ORIGINAL INVESTIGATION

Assessment of Limb Volume by Manual and Automated Methods in Patients with Limb Edema or Lymphedema

Harvey N. Mayrovitz, PhD; Nancy Sims, RN, LMT, MLDT; and John Macdonald, MD, FACS

ABSTRACT

OBJECTIVE: Limb edema and lymphedema due to chronic venous insufficiency or mastectomy and radiotherapy negatively effects patient well-being, lifestyle, tissue blood flow, oxygenation, and wound healing. Assessment of the efficacy of volume reduction therapy requires adequate estimation of progressive limb-segment volume changes, which are usually done manually with a tape measure. This study investigated the possibility that an optoelectronic automated method—a potentially less time-consuming and less operator-dependent method—might provide adequate limb volume assessment.

DESIGN: A total of 184 manual and automated measurements of limb volume were made in 62 consecutive patients with limb edema of the legs (n=142) and arms (n=42).

SETTING: Clinical center

RESULTS: Comparisons between automated and manual methods showed that intermethod volume estimates were highly correlated (4.14 ± 0.54% for legs; 6.97 ± 1.18% for arms). In patients with unilateral edema, the affected limb's percentage of edema was virtually identical when estimated by each method.

CONCLUSION: These findings show that the automated method of measuring limb volume is a useful alternative in suitable patients in clinical and research applications.

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Lower extremity edema due to chronic venous insufficiency[1] and limb lymphedema due to mastectomy and radiotherapy[2,3] have widespread effects on patient well-being and lifestyle. The negative impact of edema and lymphedema on local blood flow, tissue oxygenation, and wound healing are well recognized.[4-7] It has been estimated that approximately 150 million people worldwide have some form of lymphedema.[8] Until recently, lymphedema was viewed as essentially untreatable, and most affected individuals endured their progressively worsening condition[9] without therapy. However, this view is changing as the techniques and results of a few dedicated lymphedema clinics are becoming more widely known.[8,10-12]

A form of physiotherapy that has shown promise and effectiveness for lymphedema is variously termed complex physical therapy[8]; complex lymphedema therapy[11]; and complete, combined, and complex decongestive physiotherapy (CDP).[12] The CDP approach, originally introduced by the Foldis,[13-14] is a 2-phase treatment program consisting of a drainage phase that lasts for weeks and a conservation and optimization phase that lasts for years.[10] The drainage phase is performed in an outpatient setting by specially trained physiotherapists with physician collaboration and has 4 major components: (1) meticulous skin care, (2) manual lymph drainage, (3) limb compression bandaging, and (4) a specific exercise program.

One measure of the effectiveness of CDP is the quantitative assessment of the rate and amount of limb-volume reduction, typically done by repeatedly checking limb circumference with a tape measure during the course of treatment. Measurements are usually taken at 4- to 5-cm intervals over the length of each limb, with the circumference values used to estimate each limb-segment volume. This procedure is sufficiently accurate for many clinical purposes,[15] however, it is quite time-consuming and operator-dependent. In addition, limb-circumference measurements are required for both limbs,

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regardless of whether the patient has bilateral or unilateral edema.

A new optoelectronic system that uses infrared beams to rapidly and automatically estimate limb volume has received preliminary engineering evaluations for several applications, including measurement of limb volume.[16] If this automated system proves to be sufficiently accurate for clinical purposes, the clinician's time and effort could be devoted to more productive patient activities. In addition, this automated system facilitates documentation needs and could potentially enhance the reliability of measurements.

The goal of this study was to determine how well estimates of limb volume measured by the automated method would compare with standard tape measure estimates of volume in patients with either lower or upper extremity edema or lymphedema.

METHODS

Subjects and protocol

The subjects of this study included 62 consecutive patients referred to an outpatient wound healing and lymphedema center for treatment of limb edema or lymphedema of the legs (n = 43) or arms (n = 19). Bilateral limb volume measurements were performed on patients during their initial pretreatment visit. In addition, 30 patients were remeasured at a follow-up visit after 8 to 10 treatments. A total of 184 measurements of limb volume were made; 142 in legs and 42 in arms. All participants signed an informed consent form approved by the institutional review board. Because volume measurement comparisons are the focus of this study, specific features of patient-by-patient etiology, disease duration, type, and other treatment details are not presented. However, all patients had CDP as part of their treatment.

Measurements of limb volume were performed by 1 of 3 lymphedema therapists using both a tape measure and the optoelectronic system. Each patient had the same therapist for repeated measurements.

Manual method of measurement

Using a tape measure, legs were measured with patients supine. The tape measure was placed flat on the supporting surface and legs were marked at 4-cm intervals from the sole of the foot to the groin. Circumference measurements were made from ankle to groin.

Arms were similarly measured; subjects were asked to make a fist and 4-cm increments were marked from the middle metacarpal-phalangeal joint to the axilla. Circumference measurements were made from wrist to axilla.

