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Ultrasound Measurement of Brachial Artery Elasticity Before Hemodialysis Access Placement:

A Pilot Study

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Abstract

Objectives—Successful hemodialysis requires reliable vascular access that can deliver adequate blood flow. An arteriovenous fistula is preferred for access because of its longevity and low frequency of complications, but up to 60% of arteriovenous fistulas created surgically are never suitable for hemodialysis because of nonmaturation (insufficient vascular dilatation). Decreased arterial elasticity may impair dilatation, thereby affecting fistula maturation. This study evaluated the feasibility of brachial artery elasticity measurement in patients with chronic kidney disease obtained during routine preoperative mapping ultrasound (US) imaging before hemodialysis access placement and compared the measurements to those obtained in healthy volunteers.

Methods—Brachial artery functional US studies were collected from 75 patients undergoing routine preoperative mapping for hemodialysis access and 50 healthy volunteers. Vascular strain was calculated from the change in intima-media thickness between end systole and end diastole, and vascular stress was estimated from the pulse pressure. Assuming a linear elastic medium, the elastic modulus was estimated as the ratio of vascular stress to strain.

Results—Elastic modulus measurements were significantly higher in patients than in volunteers (130 versus 100 kPa; $P = .01$). With combined volunteer and patient data, there was a significant correlation between elasticity and systolic blood pressure ($R^2 = 0.23$; $P < .001$). Elasticity was correlated with age in volunteers but not in patients ($R^2 = 0.14$; $P = .017$; $R^2 < .001$; $P = .829$, respectively).

Conclusions—This analysis of clinical arterial vessel biomechanics shows that a noninvasive US measurement can detect elastic modulus differences between patients with chronic kidney disease and healthy individuals. Future studies will correlate the elastic modulus with histologic characteristics and eventual arteriovenous fistula maturation, which may provide supplemental information on arterial biomechanical properties as a useful addition to current predictors of fistula success.

Keywords

chronic kidney disease; elastic modulus; strain; stress; ultrasound

In the United States, chronic kidney disease affects 26 million adults.¹ Chronic kidney disease is a progressive disease that takes months or years to develop, with diabetes and high blood pressure the most common causes. Patients with end-stage renal disease need life-sustaining dialysis or renal transplantation. They are frequently treated with regular hemodialysis to remove toxins and fluid. Reliable vascular access is critical for adequate hemodialysis and must provide high blood flow ($\approx 400\text{--}500$ mL/min) to the dialysis circuit.² Among the 3 types of vascular access (arteriovenous fistula, synthetic graft, and catheter), the **arteriovenous fistula** is preferred because of its longevity and low frequency of complications. An arteriovenous fistula is placed surgically by creating a direct anastomosis between a native artery and vein and is the preferred method for reliable vascular access.³ However, the feeding artery of a successful arteriovenous fistula first needs to dilate to supply the estimated 500 mL/min necessary for a mature arteriovenous fistula.^{4,5} For the arteriovenous fistula draining vein to withstand arterial pressure and to accommodate greater blood flow, it also needs to enlarge and mature before use.⁶ When these necessities are met to yield a mature arteriovenous fistula, advantages of a fistula compared to other vascular access options include lower infection rates and a lower incidence of thrombosis.⁴

Preoperative vascular ultrasound (US) mapping is routinely used to assess the upper extremity arteries and veins, identifying suitable conduits for arteriovenous fistula creation.^{7,8} To optimize fistula maturation, minimum vascular diameter criteria aid in selection of vessels that are likely to support successful fistula maturation, and veins with stenosis or thrombosis are excluded. Although preoperative vascular mapping has had positive impact on increasing fistula placement, it has not decreased the fistula nonmaturation rate.^{4,7,9} With institutions recording 20% to 60% of fistulas failing to mature,^{9–13} other potential etiologies for arteriovenous fistula nonmaturation need to be investigated. There are currently some known technical causes of fistula nonmaturation that contribute to this failure rate, such as thrombosis, anatomic lesions, accessory veins, early vascular stenosis, and poor venous outflow.¹³ Although these circumstances can occur, they do not explain all of the failures, and the remaining reasons for arteriovenous fistula failure remain unknown. This disappointing observation suggests the existence of functional vascular parameters that may impair fistula maturation despite vessel selection by adequate structural measurement.

