calculated volume with water displacement volume examined the hand volume,[28] upper extremity minus hand volume,[28] and leg volume,[12,16,23,27] and 3 reports[16,27,28] support the use of the truncated cone formula. In 2 studies,[12,27] there was a high degree of association between the water displacement volume and the calculated volume (r>.9), while in another study,[28] the degree of association between the water displacement and geometric measurements ranged from r=.81 to r=.91 in the hands and from r=.97 to r=.98 in the upper extremities minus the hands. In 1 study,[16] there was a degree of association between the calculated volume and water displacement volume at r=.60 in nonedematous limbs and r=.80 in edematous limbs. However, differences between the 2 methods were described by Pani et al[16] (water displacement volume was higher than calculated volume) and Stranden[27] (calculated volume was higher than water displacement volume). Sander et al[28] also reported that the calculated frustum volumes were smaller than the water displacement volumes in the upper extremity minus the fingers, but larger in the hand. Based on the results of these studies, we felt able to proceed with our study related to the upper extremities.

Circumference measurements, in our opinion, may be used frequently in the clinic, and the incidence of lymphedema can be fairly high.[2–7] We contend, therefore, that it is important to know whether using the calculated volume derived from girth measurements is a valid alternative to using water displacement volumetrics. We considered water displacement volume our criterion measurement because it has been reported as the accepted standard of measurement to determine limb volume.[12–15] Therefore, the purpose of our study was to determine the concurrent validity of calculated volume derived from circumference measurements and water displacement volume in edematous (lymphedematous) and nonedematous upper extremities. To do so, we compared calculated volume and water displacement volume measurements using 3 measurement variations.

First, we compared calculated volume with upper-extremity water displacement volume. *Calculated volume* was volume generated from girth measurements in regular intervals from the finger metacarpophalangeal (MCP) joints proximal to the upper arm between the mid-humerus and the axilla. *Upper-extremity volume* was the volume from water displacement including the hand, forearm, and arm. Second, we corrected for one known source of variation between these measures by comparing calculated volume with upper extremity minus fingers volume. *Upper extremity minus fingers (UE-F) volume* was determined by subtracting finger volume from the upper-extremity volume. This was important because calculated volume did not include volume of the fingers. Third, knowing that clinicians are often more interested in side-to-side differences in volume than they are in absolute limb volume, we compared calculated volume side-to-side differences and water displacement volume side-to-side differences (upper-extremity and UE-F volumes).

We hypothesized that there would be correlations between calculated volumes and water displacement volumes (including both upper-extremity water displacement volumes and UE-F water displacement volumes). We further hypothesized that although the measurements would be highly correlated, there would be differences between the measures, with larger differences between calculated volumes and upper-extremity water displacement volumes than between calculated volumes and UE-F water displacement volumes. Finally, we hypothesized that all 3 of the measures would generate similar side-to-side differences.

Methods

Subjects

Using a sample of convenience, 14 women were selected in a consecutive manner to participate in the study at a clinic that specializes in women's health. Inclusion criteria required that participants have a diagnosis of upper-extremity lymphedema and that they were receiving intervention for their lymphedema at this clinic. Thirteen of the women had postmastectomy lymphedema, and 1 woman had lymphedema resulting from a traumatic accident. They ranged from 44 to 71 years of age. Measurements were taken on the edematous and nonedematous upper extremities on all subjects. Measurements from only 14 lymphedematous upper extremities and 13 nonedematous upper extremities were used in the analyses because the data were incomplete for one of the nonedematous upper-extremity measurements. Consequently, a total of 27 upper-extremity measurements were used. All subjects voluntarily agreed to participate in the study and signed a written consent form.

Procedure

After establishing reliability for the measurements obtained by our therapist, volumetric and circumferential measurements were taken on the 14 women (14 lymphedematous upper extremities and 13 nonedematous upper extremities). Participants were instructed on how to appropriately place their hands in the volumeter[†] using guidelines given by Schultz-Johnson[29] and the manufacturer.[30] The volumeter was placed on the floor with the rod positioned in the appropriate position for upper-extremity length. The volumeter was filled with tepid water until the water overflowed out of the spout.[29–31] When the water stopped dripping from the spout, the "topping off" procedure was complete. The initial "topping off" fluid was discarded from the collecting container. The container was then dried out and put back under the spout of the volumeter to collect the

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[†] Smith and Nephew Rolyan Inc, One Quality Dr, PO Box 1005, Germantown, WI 53022-8215.

