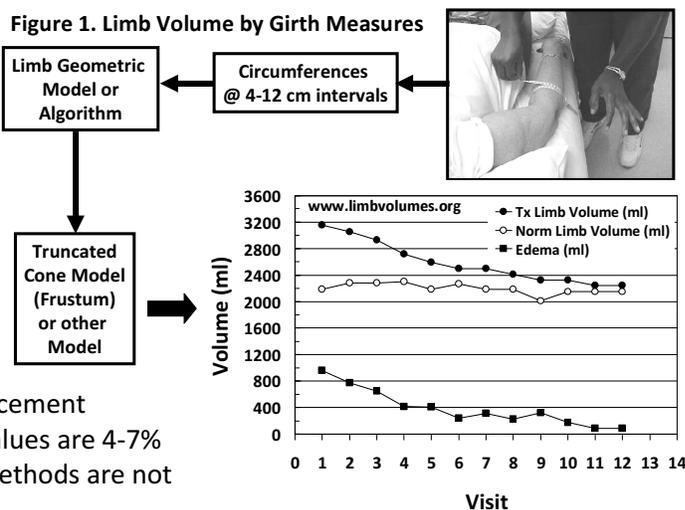
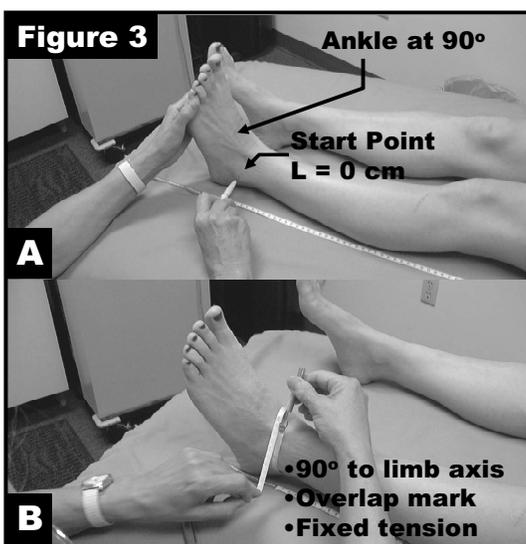
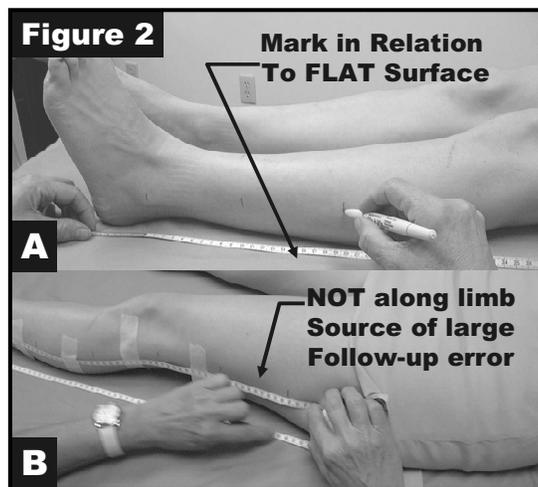


INTRODUCTION: Determining limb volume and its change based on tape-measure measurements of limb circumference (girth) is routinely done to assess efficacy of lymphedema therapy and other conditions for which limb volume changes are of importance. A typical generic procedure is schematized in Figure 1 that depicts manual girth measurements and their use to calculate and track limb volume changes. When girth measurements are done with consistent tension and limb position and measurement sites are standardized and an appropriate volume calculation algorithm is used, this method has shown itself to reliably reflect limb volumes (1-8). Volumes obtained are similar to those obtained by other methods including water displacement and automated optical methods (3, 9-11) but manual values are 4-7% less than determined by optical methods (10) and the methods are not generally interchangeable (7-9, 12).