Evaluation of the vessel diameter alone provided by preoperative vascular mapping is not sufficient to determine vascular properties such as distensibility and capacity. Thus, for example, a heavily calcified inflow artery may not be able to dilate sufficiently to supply a mature arteriovenous fistula.^{4,5,14} Elasticity has been shown to identify abnormalities within biological tissues, and imaging these elastic properties has become a pivotal point of many research efforts.^{15,16} Tissue characterization can estimate elastic properties of tissue, which is known to change with disease. The high temporal resolution of US and its ability to image small changes in vessel motion have proven useful for visualizing abnormalities in the vascular system.^{17–21}

Stress is naturally applied to the arterial vessels by the cardiovascular pulsations from each individual.^{16,22–24} For a given stress field, one can attain high strain for lower moduli due to collagen fibers engaging to maintain the wall shape.^{25,26} Basic theory from engineering mechanics points us to the conclusion that the stiffer the material, the less deformation will occur under an applied stress. Ultrasound can be used to track vessel wall motion and overall vessel deformation.²⁷ Thus, US-based noninvasive elasticity measurements may be a useful addition to current predictors, yielding supplemental information on the biomechanical properties of arteries. The ability to adapt algorithms to image data currently being collected clinically helps minimize cost and learning curves associated with adopting new imaging technology. The long-term goal of this research is to investigate the use of US

and image processing to noninvasively measure the elasticity of human brachial arteries in patients with chronic kidney disease. This investigation presents the results of a pilot study to assess the feasibility of this approach.

Materials and Methods

Theoretical Background

Conventional vascular elasticity imaging techniques track vessel wall deformation (strain) resulting from mechanical forces (stress) inherent to natural cardiac activity. Assuming that vascular tissue can be considered a homogeneous, isotropic, and linear elastic medium, the intrinsic elastic modulus, E (kPa), under small radial strain conditions can be approximated as follows²⁸:

$$E \cong \frac{\sigma}{\varepsilon}, \quad (1)$$

where σ and ε denote tissue stress and strain, respectively. Because stress is difficult to quantify in practice, differences between systolic (P_{sys}) and diastolic (P_{dias}) blood pressure measurements (referred to as pulse pressure, ΔP [mm Hg]) can be used as a surrogate measure.²³ Specifically, assuming that extravascular pressure is insignificant, physiologic stress from cyclic blood flow exerts radial pressure on the vessel wall, estimated as

$$\sigma \cong \Delta P = P_{\text{sys}} - P_{\text{dias}}. \quad (2)$$

For the purpose of our study, pulse pressure represents the intrinsic stress that causes vascular wall motion between extreme states of blood pressure associated with the human cardiac cycle. Given that the diameter of an arterial vessel wall is proportional to the intima-media thickness, as the vessel diameter increases to end systole, the vessel wall and intima-media are at minimal thickness. Conversely, at end diastole, the vessel wall and intima-media are at maximal thickness. Therefore, we propose the use of thin arterial cross-sectional image planes for strain measurement given subtle changes in the intima-media thickness during end systole and end diastole. To minimize variability within a person's measurements, intima-media thickness was used in this model because it is independent of the person's daily habits. The intima-media thickness is clearly visualized on US imaging, and there are standard algorithms for measurements. Another option for measuring strain would be to use the diameter of the artery, yet the diameter can vastly change depending on the person's food, drink, medication, and exercise that occurred before the measurements. As illustrated in Figure 1, tissue strain ($\alpha\text{m}/\alpha\text{m}$ or unitless) is derived from changes in intima-media thickness measurements as follows:

$$\varepsilon = \frac{\Delta IMT}{IMT}, \quad (3)$$

where ΔIMT is measured by the difference in the intima-media thickness at end systole and end diastole, and IMT is represented by the end-diastolic intima-media thickness measurement.

