Measurement Decisions for Clinical Assessment of Limb Volume Changes in Patients With Bilateral and Unilateral Limb Edema

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Background and Purpose

Therapy-related changes in limb volumes often are estimated using summated segmental volumes based on adjacent circumference measurements. The purposes of this study were: (1) to determine the effect of different segment lengths on calculated volume reductions after complete decongestive therapy and (2) to determine the effect of excluding posttherapy control limb volumes on calculated reductions in edema volume in patients with unilateral limb lymphedema.

Subjects

This two-part retrospective study was conducted using data from patients with bilateral leg lymphedema (n=70) and data from patients with unilateral arm lymphedema (n=75) and patients with unilateral leg lymphedema (n=45).

Methods

For the bilateral leg lymphedema group, pretreatment to posttreatment changes in limb volume were determined using segment lengths of 4, 8, and 12 cm. For the unilateral lymphedema group, pretreatment to posttreatment changes in edema volume were determined and compared using or not using posttreatment control limb volumes.

Results

Bilateral leg volume changes were similar for all segment lengths but not significantly different from each other. Unilateral edema volume changes were significantly overestimated in both arms and legs when posttherapy control limb volumes were not used.

Discussion and Conclusion

The results indicate that segment lengths of 4 cm generally are not needed to obtain adequate estimates of leg volume changes. Both limb volumes should be measured to properly assess therapeutic outcomes in patients with unilateral limb lymphedema.

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Treatment outcomes of therapy for limb edema and lymphedema with respect to changes in edema volume often are assessed in the clinic based on limb circumferences, which are used to estimate limb volume changes from suitable geometric models and mathematical formulas or algorithms.[1-4] Previous work has established the validity of such circumference-based measurements as good estimators of arm and leg volumes,[5-9] although different algorithms may be needed for volume determinations of the hand[10] and foot.[11] Determination of lymphedematous arm volumes based on circumferential methods has been reported to correlate highly with volumes determined by water displacement, with Pearson correlation coefficients (r) ranging from .97 to .99.[5,8,9] Circumference-based volume determinations of 19 lymphedematous arms by 2 evaluators resulted in excellent interrater reliability, with interclass correlation coefficients of .99 when a segment length of 3, 6, or 9 cm was used[8] and .97 to .99 when 5 anatomical landmarked based circumferences were used.[9] Intrarrater reliability, based on 2 evaluators making repeat measurements, also was excellent, yielding an interclass correlation coefficient of .99 when measurements were taken at 3, 6, or 9 cm[8] or at 4- and 8-cm[7] separations. Thus, circumference-based measures of limb volume provide a rapid and valid way to evaluate limb volume changes in a clinical environment as an alternative to water displacement or other, more sophisticated methods.

In clinical practice, application of circumference-based methods to determine limb volume requires a decision as to the number of limb circumference measurements to be made. Segment lengths (distance between consecutive circumference measurements) that have been used to track limb volume changes include 4 cm,[3] 5 cm,[12] and 10 cm.[13,14] Using larger segment lengths means fewer required circumference measurements and fewer segmental volumes that need to be determined, which, in a busy clinic, may mean a considerable saving of time. However, with one possible exception,[15] there has been little systematic study of the effect of chosen segment lengths on estimated changes in limb volume. Thus, one of our goals was to investigate the extent to which estimated outcomes of lymphedema therapy are affected by choice of segment length. This analysis, designated as study A, was done retrospectively based on data previously obtained from 70 patients with bilateral lower-extremity lymphedema who had previously been treated by certified lymphedema therapists in a single lymphedema treatment center. The standard protocol for the clinic measurement was to measure circumferences at 4-cm intervals along the limb.

