

FOOT VOLUME ESTIMATES BASED ON A GEOMETRIC ALGORITHM IN COMPARISON TO WATER DISPLACEMENT

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ABSTRACT

Assessing lower extremity limb volume and its change during and after lymphedema therapy is important for determining treatment efficacy and documenting outcomes. Although leg volumes may be determined by tape measure and other methods, there is no metric method to routinely assess foot volumes. Exclusion of foot volumes can under- or overestimate therapeutic progress. Our aim was to develop and test a metric measurement procedure and algorithm for practicing therapists to use to estimate foot volumes. The method uses a caliper and ruler to measure foot dimensions at standardized locations and calculates foot volume (V_M) by a mathematical algorithm. V_M was compared to volumes measured by water displacement (V_W) in 30 subjects (60 feet) using regression analysis and limits of agreement (LOA). V_W and V_M (mean \pm sd) were similar 857 ± 150 ml vs. 859 ± 154 ml, and were highly correlated $V_M = 1.00V_W + 1.67$ ml, $r=0.965$, $p<0.001$. The LOA for absolute volume differences and percentages were respectively ± 79.6 ml and ± 9.28 %. These results indicate that this metric method can be a useful alternative to water displacement when foot volumes are needed, but the water displacement method is contraindicated, impractical to implement, too time consuming or is not available.

Limb edema is a component of many medical conditions including acute trauma,

chronic venous insufficiency, lymphedema, and cardiac and renal disease. It is also an inhibiting factor in healing of chronic wounds. Determining the amount of edema and its change with time or therapy is thus an important part of the clinical picture. Assessing edema by determining the depth and persistence of pitting is widely used clinically but is highly subjective and gives little information about the total amount of edema present in the limb. In contrast, measurement of limb volume and its changes over time offers an objective measure of the amount of edema present and the effectiveness of edema reduction therapy. Measurement of total limb volume avoids the problem in which mobile edema fluid is simply shifted to an adjacent area without removing it from the affected limb. Several methods of determining limb volume are currently available, and each has its own specific advantages and disadvantages. These methods include water displacement (1), circumferential measurements combined with suitable calculations (2,3), photoelectric measurements (4,5) and bioimpedance methods (6,7).

Water displacement can measure entire limbs, including hands and feet, and is accurate for limbs with distorted shapes. It is time consuming, requires special equipment, and preparation and cleaning add to measurement time. Care must be taken to accurately measure the same limb segment repeatedly over time; and patients with extremely large limbs, impaired balance or

limited range-of-motion may require special equipment. Limbs with open wounds cannot be measured with water displacement.

Limb volumes obtained via circumferential measurements compare favorably to water displacement (1,2,8). Needed equipment is a simple tape measure that has a spring device to assure consistent tension for more accurate and repeatable measurements. Mathematical formulas are used to calculate limb volumes from circumference measurements and computer programs that calculate, track and generate reports are now available. Thus, this method is fast, simply done and repeat measurements of the same limb segments are easily determined. However, hands and feet are not usually included in these measurements because suitable mathematical algorithms are not generally available. One such metric method has been recently described for hands (8). Limbs with open wounds, very large limbs, and patients with impaired balance or range-of-motion *can* be measured with this method.

Optoelectric devices use infrared light beams (9) to measure volume by calculating data obtained from the light obstructed by the limb. These machines are fast, use computer programs to calculate and track volume, and generate graphic reports (4,5). The initial cost of equipment is high, and is only cost effective in settings where a large number of measurements are performed. Correct patient positioning is essential for accurate measurements; patients with impaired range-of-motion or very large limbs can be difficult to position. Feet and hands are *not* included in the limb measurement.

Thus, although hands and feet are often the sites of significant edema, volume measurements are rarely done due to the drawbacks of the water displacement method. The development of a metric measurement procedure together with a suitable algorithm to calculate foot volume would provide clinicians with an alternative method to track and document the effectiveness of edema reduction therapy. The present report describes

our efforts in this direction, with the specific focus on assessing foot volumes using readily available and inexpensive measuring tools.