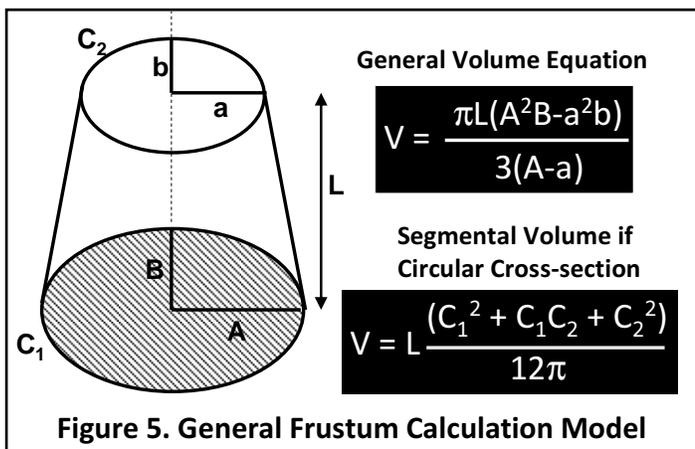
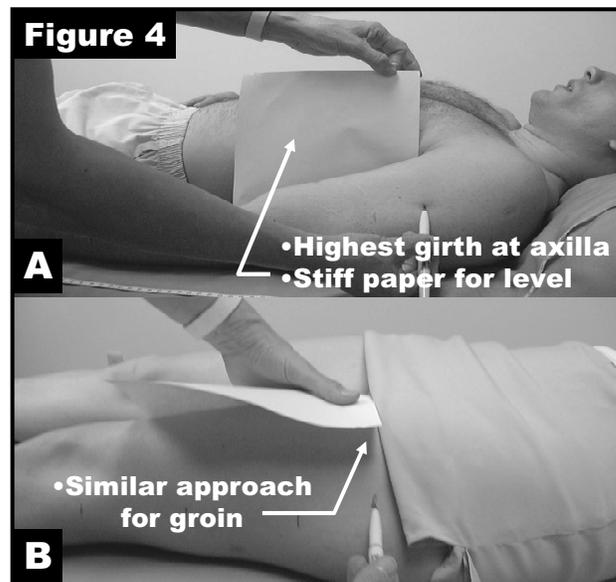
MARK and MEASURE METHODS: Factors to be considered in applying this method in general and importantly to the same patient over time include consistency of limb position, the number and location of girth measurements and limb cross-sectional shape changes. With respect to the measurement procedure itself, certain approaches can help to minimize measurement errors. One source of substantial follow-up measurement error is the way that limb sites are marked initially and at follow-up visits. An optimal way is to mark the sites in relation to a flat surface (Figure 2A) not along the limb (Figure 2B). Holding the tape against the limb will result in inaccurate follow-up measurements. If the curve of the normal leg in Figure 2 is followed, a two centimeter difference in site location results. On an edematous limb this discrepancy would even be greater. So if not marked properly, interval marks for repeated measurements will be at different levels causing volume change sequential errors since the limb contour changes with time and treatment. Another aspect that impacts sequential errors is the limb position and the details of the tape-measuring procedure. Because changes in



edema over time may alter visualization of anatomical landmarks it is useful to initially measure and record the distance from the nail bed of the middle finger to styloid process of the wrist, or from the sole of the foot to the middle of the lateral malleolus. When done the ankle should be flexed as shown in Figure 3. This site becomes the starting point for all subsequent girth measurements (for the leg). Other start points and sites have been suggested (13-16). When measuring girth it is useful to keep the tape at right angles to the limb length axis and to overlap the tape with the interval mark to increase consistency of subsequent measurements. Use of a spring-attached tape measure will help insure consistent firm tension. A slight indentation of loose skin may occur but this is to be expected.

