Limb volumetry using an iPad-based three-dimensional scanner for assessment of edema

Seshadri Raju, MD, Sara Matheson, BS, Slade Smith, BS, Jack Owens, BS, *and*
Vijay M. Adaikkappan, BS, *Jackson, MS*

ABSTRACT

Objective: Quantifying limb edema is challenging owing to the lack of an easily accessible clinical technique. This study evaluates the reproducibility of an iPad-based three-dimensional (3D) scanning system for lower limb volumetry and identifies factors influencing measurement variability.

Methods: Twenty limbs from 10 healthy volunteers were scanned using an iPad-based Structure Sensor and software. Initial scans followed standard manufacturer instructions, but high variance rendered data unsuitable for clinical use. To improve accuracy, a standardized scanning protocol was developed, incorporating anatomical calibration, scanning distance standardization, and scanning time control. A 254-mm calf segment was defined using a 3D marker placed on the medial malleolus to ensure consistent volume measurement. The scanning distance was fixed between 50 and 59 cm to reduce zoom parallax errors, and scans were conducted after 3 PM to minimize diurnal volume fluctuations. Multiple technicians performed repeat scans on the same limb to assess intraobserver and interobserver scan reliability.

Results: Implementing the standardized protocol significantly decreased measurement variability. Defining a consistent anatomical scan region improved reproducibility, with the mean volume difference decreasing from 4.7% ± 3.6% to 2.1% ± 1.6%. Standardizing scanning distance reduced zoom-related errors, improving measurement consistency from 2.6% ± 1.5% to 2.0% ± 1.2% ($P = .037$). Time standardization further optimized accuracy, yielding a final mean volume difference of 1.8% ± 0.9%. No statistically significant differences were observed between measurements taken by different technicians ($P > .05$), demonstrating high interobserver reliability.

Conclusions: iPad-based 3D scanning provides a clinically reliable and cost-effective method of lower limb volumetry. The standardized protocol as described improves scan accuracy and reproducibility. Future studies should evaluate this method in a clinical population to validate its usefulness in disease assessment and progression tracking. (J Vasc Surg Venous Lymphat Disord 2025;■:102275.)

Keywords: Leg swelling; 3-D volumetry; Phlebolymphedema; CEAP clinical class 3; Limb plethysmography; Lymphedema

Lower limb edema is a common manifestation of advanced chronic venous disease, requiring interventional treatment if conservative options fail. However, swelling is notoriously difficult to quantify because it is variable, progressing through the day with orthostasis.[1] Patient perception of edema is often clouded by associated pain. Painful edema is perceived as severe, whereas some patients may be unaware of its presence if painless.

Several clinical grading methods of edema are in common use, such as Venous Clinical Severity Scoring, based on the time of day when edema becomes maximum (morning, noon, evening, or permanent).[2] Edema severity on physical examination may be described as mild, moderate, or severe; the extent to which edema involves the limb (pitting, ankle edema, or entire limb) may be used as well.

Tape measurement of the calf is commonly used, though edema quantification is gross at best. Water plethysmography is accurate but cumbersome for routine clinical use. Air plethysmography is suitable for clinical use, but limb volume may vary if cuff positioning on the leg is not constant.

The advent of Apple iPad-based three-dimensional (3D) scanner opens a new avenue for measuring limb volume. The latest ambient light scanner model, STO3 sensor (Structure Inc., Boulder, CO), was used for the current study. This 3D scanning technology has gained broad industrial use, including the manufacturing of high-precision tools. A commercially available software package was used for limb volumetry. The aim of this study was to assess lower limb volume using the hardware and software to describe its reproducibility (variance), sources of high variance, and measures to minimize it. The scanning technique had to be refined as described in this article to obtain consistent results. This is a

From The RANE Center for Venous & Lymphatic Diseases.

Correspondence: Seshadri Raju, MD, The RANE Center, 971 Lakeland Dr, Ste #401, Jackson, MS 39216 (e-mail: rajusybil@earthlink.net).

The editors and reviewers of this article have no relevant financial relationships to disclose per the Journal policy that requires reviewers to decline review of any manuscript for which they may have a conflict of interest.

2213-333X

https://doi.org/10.1016/j.jvsv.2025.102275

single-center study of prospectively collected data analyzed retrospectively. Informed consent was obtained from volunteer participants for performing the study and publication of the results in deidentified form institutional review board permission was granted for the study and its publication. The NCT (NCT06944041) was obtained from Clinicaltrials.gov.

METHODS

Participants. Ten healthy participants without a history or signs of limb edema volunteered for the study.

