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Venous Elastography: Validation of a Novel High-Resolution Ultrasound Method for Measuring Vein Compliance Using Finite Element Analysis

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ABSTRACT

Ultrasonography for the noninvasive assessment of tissue properties has enjoyed widespread success. With the growing emphasis in recent years on arteriovenous fistulae (AVFs) for dialysis vascular access in patients with end-stage renal disease, and on reducing AVF failures, there is increasing interest in ultrasound for the preoperative evaluation of the mechanical and elastic properties of arteries and veins. This study used high-resolution ultrasound with phase-sensitive speckle tracking to obtain in vivo vein elasticity measurements during dilation. The results of this novel ultrasound technique were then compared to a computer model of venous strain. The computer model and ultrasound analysis of the vessel wall demonstrated internally consistent positive and negative longitudinal strain values as the vein wall underwent dilation. These results support further investigation of the use of phase-sensitive speckle tracking for ultrasound venous mapping for preoperative vascular access evaluation.

Recently, there has been increasing emphasis on optimizing fistula use for end-stage renal disease (ESRD) patients (1). It has been shown that the use of preoperative venous mapping by conventional ultrasound can decrease the early failure rate of arteriovenous fistulae (AVFs) (2). Preoperative venous mapping has also been shown to increase the number of created AVFs, double patency rates, and decrease early failure rates from 36% to 8% (3). Elasticity imaging using high-resolution ultrasound and speckle-tracking algorithms has the potential to quantitatively measure mechanical properties and arterial compliance in ESRD patients with higher spatial resolution than conventional ultrasound and with unprecedented accuracy (4).

Multiple studies suggest that vein size is a reliable predictor of fistula outcome (5,6). Furthermore, the tendency of a vein to dilate may also be a reasonable predictor of fistula outcome. One study found that a quantitative measurement of vein distensibility by strain-gauge plethysmography could reliably predict AVF success (2).

Even with the aforementioned success, the reliability of venous ultrasonography is still being debated (7). Recent advances in ultrasound phase-sensitive speckle tracking may dramatically improve the accuracy and utility of preoperative venous ultrasonography (4,7). We applied an experimental ultrasound technique using high-resolution, phase-sensitive speckle-tracking algorithms and compared these clinical results to theoretical models of vein-strain images. In the future, instead of getting only a general idea of the distensibility of a vessel, this method may provide detailed, highly accurate strain data for specific points along the vessel wall.

Methods

The study subject was a 63-year-old man nearing ESRD resulting from diabetes and hypertension who was being evaluated for fistula creation for dialysis access. The subject underwent an IRB-approved study to collect ultrasound data by the standard technique of observing the dilation of the cephalic vein at the wrist while a sphygmomanometer was inflated on the upper arm from 0 to 80 mmHg (4). The vein was allowed to distend while being imaged. High-resolution ultrasound with phase-sensitive speckle tracking was applied to

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accurately track the motion of structures within regions of interest (ROIs) using the specific signal signature contained in the underlying radiofrequency (RF) signal along the beam at the frequency of the transducer (Fig. 1) (8,9). The gradient of motion along the outside of the vein wall gives an accurate measurement of strain induced by the pressure. Thus, the deformation of the vein wall and surrounding tissues can be accurately measured.

A Philips (Bothell, WA) IU22 was used in the study, and data were analyzed offline using methods previously described (4,8,9). The displacement of an object between two ultrasound image frames, which may not be adjacent, provides an estimate of the motion of that object. The technique used in this study to estimate frame-to-frame displacement combined two-dimensional, correlation-based algorithms to track relatively large internal displacements with highly precise phase-sensitive methods (10). Frame-to-frame lateral and axial displacements were estimated using the position with the maximum correlation coefficient, where the correlation kernel size approximately equals that of the speckle spot (0.2 mm^2) for optimal strain estimation. Axial displacements were refined using the phase zero-crossing of the complex correlation function. Spatial derivatives of the axial displacements were computed to estimate the longitudinal strain.

