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ORIGINAL REPORT

A Simple and Innovative Device to Measure Arm Volume at Home for Patients With Lymphedema After Breast Cancer

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ABSTRACT

Purpose
We designed an arm volumeter specifically for home use based on the water displacement method. The objective of this study was to determine its accuracy and precision, and compare it with a standard volumeter used in lymphedema clinics worldwide.

Patients and Methods
Using a standard model hospital volumeter and our own device, we took three consecutive measurements of 11 specially cast cylinders, which had known volumes ranging from 10mL to 4 L, and measurements of both arms of 15 volunteers.

Results
Measurements with both volumeters were highly accurate ($R^2 = 0.9999$) when compared with the known volumes of the cast cylinders, and were strongly correlated ($R^2 = 0.9974$) when each arm volume was compared between volumeters. Measurements with our volumeter were more precise both with the cylinders (average standard deviation [SD], 3.2 *v* 8 mL; $P = .0553$) and with the arms (average SD, 11.1 *v* 19 mL; $P = .0034$). Whereas the standard volumeter is expensive, fragile (acrylic), and prone to leaks, our volumeter is inexpensive, virtually indestructible, leak proof, and suitable for home use.

Conclusion
Arm volumes can be measured quickly and accurately at home using a simple, inexpensive, and robust device based on water displacement. Readily accessible arm volumetry at home may have widespread influence on the management of lymphedema after breast cancer.

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INTRODUCTION

Lymphedema is caused by the accumulation of protein-rich fluid and secondary increased oncotic pressure in soft tissues when lymph volume exceeds transport capabilities. It affects 15% to 30% of women after breast cancer surgery and radiation therapy.[1]

To observe arm volume, patients usually are instructed to measure the arm's circumference at specific points using a measuring tape. It is technically difficult to measure with one hand and ensure consistent tape tension on the skin. Because tape measurement is imprecise, only differences greater than 2 cm are considered clinically significant.[2,3] More importantly, a variation of 2 cm at one point, 1 cm at another, and so forth, is conceptually difficult to extrapolate to the number that is sought—the arm volume in milliliters.

Attempts have been made to extrapolate arm girth measurements to arrive at arm volume by a mathematical tour de force, assuming that the arm and hand are a series of cylinders, frustums, and trapezoid, but geometric extrapolation is too imprecise to be of clinical use to assess therapeutic interventions.[4] Other techniques such as perometry[5] and bioimpedance[6,7] are too expensive for home use.

The gold standard for arm volume measurement is the 2,000-year-old water displacement principle discovered by Archimedes. Unfortunately, the standard model water displacement arm volumeter is too large, fragile, cumbersome, and expensive for home use. Patients often do not have routine access to hospital volumeters outside a research setting.

We therefore designed an arm volumeter specifically to achieve optimal accuracy and precision, but which was conceived for home use. The objective of this study was to compare its accuracy, precision, and design features with that of a standard water displacement model.

PATIENTS AND METHODS

Standard Volumeter

The standard reference water displacement volumeter used in our study was an arm volumeter (Sammons Preston Rolyan, Bolingbrook, IL; Fig 1), parallelepiped in