Table 1.
Sample of How to Use the Calculated Volume Formula

Calculated volume[21]$=(h)(C^2+Cc+c^2)/12(\pi)$
C=girth measurement of distal section
c=girth measurement of proximal section
h=distance between distal and proximal girth sections
$\pi=3.14159$

Distance From Distal Measurement Site (cm)	Distance Between Girth Measurements (cm)	Measurement Site	Girth Measurement Site	Girth Measurements (cm)	Segmental Volume	Upper-Extremity Calculated Volume
46	4	Arm	M	36.4	LM 410.27 mL	Sum of segmental volumes=3,392.32 mL
42	4	Arm	L	35.4	KL 385.52 mL	
38	4	Arm	K	34.2	JK 365.82 mL	
34	4	Arm	J	33.6	IJ 342.52 mL	
30	4	Elbow	I	32.0	HI 344.63 mL	
26	4	Forearm	H	33.8	GH 353.00 mL	
22	4	Forearm	G	32.8	FG 311.10 mL	
18	4	Forearm	F	29.7	EF 250.74 mL	
14	4	Forearm	E	26.4	DE 195.27 mL	
10	4	Forearm	D	23.1	CD 153.50 mL	
6	3	Wrist	C	20.8	BC 130.68 mL	
3	3	Thumb MCP[a] joint	B	25.9	AB 149.27 mL	
0		Finger MCP joints	A	24.1		

Examples using calculated volume formula[21]:
Segmental volume A:B $V=(3)(24.1^2+(24.1)(25.9)+25.9^2)/(12)(3.14159)=149.27$ mL
Segmental volume B:C $V=(3)(25.9^2+(25.9)(20.8)+20.8^2)/(12)(3.14159)=130.68$ mL
Segmental volume C:D $V=(4)(20.8^2+(20.8)(23.1)+(23.1^2)/(12)(3.14159)=153.50$ mL
Segmental volume D:E $V=(4)(23.1^2+(23.1)(26.4)+26.4^2)/(12)(3.14159)=195.27$ mL

[a] MCP=metacarpophalangeal.

water from the volumetric measurement. Participants were seated and slowly lowered their upper extremities into the volumeter until their ring and middle fingers straddled the rod.[29,30,32] Participants were instructed to keep their upper extremities vertical and stationary with the palm turned inward and the thumb pointing in the direction of the spout. Contact between the upper extremity and the sides of the volumeter was avoided. When the water stopped dripping from the spout, the participants' upper extremities were marked at the level where the water ended (between the region of the mid-humerus and axilla) for future use as the most proximal mark for the circumference measurements. The women then removed their upper extremities from the volumeter.

The overflow from the volumeter was collected in a large container and measured in a 1,000-mL graduated cylinder (with 10-mL increments), which sat on a flat surface.[29,30] The amount of water was recorded as the upper-extremity water displacement volume of the limb.

A second volumetric measurement was taken as the women lowered their hand into the water to the level of the finger MCP joints. The overflow water was collected directly into the graduated cylinder and was recorded as the finger volume. The UE-F water displacement volume was determined by subtracting the finger volume from the upper-extremity volume. This was an important step because the circumference measurements started at the finger MCP joints and, therefore, the calculated volume did not include finger volume.

In our study, the participants were seated during the volumetric measurement based on the results of a study by Stern.[32] He recommended using a sitting posture because mean hand volumes were lower in a sitting posture, even though the test-retest reliability values were equally acceptable for sitting and standing postures while assessing hand volumetrics. The water temperature used for the volumetric measurements in our study was "cool" or "tepid," which was found to be acceptable in a study by King.[31] King reported that cool or tepid water is commonly used for volumetric measurements of hand edema, and that water temperature most likely falls within the range of 20° to 35°C that he used in his study. King reported a deviation of only 0.5% of the mean (coefficient of variation) when comparing hand volumes at these 2 temperatures, which was not statistically significant. Boland and Adams[13] also reported that water temperatures between 20° and 32°C were not found to affect the volume of the segments measured.