Significant interval strain (more than several percent) between frames can result in poor signal-to-noise ratio and significant errors in strain measurements. This limitation was overcome by capturing and retrospectively processing a large set of real-time frames acquired during surface deformations to enable adaptive strain estimation, incompressibility processing, and strain hardening (i.e., nonlinear elasticity) imaging (10–12).

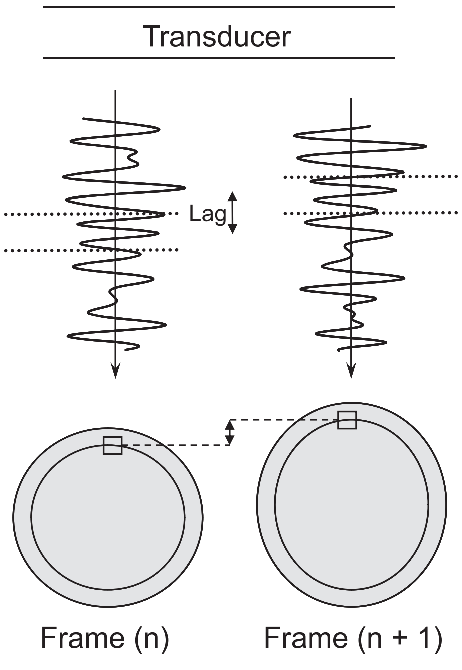

FIG. 1. The transducer tracks a specific underlying radiofrequency to determine the positional changes of specific regions within a vessel.

The longitudinal (along the beam) RF signal allows spatial resolution of strain to be measured with at least an order-of-magnitude greater accuracy than the lateral (across beam) direction. Therefore, as shown in Fig. 2, the deformations of the ROIs are measured along the axis of the beam (arrows). So as the vessel dilates, dimensional changes in the longitudinal direction will be detected by the transducer.

To assess the validity of the ultrasound strain measurements, we generated a computer simulation of a venous strain map (Fig. 3B) using a finite element analysis (FEA) program, Abaqus 6.4 (Simulia, Providence, RI). Parameters included internal pressure, external applied pressure (from transducer), and the Young's moduli of both the vein wall and surrounding tissue. The values used for Young's modulus estimates for the vein wall and the surrounding tissue were obtained in our laboratory from experimental data on bovine venous and muscle tissue samples, respectively, using a Micro-Elastometer 0301 device (Artann Laboratories, West Trenton, NJ). The vein wall measurements were approximately equal to values obtained by other investigators (13). The Young's modulus of the vein was nonlinear (Fig. 4) and the Young's modulus of the surrounding tissue was estimated to be 80 kPa. We assumed the external pressure created by the transducer to be negligible and used an internal pressure of 80 mmHg to simulate a fully dilated vein in diastole to correspond to the clinical protocol used to collect the ultrasound data from the

