Lymphology 39 (2006) 95-103

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

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ABSTRACT

Assessing changes in upper extremity limb volume during lymphedema therapy is important for determining treatment efficacy and documenting outcomes. Although arm volumes may be determined by tape measure, the suitability of circumference measurements to estimate hand volumes is questionable because of the deviation in circularity of hand shape. Our aim was to develop an alternative measurement procedure and algorithm for routine use to estimate hand volumes. A caliper was used to measure hand width and depth in 33 subjects (66 hands) and volumes (V_E) were calculated using an elliptical frustum model. Using regression analysis and limits of agreement (LOA), V_E was compared to volumes determined by water displacement (V_W), to volumes calculated from tape-measure determined circumferences (V_C), and to a trapezoidal model (V_T).

V_W and V_E (mean±SD) were similar (363±98 vs. 362±100 ml) and highly correlated; $V_E = 1.01V_W - 3.1$ ml, r=0.986, p<0.001, with LOA of ±33.5 ml and ±9.9 %. In contrast, V_C (480±138 ml) and V_T (432±122 ml) significantly overestimated volume (p<0.0001). These results indicate that the elliptical algorithm can be a useful alternative to water displacement when hand volumes are needed and the water displacement method is contra-indicated, impractical to implement, too time consuming or not available.

Keywords: hand edema, edema measurement, hand volume, hand models

Edema of the hand often accompanies upper extremity lymphedema that develops after breast cancer related surgical and/or radiation interventions. Although measurements of arm volume and its changes over time can provide objective measures of the amount of edema present in the arm and help track the effectiveness of therapy, the added edema attributable to the hand is infrequently included as a component of the overall upper extremity limb volume assessment. As a consequence, there is the possibility that mobile edema fluid is shifted to or from the hand without actually altering total upper extremity limb volume. Further, the exclusion of the hand volume and its change can under or over estimate the efficacy of the lymphedema therapy.

A major reason for the omission of hand volume as part of routine assessments is the absence of a readily available and clinically friendly method to accurately estimate hand volume. Among the various methods available to estimate arm or leg volumes (1-8), the water displacement method is arguably the "gold-standard" for hand volume measurements. However, this method is time consuming, and the needed preparation and clean-up add significantly to overall measurement time. Further, patients with very large hands or impaired or limited range-of-motion may require special equipment, and hands with open wounds cannot safely be measured by water displacement. Thus, there is a clear and present need for an alternate method of estimating hand volume.

Inroads toward this end have been made by using various geometrical models to represent the hand (e.g., rectangular and trapezoidal) from which hand volume is calculated based either on circumferences or girth (width and depth) measurements using formulas or algorithms (8). An intrinsic limitation of using circumferences as inputs to an associated model for subsequent volume calculations is the need for the body part to have a circular cross-sectional shape (9). Although this condition is often approximately satisfied for arms, it is infrequently true for hands, which in general have width and depth dimensions that are considerably different from each other. Previous work has shown that by representing sections of the foot by an elliptical cross-section model, foot volumes determined from width and depth measurements agreed with those obtained by water displacement with a limit of agreement of less than 10% (10). We hypothesized that a similar approach applied to the hand would also provide a useful method to estimate volume and thereby provide clinicians with an alternative way to track and document the effectiveness of upper extremity edema reduction therapy that includes hand volume. The present report describes our efforts in this direction, with the specific focus on assessing hand volumes using readily available and inexpensive measuring tools.

METHODS

Subjects

Thirty-three volunteer subjects participated in this study (13 male). Each subject signed an informed consent that was approved by the university's institutional review board. Demographic and other data are reported as Mean±SD (standard deviation) unless otherwise noted. Ages of subjects ranged from 22 to 56 years (27.5±8.6), height ranged from 1.55-1.96 meters (1.70±.11), weight ranged from 48.2-118.2 kg (71.8±19.7) and body mass index (BMT) ranged from 17.7 to 41.3 kg/m^2 (24.7±5.3). By the World Health Organization criteria, six subjects were overweight (BMT = 25-29.9) and four were obese (BMT >= 30). Exclusionary criteria were cuts or open wounds on the hand and a recent acute hand injury. Although not a requirement, the right hand was the dominant hand of all subjects studied.