Table 2.
Reliability Study[a]

	Calculated Volume	Upper-Extremity Water Displacement Volume	Upper Extremity Minus Fingers (UE-F) Water Displacement Volume[b]
ICC (2,1)	.99	.99	.99
SEM	9.35 mL	11.46 mL	11.82 mL
Repeated-measures ANOVA	F=0.15, *P*=.86	F=4.37, *P*=.03	F=4.37, *P*=.03

[a] ICC=intraclass correlation coefficient, SEM=standard error of the measurement, ANOVA=analysis of variance.

[b] UE-F water displacement volume=upper-extremity water displacement volume minus fingers water displacement volume.

Circumference measurements were taken on the upper extremities of the 14 women with a standard retractable tape measure.[25] Measurements were taken at the following points on each upper extremity: finger MCP joints, thumb MCP joint (including the palm of the hand at that level), wrist, and proximally from the wrist in 4-cm increments, with adjustments made to include a measurement of the elbow. The most proximal measurement point was the water level from the water displacement measurement, which was between the mid-humerus and axilla on the upper extremity.

From those measurements, the data were entered into a computer, and the volume was calculated based on the frustum formula mentioned by Casley-Smith,[21] which is as follows: $V=(h)(C^2+Cc+c^2)/12(\pi)$. The volumes from each section of the arm were added together for the calculated volume (Tab. 1). Even though 10-cm increments were used more commonly with the frustum formula,[21,22] we felt the 4-cm increments would accommodate more for the irregularities seen in extremities with lymphedema.

Reliability Testing

In order to establish reliability for the measurements obtained by the therapist in our study, we determined the measurement reliability prior to our study. Volumetric and girth measurements, taken according to the procedures described, were done 3 times each in a time span of 30 to 40 minutes on 8 subjects who voluntarily agreed to participate by signing a written consent form. These participants were not part of the main study. Testing was performed on 11 upper extremities (5 lymphedematous and 7 nonedematous). Reliability was tested for the calculated volume and water displacement volume measurements using a repeated-measures analysis of variance (ANOVA) and ICCs (2,1) as described by Shrout and Fleiss.[33] Standard errors of measurement were determined for each measurement technique as described by Baumgartner.[34]

Results of the reliability testing (ICCs, SEMs) are shown in Table 2. In general, reliability is the "extent to which measurements are repeatable."[35(p508)] The ICCs for the calculated volume derived from girth measurements were similar to values given by Whitney et al[25] (ICC=.91–1.00). The overall percentage of difference between the highest and lowest measurements was less than 2% of the volume for all 3 measures, with the percentage of difference for the upper-extremity water displacement volume and the UE-F water displacement volume being slightly higher than that reported by DeVore and Hamilton[8] and Engler and Sweat[9] (measurements within 1.00% of each other). Based on the ICCs, we felt that all 3 measures had good reliability. We also believed that there was good reliability based on the small percentages of difference and the small SEMs. Thus, we elected to take one measurement at each girth site and one volumetric measurement during the study.

Data Analysis

Correlations (relative association) between calculated volume and water displacement volumes (upper-extremity and UE-F) were computed for bilateral upper extremities (14 lymphedematous and 13 nonedematous) using Pearson product moment correlations (*r*).[35] Correlations between calculated volume and water displacement volumes (upper-extremity and UE-F) side-to-side differences (13 edematous and nonedematous pairs) also were computed using Pearson product moment correlations.[35] Absolute concordance (degree of difference between calculated volume and water displacement volume) was assessed through paired *t* tests and linear regression methods. Moreover, the use of linear regression also allowed us to compare our results directly with those of previous studies.

Results

The means, standard deviations, and ranges for measurements of calculated volume, upper-extremity water displacement volume, and UE-F water displacement volume are shown in Table 3. The means, standard deviations, and ranges for the side-to-side differences for the calculated volume, upper-extremity water displacement volume, and UE-F water displacement volume also are shown in Table 3. For the side-to-side differences, the volume of the nonedematous limb was subtracted from the volume of the edematous limb. A negative value for this volume indicated that the nonedematous limb had a greater volume than the edematous limb. This differ-