Hardware and software. A tablet computer (iPad 9th generation; Apple, Cupertino, CA) was used in combination with the ST03 sensor (Structure, Boulder, CO); for 3D limb volumetry (Fig 1). The 3D scanning software (3DsizeME) was provided by TechMed3D (Québec, Canada). The 3D images are uploaded to a computer for further processing to obtain limb volume (Fig 2). Several modifications of the standard scanning protocol were required to achieve scanning accuracy.

Fig 1. Apple iPad attached to the scanner. The STO3 scanner is shown separately in the insert.

ARTICLE HIGHLIGHTS

- **Type of Research:** A global, multicenter, prospective, nonrandomized, single-arm, investigational device exemption study
- **Key Findings:** Treatment of symptomatic iliofemoral venous outflow obstruction using the Zilver Vena venous stent (Cook Ireland, Ltd, Limerick, Ireland) in 243 patients resulted in a 30-day freedom from major adverse events (MAE) rate of 96.7% and 12-month primary quantitative patency rate of 89.9%, which surpassed the corresponding performance goals. Also, significant improvement in clinical symptoms was demonstrated through 12 months.
- **Take Home Message:** The 12-month results indicate that the Zilver Vena venous stent is safe and effective.

Scanning the limb for volumetry. The participant is asked to stand comfortably holding on to a support with the leg to be scanned slightly forward. The limb was scanned circumferentially. The captured image was then uploaded to the MSoft software platform to obtain the limb volume.

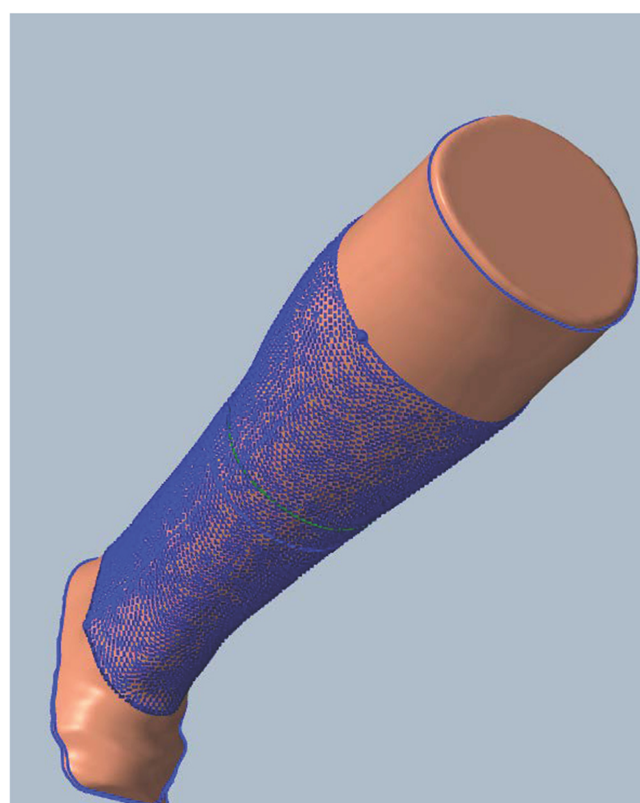

Fig 2. Three-dimensional (3D) image in the software platform for volumetry. The segment of the limb denoted in blue is used for volume calculation. The software allows manipulation of the image in a 3D plane.

Modification of the scanning technique and software processing. Several modifications of the casual scanning technique and subsequent processing on the software platform were required to minimize the percentage difference of repeat volume measurements. Repeat measurements were carried out within 20 minutes of the first scan to minimize any interval fluid volume change in the limb. Repeat measurements on the same limb by the same technician were analyzed for intraobserver variation. Interobserver variation was also tested by using different technicians for the repeat scans. Volumetry of the foot was attempted but failed owing to high variance related to the shape of the foot with toes. A 10-inch-long (254-mm) calf segment was used for volume measurement.

RESULTS

Limb volumetry using standard instructions out of the box resulted in a large percentage volume difference. Four sources of error were identified while standardizing a protocol for limb volume computation.

Sources of error

Target volume boundaries. The first source of error was from measurement of limb volume without accurately defining the upper and lower boundaries for the volumetric scans. Initially, a 10-inch (254-mm) calf segment roughly centered the bulk of the muscle in the upper calf without more precise anatomic localization was chosen ad lib for volumetric measurement. This yielded a mean volume difference of 4.7 ± 3.6 mL. It was found that the 10-inch (254-mm) calf segment had to be anatomically constant for reproducible measurements. Commercially available self-adhering silicone bumper (10 mm diameter; 3M, Saint Paul, MN) was used to mark the medial malleolus to demarcate the lower border of the calf scan. The upper scan border of the limb segment was digitally marked at 254 mm vertically above the silicone bumper. Variance was improved from 4.7 ± 3.6 mL to 2.1 mL ± 1.6% by constant anatomic localization of the measured calf segment as described (Table).