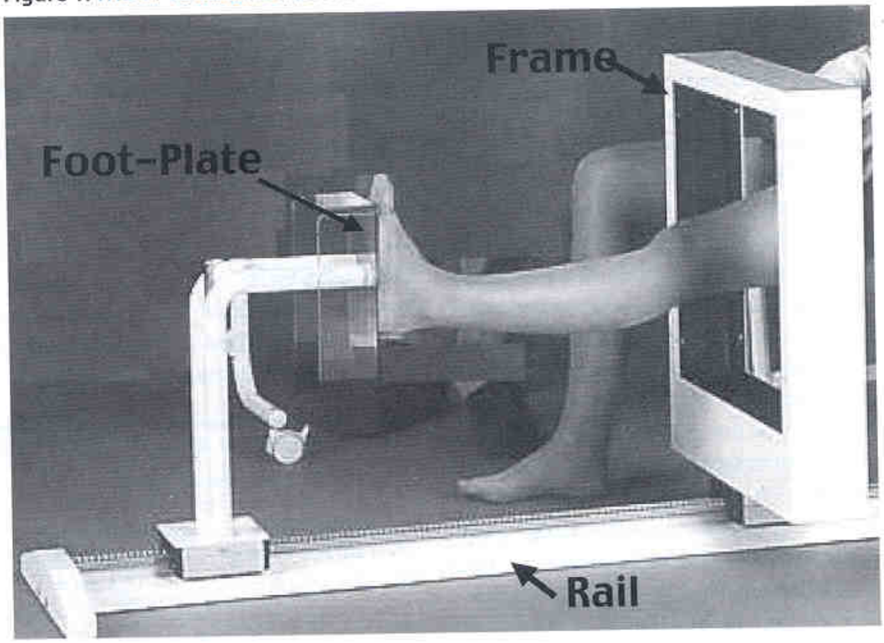
All circumference measurements were made with a Gulick tape measure with a spring attachment to ensure the same tension for each measurement.

Automated method of measurement

The optoelectronic system used in this study (Pero-System, Perometer Model 350S; Juzo, Inc, Cuyahoga Falls, OH; Figure 1) utilized infrared rays to capture the limb measurements. It consisted of a movable frame with embedded light emitters and detectors around its perimeter. The frame surrounded the limb and was rapidly moved along its length. The scanning procedure took less than 5 seconds—the time necessary to manually move the frame over the length of the limb. The frame position and the data obtained from the light obstructed by the limb were used to automatically calculate volume, girth profile, and girth at different positions of the limb. Volume was determined by calculating the elliptical cross-section area by any 2 perpendicular diameters measured by the frame. The cross-section area of each "slice" was multiplied by the width by which the black and white stripes on the rail were separated, resulting in the volume. Measurements were viewed graphically, stored in the computer, and printed. Segmental volumes were determined with an axial resolution of less than 5 mm.

When using the automated system for measuring leg volume, a subject was positioned with hips on the edge of the

Figure 1. THE OPTOELECTRONIC SYSTEM



seat and the unmeasured leg out to the side to obtain the maximum leg-length measurement. The subject's feet were positioned with the sole and heel flat against the foot-plate. The subject's leg was then positioned directly over the rail of the machine with the knee straight.

To measure arm volume, the subject was seated at a right angle to the axis of the machine. The subject was instructed to make a fist and lean toward the foot-plate to obtain the maximum arm-length measurement. The metacarpal-phalangeal joint and the flat surfaces of the fingers were positioned against the foot-plate, with the thumb in the superior position. The arm was then positioned directly over the rail of the machine with the elbow straight.

The frame (Figure 1) was moved along the rail, starting at the foot-plate, until it had crossed the full length of the limb. Data were automatically acquired by the computer and were saved or printed as desired. Segment volumes of measured limbs were obtained.

Limb volume calculations

For the manual method, the corresponding limb segmental volume (V_{SEG}) from 2 adjacent limb circumference values (C_1 and C_2 separated by L = 4-cm intervals) was calculated from the equation for a truncated cone model as $V_{SEG}=L(C1^2 + C_1C_2 + C2^2)/12\pi$. Total limb volume was calculated as the sum of all measured segments. This method for estimating limb volume has been shown to be essentially interchangeable with water displacement measurements.[17] For the automated method, segmental and total limb volumes were determined automatically by the instrumentation software, which processed the infrared light beam information. In patients with unilateral leg edema, the percentage of edema[15] was calculated from the limb volumes as percentage edema = (affected limb volume - control limb volume) x 100 (control limb volume) and was compared based on each method of volume measurement.

Table 1. COMPARISON OF MANUAL AND AUTOMATED VOLUMES

Limbs (N=184)	Automated Volume (L)	Tape Measure Volume (L)	Percentage Difference	Correlation Coefficient
Legs (n=142)	7.16 ± 0.17*	6.90 ± 0.17	4.14 ± 0.54	0.977
Arms (n=42)	2.70 ± 0.09*	2.53 ± 0.09	6.97 ± 1.18	0.961

Entries are volume (liters, mean ± sem). Automated estimates were slightly but significantly greater than manual estimates for both legs and for arms (* = P <.01).

Analysis

Limb volumes determined by automated and manual methods were compared using a paired t test, with legs and arms tested separately. The null hypothesis of no difference was rejected at a P value of .05 or less.