Image Acquisition

This prospective study was approved by the Institutional Review Board at the University of Alabama at Birmingham and performed in a Health Insurance Portability and Accountability Act-compliant manner. Longitudinal images of the brachial artery 2 cm cranial to the antecubital fossa were obtained in healthy (non-chronic kidney disease) volunteers ($n = 50$)

and patients with chronic kidney disease during preoperative vascular mapping for hemodialysis access placement ($n = 75$) with an iU22 scanner (Philips Healthcare, Bothell, WA) equipped with an L17-5 transducer. The patients and volunteers alike were positioned in the same routine currently used at this institution for prehemodialysis US mapping. All participants were in an upright position; simultaneous electrocardiographic recordings and US data from at least 10 cardiac cycles were acquired using several cine clips of 5 seconds in length. Several sonographers were used throughout this study in an outpatient **American College of Radiology–accredited** US facility; therefore, there may have been some variability between US scans, although the protocol and sonographer training were standardized. Healthy (non–chronic kidney disease) volunteers were defined as any person (19 years or older) without a chronic kidney disease history. Other than age, no other information was gathered from the volunteers. Patients with chronic kidney disease were defined as those patients undergoing US mapping before hemodialysis access placement. Because of this definition, the patients had varying degrees of disease and medications, and some may have had previously failed arteriovenous fistulas. These varying degrees are not presented in this article.

Elasticity Measurements

Arterial Health prototype software (Siemens Medical Solutions, Mountain View, CA) was used to determine the intima-media thickness of the arterial wall (Figure 2) during both end systole and end diastole. The prototype software is semiautomatic, using postprocessing of US images to calculate the intima-media thickness of the brachial artery. If a participant had a brachial artery that bifurcated in the proximal third of the arm, both arteries were imaged. The boundary edge of the top (inner lumen) and bottom (media-adventitia border) of the intima-media thickness is calculated by changes in pixel intensity values on the US images (uploaded in the Digital Imaging and Communications in Medicine format). The user verifies each intima-media thickness measurement, adjusts the boundaries if needed, and confirms the designated region of interest. The software uses pixel counts to calculate the measured intima-media thickness (the highlighted region as shown in Figure 2) and calculates an average thickness of the intima and media in micrometers. The midportion of the artery imaged is used to avoid error calculations in oblique or transverse transducer placements that could be made during the US examination.

Up to 6 intima-media thickness measurements are made for each vessel: 2 measurements from each cine clip. Six measurements were taken most of the cases; however, because of circumstances in which participant movement during the scans halted the ability to collect all 6 measurements, as many as possible were collected. If at least 3 measurements were not able to be collected, the participant was not included. The participant's electrocardiographic data and visual analysis of the vessel diameter helped determine the extreme states of vessel distension and contraction. The pressure wave in the distal artery is delayed from the QRS wave, and timing of maximum distension is located at the T wave of the cardiac cycle.²⁹ With Equation 3, strain was computed for each measurement, and each measurement was calculated from a separate cardiac cycle as the difference in intima-media thickness measurements at end systole and end diastole divided by the intima-media thickness at end diastole. Elastic modulus measurements were calculated with Equation 1 (pulse pressure for stress and each strain measurement), and then an average elastic modulus was calculated. More specifically, the pulse pressure defined by Equation 2 was taken as the difference between systolic and diastolic blood pressure measurements in the upper arm, proximal to the strain measurement in the brachial artery 2 cm cranial to the antecubital fossa. Last, the elastic modulus of the vessel wall was estimated as the ratio of vascular stress to strain as defined by Equation 1.