Metric Measurements

With the subject comfortably seated and the hand placed palm down on a pre-marked paper grid, the hand was marked at three cm intervals starting at the level of the ulnar head *(Fig. 1)*. The width and depth at each marked section was measured with a digital caliper and the circumference was measured with a Gulick-type tape measure pulled to a constant tension. The depth measurement was done using the zero offset of the caliper to account for the thickness of the surface on which the hand rested. All measurements were done with the hand on the surface. The procedure was then repeated on the other hand.

Hand Volumes by Water Displacement

Subjects were evaluated while seated on an armless chair with their backs supported and their arms comfortably hanging. A standard acrylic hand volumeter was placed on top of a hand-controlled jack. The volumeter-jack combination rested on the floor *(Fig. 2)*. The volumeter was positioned so that during a test run it could be raised by the jack such that the hand was in the center of the volumeter. The volumeter was then filled to overflow and, after stabilization of

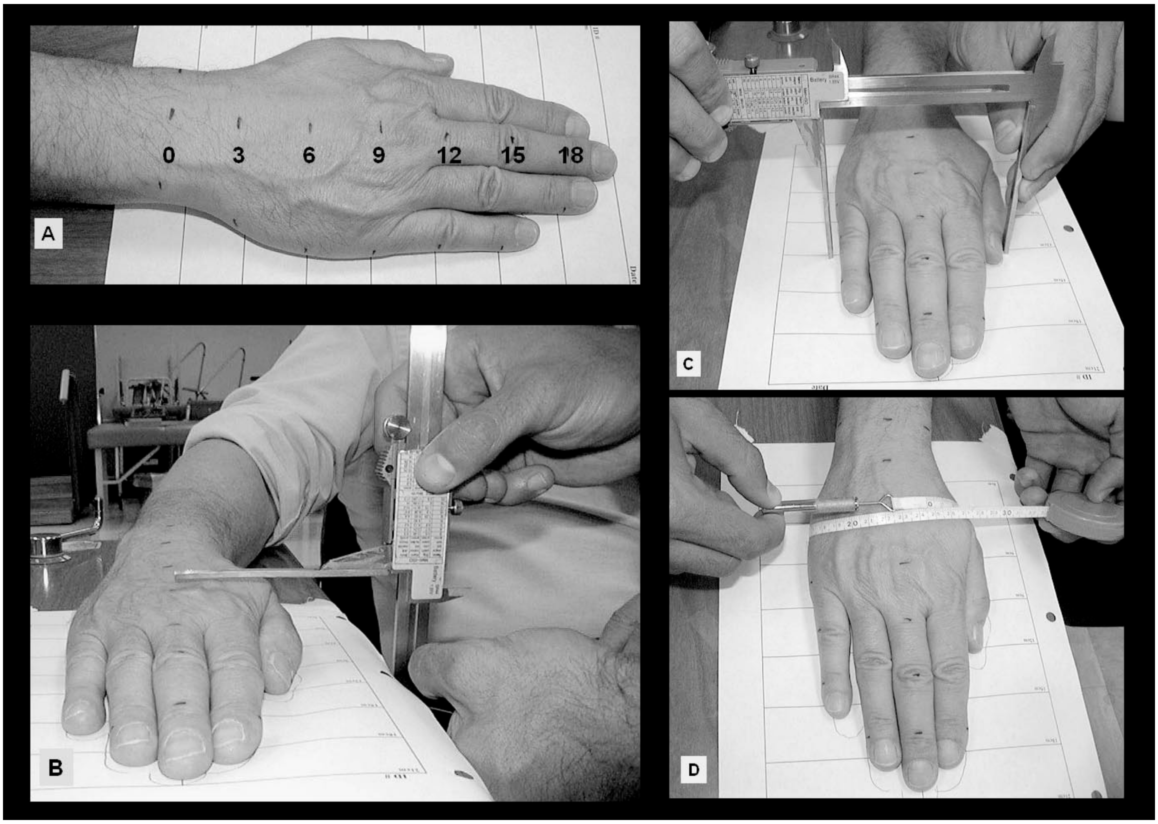

Fig. 1. Metric Measurement Procedure. (A) Hand with reference marks placed three cm apart; (B and C) Depth and Width measurements with digital caliper; (D) Circumference measurements at corresponding reference marks. See text for further descriptions.

the water level, the jack was slowly raised until the hand was immersed in water up to a horizontal line previously drawn at the level of the ulner head. The displaced water from the volumeter was collected from the outflow tube in a plastic container of known weight. The volume was determined by weighing the collected water using a digital scale with a tare feature. This procedure was then repeated on the other hand. For metric and water measurements, the choice as to which hand was to be measured first was done on a random basis.