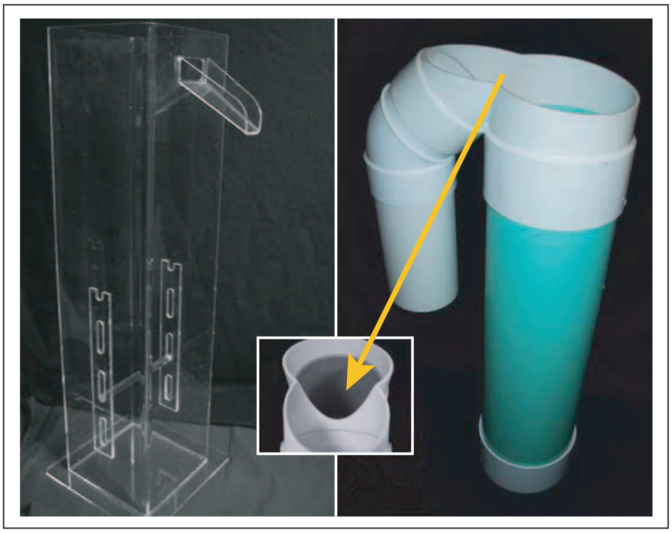

Fig 1. The standard model volumeter (Sammons Preston; Bollingbrook, IL) is on the left and our home use volumeter is on the right. Our volumeter is more precise because of the junction between the water cylinder and the spout (magnified view); it is lighter and easier to handle because it requires less water (10.6 *v* 22.5 L).

shape, made of methyl methacrylate ester polymer with solvent welded joints, measuring 17.5 cm wide by 17.5 cm diameter by 75 cm high with a volume of 22.5 L.

Design and Construction of Our Volumeter

After a period of trial and error and many prototypes, we arrived at the design depicted in Figure 1, a cylindrical water container with a cap on the bottom and an outflow spout on the top. The morphology of the junction between the container of water and the outflow spout was designed to minimize the size of the meniscus at the top of the cylindrical container, which we identified as an important determinant of precision during the early testing phase with prototypes. Simplicity and ease of handling for home use were major considerations during planning and construction, including cost and availability of materials, sturdiness, risk of leaks, risk of spout breakage, volume and weight of water required, ability to customize to arm length, axillary impediment at the top of the cylinder during arm immersion, and other issues such as rapidity of measurement and ease of disinfection. The cylindrical water container measures 15 cm diameter and 60 cm high (customizable) with a volume of 10.6 L, is made from readily available polyvinyl chloride (PVC) piping used in plumbing, and is welded using solvent glue made to resist high water pressures. With our volumeter, total time to take three consecutive measurements (including filling, emptying, and storing the volumeter; and preparing the collector pitcher and the scale) was approximately 15 minutes.

Measurement Procedure

The volumeter is filled with water at a temperature of 28 to 31°C (average 28°C in this study) to the level of the spout. When air bubbles and waves have subsided, the water is topped off until overflow begins, then stops, indicating that maximum water level is achieved. The volume (either the cast cylinder hanging from a fine metal wire or the arm of a volunteer) is slowly submerged into the full volumeter, causing the water to overflow through the spout. The amount of water displaced is equivalent to its volume. The displaced water is collected into a jug and weighed on a digital kitchen or postal scale with accuracy of 1 g. Water volume is derived from the weight based on the simple formula: 1 L of water weighs 1 kg (corrected for the weight of the pitcher). The displaced water volume is weighed because it is difficult to purchase large enough jugs with precise graduations and minimal meniscus effect and because smaller variations in volume are far more easily and accurately gauged by weighing.

Cylinders of Known Volume

Eleven cylinders of known volume (volume $= \pi r^2 H$; where r is radius and H is height) ranging from 10 mL to 4 L (10, 20, 50, 100, and 500 mL; 1, 2, 2.5, 3, 3.5, and 4 L) were constructed by casting plaster into cylindrical molds, coated with a thin layer of lacquer. Each cast cylinder was immersed three times in succession into each volumeter for a total of 66 measurements ($11 \times 3 \times 2$).

Volunteers

A total of 30 arm volumes were measured in 15 volunteers (mean age, 46 years) with a mean weight of 65 kg (range, 51 to 85 kg). The study was explained to all participants who signed an informed consent form; participants were free to withdraw from the study at any time. The study and consent form were approved by the hospital's institutional review board. With the