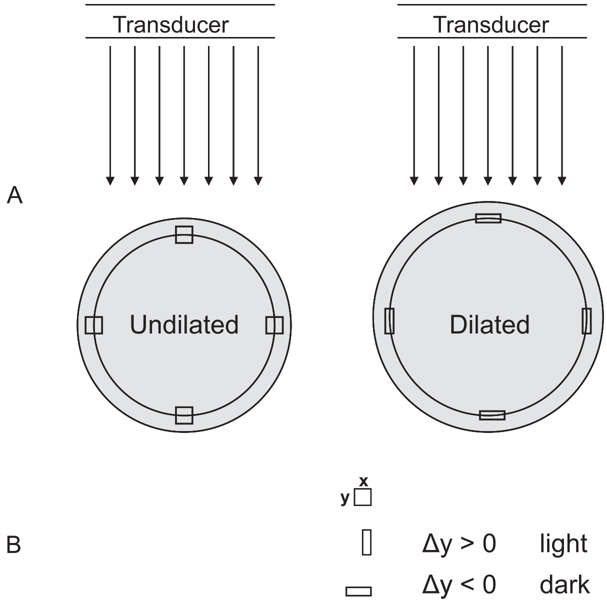

FIG. 2. (A) The deformations of the regions of interest are measured along the axis of the beam (arrows). As the vessel changes shape, changes in the longitudinal direction are measured by the transducer. Undilated and dilated vessels are displayed on the left and right, respectively. (B) Positive strain occurs at the sides of the vessel as the region of interest lengthens along the beam ($\Delta y > 0$), and negative strain is apparent at the top and bottom of the vessel with shortening of the region of interest along the beam ($\Delta y < 0$). In the computer-simulated and ultrasound strain maps, regions of positive and negative strain are depicted, respectively, as lighter and darker regions.

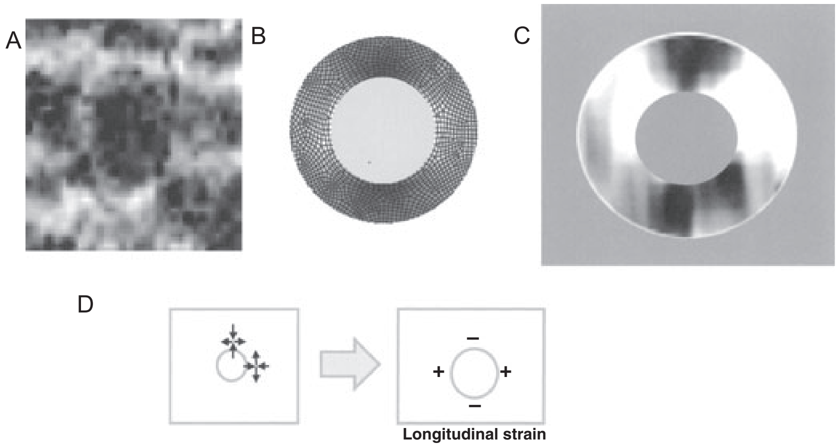

FIG. 3. (A) B-scan image of a vein wall. (B) A computer simulation of a vein strain map developed using Abaqus (Simulia, Providence, RI) finite element analysis software. The solid inner circle represents the lumen of the vein and the outer circle represents the vein wall. (C) A venous strain-map obtained by ultrasound from subject. (D) Longitudinal lengthening and shortening of regions of interest at the sides and top/bottom of the wall of the vessel are shown as positive (light regions) and negative (dark regions) strains, respectively.

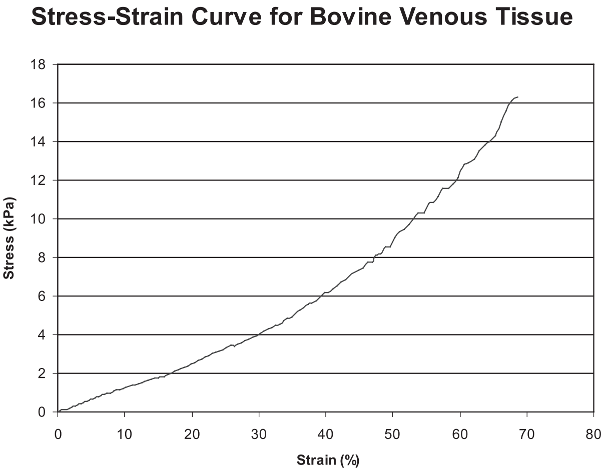

FIG. 4. The stress–strain relationship in bovine venous tissue, calculated by a microelastometer, was used as the Young's modulus of the vein wall in the computer simulation.

study subject. Lighter regions in the strain map (Fig. 3C) are under positive strain (lengthening along the ultrasound beam), whereas darker regions are under negative strain (shortening along the beam).