Volume Calculation Algorithms

The cross sectional area (S_i) at each hand section was calculated on the basis of an elliptical area according to the relation $S_i = \pi W_i D_i/4$. The segmental volumes (V_S) contained within regions bounded by consecutive sections were calculated using an elliptical frustum model (9) as $VS_E = (Z_{i,i+1}/3) \{S_i + S_{i+1} + (S_i S_{i+1})^{1/2}\}$ in which $Z_{i,i+1}$ is the length between consecutive sections. In accordance with the manner in which metrics were obtained, the Z value used for all sections was three cm except for the last section at the fingers, which could be less than three cm. As a comparison to this algorithm, hand volume was also determined using a trapezoidal model. For this case the area of each section is $A_i = W_i D_i$ in which W_i and D_i are the same width and depth measurements that are used in the elliptical model. However, segmental volumes for the

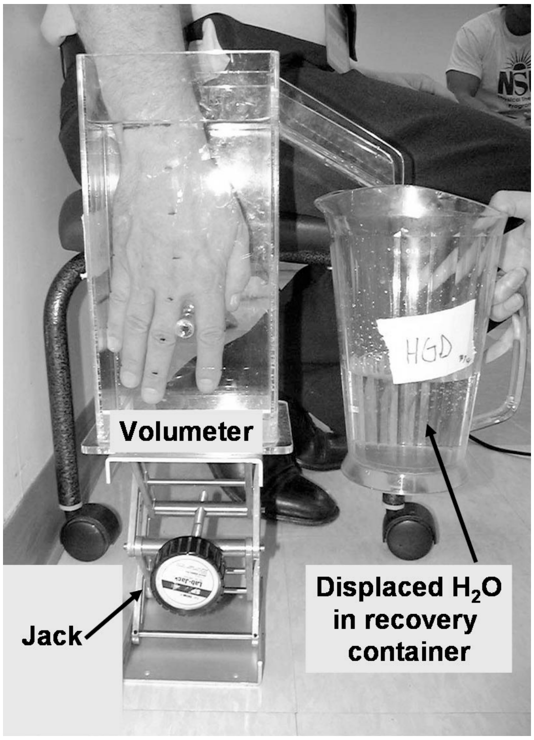

Fig. 2. Water Displacement Procedure. Final position of hand in volumeter is shown. The jack was slowly raised so that the hand was immersed in water up to a horizontal line previously drawn at the level of the ulner head. Hand volume was determined by weighing the displaced water.

trapezoidal model are determined as $VS_T = (Z_{i,i+1}/3) \{A_i + A_{i+1} + (A_i + A_{i+1})/2\}$ in which the A_i have the same meaning but different values as the S_i for the elliptical model. Segmental volumes were calculated from the measured circumferences using the right circular frustum model (1) as $VS_C = (Z_{i,i+1}/12\pi) \{C_i^2 + C_iC_{i+1} + C_{i+1}^2\}$in which C_i and C_{i+1} are the measured circumferences for the sections that define the segment of length $Z_{i,i+1}$. Total hand volumes were determined as the sum of the volumes of the segments and designated as V_E, V_T and V_C for the elliptical, trapezoidal and circumferential methods respectively.

Hand Model

To test the ability of the width-depth metric measurement procedures and algorithm to estimate volumes of altered hand shapes and increased volumes, measurements were done using a cast of a human hand. Modeling clay was used to change the hand contour and to add volume to the 'non-edematous' model of the hand thereby simulating hand "edema" *(Fig. 3)*. The volume of the unmodified hand cast, determined by water displacement, was 400 ml. Clay was added to achieve volumes up to 606 ml which represented a simulated 50% edema. Three therapists independently measured the width and depth of the model in duplicate at each volume. *Fig. 4* shows the comparison of volumes as determined by the elliptical algorithm versus volume by water displacement.