Table 3.
Descriptive Statistics

	N	Minimum	Maximum	$\bar{X}$	SD
Calculated volume	27	1,429.13 mL	3,392.32 mL	2,022.90 mL	511.27 mL
Upper-extremity volume	27	1,510.00 mL	3,640.00 mL	2,217.41 mL	613.45 mL
UE-F[a] volume	27	1,375.00 mL	3,530.00 mL	2,118.52 mL	605.24 mL
Calculated volume differences[b] (edematous limb−nonedematous limb)	13	−143.74 mL[c]	1,458.26 mL	343.57 mL	479.75 mL
Total volume differences[b] (edematous limb−nonedematous limb)	13	−135.00 mL[c]	1,740.00 mL	443.85 mL	580.02 mL
Upper-extremity volume differences[b] (edematous limb−nonedematous limb)	13	−160.00 mL[c]	1,720.00 mL	449.62 mL	579.06 mL

[a] UE-F=upper-extremity water displacement volume minus fingers water displacement volume.
[b] Side-to-side differences (edematous limb minus nonedematous limb).
[c] Negative numbers indicate that the volume of the nonedematous limb was greater than the volume of the edematous limb.

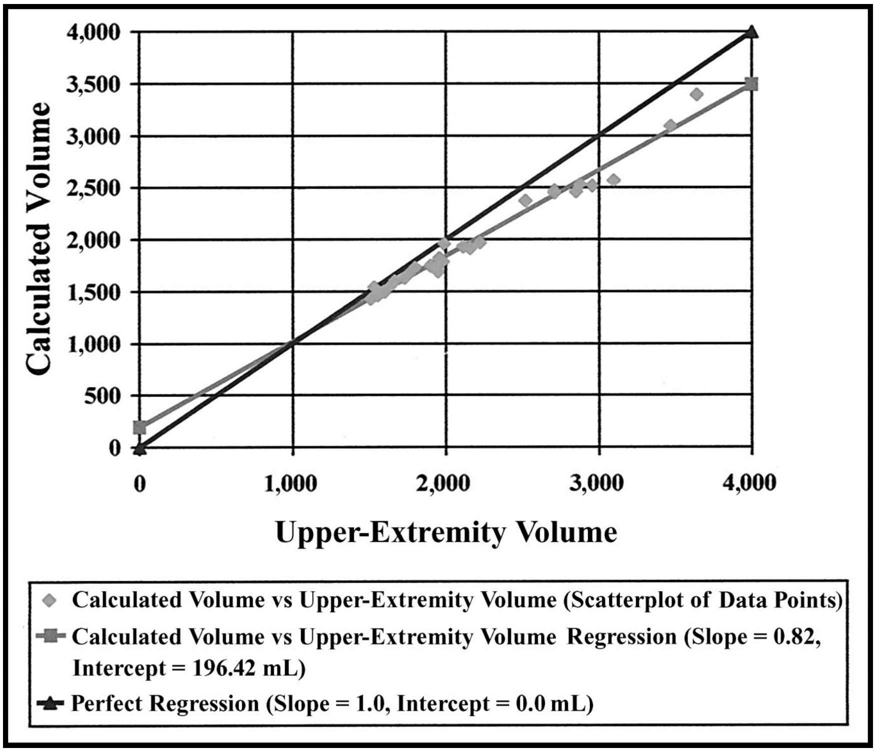

Figure 1.
Linear regression for calculated volume versus upper-extremity water displacement volume.

ence can be related to limb dominance[26,36] or may be due to tissue resection, fibrosis, or atrophy.[36]

Calculated volume was the volume generated from the girth measurements. Upper-extremity volume was the volume from water displacement of the whole upper extremity, and UE-F volume was the volume of the upper extremity minus the finger volume. The correlations between calculated volume and upper-extremity water displacement volume and between calculated volume and UE-F water displacement volume were both high (r=.99, P<.001). The coefficient of determination (r^2) values were .98 for calculated volume versus upper-extremity water displacement volume and for calculated volume versus UE-F water displacement volume. Paired t-test results indicated a difference between calculated volume and upper-extremity water displacement volume ($t=-7.58$, $P<.001$, mean difference=−194.51 mL) and a difference between calculated volume and UE-F water displacement volume ($t=-3.88$, $P=.001$, mean difference=−95.62 mL). The linear regression for calculated volume versus upper-extremity water displacement volume had a slope of 0.82 and an intercept of 196.42 mL (Fig. 1), whereas the linear regression for calculated volume versus UE-F water displacement volume had a slope of 0.83 and an intercept of 255.28 mL (Fig. 2).