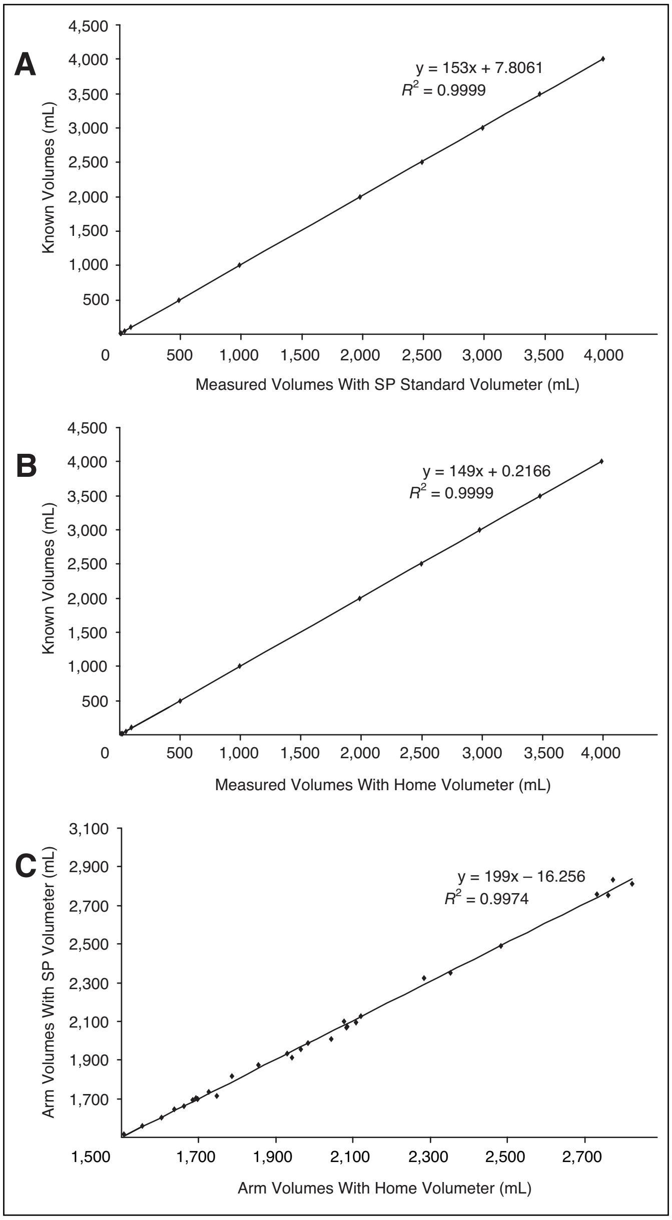

Fig 2. Scatterplots of the standard known volumes and the average measured volumes for each volumeter separately for the cast cylinders [(A) for the standard model volumeter; (B) for our home use volumeter], and (C) of the mean arm measurements with both volumeters. SP, Sammons Preston volumeter (Bolingbrook, IL).