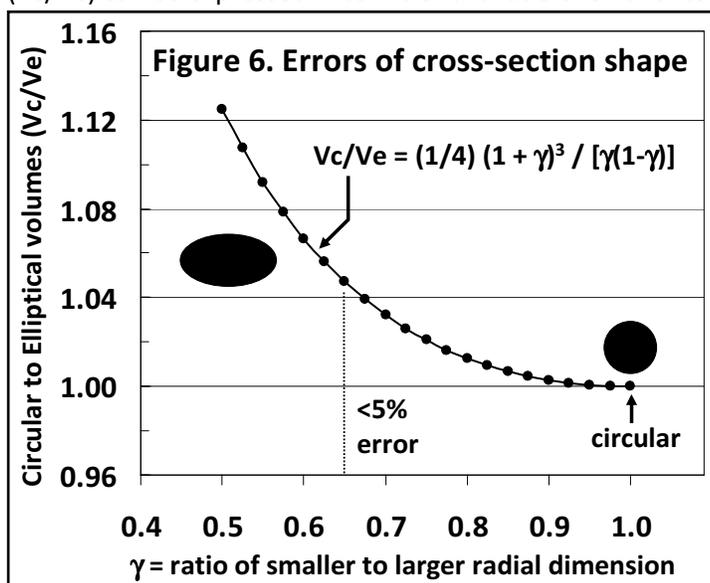
LIMB and SEGMENT LENGTHS: It is also important to define and maintain the upper-most measurement site as either the axilla or groin (Figure 4) or for certain circumstances at a fixed distance from the L = 0 start point. The number of segments to include in the volume calculation depends on whether arms or legs are being evaluated. Smaller intersegment lengths provide better resolution but values between 4 and 12 cm have been used with good outcomes (17, 18).

CALCULATION MODEL: In addition to possible errors associated with girth marking and measurements, the analytical method used to calculate limb volume from girth measurements should be considered. A commonly used equation is based on a circular frustum model of a limb segment. For this model an equation that relates segmental volume (Vs) to the measured circumferences (C₁ and C₂) at each end of the segment of length L is given by $V_s = (L/12\pi) \times (C_1^2 + C_1C_2 + C_2^2)$ as shown in Figure 5. The total limb volume is then determined as the sum of the

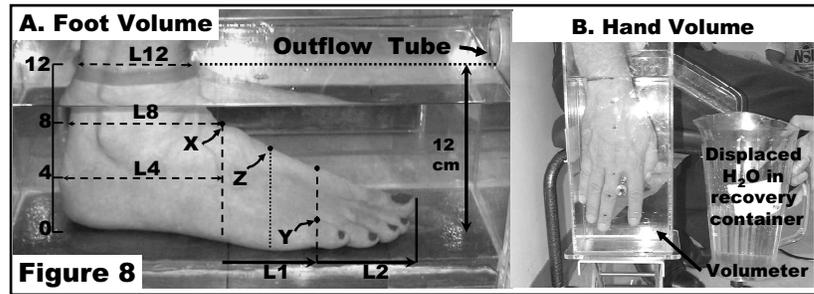
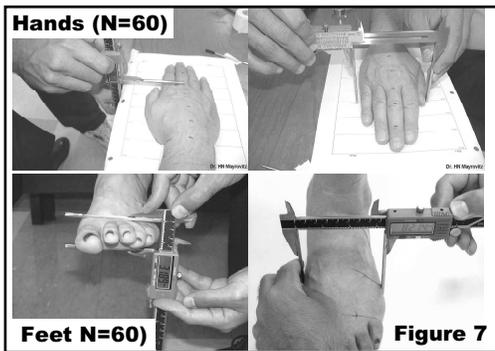


individual segment volumes. However, it is not generally true that the cross-section of a limb is exactly circular. A more general relationship for segmental volume calculations is needed. For sections that are elliptical the radial dimensions may be different (A, B and a, b in Figure 5). The appropriate general volume calculation equation is given in Figure 5. To directly apply this equation requires independent measures of limb diameters using for instance a digital micrometer of suitable design. But, most clinical measurements are of limb girth so it is useful to estimate the amount of error to be expected if the cross section deviates from true