Because we hypothesize that vascular elasticity is correlated to fistula maturation, it is anticipated that a range may be established for patients with low elastic modulus values that will show a higher percentage of fistula maturation. To further analyze the data, 3 arbitrary arterial elastic modulus categories were created: low values of less than 100 kPa, midrange values of 100 to 150 kPa, and high values of greater than 150 kPa. The arbitrary categories were based on separating limits within the healthy volunteer data because to our knowledge there are no current standard values for normal arterial elasticity. The information from the patients with chronic kidney disease was then compared to the values set with the volunteer categories.

Statistical Analysis

Data were summarized as mean $\pm$ standard error. Statistical analyses were performed with the SAS version 9.2 software package (SAS Institute Inc, Cary, NC). Linear regression analysis was conducted to correlate elasticity with patient characteristics. Two-sample independent t tests were used to assess differences between volunteer and patient data. Analysis of variance statistical testing was used to evaluate elasticity differences in various elasticity groups. A Pearson rank correlation test was used to find correlation coefficients between elasticity or blood pressure and age. $P < .05$ was considered statistically significant.

Results

The patients with chronic kidney disease were significantly older than the healthy volunteers ($P < 0.001$). Preliminary results in the volunteers (mean age, 43 years; range, 20–65 years) were used to establish a database for comparison to the patients who underwent preoperative vascular US mapping before hemodialysis access placement. The mean brachial artery elasticity measurement in the volunteers was 100.85 ± 8.1 kPa (range, 39.3–267.7 kPa). The relatively low standard error shows feasibility and indicates low variability in healthy brachial arterial elastic modulus measurements. The volunteers showed a significant linear correlation between age and the elastic modulus ($R^2 = 0.14$; $P = .017$). The corresponding mean intima-media thickness measurement was $179 \mu\text{m}$ (range, 100–240 μm). The mean elastic modulus measurement in the patients with chronic kidney disease at preoperative US mapping (mean age, 56 years; range, 34–76 years; 52% female and 48% male) was 129.89 ± 6.44 kPa (range, 47.04–266.5 kPa). The corresponding mean intima-media thickness measurement was $228 \mu\text{m}$ (range, 130–387 μm). The arterial elasticity of the patients showed no correlation with age ($R^2 < 0.001$; $P = .829$). There were also no differences between male and female vascular modulus estimates among the patients ($P = .63$), with mean values of **138.41 ± 10.60** kPa for male patients and **124.65 ± 11.25** kPa for female patients; this information was not recorded for the volunteers.

Elastic modulus measurements in the patients before hemodialysis access placement were significantly higher than those in the volunteers ($P = .01$), as shown in Figure 3. A higher elastic modulus indicates a less elastic artery. The mean pulse pressure was significantly higher in the patients than in the volunteers: 64.7 ± 2.1 versus 55.3 ± 2.1 mm Hg, respectively ($P = .002$), as shown in Figure 3. Systolic blood pressure also showed a significant increase in the patients compared to the volunteers ($P < .001$), as did diastolic blood pressure ($P = .02$). The intima-media thickness was significantly increased in the patients compared to the volunteers ($P < .001$). With combined volunteer and patient data, it was shown that there was a significant correlation between the elastic modulus and systolic blood pressure ($R^2 = 0.23$; $P < .001$), as shown in Figure 3.

In a stratified analysis of the 3 main arterial elastic modulus categories for the healthy volunteers, 66% remained in the low elastic modulus group (<100 kPa), 22% in the midrange group (100–150 kPa), and 12% in the high group (>150 kPa), as detailed in Figure

4. In the patients with chronic kidney disease, the same stratification yielded 30% of patients in the high group, 40% in the midrange group, and 30% in the low group.

Discussion

Ultrasound-based elasticity measurements can be used to investigate the biomechanical properties of tissue. A decrease in elasticity is an early sign of vascular changes that occur in major vascular diseases.³⁰ Clinical studies suggest that the ability of the vessel to dilate helps determine fistula success.^{5,14} Previous results have shown low elasticity in arterial vessels to be correlated to fistula nonmaturation.²³ Identifying abnormally stiff arteries that will not be able to dilate sufficiently to provide adequate (at least 500 mL/min) blood flow through a hemodialysis arteriovenous fistula or graft may provide insight into why up to 60% of surgically placed fistulas fail to mature. Preoperative detection of those patients would decrease surgical placement of those access pathways that are unlikely to succeed.