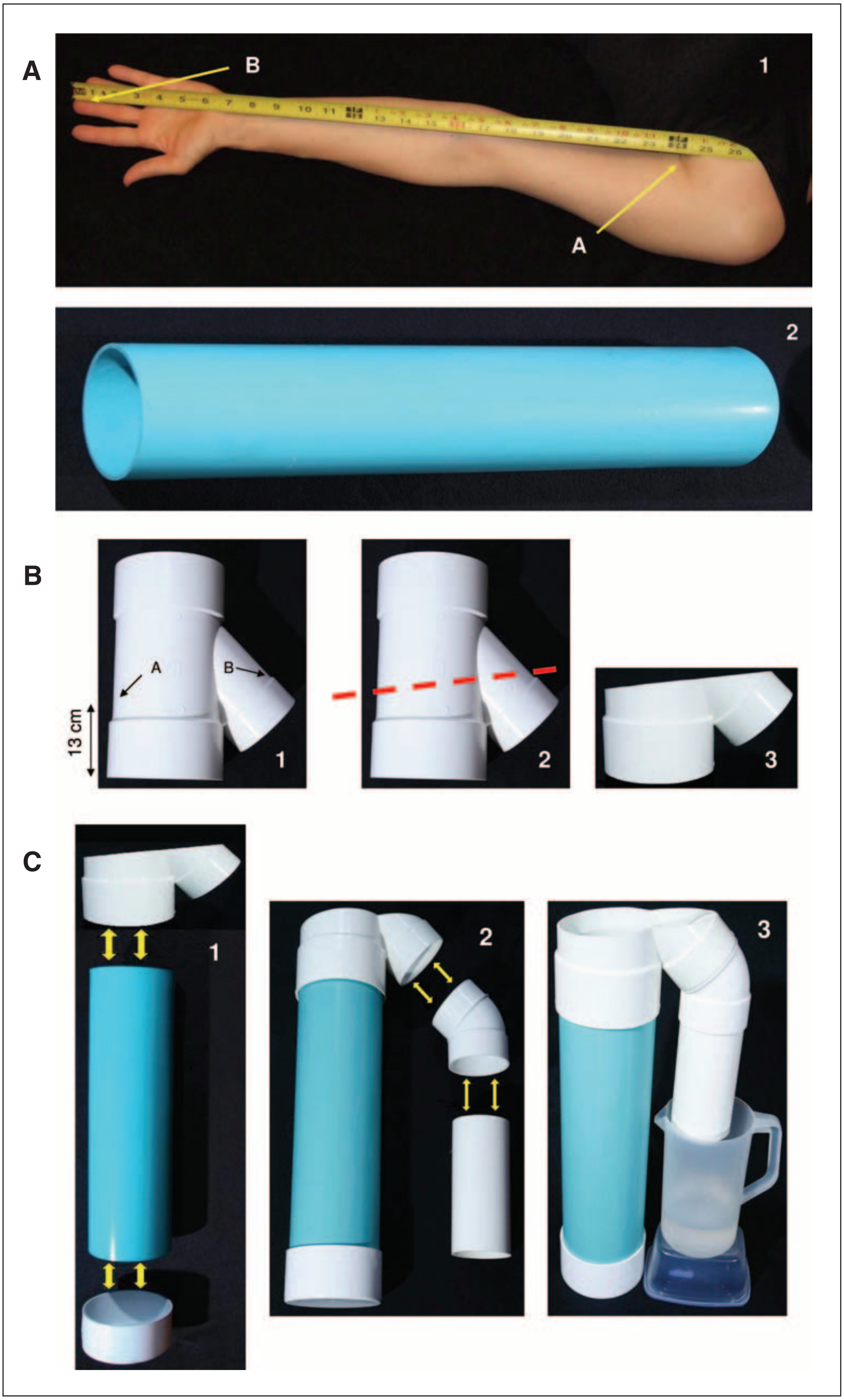

Fig 3. How to construct and use a home arm volumeter. (A, B) Preparation of parts, (C) assembly, and (D) arm volume measurement procedure, including a longitudinal cross-section view. (Continued on following page)

Fig 3. Continued

standard volumeter, participants were instructed to lower the arm slowly into the volumeter and to stop when the top of the volumeter came into contact with the axilla. Solely for the purpose of comparing the performance of the two volumeters, we added a supplementary step of making an ink mark on the proximal arm at the water line. With our volumeter, the depth of immersion of the arm was dictated by the ink mark. Each arm was measured three times in succession in each volumeter for a total of 180 measurements ($30 \times 2 \times 3$). The volumeters were disinfected between participants.

The role of the investigators (the author and an assistant) was limited to explaining the principles of water displacement, the design of the volumeter, and measurement procedure to the volunteers; making the ink mark as required to compare the two volumeters (but unnecessary for home use); observing the measurement; helping refill the volumeter between measurements; and carrying the filled pitcher to the scale (simply to lessen the time necessary to do 12 measurements per participant). The rationale of the volumeter is self-evident from its design; the most critical instruction was to remind the participant to immerse the arm slowly and gently to avoid splashing. The actual measurements were self-measurements (as opposed to measurements done by investigators); in other words, had the volunteers been lymphedema patients, they could have gone home with a volumeter and measured their arm at home without any additional instructions or coaching. Indeed, the reproducibility of measurements (ie, precision—the most important variable from a clinician's point of view) can be quantified by having the patient systematically measure arm volume three times in succession and determine the average standard deviation.