When limb lymphedema is unilateral, a second decision that needs to be made is how to best use the nonaffected limb's volume in the determination of edema volume reduction. Outcomes of therapy for unilateral limb lymphedema are sometimes determined using limb volumes of affected and control limbs to calculate changes in edema volume from pretreatment values through end-treatment values. Based on personal experience and discussions with many therapists, it appears that some clinics measure the control limb at all visits but other clinics measure it only at initial visits and use these initial values to determine final edema volumes. Not measuring control limb volume at each visit also is timesaving. However, the effect of using a single pretreatment control limb volume as a reference from which final posttherapy edema volume is determined has not been systematically studied. Thus, our second goal was to evaluate and compare edema volume outcomes based on inclusion and exclusion of end-therapy control limb volumes. This analysis, designated as study B, was done based on retrospective data from patients with unilateral lymphedema of the arms (n=75) and legs (n=45) who had been treated at the same lymphedema treatment center by experienced certified lymphedema therapists.

Data sets used in the analyses were completely de-identified by clinic personnel prior to analysis except for measured numerical values, sex, and diagnosis of lymphedema origin.

Method
Study A
Based on retrospective data from 70 patients with bilateral leg lymphedema (24 male, 46 female; mean age=74.5 years, SD=12.5, range= 26–104), leg volumes of each leg and the change in leg volume with therapy were determined retrospectively using circumference separations previously made on all legs at 4-cm intervals. For this group, lymphedema etiology was: gynecological surgery (n=18), prostate surgery (n=6), chronic venous insufficiency with or without venous ulcers (n=22), other surgeries or conditions (n=13), and unknown origin (n=11).

Original circumference data were obtained from tape measure measurements during each patient's clinical visits, starting at the ankle and at 4-cm intervals extending up the leg toward the groin. Each circumference measurement was done once. Two experienced certified lymphedema therapists were involved in the measurements for study A and for study B described subsequently. In general, any given patient would be treated and measured by the same therapist throughout the patient's

course of therapy. The exact distribution of the number of patients evaluated by each therapist is unknown but was approximately equally divided. The retrospective analysis determined leg volumes based on the measured 4-cm separations and also by using 8- and 12-cm separations derived by excluding in the volume calculation appropriate intermediate measured circumference values. For each of the separations, volumes were determined before treatment and after at least 10 complete decongestive physical therapy (CDP) treatments using a truncated-cone model and validated automated software.*

For this algorithm, the segmental volume (V_S) is determined by the formula:

$$V_S = L/12\pi(C_1^2 + C_1C_2 + C_2^2),$$

where C_1 and C_2 are the measured circumferences at either end of the chosen segment of length (L). This formula is the same as that used in previous studies that have demonstrated its accuracy.[5,7–9] The limb volume of interest was determined by the sum of the segment volumes. Pretreatment and posttreatment leg volumes, determined on the basis of the 4-, 8-, and 12-cm length segments, were compared using a general linear model for repeated measures with *post hoc* Bonferroni tests for within-subject differences after adjustment for multiple comparisons using a statistical software package (SPSS, version 9.0).[†] Analyses were done on right and left legs independently (n=70), with results of both analyses presented for completeness. Outcome efficacy of the therapy, which is the primary clinical parameter of interest to patient and

therapist, was assessed by comparing calculated leg volume reductions for each of the 3 circumference separations for each leg separately.

Study B
This analysis was based on retrospective data from 75 female patients (mean age=73.1 years, SD=10.7, range=46–93) with unilateral arm lymphedema that developed secondary to treatment for breast cancer and from 45 patients (22 male, 23 female; mean age=62.5, SD=12.2, range=33–79) with unilateral leg lymphedema. For the unilateral arm lymphedema group, etiology: mastectomy (n=24), mastectomy + radiation (n=30), lumpectomy (n=10), and lumpectomy + radiation (n=11). For the unilateral leg lymphedema group, etiology was: gynecological or prostate surgery for cancer (n=24), gynecological or prostate surgery + radiation (n=16), chronic venous insufficiency (n=3), and unknown origin (n=2).