The chronic kidney disease population in our study had significantly lower elasticity (higher elastic modulus, which computes to stiffer vessels) compared to the healthy volunteers with no history of chronic kidney disease ($P = .01$). The difference in the pulse pressure between the volunteers and the patients in this study is comparable to the results of Weitzel et al,²³ with both studies showing a greater pulse pressure in patients with chronic kidney disease. Using a large volunteer and patient population, our study examined an image-processing technique that uses clinically collected US data to noninvasively estimate arterial elasticity.

The use of US data for estimation of vascular elasticity is a diverse field. Several groups have used radiofrequency data and speckle-tracking algorithms to estimate vessel wall motion and strain.^{23,30,31} Another recent study used noninvasive radiofrequency data-based common carotid artery intima-media thickness measurements to evaluate arterial elasticity and early vascular disease in patients with isolated systolic hypertension,³⁰ concluding that intima-media thickening is associated with vascular stiffness. In our study, strain estimates were calculated by a simplified image-processing technique that could potentially be implemented in the clinical setting without disrupting the normal work flow. Our estimates of strain were similar to data presented by Weitzel et al²⁸ of around 5% for healthy participants and significantly less strain for patients with vascular disease. Jaber et al³² used an image-processing technique similar to our method to assess vein wall morphologic characteristics and cannulation readiness in patients with arteriovenous fistulas.

In a prospective cohort study, Kheda et al³³ speculated that low arterial vascular compliance promotes development of stenosis. They showed a significant difference between the small arteries (arterioles and smallest diameter arteries) of mature and failed fistulas with a linear correlation between the elasticity index and systolic blood pressure.³³ Vascular elasticity is negatively influenced by the presence of arterial calcifications and increased age^{34–36} and is dependent on the compositions of elastic fiber and collagen. The ratio of collagen to elastic fiber within arteries naturally increases with age, causing increased stiffness.³⁷ Importantly, analysis of the healthy volunteer population in our study showed a correlation between age and vascular elasticity ($R^2 = 0.14$; $P = .017$), which confirms age-dependent vascular stiffening.^{26,35,38} However, the arterial elasticity measurements from the patients with chronic kidney disease in our study showed no apparent correlation with age ($R^2 = 0.001$; $P = .83$). These results indicate that there is an additional outside affect causing the observed increased elastic modulus values in some patients with chronic kidney disease beyond age alone. This outside influence is hypothesized to be connected to etiologies such as increased arterial fibrosis or calcification; however, there are currently no histologic data to reinforce those hypotheses. The observation of an elasticity correlation in the volunteers but not in the patients could also suggest that chronic kidney disease accelerates vascular aging.

Data presented from our currently ongoing clinical study revealed significant differences between vascular elasticity estimates obtained from the healthy volunteers and the patients with chronic kidney disease. Ultrasound vascular mapping recommendations for access placement are currently based primarily on vessel size and location, with some variation by institution. There is currently no universal application of optimized baseline values for vessel anatomy, vessel distensibility, and vessel mechanics to optimize fistula use.¹⁶ However, there are vessel anatomy guidelines from the Society of Vascular Surgery (ie, minimum of 2 mm internal artery diameter), and each hospital has its own standardized guidelines for suitable vessel anatomy.³⁹ As the elastic modulus increases, stiffness of the vessel ensues.²⁶ It is hypothesized that patients who undergo fistula surgery and remain in the high elastic modulus group may have an increased fibrotic score (increased percentage of arterial fibrosis by histologic analysis) as well as a decreased likelihood of fistula maturation. Preoperative elastic modulus brachial artery quantification in patients with chronic kidney disease before arteriovenous fistula placement may improve the prognosis and vessel selection for successful fistula creation and maturation. Follow-up correlation of elasticity with arterial histologic characteristics and the fistula maturation outcome will provide a more complete answer.