Statistical Analysis

Each measured volume (cast cylinder or arm) was expressed as mean ± standard deviation based on three consecutive measurements.

Accuracy. Scatterplots were created for the standard known volumes and the mean measured volumes for each volumeter separately for the cast cylinders (Figs 2A and 2B), and for the mean volume of each arm volume as measured by both volumeters in the volunteers (Fig 2C). Linear regression analysis and calculation of the correlation coefficient was performed on the scatterplots.

Precision. The average standard deviations on the measurements of both the cast cylinders and the arms were compared between both volumeters using a paired Student's *t* test. A *P* value of .05 was considered significant.

RESULTS

Accuracy

There was a high degree of correlation between the known and measured volumes of the cast cylinders for both the standard volumeter ($y = 1.0053x + 7.8061$; $R^2 = 0.9999$; where y is the known volume and x is the measured volume) and our volumeter ($y = 1.0049x + 0.2166$; $R^2 = 0.9999$; where y is the known volume and x is the measured volume), and between arm volume measurements by both volumeters ($y = 1.0099x - 16.256$; $R^2 = 0.9974$; where y is measurements with the standard Sammons Preston volumeter and x is measurements with our volumeter). The (−16 mL) y intercept is attributable to the systematic slight difference in depth of arm immersion between the two volumeters because of differences in design, and is unrelated to accuracy per se.

Precision

The average standard deviation tended to be smaller with our volumeter compared with the average standard volumeter for the cast cylinders (3 *v* 8 mL; $P = .0553$) and was significantly smaller with our volumeter when arm volumes were measured (11 *v* 19 mL; $P = .0034$).

DISCUSSION

Our study shows that arm volume can be measured quickly using a simple and robust device constructed from readily available and inexpensive plumbing materials. Measurements are as accurate as and more precise than those obtained with the standard hospital model volumeter. Our volumeter is designed specifically for home use, thereby eliminating the risk of transmission of bacterial and fungal skin infections—a serious concern for lymphedema patients. In the Appendix and Figure 3, we explain how to build the device, customized to arm length, and how to take arm volume measurements. Equipped with these technical specifications, individual patients or patient associations can approach a handyman or a local workshop to have the volumeter constructed. All pieces are made from standard PVC components that can be ordered and require only cutting, gluing, and fitting together.

In clinical lymphology, therapeutic interventions often are prescribed on the basis of clinical studies that look primarily at average responses in study populations.[8] Lymphedema patients spend time and money experimenting with an array of expensive and insufficiently tested therapies and devices, and often perform some form of self-therapy (self-massage and so on)[9] without clear evidence of effectiveness. With home volumetry, specific therapies and devices can be validated based on the patient's individual response. Increased volume due to aggravating factors (eg, summer heat, air travel, and so on) can be detected and reversed early.

Complex decongestive therapy (CDT) involves daily sessions of manual lymphatic drainage (a type of massage) and wrapping the arm with foam padding and multiple layers of low-stretch bandages worn for 24 hours a day for fixed and arbitrary periods of time, usually from 3 to 5 weeks. Although CDT is effective,[10,11] in the face of such a life disruption some patients delay for months or years any kind of treatment due to work or family obligations, the cost of therapy, the need to find temporary lodgings if they live far from the therapist, discomfort of bandaging during summer heat, and so on. Given that the most significant reduction in volume occurs during the first 7 to 14 days,[12,13] daily monitoring of arm volume will allow the therapist to identify when a plateau in volume reduction has been reached. This may shorten the duration of treatment markedly for many patients and ensure that the minority of patients who have a slower response (due to skin fibrosis) consider prolonging therapy.