METHODS

Subjects

Thirty volunteer subjects participated in this study (24 female). Each subject signed an informed consent that was approved by the university's institutional review board. Demographic and other data are reported as mean \pm sd (standard deviation) unless otherwise noted. Ages of subjects ranged from 22 to 41 years (26.7 ± 5.1), height ranged from 1.52-1.80 meters ($1.66 \pm .08$), weight ranged from 48-105 kg (66.7 ± 13.3), and body mass index (bmi) ranged from 19 to 35 kg/m² (23.9 ± 3.5). By the World Health Organization criteria, six subjects were overweight (bmi = 25-29.9) and three were obese (bmi \geq 30). Exclusionary criteria were cuts or open wounds on the foot and a recent acute foot injury.

Water Displacement

Two standard acrylic foot volumeters were modified by building up the bottom surface such that the vertical distance from the bottom of the foot to the water outflow section of the volumeter was 12 cm (*Fig. 1*). The volumeters were first filled to overflow and, after stabilization of the water level, a seated subject slowly placed one foot into one volumeter and the other foot into the second volumeter. The subject then rose to a standing position. The displaced water from both volumeters was collected from the outflow tube and the volumes measured with a calibrated graduated cylinder. The choice as to which foot (right or left) to be placed in which volumeter was made on a random basis.

Metric Measurements

A series of reference lines were made at

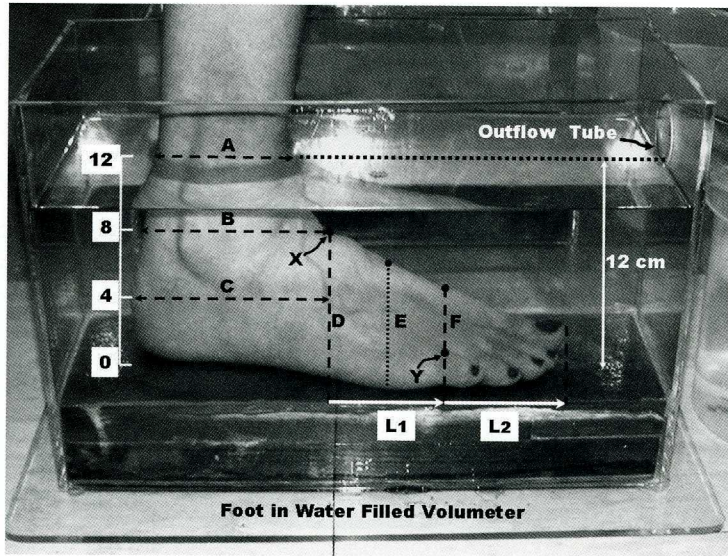


Fig. 1. Metric Measurement Procedure. Reference lines were made at sites shown. The line at section B was extended to its endpoint (point x) so that a vertical line at section D defined a zero reference for the distal portion of the foot. The distance (L_1) from section D to section F was measured. The location of section E was defined as $L_1/2$. The maximum distance between point y and the end of the foot (L_2) was then measured. Using a digital caliper, the maximum widths and depths were measured at each of sections A, B and D through F. For section C and the foot bottom, the lateral-medial maximum width was measured and the posterior-anterior depth at section B used as the other dimension. See text for further descriptions.

standardized sites using a ruler and surgical pen (Fig. 1). Using the bottom of the foot as the zero for the vertical reference, lines were placed on the foot at 12, 8 and 4 cm corresponding to sections A, B and C shown in Figure 1. The line at 8 cm (section B) was extended to its endpoint (point x) so that a vertical line drawn from point x toward the foot bottom (section D) defined a zero reference for the distal portion of the foot. The distance (L_1) from section D to the start of the crease at the junction of toes 5 and 4 (point y at section F) was measured. The location of section E was defined as $L_1/2$. The maximum distance between point y and the end of the foot (L_2) was then measured. Using a digital caliper, the maximum widths (W_i) and depths (D_i) were measured at each of sections A, B and D through F. For section C and the foot bottom, the lateral-medial maximum width was measured and the posterior-anterior depth at section B used as the other dimension.