Side-to-side differences were comparisons of edematous and nonedematous upper-extremity volumes on the same participant. The correlations between the calculated volume versus upper-extremity water displacement volume side-to-side differences (edematous minus nonedematous) and between the calculated volume versus UE-F water displacement volume side-to-side differences were both high (r=.96, P<.001). The r^2 values were .92 for both comparisons. Paired t-test results indicated no difference between calculated volume versus upper-extremity water displacement volume side-to-side differences ($t=-1.98$, $P=.07$, mean difference=−100.27 mL) and no difference between calculated volume versus UE-F water displacement volume side-to-side differences ($t=-2.08$, $P=.06$,

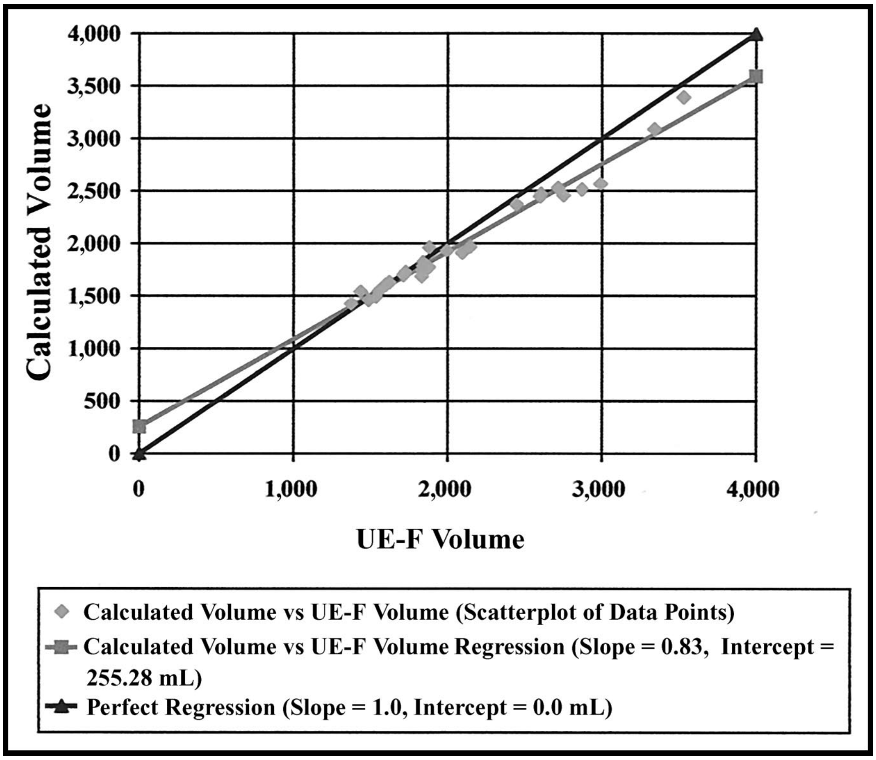

Figure 2.
Linear regression for calculated volume versus UE-F (upper extremity minus fingers) water displacement volume.