Target volume orientation. Another possible source of error was the angle of the limb axis for scan measurement. The limb was tilted to an angle of 45° to the right or left for scan measurement (Fig 3). This tilt factor showed minimal error ($P =$ not significant), indicating its relative insignificance for reproducibility.

Zoom error. Another source of error was caused by the zoom effect, if the distance between the scanning sensor and the limb was not standardized. Scans taken randomly at distances varying between 0.38 m and 0.70 m yielded a mean volume difference of 2.6±1.5%. Standardizing the scan distance between 0.50 and 0.59 m (a 9-cm difference) proved to be the optimal distance yielding a mean volume difference of 2.0±1.2 % this was significantly ($P = .037$) better than random distance measurement. A Hula-hoop of this diameter was a practical aid in the scanning (Fig 4). This distance was also found to be convenient for scanning the limb by the technician. Limb volume variations owing to the zoom error in combination with variations of time and distance at scanning are shown in Table.

Time standardization. The third source of error was the time of day when scan measurements were made. There were large variations in measured calf volume if the scans were performed randomly at varying times before

Table. Standardizing scan protocol for limb volumetry with iPad scanner

Variation	Mean volume, mL, Tech 1	Mean volume, mL, Tech 2	Mean volume, mL, % difference ± SD	*P* value	Standard error of mean (RSE) Tech 1	Standard error of mean (RSE) Tech 2
10-inch calf segment chosen ad lib (n = 18 limbs)	1663	1658	4.7 ± 3.6%	.79	3.5%	3.5%
10-inch anatomically constant calf segment (n = 18 limbs)	1684	1674	2.1 ± 1.6%	.51	4.0%	4.1%
Variable scan distance any time of day (n = 20 limbs)	1878	1875	2.6 ± 1.5%	.86	2.6%	2.7%
Variable scan distance between 3 and 4 PM (n = 20 limbs)	1837	1857	3.0 ± 1.8%	.15	2.8%	2.9%
Standardized scan distance any time of day (n = 20 limbs)	1557	1561	2.0 ± 1.2%	.41	1.9%	2.1%
Standardized scan distance between 3 and 4 PM (n = 20 limbs)	1831	1832	1.8 ± 0.9%	.72	3.0%	2.8%

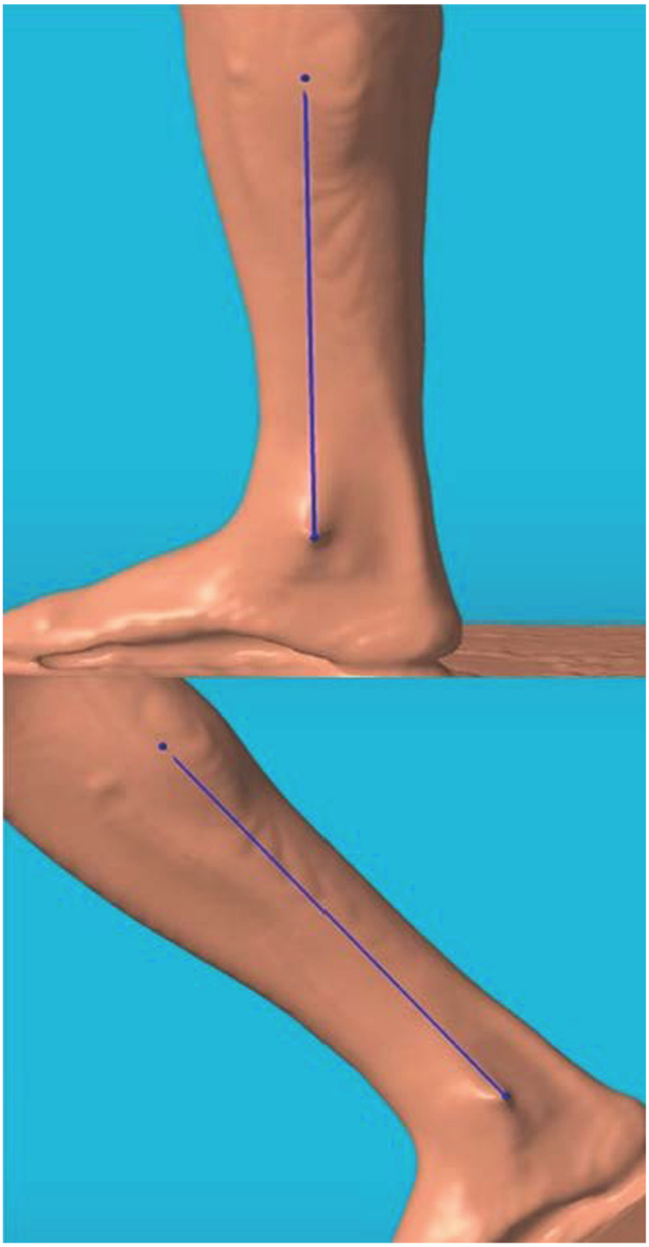

Fig 3. (Top) Scan image of the leg. The medial malleolus is marked by a 3-mm bumper to delineate the lower border of volumetric measurement. The upper border is digitally marked on the scan image at 10 inches (254 mm) vertically above the medial malleolus. The blue line is a digital mark on the image for the measurement. **(Bottom)** A leg tilt did not affect the digital volumetric measurement from the scan. The images shown are a flat (two-dimensional) rendition of the three-dimensional (3D) modeling on the Msoft platform.