Limitations of this study include a linear estimation of arterial wall mechanics in an intrinsically nonlinear vessel wall. However, the arterial elastic modulus has been shown to be roughly linear in the normal physiologic blood pressure ranges evaluated.⁴⁰ Another limitation is the frequency ranges used in current state-of-the-art US scanners available for clinical work; increased frequency in imaging would increase spatial resolution and likely further decrease variability in those patients with a high elastic modulus. In addition, more details for both healthy individuals and patients with chronic kidney disease (ie, presence/absence of cardiovascular disease, diabetes, smoking history, and hypertension) could possibly give increased information regarding variations between elastic modulus results among patients. This pilot study shows feasibility; histologic evaluation and correlation with arteriovenous fistula outcomes is ongoing.

In conclusion, this study suggests that high-resolution US imaging with dedicated image processing is a promising technique in the noninvasive estimation of brachial artery elasticity in both patients with chronic kidney disease and those without renal disease. Future research is ongoing to correlate preoperative brachial artery elasticity measurements and subsequent arteriovenous fistula maturation. This technique gives additional clinical information and in the future may help explain why select fistulas fail to successfully mature after surgical creation.

Acknowledgments

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Abbreviations

US ultrasound

References

1. National Kidney Foundation. Diabetes and Chronic Kidney Disease. National Kidney Foundation; New York, NY: 2011.
2. National Kidney Foundation. KDOQI clinical practice guidelines and clinical practice recommendations for vascular access 2006. *Am J Kidney Dis.* 2006; 48(suppl):S176–S322. [PubMed: 16813989]