Figure 4 depicts the volumetric chart recordings of the first patient with lymphedema after breast cancer in medical literature to record arm volumes using a home volumeter, and illustrates some of the pitfalls of volumetric chart interpretations. The patient left for vacation (which included air travel) at point A, arrived back home and was symptomatic (painful and heavy arm) at point B, and underwent CDT (manual lymphatic drainage and bandaging) between points B and C, which relieved her symptoms. Measurements between points C and E represent subsequent natural fluctuations in arm volume. It is noteworthy that the patient was symptomatic (painful and heavy arm) at point B (1,710 mL) but asymptomatic at point D when the volume was similar (1,694 mL). The author had initially misinterpreted volumetric data by concluding that air travel was probably responsible for the increase in volume between point A (1,666 mL) and point B (1,710 mL), and that CDT should be credited for the subsequent reduction in volume (1,664 mL at point C). However, subsequent serial measurements (between points C and E) show that both the increase in volume and subsequent improvement were within the range of daily fluctuations. The human propensity to look for patterns and be misled by randomness has existed since the time of ancient Roman augurs, and is well-described in psychology[14] and finance.[15]

In conclusion, measurement of arm volume at home may foretell a new era in lymphedema management. For patients and health providers facing a myriad of therapies, devices, and claims of effectiveness, readily accessible arm volumetry will level the playing field. This volumeter will assist clinicians to evaluate, to critique, to refute, or to accept devices and interventions based on their effect on arm volume on an individual basis. For physicians and therapists, home arm volumetry may facilitate the ongoing transition of lymphedema management from the dictates of tradition to evidence-based medicine and customized therapy.

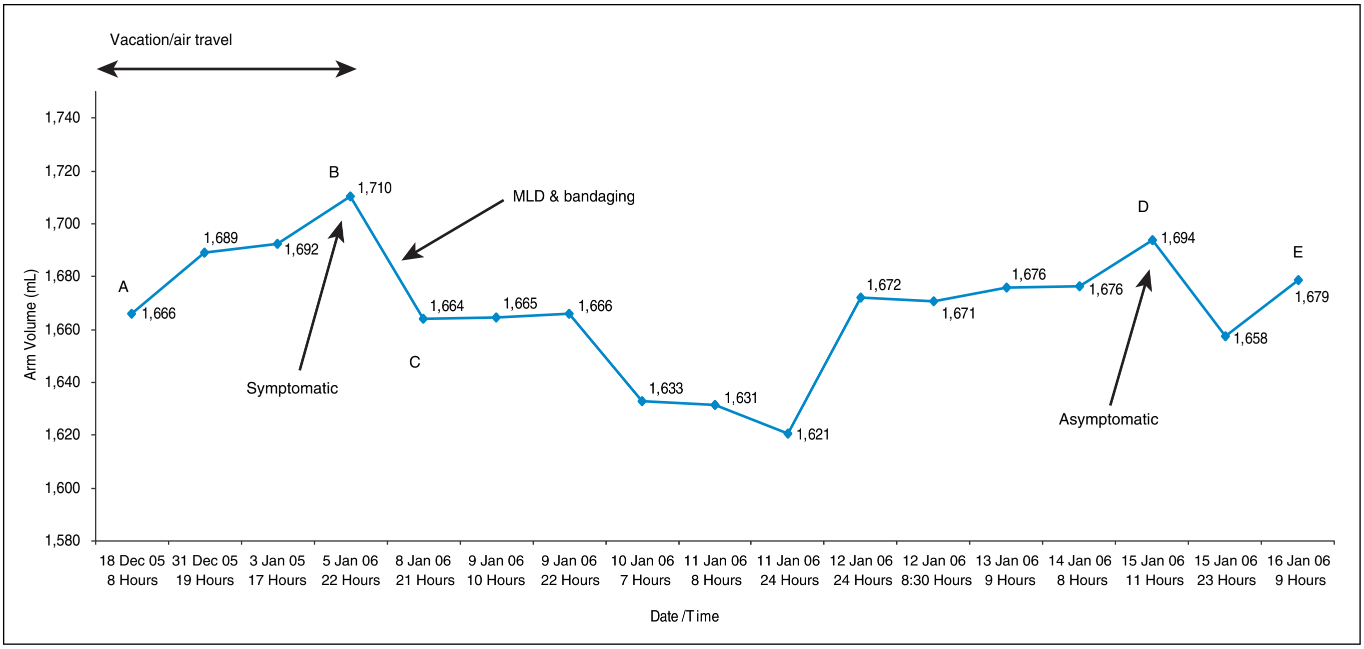

Fig 4. Serial arm volume recordings in a patient with lymphedema of the right arm after breast cancer. Mean arm volume was based on three consecutive measurements. MLD, manual lymphatic drainage.