Fig 4. The scan distance was standardized to 0.50 to 0.59 m to minimize zoom error. A commercially available hula-hoop ring was a convenient aid to mark the scan distance.

3 PM. Measurement differences (standard deviation) were less if the scans were made after 3 PM, when leg swelling had apparently maximized (Table).

The standardized protocol involves anatomically defining scan borders, as described, limiting the scan distance between 0.50 and 0.59 m, and standardizing the time of scan after 3 PM. With this standardized protocol a mean volume difference of 1.8 ± 0.9% was obtained. Multiple scans of the same limb by multiple technicians yielded a low level of relative standard error (≤3%), as shown in the Table.

DISCUSSION

Limb volume can be measured with good accuracy using 3D scanning with iPad. Accurate 3D scanners and applicable software have become available recently. This equipment can replace laser scanning, which is expensive. The newer device allows broader clinical use than before.

The current study shows the results of limb volumetry in healthy volunteers using the newer iPad-based 3D scanners. The scanning protocol and the required modifications of out-of-the-box instructions for optimal clinical application are described. The-10 inch (254-mm) long limb segment scanned must be anatomically constant. We chose the medial malleolus as the lower border of the scan. The scannable limb volume is 254 mm long, measured up from the malleolus. Without an anatomically constant fixation point, the scanned segment volume will vary because of the irregular shape and taper of the limb. The scanning distance must be controlled to avoid zoom error. The scanning distance between 0.5 and 0.59 m was found to be optimal. Swelling progressively increases during the day with orthostasis.[1] However, scans carried out between 3 and

4 PM showed low variance, presumably because swelling in the limb had maximized by this time. This time frame is fortuitously convenient for clinical measurement. Other reports using the iPad-based scanner have appeared in literature recently, but without the necessary technical details and modifications necessary for precise limb measurement.[3]

Excellent interobserver and intraobserver variance was obtained in this study, with a relative standard error of 3% or less. The study provides proof of methodology. Similar results are expected in edematous patients. The leg volume below the knee in an average adult is approximately 2000 mL. Edema accumulation of 100 to 150 mL (5.0%-7.5%) becomes clinically evident. Gross edema often results in a 50% increase in limb volume.[4]

Foot volume was not measured because an accurate scan was difficult to obtain because of the irregular shape of the foot with toes. For the same reason, we could not validate the scanner methodology using water plethysmography. The foot would be included in water plethysmography. Air plethysmography also measures a different calf segment owing to length and positioning of the measuring cuff.

The target population for limb volumetry are patients with limb edema. Edema quantification in this subset was largely qualitative until now. Quantification is possible with the new devices for initial assessment as well as to measure treatment outcomes. Compression therapy, manual lymphatic massage, and endovenous stenting are commonly used therapeutic options. Chronic venous disease is the pathology in most of these patients. Lymphatic dysfunction is present in approximately 30% of patients with chronic venous disease either owing to obstruction, reflux, or a combination.[5] Many of these patients are treated in clinics specializing in manual drainage. The scanner methodology described can be a useful clinical tool for managing these patients.

LIMITATIONS

Volumetric method was internally tested (test-retest) for validity. No external or different methodological construct (eg, water plethysmography) was used for validation.

CONCLUSIONS

Clinically useful edema quantification can be obtained in patients with limb swelling using commercially available 3D scanners paired with iPad. The equipment is relatively inexpensive and easy to use. However, standardization of the scanning protocol is necessary for maximum possible accuracy.

The authors thank Jennifer Stafford, BS, MEd, EdD, for her supervision of statistical analyses for this project.

AUTHOR CONTRIBUTIONS

Conception and design: SR, VA
Analysis and interpretation: SR, SM, VA, SS, JO
Data collection: SR, SM, SS, JO
Writing the article: SR, SM, VA, SS, JO
Critical revision of the article: SR
Final approval of the article: SR, SM, VA, SS, JO
Statistical analysis: SR, SM, VA, SS, JO
Obtained funding: SR
Overall responsibility: SR

FUNDING

None.

DISCLOSURES

S.R. reports US Patents for Venous Stent Design and IVUS Diagnostics.

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Submitted Mar 18, 2025; accepted Apr 30, 2025.