Volume Calculation Algorithm

The cross sectional area (S_i) at each section was calculated on the basis of an elliptical area according to the relation $S_i = \pi W_i D_i / 4$. The volumes (V) contained within regions bounded by consecutive sections were calculated using a frustrum model (3) according to the relationship $V = (h_{i,i+1}/3) \{S_i + S_{i+1} + (S_i S_{i+1})^{1/2}\}$ in which $h_{i,i+1}$ is the distance between consecutive sections. In accordance with the manner in which metrics were obtained, the h values for the vertical sections from A to the foot bottom were each 4 cm. The h values for sections D through F were $L_1/2$, which varied foot-by-foot. The volume distal to section F was calculated on the basis of an elliptical paraboloid according to the relationship $V = \pi L_2 W_i D_i / 8$ in which the W_i and D_i values are those measured at section F. The total foot volume was calculated as the sum of the volumes of all segments.



Fig. 2. Foot Model with Superimposed Clay. Clay was added to the foot cast to alter its volume and shape.

Foot Model

To test the ability of the metric measurement procedure and algorithm to estimate volumes of altered foot shapes and increased volumes, a series of measurements were done using a cast of a human foot. Modeling clay was used to change the foot contour and to add volume to the 'non-edematous' model of the foot thereby simulating foot 'edema'. The volume of the unmodified foot cast was measured in triplicate in each volumeter and was determined to be 901 ± 2.0 ml in one volumeter and 899 ± 1.9 in the other. *Figure 2* shows the foot model with added clay to result in a total foot volume (by water displacement) of 1243 ml. This represents a 38% larger volume than that of the unmodified model, i.e., a simulated 38% edema volume. *Figure 3* shows the comparison between model volumes as determined by metric and water methods for different amounts of added volume.

RESULTS

Volumes and Correlations:

Volumes determined by each method are summarized in *Table 1*. There was no significant difference in volumes obtained by water displacement (V_W) as compared to the metric procedure determined volume (V_M). There was also no significant difference between right and left foot volumes whether determined by water displacement or by the metric procedure. There was a highly significant correlation ($r=0.965$, $p<0.001$) between volumes obtained by the two methods. The overall regression equation between metric and water determined volumes is $V_M = 1.00 V_W + 1.67$ ml (*Fig. 4*). Parenthetically, there were highly significant correlations between foot volumes determined by either method and subject weight in kg (WT). For the water determined volumes the regression relation was $V_W = 11.5 \times WT + 100$ ml, $r=0.852$, $p<0.001$ and for metric determined volumes, the relationship was $V_M = 12.2 \times WT + 53.6$ ml, $r=0.852$, $p<0.001$. The relationships to body weight were determined with the exclusion of the three obese subjects ($N=27$).

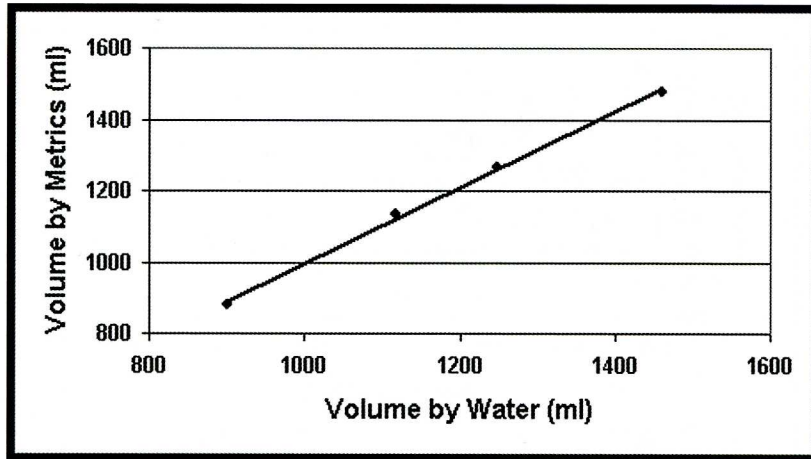


Fig. 3. Foot Model Volumes. Volumes were determined using both water displacement and the metric procedure.