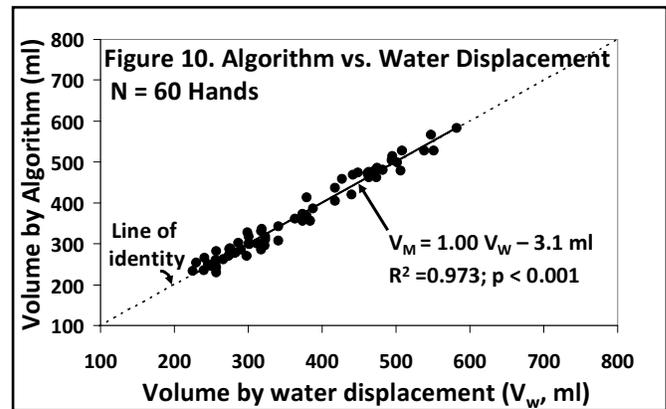
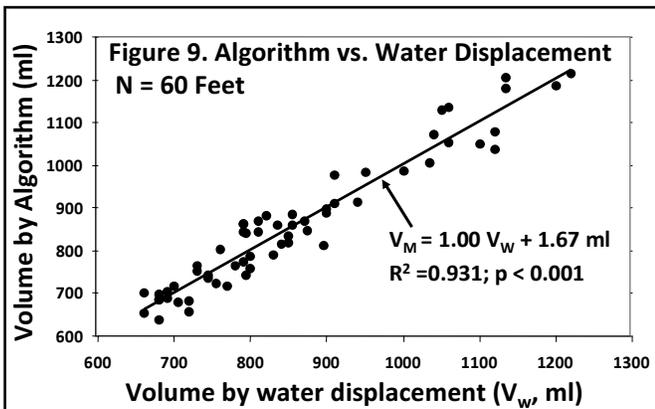
circular. This has been done (6) and a result is shown graphically in Figure 6. The ratio of volumes calculated on the basis of a circular cross section to an elliptical one (V_c/V_e) can be expressed in terms of the ratio of smaller to larger radial dimension (γ) and graphed as shown. The result indicates that for γ values >= 0.65 the error will be less than 5%. The conclusion then would be that the model is useful for limb calculations that do not significantly differ from circularity as defined by the γ value. However, the use of this, or other calculation models (12) to determine foot or hand volumes as part of overall limb volume assessments, is of little or no value. In fact one of this methods limitations had been the difficulty of accurately including foot or hand volume to overall limb volume whereas other methods such as water displacement (1, 5, 7, 12, 19) intrinsically include hand or foot as part of the measurement. However, recently developed algorithms appear to suitably solve this problem as demonstrated by comparisons with volumes measured by water displacement (20, 21) as briefly described in the next section.



HAND and FOOT VOLUMES: Multiple metric measurements of hands and feet were made (20, 21) in 60 normal subjects as partially illustrated in Figure 7. Foot and hand volumes were then determined by water displacement as shown in Figure 8 (A & B). Metric-based volume algorithms were then developed that minimized the difference between calculated volumes and volumes by water displacement.



Results of these algorithms show remarkable correlations with volumes determined by water displacement as shown in Figures 9 and 10 for feet and hands respectively. Further analyses using the Bland – Altman procedure (22) showed a mean difference between methods of $0.21 \pm 4.64\%$ with limits of agreement (LOA) of $\pm 9.28\%$ for feet (20) and a mean difference of $0.9 \pm 4.9\%$ with an LOA of $\pm 9.8\%$ for hands (21). Fortunately implementation of the associated algorithms into a software package has been achieved and is widely available (www.limbvolumes.org).



DISCUSSION and CONCLUSIONS

In summary, this report has tried to illustrate and further clarify some of the several factors that relate to limb volume determination based on manually made limb girth measurements and their subsequent use in assessing limb volumes. It may be concluded that the following apply. [1] Use of girth measurements to obtain limb volumes can be a useful and reliable method to assess changes in edema and lymphedema over time and with various treatments. [2] Accuracy and reliability depend on careful attention to detail in the measurement process. [3] Utility and versatility is enhanced via the use of a suitable calculation algorithm that adequately takes into account limb cross-sectional shape and also appropriately takes into account hand or foot volumes. [4] Most literature studies indicate that this method of volume determination compares well with other methods including water displacement and optical methods but in general the methods though highly correlated are not fully interchangeable. [5] Intersegment length (Ls) to use is a balance between needed resolution and accuracy and clinical time expenditure permissible. Segment lengths from 4 – 12 cm may be used depending on if arm or leg and extent of uniformity of the limb contour. [6] Although not specifically related to the method used, accuracy and repeatability considerations dictate that contralateral limb measurements be done at each follow-up visit. This point has been previously emphasized (1, 23, 24) but is often neglected. Not including visit-specific contralateral limb measurements has resulted in overestimates of edema reduction of 25-27% (18).

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