RESULTS

Volume and Correlations:

Volumes determined by each method are summarized in *Table 1*. There was no significant difference in the overall volumes obtained by water displacement (V_W) as compared to the metric procedure when using the elliptic model (V_E). However both the trapezoidal (V_T) and circumferential (V_C) methods resulted in large and highly significant overestimations of hand volume as compared to water displacement. All methods demonstrated a significantly smaller volume associated with the left hand as compared with the right (dominant) hand. The statistical significance of the handedness difference was greater when using water displacement and the elliptical model. Volumes obtained by all three metric methods were significantly ($p<0.001$) correlated with volumes determined by water displacement *(Fig. 5)*. However, the magnitude of the correlation coefficient was greatest for the elliptical method ($r=0.986$) and the linear regression between V_E and V_W, $V_E = 1.01 V_W - 3.1$ ml, showed the best agreement

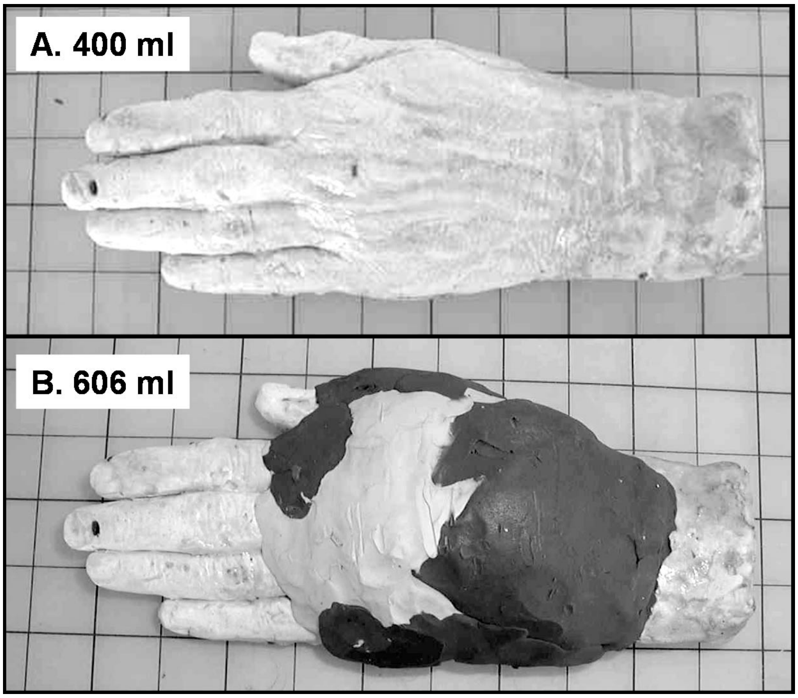

Fig. 3. Hand Model with Superimposed Clay. Clay was added to the hand cast to alter its volume and shape. Shown are the basic hand cast which had a volume of 400 ml and simulated edema at a volume 606 ml.

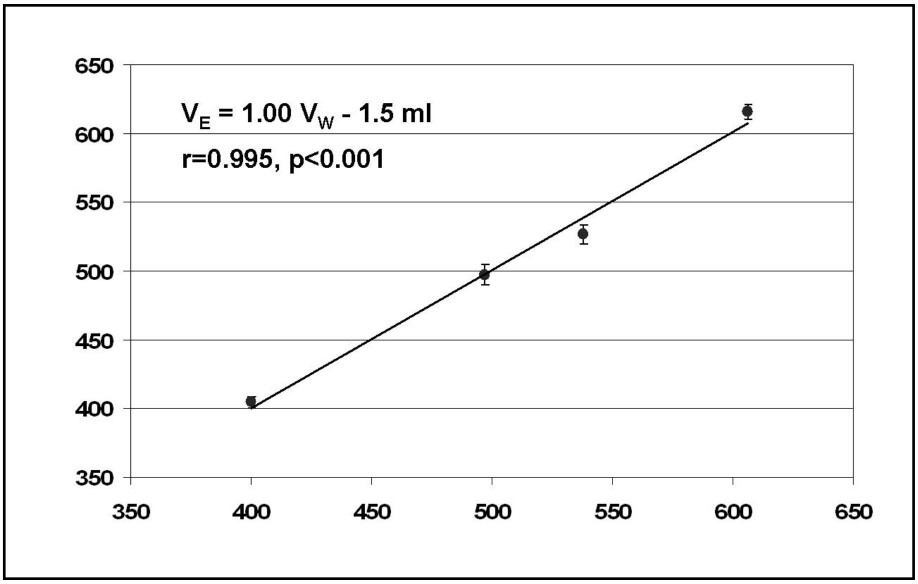

Fig. 4. Hand Model Volumes. Three therapists independently measured the width and depth of the model in duplicate at each volume. The regression line and equation show the comparison between volumes determined by the elliptical algorithm (VE) versus water displacement (VW). Error bars are ±1 SD.