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Appendix

I. How to Construct a Home Arm Volumeter

A. Parts. All parts are made of common polyvinyl chloride (PVC) piping used in plumbing. All parts are unthreaded. (Note: Phrases set in quotation marks in this section indicate the phrase to use when purchasing materials at the hardware store.)

- one 6-inch (15-cm) internal diameter PVC pipe of approximately 1/4-inch (6-mm) standard thickness (called "6-inch Pipe"); length equal to arm length;
- one 4-inch (10-cm) internal diameter PVC pipe (called "4-inch Pipe"), 9 inches (23 cm) long;
- one asymmetric "Y" PVC all female connector (called "Asymmetric Y connector"; also called "Wye" in some plumbing catalogs), designed to connect two 6-inch and one 4-inch pipes;
- one PVC 45-degree elbow (called "Elbow") with one male and one female connecter end, designed to connect two 4-inch–diameter PVC pipes, also called a "45-degree 4-inch male-female PVC angle";
- one 6-inch PVC cap (called "6 inch Cap");
- PVC solvent glue.

B. Assembly instructions.

1. Arm length (Fig 3A, Step 1). Determine arm length by measuring the arm from the inner fold of the armpit (anterior axillary fold; Point A) along the inside (anterior aspect) of the arm to the tip of the middle finger when the hand is outstretched in a taut position (Point B).

2. Cutting and gluing. Warning: It is dangerous to cut PVC pipe with a power saw and to handle PVC glue, which emits toxic vapors; these tasks should be left to a properly trained person.

Reference for metric equivalents: Conversion factor: 1 inch = 2.5 cm. Approximate equivalents: 1/4 inch = 6 mm; 4 inches = 10 cm; 5 inches = 13 cm; 6 inches = 15 cm; 9 inches = 23 cm.

a. Cut the 6-inch pipe to a length equal the length of the arm (Fig 3A).

b. Cut the 4-inch pipe to a length of 9 inches (23 cm).

c. Cut the asymmetric Y-connector as illustrated in Figure 3B. Stand the asymmetric Y-connector with the 4-inch connector end facing down. Measure 5 inches (13 cm) up from the bottom of the 6-inch connector end and mark point A. Mark point B just above the ridge of the 4-inch connector end (Step 1). Cut across the asymmetric Y-connector in a straight line spanning from point A to point B (Step 2). File and sand the newly cut top edge to make a smooth, curved lip (Step 3).

d. Glue the 6-inch cap to one end of the 6-inch pipe to seal the bottom of the volumeter (Fig 3C, Step 1).

e. Glue the asymmetric Y-connector to the other end of the 6-inch pipe (Fig 3C, Step 1).

3. Fitting. Attach the 4-inch pipe to one end of the elbow and attach the elbow to the asymmetric Y-connector (Fig 3C, Step 2). The volumeter's spout is now in place. The spout also serves as a handle to lift, drag, or carry the volumeter.

C. Filing, sanding, cleaning, and disinfecting. Clean all parts before assembly. Carefully check the assembled volumeter, inside and out. File and sand any sharp edges or points. Clean and disinfect the volumeter using a bleach solution. Rinse thoroughly with water to remove any trace of bleach.