Limb volumes of affected limbs (V_A) and contralateral control limbs (V_C) were determined based on previously measured limb circumferences at 4-cm intervals before (V_1) and after (V_2) 10 CDP sessions using circumference measurements starting at either wrist or ankle and progressing toward the axilla or groin. Limb volumes were determined from circumferences using the truncated-cone model method previously described. Initial edema volume (E_{V1}) was calculated as the difference between limb volumes ($V_A - V_C$) prior to treatment. End-treatment edema volume was calculated as the difference between limb volumes at the end of treatment using both end-treatment limb values ($V_{A2} - V_{C2}$) and was designated as E_{V2}. When end-treatment edema volume was calculated using the control limb's pretreatment value as the reference value ($V_{A2} - V_{C1}$), it was designated as E'_{V2}. Pretreatment percentage of

edema was calculated as $100 \times (V_{A1} - V_{C1})/V_{C1}$, and percentage of reduction in edema from its pretreatment value to its posttreatment value was determined as $100 \times$ (calculated change in edema volume/pretreatment edema volume). Comparisons of differences between limb volumes and E_{V2} and E'_{V2} were done using paired *t* tests. All numeric results are presented as means and standard deviations unless noted otherwise.

Results
Study A—Segment Length and Volume Reductions
Overall pretreatment and posttreatment leg volumes determined for each leg are presented as mean values and standard deviations in Table 1. Right and left leg volumes, compared at corresponding circumference separations (4, 8, or 12 cm), were similar, with no significant difference between left and right leg volumes ($P>.5$). Measurements of limb volume reduction, either in milliliters or as a percentage of the pretreatment value, which are primary clinical outcome measures, were not significantly different among the 3 separations used to calculate volume ($P>.5$).

Because the mean values of pretreatment leg volumes appeared to trend upward with increasing separation between circumference measurements (Tab. 1), a general linear analysis for repeated measures was done to test for an overall volume difference among separations. Results of this ancillary analysis revealed a highly significant overall difference ($P<.0009$). Subsequent *post hoc* analyses revealed that paired differences between volumes determined using a 4-cm separation were 28 mL less than those determined using an 8-cm separation ($P=.003$) and 79 mL less than those determined using a 12-cm separation ($P<.001$). The volume at the 8-cm separation was 52 mL less than that at the 12-cm sepa-

Table 1.
Leg Volumes and Reductions Based on Different Segment Lengths[a]

Segment Length	Right Leg (n=70)			
	Volume (mL)		Volume Reduction	
	Pretreatment	Posttreatment	mL	%
4 cm	6,658±2,491	5,453±1,954	1,204±775	17.6±7.0
8 cm	6,681±2,511	5,477±1,969	1,205±803	17.5±7.2
12 cm	6,762±2,560	5,570±2,013	1,248±823	17.9±7.3
Segment Length	Left Leg (n=70)			
	Volume (mL)		Volume Reduction	
	Pretreatment	Posttreatment	mL	%
4 cm	6,639±2,490	5,477±1,998	1,162±787	16.9±7.3
8 cm	6,670±2,499	5,515±2,026	1,155±766	16.8±7.3
12 cm	6,728±2,508	5,537±2,004	1,254±738	16.9±6.8

[a] Data entries are mean (±SD) for 70 patients with bilateral limb lymphedema. All posttreatment volumes are significantly less than corresponding pretreatment volumes ($P<.001$). Volume reductions (in milliliters and as percentage of reduction) for each leg calculated for 4-, 8-, and 12-cm segment lengths were not significantly different from each other ($P>.5$).

ration ($P=.009$). Thus, although these differences were small, they indicate a significant trend for larger volume estimates with increasing separations between circumference measurements.

Study B—Control Limb and Edema Volume Reductions

For the arm lymphedema group, the affected arm volume prior to treatment was 3,367±1,115 mL, which decreased to 2,930±963 mL at the end of treatment ($P<.0001$). Control arms of this group had an initial volume of 2,428±949 mL, which decreased to 2,359±877 mL at the end of treatment ($P=.002$).