TABLE 1
Summary of Hand Volume Determinations

Hand Volumes (ml)				
Method/Model	All Hands (n=66)	Right Hand (n=33)	Left Hand (n=33)	Right-Left (% difference)
Water (VW)	363±98	368±100	357±98^{++}	4.6±3.3
Elliptical (VE)	362±100	368±104	356±98^{++}	4.3±3.4
Trapezoidal (VT)	432±122*	437±128	427±118^{+}	4.9±3.9
Circumference (VC)	480±138*	488±141	472±138^{+}	5.0±4.3

Values are mean ± SD. * = p<0.0001 compared to water; $^{++}$=p<0.001 compared to right hand; $^{+}$=p<0.01 compared to right hand.

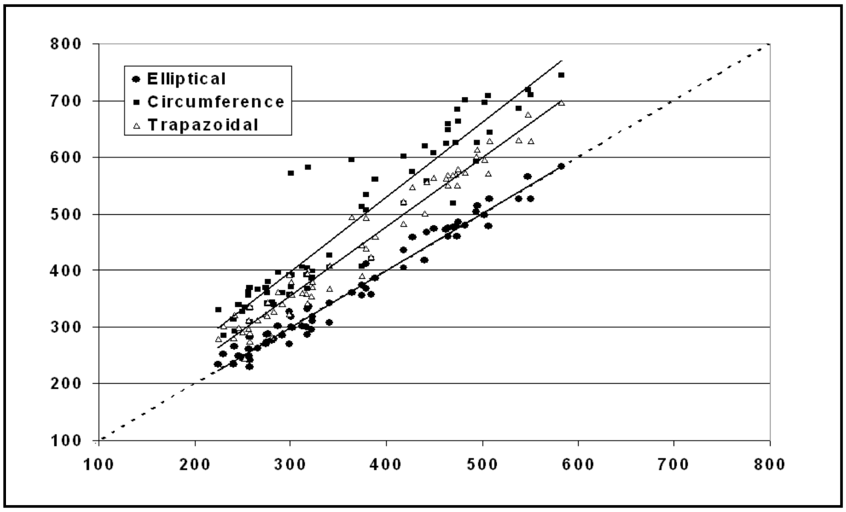

Fig. 5. Subject Hand Volumes. Relationship between paired-volumes as determined by water displacement (VW) and the elliptic (VE) trapezoidal (VT) and circumference (VC) algorithms. The solid lines are the linear regressions defined by the equations and parameters in the figure. The dashed line is a line of identity.

among the metric methods, nearly coinciding with the line of identity *(Fig. 5).*

Limits of Agreement Between Water Displacement and Elliptic Model Methods

Fig. 6 shows the difference in volumes determined by the elliptic and water methods (V_E- V_W) in ml (*Fig. 6A*) and as a percentage of the volume obtained by water (*Fig. 6B*). Each measurement-pair is plotted vs. the average of the two measurements, (V_E + V_W)/2. The central dashed line is the mean value of the difference, the solid upper and lower lines are located at ±2SD from the mean and define the limits of agreement