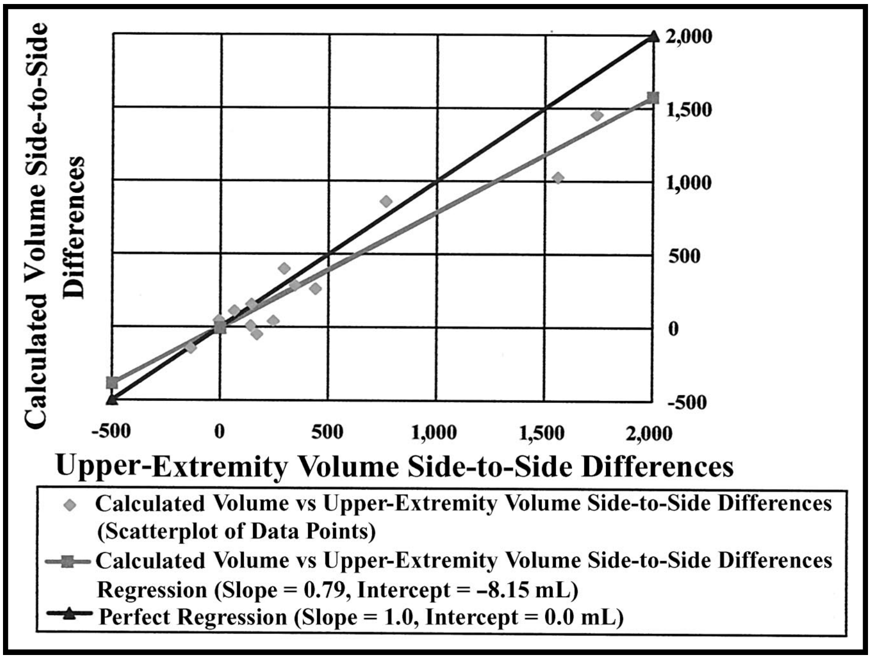

Figure 3.
Linear regression for calculated volume versus upper-extremity water displacement volume side-to-side differences.

mean difference=−106.04 mL). The linear regression for calculated volume versus upper-extremity water displacement volume side-to-side differences had a slope of 0.79 and an intercept of −8.15 mL (Fig. 3). The linear regression for calculated volume versus UE-F water displacement volume side-to-side differences had a slope of 0.79 and an intercept of −12.99 mL (Fig. 4).

Discussion

We found that calculated volume measurements versus upper-extremity and UE-F water displacement volume measurements were highly associated, yet different from each other, which was in agreement with our first 2 hypotheses. Based on our results, we concluded that calculated volume and water displacement volume measurements provide similar estimates of upper-extremity volume, which is in agreement with results from Sander and associates.[28] However, our results showed that calculated volume and water displacement volume measures cannot be substituted for one another because of the differences in values, which was also recommended by Sander et al.[28] Our mean differences ranged from 96 to 195 mL between calculated volume versus UE-F and upper-extremity water displacement volumes (Tab. 3). Thus, the mean differences were 4.3% to 9.6% of the mean calculated volume, upper-extremity volume, and UE-F volume values. These differences found between measures indicated the potential for error in both calculated volume and water displacement volume measurement methods.

We showed a slightly higher correlation (r=.99) between the measurement techniques than reported by Pani et al[16] and similar correlations to those reported by Kaulesar Sukul et al,[12] Stranden,[27] and Sander et al.[28] Pani et al[16] found correlations between the 2 methods of measuring volume of r=.61 for nonedematous lower legs and r=.80 for

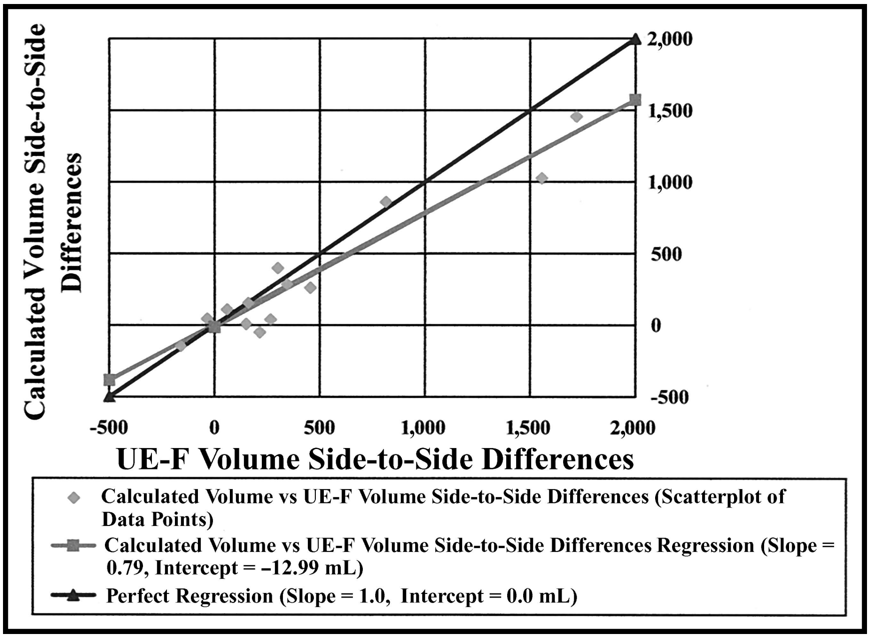

Figure 4.
Linear regression for calculated volume versus UE-F (upper extremity minus fingers) water displacement volume side-to-side differences.

edematous lower legs. Stranden[27] demonstrated a high correlation (r=.98) for measurements of leg volume and leg volume minus foot volume, and Kaulesar Sukul et al[12] reported correlations of r=.99 and r=.93 for measurements of leg volume minus foot volume. Sander et al[28] reported correlations between water displacement and geometric measurements in the hand of r=.81 to r=.91, and in the upper extremity minus the hand of r=.97 to r=.98.