Corresponding edema volumes and their percentage changes are summarized in Table 2. Edema volume at the end of treatment, obtained using end-treatment control arms as the reference (E_{V2}), was significantly greater than edema volume based on using just pretreatment control arms as the reference (E'_{V2}) ($P=.002$). These overall differences were attributable to the distribution of pretreatment to posttreatment changes in the control arm volume, which, as shown in Figure 1A, had a preponderance of volume decreases that resulted in an overall average decrease of 70±190 mL. The corresponding percentage decreases had a similar

distribution pattern, as shown in Figure 2A, which resulted in an overall average decrease of 2.3%±6.8%. The number of control arms demonstrating a volume decrease greater than 4% of their initial value was 28 (37.3%), and the number demonstrating a volume increase greater than 4% was 10 (13.3%). To determine whether changes in control arm volume were related to the initial volume, pretreatment to posttreatment control arm volume changes were regressed on control arm pretreatment volumes. Results revealed a weak ($r^2=.12$), but statistically significant ($P<.05$), inverse relationship.

Table 2.
Edema Volumes and Reductions in Unilateral Limb Lymphedema[a]

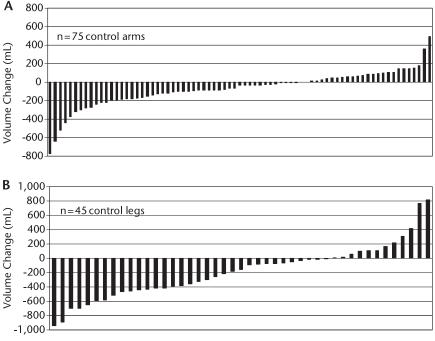| Limbs	Pretreatment Edema Volume		Posttreatment Edema Volume (mL)		Reduction in Edema Volume (%)	
	mL	%	E_{V2}	E'_{V2}	E_{V2}	E'_{V2}
Arms	939±567	42.7±30.2	571±380	502±414	39.2±26.4	49.5±30.7
Legs	2,272±2,302	30.6±29.5	1,388±1,811	1,206±1,778	47.0±35.6	60.0±37.3

[a] Data entries are mean (±SD) for 75 arm pairs and 45 leg pairs. Pretreatment edema volumes (milliliters and percentage) are those measured prior to start of therapy. E_{V2}=edema volume (milliliters and percentage) calculated using pretreatment and posttreatment control limb volumes. E'_{V2}=edema volume (milliliters and percentage) calculated using only the pretreatment control limb volume. Posttreatment edema volume (based on either E_{V2} or E'_{V2}) was significantly less than pretreatment edema volume ($P<.001$). Posttreatment edema volumes (in milliliters) obtained using E_{V2} were significantly greater than edema volumes obtained using E'_{V2} ($P=.002$). Reductions in edema volume (percentage) determined using E_{V2} were significantly less than reductions in edema volume obtained using E'_{V2} ($P=.002$).

For the leg lymphedema group, the affected leg volume prior to treatment was 10,053±3,434 mL, which decreased to 8,987±2,966 mL at the end of treatment (P<.0001). Control legs of this group had an initial volume of 7,780±2,292 mL, which decreased to 7,599±2,241 mL at the end of treatment (P=.002).

The edema volume at the end of treatment, obtained using end-treatment control legs as the reference (E_{V2}), was significantly greater than edema volume based on using just pretreatment control legs as the reference (E'_{V2}) (P=.002). Corresponding edema volumes and their percentage changes are summarized in Table 2. As in the case of the arms, these overall differences were attributable to the distribution of pretreatment to posttreatment changes in the control leg volume, which, as shown in Figure 1B, had a preponderance of volume decreases resulting in an average decrease of 181±375 mL. The corresponding percentage decreases had a similar distribution pattern, as shown in Figure 2B, that resulted in an overall average decrease of 2.2%±4.6%. The number of control legs demonstrating a volume decrease greater than 4% of their initial value was 20 (44.4%), and the number demonstrating an increase greater than 4% was 4 (8.9%). To determine whether changes in control leg volume were related to the initial volume, pretreatment to posttreatment control leg volume changes were regressed on control leg pretreatment volumes. Results revealed no statistically significant relationship to control leg pretreatment volumes (r^2=.046, P=.16).
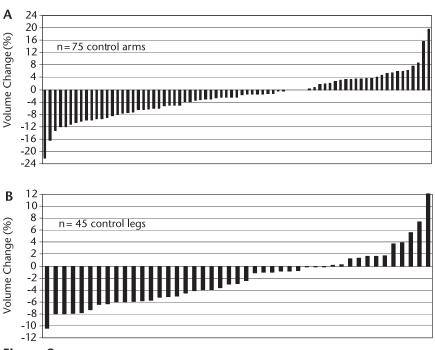
Discussion and Conclusions