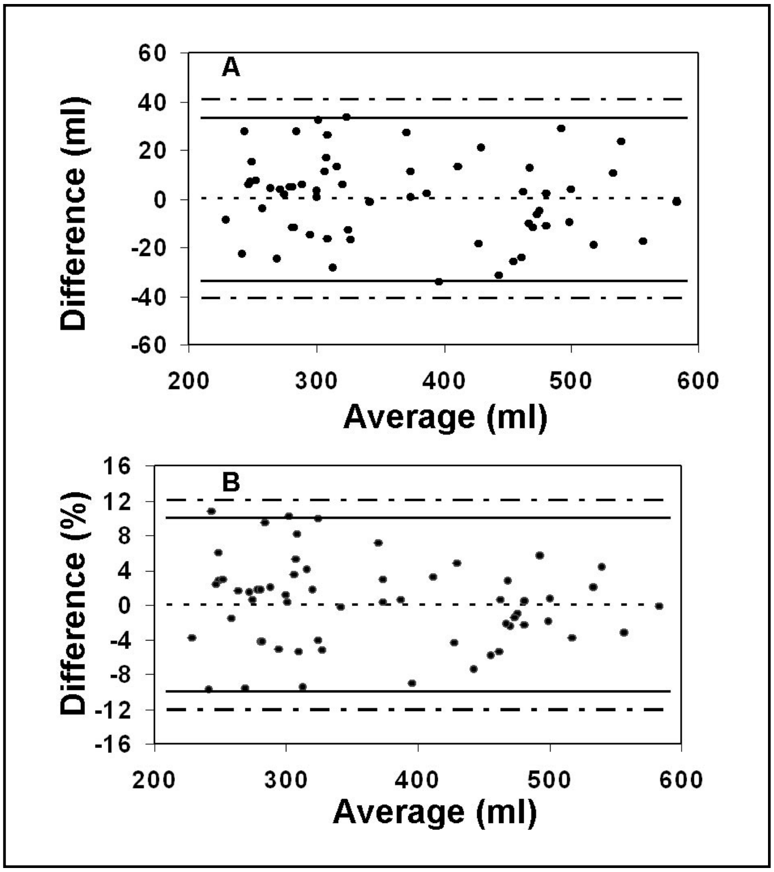

Fig. 6. Limits of Agreement. Bland-Altman plots showing differences between elliptic and water determined volumes (VE-VW) vs. the average volume determined by each method (VE +VW)/2. The central dashed line is the mean value of the difference, the solid upper and lower lines are located at ±2SD from 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. Part A shows the absolute differences and part B shows the percentage differences.

(LOA) between methods as described by Bland and Altman (11). 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 (12). *Table 2* summarizes the data pertinent to *Fig. 6.*

DISCUSSION

Determining changes in limb volume during lymphedema therapy is important for determining treatment efficacy and documenting outcomes (1). Methods to assess arm (3,5,8) and leg volumes (2,13) range from the use of a tape measure to the use of sophisticated optoelectronic apparatus (3,4,14). Because of the shape of the hand and foot, the only accurate method to determine their volume until recently was water displacement. Although accurate, this method is time consuming and is not applicable to patients with open wounds or with some patients who have limitations in mobility and range of motion. As a consequence, water displacement is not routinely used in a clinical setting and thus hand or foot volumes determined by this method are not routinely

TABLE 2
Limits of Agreement Between Water and Elliptical Metric Methods

	Mean Difference	LOA	95% CI
V_E - V_W (ml)	0.06 ± 16.7	±33.5	+40.7 to -40.5
(V_E - V_W)/V_W (%)	0.04 ± 4.96	±9.9	+12.1 to -12.0

V_E is the volume determined by the metric measurement procedure and the elliptic model 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.

included in upper or lower extremity lymphedema assessments. Exclusion of hand or foot volumes can under or over estimate therapeutic progress. Recently, a metric measurement and calculation algorithm procedure that accurately determines foot volume has been described (10), but no similar procedure for the assessment of hand volume has been evaluated. Thus, our goal was to develop and test a metric measurement procedure and algorithm that could be used by the practicing therapist to estimate hand volumes using readily available and inexpensive tools. The results indicate that the most accurate metric measurement procedure uses a caliper to measure hand dimensions from which hand volume is calculated according to a mathematical algorithm based on an elliptical frustum model.

Thus, one important result of this study is the demonstration that hand volumes determined using the elliptic model, but not the trapezoidal or circular frustum model, compare favorably with hand volumes determined by water displacement. The overestimation in absolute volume demonstrated by the trapezoidal and circular frustum model and the reduced correlation to water displacement determined volumes is a direct result of the mismatch between the hand shape and the assumed cross sectional areas for these approaches. In contrast, the use of the elliptical model, which more closely matches the hand shape, resulted in near identical overall hand volume estimates and showed the best correlation with the water displacement volume.

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 (11). 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 hand and the other for the left hand. The present results indicate that under conditions in which differences of about ± 10% are acceptable, the elliptical frustum model based on width and depth measurements would be interchangeable with the water displacement method for assessing hand volume.

Independent of whether the methods are viewed as being interchangeable, the present results indicate that the V_E method can be a useful alternative to water displacement when hand volumes are needed, and 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 hand volumes obtained by the elliptic model and water displacement methods provides a quantitative basis for this approach. Although the present data indicates the utility of using the V_E method, it does not rule out the possibility that some clinics that use the V_C or V_T methods may find them sufficiently reproducible to measure changes due to treatment.

One limitation of the present study is the fact that none of the hands measured were significantly edematous. As a consequence, we can not yet provide definitive statements as to the full range of applicability of the algorithm. However, the results of measurements on the hand model, in which the model shape was varied and various degrees of "edema" were simulated, suggest that the method may also closely parallel water displacement for these larger volumes and altered shape conditions.

In summary, the present method takes into account the shape of the hand and its deviation from circularity via separate width and depth measurements that are subse-quently integrated into a reasonable mathematical formulation that provides an accurate alternative to water displacement for estimating hand volume.

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