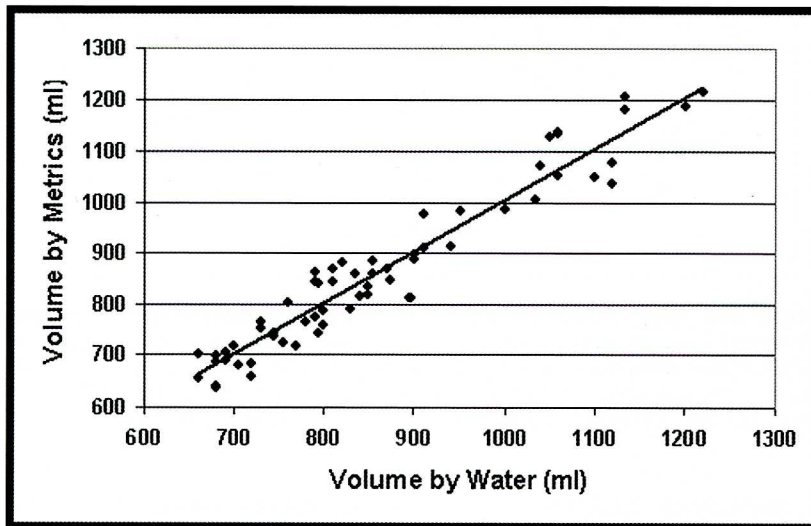


Fig. 4. Subject Foot Volumes. Relationship between paired-volumes as determined by water displacement and the metric procedure. The solid line is the linear regression defined by the equation and parameters in the figure.

Limits of Agreement Between Methods:

Figure 5 shows the difference in volumes determined by metric and water methods ($V_M - V_W$) in ml (A) and as a percentage of the volume obtained by water (B). Each measurement-pair is plotted vs. the average of the two measurements, $(V_M + V_W)/2$. The central dashed line is the mean value of the difference, the solid upper and lower lines are located at $\pm 2SD$ from the mean and define

the limits of agreement between methods, LOA as described by Bland and Altman (10). The line (long-dash, short-dash) above and below the LOA are the upper and lower 95% confidence intervals on the LOA calculated as previously described (11). Table 2 summarizes the data pertinent to Fig. 5.

DISCUSSION

Assessing limb volume and its change

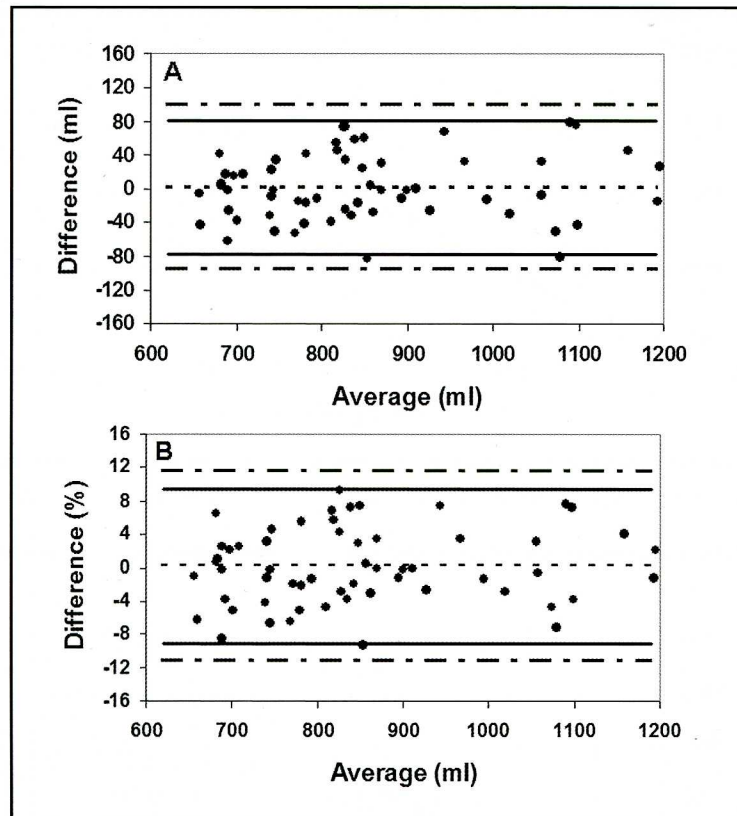


Fig. 5. Limits of Agreement. Bland-Altman plots showing differences between volumes (metric-water) vs. the average volume determined by each method (metric + water)/2. The central dashed line is the mean value of the difference, the solid upper and lower lines are located at $\pm 2sd$ from the mean and define the limits of agreement between methods (LOA). The line (long-dash, short-dash) above and below the LOA are the upper and lower 95% confidence intervals on the LOA. A) absolute differences and B) percentage differences.