II. How to Measure Arm Volume

A. Equipment.

- Home arm volumeter;
- Beverage pitcher (The pitcher does not need to have volume gradations because the water volume is measured by weighing);
- Digital gram kitchen scale or postal scale (The scale should read up to 5,000 g, be accurate to 1 g, and have a platform large enough to hold the pitcher. The display must be in grams [not ounces] because water weight in grams is equivalent to water volume in milliliters, which is the only way the water volume can be determined through weighing. The author strongly recommends that patients weigh the water and not use graduated containers, which are too imprecise and yield misleading volumetric readings.)

B. Measurement procedure. (Fig 3D illustrates each step, using a longitudinal cross-section of the volumeter.)

1. Weigh the empty pitcher and record its empty weight (Step 1). This will be a constant that you always subtract from the weight of the pitcher of water.

2. Place the volumeter on a level-surfaced floor. To achieve comparable measurements, try to place the volumeter in the same location each time.

3. Prepare a comfortable seat beside the volumeter, for example, a stool or low chair. A closed toilet seat may also be convenient with the volumeter placed beside the toilet.

4. Place the pitcher under the volumeter spout. Under the pitcher, place any type of flat base, such as a plastic food storage container, to raise the pitcher up to the edge of the spout. This base is necessary so that no drops of water splash outside of the pitcher (Step 2).

5. Fill the volumeter with lukewarm water until it overflows into the pitcher. Wait for all air bubbles to settle. Top off the water level with a bit more water and wait for the overflow to completely stop dripping into the pitcher (Step 3).

6. Empty the water out of the pitcher (Step 4). Dry the pitcher with a towel. Return the dry pitcher to its original spot under the spout of the volumeter.

7. You are now ready to measure your arm volume. Sit beside the volumeter. Slowly and gently lower your arm into the volumeter. Water will rush out through the spout into the pitcher. Continue lowering your arm until your middle finger touches the bottom of the volumeter, while keeping your fingers, wrist, and elbow in a fully extended and taut position (Step 5).

8. Hold this position until the water stops dripping into the pitcher. You can best see this by watching when the water in the pitcher becomes still.

9. Remove your arm and dry it with a towel.

10. Place the pitcher filled with the overflow water on the scale (Step 6).

11. Record the gram output showing on the scale. From this number, subtract the weight of the empty pitcher (Step 1). The difference equals the volume in grams of the water in the pitcher. This amount equals the volume in millilitres of your arm.

12. We recommend that you do at least two consecutive measurements, and preferably 3 (see Helpful Hints).

13. When you have finished measuring, the volumeter can be dragged or lifted by the spout and tipped into the bathtub or shower to empty.

III. Helpful Hints

The most important procedure in measuring arm volume is Procedure 8—holding the arm immobile in the volumeter until the water stops dripping. This may take up to 1 minute. It is therefore important to be comfortable and relaxed when you take your arm measurement. Your seat should be comfortable. To avoid straining your back, try to bend from the waist and keep your back straight.

Measuring in the bathtub: since the floor of the bathtub is not a level surface, it may not be an ideal location for the volumeter. Also, sitting on the side of a bathtub (in a straddle or side-saddle position) is not usually comfortable.

We recommend that you take three measurements in a row and calculate the average, in case of an erratic measurement. By comparing three measurements, you can judge your skill at measurement. With practice, your measurements may vary by less than 10 mililiters, which is highly precise.

If you discover that the 6-inch pipe has been cut too long and your middle finger does not touch bottom before the top of the volumeter hits your armpit, you can use a “landmark,” such as a freckle on your upper arm, and stop immersion at that landmark. You can also add a “false bottom” to your volumeter by filling a plastic container with vase gems, marbles, or polished stones and placing the weighted container in the volumeter.

To lower costs of making the volumeter, patients can group together to have several made at one time.

We recommend that you not modify the design of the home use volumeter. It is the result of trial and error and numerous prototypes over 2 years. Even a minor design change may change the volume and shape of the water meniscus at the top of the cylinder of water and result in unreliable measurements.

If you have any problems following these instructions, contact the author by e-mail at jlette@lette.com.

Author’s Disclosures of Potential Conflicts of Interest

The author indicated no potential conflicts of interest.