The main result of study A indicates that there was little difference in outcome estimates resulting from CDP using 4-, 8-, and 12-cm segment lengths to determine leg volume re-

Figure 1.
Distribution of changes in control limb volumes from pretreatment to posttreatment: (A) arms, (B) legs. Negative values are decreases in volume.

Figure 2.
Distribution of percentage changes in control limb volumes from pretreatment to posttreatment: (A) arms, (B) legs. Negative values are decreases.

ductions. This was true despite the fact that the absolute leg volume estimates tended to be slightly larger when greater segment lengths were used for the leg volume calculation. A somewhat similar segment-length dependency has been reported in measurements of lymphedematous arms when a circumference-based cylindrical model was used for volume estimates.[8] In that study, when segment lengths of 6 and 9 cm were used, the circumference-based volume estimate exceeded the water displacement estimate, whereas the reverse was true for a 3-cm separation. However, because it is not absolute leg volume that is generally of interest, but rather the amount of volume change that accompanies therapy that is important to patient and therapist, our main finding suggests that any of the segment lengths could be satisfactorily used as long as a chosen segment length is consistently used throughout an evaluation interval.

The finding that there was no difference between the 8- and 12-cm outcomes suggests that a segment length of 10 cm also may be well suited to obtain adequate outcome estimates combined with reduced evaluation time. These results are consistent with findings reported for measurements of unilateral lymphedematous arms using 10- and 3.8-cm segment lengths.[15] These authors found a small difference in absolute volumes between the 2 methods, but—as in the present case for legs—there was no significant difference in therapy-related changes in edema volume of the 15 patients they evaluated. They concluded that "10-cm and 4-cm methods give very comparable results and are equally valid."[15(p164)]

None of the present results implicitly consider or address the issue of the absolute accuracy of the circumference-based method for es-

timating limb volumes; this issue has been widely discussed.[5,7–9,16] Rather, the results specifically apply to situations in which the circumference-based method is chosen to be used in preference to other methods of measuring leg volume changes, such as by water displacement or automated optically based methods.[6,17] It may be noted, however, that limb volumes determined by the manual circumference-based method compare well with those determined by water displacement[5,7,8] and by optically based automated methods.[3,17]

The main result of study B indicates that when evaluating therapy-related changes in edema volume, inclusion of the contralateral limb each time that the affected limb is measured yields a significantly different estimate of edema reduction than if the sole reference for calculating edema volume is the contralateral limb volume measured prior to treatment. In the present case, nonuse of the end-treatment contralateral limb led to a significant overestimation of the overall effectiveness of the treatment for arms and for legs. This was due to the fact that, on average, control limbs exhibited a significant reduction in their volume from their pre-treatment value. This was true for arms and for legs. The significant overestimation of treatment effectiveness, as represented by the percentage of reduction in initial edema volume (Tab. 2), occurred because of the way in which individual changes were distributed. Such changes might occur because of many factors, including normal physiological variations and systemic changes that affect both normal and affected limbs. Because we do not know what factors determine whether the contralateral arm volume will decrease or increase, we believe that the implication of these findings is that both limb volumes should be measured to properly assess therapeutic outcomes in

patients with unilateral limb lymphedema.

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