during and after lymphedema therapy is important for determining treatment efficacy and documenting outcomes (1). Previous reports have described and compared methods for assessing upper extremity (4,8,12) and lower extremity volumes via methods ranging from the use of a tape measure (2,13) to the use of sophisticated optoelectronic apparatus (4,5,9). However, the only method currently available for measuring foot volumes is water displacement. This technique is not routinely used in a clinical setting so that assessments of volume changes in lower limbs does not usually include changes that occur in the foot. Exclusion of foot volumes can under- or

overestimate therapeutic progress. Thus, our goal was to develop and test a metric measurement procedure and algorithm that could be used by the practicing therapist to estimate foot volumes using readily available and inexpensive tools. The metric measurement procedure uses a caliper and ruler to measure foot dimensions at standardized locations. From these measurements, foot volume is calculated according to a mathematical algorithm based on a combination of geometrical shapes.

One important result of this study is the demonstration that the foot volumes determined via the metric method compare favorably with foot volumes determined

TABLE 1
Summary of Measured Volumes and Correlations

	Left Foot (N=30)		Right Foot (N=30)		Both Feet (N=60)	
	Water	Metric	Water	Metric	Water	Metric
Volume (ml)	858±151	857±161	857±151	861±150	857±150	859±154
Correlation (r)	0.944		0.969		0.965	
Difference (ml)	-1.08±44.3		4.32±37.4		1.62±39.8	
p-value	0.912		0.532		0.753	

TABLE 2
Limits of Agreement Between Metric and Water Methods

	Mean Difference	LOA	95% CI
$V_M - V_W$ (ml)	1.62 ± 39.8	±79.6	+99.1 to -95.8
$(V_M - V_W)/V_W$ (%)	0.21 ± 4.64	±9.28	+11.6 to -11.2

V_M is the volume determined by the metric measurement procedure and the algorithm. V_W is the volume measured by water displacement. Mean Difference is the average volume difference ± SD between the two methods. LOA is the limit of agreement obtained between methods. This corresponds to twice the sd of the mean difference. The 95% CI lists the upper and lower bounds on LOA.

by water displacement. In comparing two methods of measurement, the limits of agreement (LOA), defined as twice the standard deviation of differences between values obtained by the two methods, defines an interval in which about 95% of all differences lie (10). The decision as to whether two methods can be used interchangeably in a clinical setting requires a judgment that is based on whether the magnitude of the LOA is sufficiently small for the clinical purpose of the measurement. Here interchangeability means that either method could reliably be used on the same patient using one method for the right foot and the other for the left foot. The present results indicate that under conditions in which

differences of about ±10% are acceptable, the metric and water methods for assessing foot volume would be interchangeable.

Independent of whether the methods are viewed as being interchangeable, the present results indicate that the metric method can be a useful alternative to water displacement when foot volumes are needed, but the use of water displacement is contraindicated, impractical to implement in a given patient, considered too time consuming or is not available. The very high correlation between the foot volumes obtained by the metric and water displacement methods provides a quantitative basis for this approach.

One limitation of the present study is the fact that none of the feet measured were

significantly edematous. As a consequence, we cannot yet provide definitive statements as to the full range of applicability of the algorithm. However, the results of measurements on the foot model, in which the model shape was varied and various degrees of "edema" were simulated, suggest that the metric method may also closely parallel water displacement for these larger volumes and altered shape conditions.

Because the metric procedure relies on measurements that are made at specific locations, the absolute accuracy of the method as a tracking tool depends on the degree to which shape changes occur within adjacent measuring sections over time. However, this same limitation applies to the widely used method of measuring arm or leg circumferences with a tape measure and then computing segment volumes via geometric formulae (2,8). As has been previously described (3), such circumference measurements are usually adequate for arms and legs, provided that the deviation in their cross-sectional shape from circularity is not large. This is generally *not* true for hands or feet so that circumference measures to determine volume have limited value. Thus, the present approach, which takes into account the deviation in circularity via separate width and depth measurements that are subsequently integrated into reasonable mathematical formulations, provides an alternative to water displacement for estimating foot volume.

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