Results

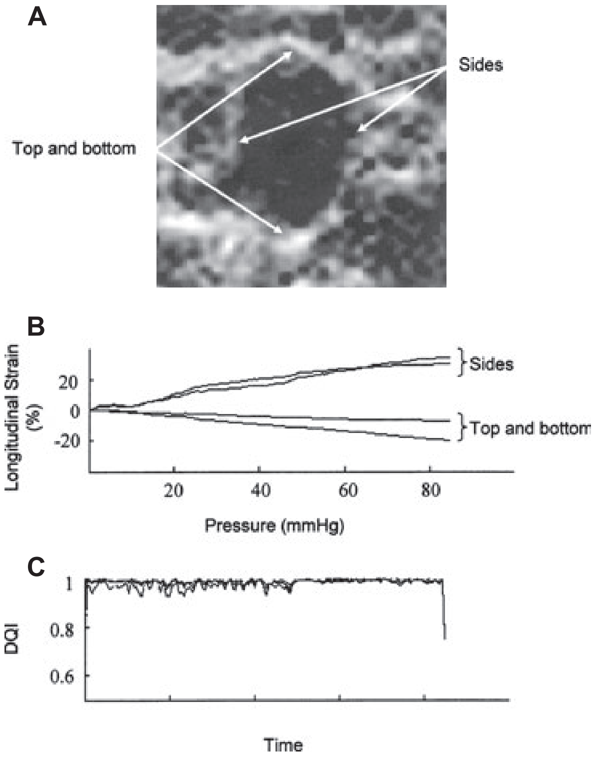

FIG. 5. (A) B-scan image of a vessel with four regions of interest (ROIs). (B) Graph of longitudinal strain of each ROI versus pressure as the vessel dilates. During this time pressure increased from 0 to 80 mmHg. (C) Graph of the data quality index (DQI) values from frame to frame as the vessel dilates.

Figure 5A shows a B-scan image of a vessel with four ROIs. Figure 5B shows the longitudinal strain of the ROIs plotted versus pressure. The pressure was read from the sphygmomanometer as the cuff inflated to distend the vein during imaging. As predicted by the computerized strain modeling, the strain on the upper and lower regions is negative as the vessel dilates and the strain on the left and right sides is positive. A graph of the data quality index, representing the peak magnitude of the speckle-tracking cross-correlation functions, is shown in Fig. 5C. This correlation coefficient tracking quantitatively estimates frame-to-frame tracking and thereby provides an estimate of the quality of the displacement and strain data. The time axis in Fig. 5C coincides with a linear increase in internal pressure from 0 to 80 mmHg. The correlation is close to a maximal value of 1 throughout the procedure, indicating accurate frame-to-frame tracking of the data and providing a high level of measurement reliability.

The B-scan motion pictures and the B-scan image (Fig. 5) show fascial planes tethered to the upper and lower edges of the vein wall, with strain images showing lower strain values in these regions of vein wall. The remainder of the vein expanded symmetrically with increasing pressure. Figure 6 shows the stress–strain relationships of all ROIs from both the ultrasound imaged vein and the computer-modeled vein tissue. Of note, the computer model gave nearly identical strain values for the top and bottom of the vein walls and for the right and left sides of the wall, respectively. However, the computer model of the vein wall was axially symmetric and did not incorporate the local boundary conditions of the tethered vein upper wall seen in the human ultrasound data acquired. These values are plotted in Fig. 6 as a pair of thick lines that encompass data from both regions. The left and right ultrasound ROIs show high-resolution speckle-tracking strain values in the range of 25–35%, in accordance with the computer model. Top and bottom ROI strain values from the computer simulation were close to 30% at the end of vein dilation, in comparison to the ultrasound speckle-tracking strain values of 5–15%. Although the top and bottom ultrasound ROIs showed lower strain values than the computer model, the increasing strain magnitude with dilation of the vessel was physiologically reasonable. The side vessel ultrasound results were entirely consistent with the modeling results for these regions.