3. Dember LM. Fistulas first—but can they last? *Clin J Am Soc Nephrol*. 2011; 6:463–464. [PubMed: 21393484]
4. Robbin ML, Chamberlain NE, Lockhart ME, et al. Hemodialysis arteriovenous fistula maturity: US evaluation. *Radiology*. 2002; 225:59–64. [PubMed: 12354984]
5. Roy-Chaudhury P, Spergel LM, Besarab A, Asif A, Ravani P. Biology of arteriovenous fistula failure. *J Nephrol*. 2007; 20:150–163. [PubMed: 17514619]
6. Allon M. Current management of vascular access. *Clin J Am Soc Nephrol*. 2007; 2:786–800. [PubMed: 17699495]
7. Robbin ML, Gallichio MH, Deierhoi MH, Young CJ, Weber TM, Allon M. US vascular mapping before hemodialysis access placement. *Radiology*. 2000; 217:83–88. [PubMed: 11012427]
8. Silva MB, Hobson RW, Pappas PJ, et al. A strategy for increasing use of autogenous hemodialysis access procedures: impact of preoperative noninvasive evaluation. *J Vasc Surg*. 1998; 27:302–308. [PubMed: 9510284]
9. Allon M, Lockhart ME, Lilly RZ, et al. Effect of preoperative sonographic mapping on vascular access outcomes in hemodialysis patients. *Kidney Int*. 2001; 60:2013–2020. [PubMed: 11703621]
10. Dember LM, Beck GJ, Allon M, et al. Effect of clopidogrel on early failure of arteriovenous fistulas for hemodialysis: a randomized controlled trial. *JAMA*. 2008; 299:2164–2171. [PubMed: 18477783]
11. Miller PE, Tolwani A, Luscyp CP, et al. Predictors of adequacy of arteriovenous fistulas in hemodialysis patients. *Kidney Int*. 1999; 56:275–280. [PubMed: 10411703]
12. Asif A, Roy-Chaudhury P, Beathard GA. Early arteriovenous fistula failure: a logical proposal for when and how to intervene. *Clin J Am Soc Nephrol*. 2006; 1:332–339. [PubMed: 17699225]
13. Dixon BS. Why don't fistulas mature? *Kidney Int*. 2006; 70:1413–1422. [PubMed: 16883317]
14. Roy-Chaudhury P, Arend L, Zhang J, et al. Neointimal hyperplasia in early arteriovenous fistula failure. *Am J Kidney Dis*. 2007; 50:782–790. [PubMed: 17954291]
15. Hoyt K, Castaneda B, Zhang M, et al. Tissue elasticity properties as biomarkers for prostate cancer. *Cancer Biomark*. 2008; 4:213–225. [PubMed: 18957712]
16. Weitzel WF. Preoperative hemodialysis fistula evaluation: angiography, ultrasonography and other studies, are they useful? *Contrib Nephrol*. 2008; 161:23–29. [PubMed: 18451654]
17. Danpinid A, Luo J, Vappou J, Terdtoon P, Konofagou EE. In vivo characterization of the aortic wall stress-strain relationship. *Ultrasonics*. 2010; 50:654–665. [PubMed: 20138640]
18. Mackenzie IS, Wilkinson IB, Cockcroft JR. Assessment of arterial stiffness in clinical practice. *QJM*. 2002; 95:67–74. [PubMed: 11861952]
19. Laurent S. Arterial stiffness in arterial hypertension. *Curr Hypertens Rep*. 2006; 8:179–180. [PubMed: 17147914]
20. Hartley CJ, Taffet GE, Michael LH, Pham TT, Entman ML. Noninvasive determination of pulse-wave velocity in mice. *Am J Physiol*. 1997; 273:H494–H500. [PubMed: 9249523]
21. Harvey CJ, Pilcher JM, Eckersley RJ, Blomley MJ, Cosgrove DO. Advances in ultrasound. *Clin Radiol*. 2002; 57:157–177. [PubMed: 11952309]
22. Fromageau J, Brusseau E, Vray D, Gimenez G, Delachartre P. Characterization of PVA cryogel for intravascular ultrasound elasticity imaging. *IEEE Trans Ultrason Ferroelectr Freq Control*. 2003; 50:1318–1324. [PubMed: 14609071]
23. Weitzel WF, Kim K, Rubin JM, Xie H, O'Donnell M. Renal advances in ultrasound elasticity imaging: measuring the compliance of arteries and kidneys in end-stage renal disease. *Blood Purif*. 2005; 23:10–17. [PubMed: 15627731]
24. Mai JJ, Insana MF. Strain imaging of internal deformation. *Ultrasound Med Biol*. 2002; 28:1475–1484. [PubMed: 12498943]
25. Wagenseil JE, Mecham RP. Vascular extracellular matrix and arterial mechanics. *Physiol Rev*. 2009; 89:957–989. [PubMed: 19584318]
26. Greenwald SE. Ageing of the conduit arteries. *J Pathol*. 2007; 211:157–172. [PubMed: 17200940]
27. Pirat B, McCulloch ML, Zoghbi WA. Evaluation of global and regional right ventricular systolic function in patients with pulmonary hypertension using a novel speckle tracking method. *Am J Cardiol*. 2006; 98:699–704. [PubMed: 16923465]