RESULTS

Table 1 summarizes the overall comparisons between limb volumes calculated from tape measure circumferences at 4-cm intervals (truncated cone model) compared with automated volume estimates of the same limbs. Highly correlated volume estimates from each method showed that automated measurements had a small but statistically significant (P <.01) greater volume estimate (mean differences = 0.25 ± 0.04 L for legs; 0.12 ± 0.02 L for arms). For patients with unilateral limb edema, there were no significant differences in percentage of edema volume as determined by the manual or automated methods at either visit (Table 2).

DISCUSSION

The main finding of this study demonstrates that a close relationship exists between limb-volume estimates obtained with a standard manual tape measure and with a relatively new automated system. Overall, the volume estimates obtained by manual and automated methods differed by less than 5% for legs and by less than 7% for arms. However, the automated method consistently and significantly (P <.01) estimated limb volumes at slightly higher values than did tape measure estimates.

In this study, it was possible to access and compare estimates of percentage of limb edema. No significant differences in volume estimates between methods were detected for either legs or arms of subjects with unilateral limb edema. In fact, mean values from manual and automated methods differed by less than 2% for legs and less than 5% for arms in these subjects. Limb volume and edema and their change following therapy are key clinical parameters that reflect treatment outcomes. Therefore, the findings of this study suggest that the automated method of measuring limb volume is useful for clinical assessments in suitable patients with either edema or lymphedema.

It is important to note that patients who are unable to keep their knee extended or have their foot consistently placed flat against the foot-plate are not good candidates for the automated system used in this study. However, after

Table 2. UNILATERAL EDEMA VOLUME AS PERCENTAGE OF UNAFFECTED LIMB

LEGS (n=32 pairs)		ARMS (n=24 pairs)	
Automated Percentage Edema	Tape Measure Percentage Edema	Automated Percentage Edema	Tape Measure Percentage Edema
14.2 ± 3.5	15.4 ± 4.4	19.5 ± 4.7	19.8 ± 4.6

Entries are percentage edema (mean ± sem). There was no significant difference between manual and automated estimates.

Table 3. METHODS FOR MEASURING LIMB VOLUME

Method/Description	Advantages	Disadvantages
Water displacement Limb is submerged in a basin of water and the amount of water displaced is measured to determine limb volume	• Gives accurate volumes, especially on irregularly shaped limbs	• Impractical for whole leg measurement • On repeated measurements, care must be taken to ensure that the same segment of limb is submerged • Equipment is bulky and must be disinfected with each use • Patients with moderate limitations of range-of-motion are difficult to assess • Not appropriate for use in patients with open wounds
Manual circumference measurement Tape measure is used to measure limb circumferences	• Reasonably priced, portable, and easy to use • Tension standardization can be achieved with a spring attachment • Whole legs and patients with limited range-of-motion can be measured	• Requires multiple separate bilateral measurements and the use of time-consuming mathematical calculations • Volume accuracy depends to some extent on the expertise of the measurer • Difficult to measure circumferences in exactly the same place each time
Optoelectric measurement Automated system that utilizes infrared rays to capture the measurements of the limb	• Quick and easy to use • Measurements automatically stored in a computer and can be printed, analyzed, or graphed • Segmental volumes easily obtained; measurements are obtained at 1/2-cm intervals, so irregularly shaped limbs can be accurately assessed • Segmental data is available for the entire limb, so any limb region's segment volume can be easily determined; different limb regions can be evaluated as the need arises	• Accuracy of measurements depends on proper positioning • Patients with limited range-of-motion may not be able to be positioned adequately in unit used in this study* • Initial cost is high ($19,500) but may be offset by staff time saved

*A newer vertical model is now available that simplifies positioning.

this study was completed, a vertical model became available to measure a patient's limbs while standing, circumventing patient-positioning issues.

Implications for clinical practice

Documenting outcomes has become increasingly important in today's health care environment. Measurement of limb volumes and changes following therapy are the most effective way to document the progress of edema or lymphedema therapy. There are several ways to measure limb volume and each has its own advantages and disadvantages. Table 3 summarizes these different methods for measuring limb volume.

As inroads toward successful lymphedema treatment have been made, there has been an increased awareness of available therapies and their positive outcomes.[18-22] In addition, the number of patients with lymphedema has dramatically increased—a trend that is anticipated to accelerate. Along with primary and secondary lymphedema, cancer surgery, total joint replacement, and cardiovascular surgery have greatly increased the number of lymphedema patients. This increased patient load combined with a renewed interest in treatment will spur new methodologies and modifications in lymphedema therapy.

Reliable and standardized documentation should be available for comparisons if appropriate clinical judgments are to be made and if alternative treatment outcomes are to be evaluated in investigative settings. In the case of limb edema, the measurement of limb volume and its change over time is the primary quantitative measure of treatment effectiveness. Although its initial cost may be a factor ($19,500), the automated system investigated in this study seems to offer an efficient and reproducible method for these purposes. The optoelectric system shows promise for both clinical and research applications for the measurement and documentation of limb volume. ●

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