Discussion

This elasticity-imaging technique using high-resolution ultrasound speckle tracking has the potential to give highly reliable and accurate measurements of the physical and mechanical characteristics of a vessel with unprecedented spatial resolution. Recently, this method has been applied to peripheral artery bypass grafts and dialysis fistula imaging (14,15). As vein mechanics may play a role in preoperative assessment for dialysis fistula creation, we sought to evaluate the feasibility of applying this method during dilation of a vein undergoing preoperative ultrasound mapping. The study was restricted to a single subject because the method of data collection was undergoing development and not yet practical for use in a larger clinical investigation. However, the high correlation values obtained in this study support a high level of confidence in accurate frame-to-frame tracking and warrant the further development of an ultrasound apparatus that is suitable for a clinical study with significant enrollment. Although this technique requires further research, we are able to draw some conclusions from the above results. First, the stress–strain measurements obtained using the ultrasound image data were consistent with the computer-model results. These laboratory measurements were in turn consistent with previously published results for vein elastic moduli (13). Additionally, the overall strain pattern from the ultrasound image was consistent with the pattern observed using FEA modeling.

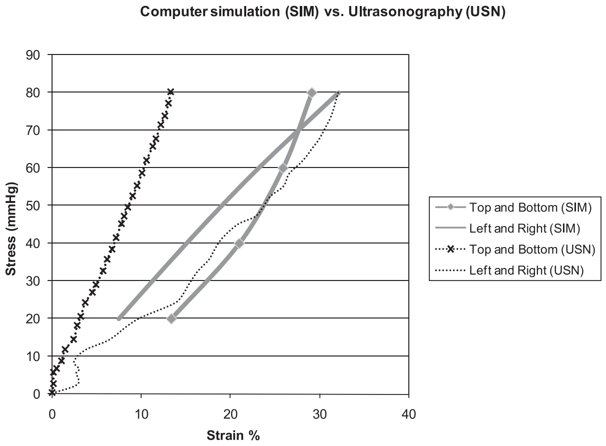

FIG. 6. Stress–strain relationships of the four regions of interest in both the imaged vein and the computer-modeled vein.

It should be noted that other models, in which strain values of vascular structures are used to estimate the Young's modulus of a vessel, make assumptions about the relative Young's modulus of vessel wall being substantially greater than that of the surrounding tissue (4). In this study, the same assumptions do not apply as high vein compliance and comparatively low Young's modulus of the surrounding tissue considerably affect the stress–strain values of the vein wall and the surrounding tissue. This has several implications. First, high-strain regions may be seen in both the vessel and the surrounding tissue, as was seen in both our clinical study images and the FEA model. Second, even though a high degree of nonlinearity may be expected with high strain values, especially in vascular structures (4), these preliminary results show a roughly linear stress–strain relationship over the observed values of vein-wall strain. More data are needed to evaluate veins for nonlinearity and this new ultrasound tool as a potentially useful technology for further in vivo vein evaluation. Another important unexpected finding was the relatively low local strain value at regions where the vein appeared to be fixed to adjacent connective tissue planes. This is important, highlighting the strength of this measurement method to interrogate and measure local effects with high spatial resolution. It also highlights the importance of interpreting results considering boundary conditions and local inhomogeneities in structures that are not often considered in simple in vitro experimental systems or vein measurements using conventional ultrasound when simple changes in diameter are observed.

In conclusion, ultrasonography has been found to be a promising tool for preoperative vascular access assessment. The importance of vein size and distensibility as predictors of fistula outcome has been previously discussed by other investigators. The results of this study suggest that phase-sensitive ultrasound speckle tracking can provide detailed, high-resolution and spatially accurate maps of vein-wall mechanics. Further study is required using this technique to determine if it will allow nephrologists, surgeons, and radiologists to improve preoperative fistula planning. More study is needed to evaluate novel tools such as these to optimize access care for ESRD patients.

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