We demonstrated regression slopes that were similar to those reported by Kaulesar Sukul et al[12] and Stranden[27]; however, our intercepts were closer to zero than those of Kaulesar Sukul et al[12] and Pani et al[16] (Figs. 1 and 2). The linear regression model also showed strong relative agreement and a degree of agreement that approaches absolute concordance (Figs. 1 and 2). Thus, our results demonstrated that calculated volume was a valid measure of edema when compared with the water displacement volumetric measure. This finding, in our view, was important because circumference measurements are easy to obtain, useful, and feasible to use in any setting. There were, however, differences between the calculated volumes and the upper-extremity water displacement volumes and between the calculated volumes and the UE-F water displacement volumes. These differences appeared to be greater with larger upper-extremity volumes (Figs. 1 and 2), and they indicated a need for future investigation. We believe the presence of these differences reinforces the need for careful measurement procedures because there is a potential for error in both measurement techniques.

Our study of side-to-side volume differences, we contend, was important because clinicians often compare the volume differences between limbs as a percentage of the nonedematous limb to provide an overall percentage of edema. Our results indicated that there was high relative association (r=.96) between calculated volume versus upper-extremity water displacement volume side-to-side differences and between calculated volume versus UE-F water displacement volume side-to-side differences. The regression slopes (0.79) for both measures were not as high as our overall regression slopes. The paired t-test results, however, indicated no differences between the calculated volume and water displacement volume (upper-extremity and UE-F) side-to-side differences (Figs. 3 and 4). These results indicated to us that even though there were overall differences in volume depending on the method used, the 3 measurement methods were fairly close in predicting side-to-side differences, which was in agreement with our third hypothesis.

There are a few factors that may have influenced our results. One factor was the amount of pressure that participants placed on the Plexiglas rod when their hands were maximally immersed in the water in the volumeter. Increasing the amount of pressure would cause their limbs to be immersed further, thus giving a greater volume. Our reliability study showed that the 3 volumetric measures were very similar and yielded reliable measurements.

A second factor that may have influenced our results was the tape measure tension during girth measurements. A spring-loaded tape measure was used on the first subject in the reliability study. However, we noted that the girth measurements were more consistent when the therapist used her usual retractable tape measure. This was confirmed by the high reliability values from our pilot study. Consequently, the spring-loaded girth measurements from the first subject were not used.

A third factor that may have influenced our results was that the girth measurements were 4 cm apart from the wrist proximally, and they were adjusted to allow for a measurement at the elbow. We chose the 4-cm distance because we were measuring the upper extremities of women with lymphedema and expected girth irregularities because of their clinical condition. The 4-cm increments were common with the cylinder formula,[14,18,19] but were not reported with the frustum formula that we used (10-cm increments).[21,22] According to our results, a 4-cm distance between measurement sites appeared to be acceptable to obtain reliable measurements for this group of subjects. However, Sander et al[28] recommended 3-cm increments when using the frustum formula in the hand, and suggested 6- and 9-cm segments when measuring the forearm and arm.

A fourth factor for consideration is the fact that our calculated volume measurements (n=27) averaged 95.6 mL less than our UE-F volume measurements and 194.5 mL less than our upper-extremity volume measurements. We anticipated that the UE-F volume and calculated volume measurements would be the closest because that was the most direct comparison. The finding that our calculated volume measurements were less than the UE-F and upper-extremity volume measurements was consistent with the results reported by Pani et al[16] was consistent with results reported by Sander et al[28] for the frustum volume versus upper extremity minus hand water displacement volume, but was the opposite of what Stranden[27] reported.

Conclusion

The reliability of the calculated volume measurements was comparable to the reliability of the water displacement volume measurements. The calculated volume and water displacement volume measures were highly associated, whether looking at volume or side-to-side differences. Clinicians or researchers should feel confident in using either the calculated volume measure or the water displacement volume measure for clinical and research purposes. However, the differences between the measures indicated that the measures were not interchangeable. Therefore, clinicians or researchers should not mix or substitute measurement methods with a single patient or in a single study.

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