28. Weitzel WF, Kim K, Park DW, et al. High-resolution ultrasound elasticity imaging to evaluate dialysis fistula stenosis. *Semin Dial.* 2009; 22:84–89. [PubMed: 19000117]
29. Bertino RE, Grassi CJ, Bluth EI, et al. Practice guideline for the performance of physiologic evaluation of extremity arteries. *J Vasc Interv Radiol.* 2007; 18:1203–1206. [PubMed: 17911508]
30. Dan HJ, Wang Y, Zeng MX, Luan YY, Hu B. Evaluation of intima-media thickness and vascular elasticity of the common carotid artery in patients with isolated systolic hypertension using ultrasound radiofrequency-data technology. *Clin Physiol Funct Imaging.* 2011; 31:315–319. [PubMed: 21672140]
31. Lubinski MA, Emelianov SY, O'Donnell M. Speckle tracking methods for ultrasonic elasticity imaging using short-time correlation. *IEEE Trans Ultrason Ferroelectr Freq Control.* 1999; 46:82–96. [PubMed: 18238401]
32. Jaber A, Muradali D, Marticorena RM, et al. Arteriovenous fistulas for hemodialysis: application of high-frequency US to assess vein wall morphology for cannulation readiness. *Radiology.* 2011; 261:616–624. [PubMed: 21878614]
33. Kheda MF, Brenner LE, Patel MJ, et al. Influence of arterial elasticity and vessel dilatation on arteriovenous fistula maturation: a prospective cohort study. *Nephrol Dial Transplant.* 2010; 25:525–531. [PubMed: 19755475]
34. Stein JH, Fraizer MC, Aeschlimann SE, Nelson-Worel J, McBride PE, Douglas PS. Vascular age: integrating carotid intima-media thickness measurements with global coronary risk assessment. *Clin Cardiol.* 2004; 27:388–392. [PubMed: 15298037]
35. Benetos A, Waeber B, Izzo J, et al. Influence of age, risk factors, and cardiovascular and renal disease on arterial stiffness: clinical applications. *Am J Hypertens.* 2002; 15:1101–1108. [PubMed: 12460708]
36. Guérin AP, London GM, Marchais SJ, Metivier F. Arterial stiffening and vascular calcifications in end-stage renal disease. *Nephrol Dial Transplant.* 2000; 15:1014–1021. [PubMed: 10862640]
37. Levy L, Castlebury LA, Carris LM, Meyer RJ, Pimentel G. Internal transcribed spacer sequence-based phylogeny and polymerase chain reaction-restriction fragment length polymorphism differentiation of *Tilletia walkeri* and *T. indica*. *Phytopathology.* 2001; 91:935–940. [PubMed: 18944119]
38. Mitchell GF, Parise H, Benjamin EJ, et al. Changes in arterial stiffness and wave reflection with advancing age in healthy men and women: the Framingham Heart Study. *Hypertension.* 2004; 43:1239–1245. [PubMed: 15123572]
39. Sidawy AN, Spergel LM, Besarab A, et al. The Society for Vascular Surgery: clinical practice guidelines for the surgical placement and maintenance of arteriovenous hemodialysis access. *J Vasc Surg.* 2008; 48(suppl):2S–25S. [PubMed: 19000589]
40. Park DW, Richards MS, Rubin JM, Hamilton J, Kruger GH, Weitzel WF. Arterial elasticity imaging: comparison of finite-element analysis models with high-resolution ultrasound speckle tracking. *Cardiovasc Ultrasound.* 2010; 8:22. [PubMed: 20565833]

Figure 1.

As the cardiac cycle moves from peak systolic pressure to peak diastolic pressure, the intima-media thickness (IMT) changes. This change allows calculation of strain. Blood pressure acting perpendicularly on the vessel wall allows stress estimation. The estimated elastic modulus is measured by application of stress and the subsequent strain resulting from the applied force.

Figure 2.

Arterial Health prototype software used in intima-media thickness (IMT) measurement changes. Postscan US images are used to measure the intima-media thickness of the brachial artery at end systole (largest diameter) and end diastole (smallest diameter) for elastic modulus assessment. The image shown here is in end diastole.

Figure 3.

A, Comparison of blood pressure measurements between patients with chronic kidney disease (CKD) and healthy volunteers. **B**, With all participants combined, the correlation between the elastic modulus and systolic blood pressure was significant ($R^2 = 0.14$; $P < .001$). **C**, Comparison of elastic modulus values for the patients and volunteers plotted in ascending order. The patients overall had an increased elastic modulus compared to the volunteers. As the elastic modulus increases for both groups, variability also increases.

Figure 4.

Stratification of the results into 3 groups (low, medium, and high elastic modulus values) gives further insight into the differences in vessel biomechanics between the patients with chronic kidney disease (CKD) and healthy volunteers. With additional information, a range could be set that will help predict fistula maturation.