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Superficial Ultrasound Shear Wave Speed Measurements in Soft and Hard Elasticity Phantoms: Repeatability and Reproducibility Using Two Different Ultrasound Systems

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Abstract

Background—There is a paucity of data available regarding the repeatability and reproducibility of superficial shear wave speed (SWS) measurements at imaging depths relevant to the pediatric population.

Conflicts of interest

An ultrasound imaging system used in this study was provided to Dr. Dillman by Siemens Medical Solutions USA for a separate investigator -initiated investigation.

Purpose—To assess the repeatability and reproducibility of superficial shear wave speed (SWS) measurements acquired from elasticity phantoms at varying imaging depths using three different imaging methods, two different ultrasound systems, and multiple operators.

Methods and Materials—Soft and hard elasticity phantoms manufactured by Computerized Imaging Reference Systems, Inc. (Norfolk, VA) were utilized for our investigation. Institution #1 used an Acuson S3000 ultrasound system (Siemens Medical Solutions USA, Inc.) and three different shear wave imaging method/transducer combinations, while institution #2 used an Aixplorer ultrasound system (Supersonic Imagine) and two different transducers. Ten stiffness measurements were acquired from each phantom at three depths (1.0, 2.5, and 4.0 cm) by four operators at each institution. Student's t-test was used to compare SWS measurements between imaging techniques, while SWS measurement agreement was assessed with two-way random effects single measure intra-class correlation coefficients and coefficients of variation. Mixed model regression analysis determined the effect of predictor variables on SWS measurements.

Results—For the soft phantom, the average of mean SWS measurements across the various imaging methods and depths was 0.84 ± 0.04 m/s (mean $\pm$ standard deviation) for the Acuson S3000 system and 0.90 ± 0.02 m/s for the Aixplorer system ($p=0.003$). For the hard phantom, the average of mean SWS measurements across the various imaging methods and depths was 2.14 ± 0.08 m/s for the Acuson S3000 system and 2.07 ± 0.03 m/s Aixplorer system ($p>0.05$). The coefficients of variation were low (0.5–6.8%), and inter-operator agreement was near-perfect (ICCs = 0.99). Shear wave imaging method and imaging depth significantly affected measured SWS ($p<0.0001$).

Conclusions—Superficial SWS measurements in elasticity phantoms demonstrate minimal variability across imaging method/transducer combinations, imaging depths, and between operators. The exact clinical significance of this variability is uncertain and may vary by organ and specific disease state.

Introduction

Shear wave elastography, a form of ultrasound elasticity imaging, can be used to noninvasively assess the stiffness (hardness) of human tissues *in vivo* [1–5]. Using clinical ultrasound transducers and a variety of techniques, shear waves can be generated remotely in human tissues and tracked. Based on shear wave propagation versus time, shear wave speed can be measured (m/s) and Young's modulus (kilopascals, or kPa) can be estimated [1–5]. While tissue stiffness also can be noninvasively assessed using magnetic resonance imaging [6,7], shear wave elastography has numerous advantages over MR elastography, including lower cost, faster examination times, no need for sedation or general anesthesia in young and certain older children, and no need for an external source of shear wave generation (other than the ultrasound transducer). Additionally, shear wave elastography can be performed in individuals with contraindications to MRI.

Ultrasound has played an indispensable role in the radiologic assessment of children for several decades. While pediatric ultrasound examinations have traditionally relied upon some combination of gray-scale and Doppler imaging, there is a small but increasing body of literature demonstrating the value of ultrasound shear wave elasticity imaging in children

[8–12]. Unfortunately, there is a paucity of data regarding the repeatability and reproducibility of ultrasound-derived stiffness measurements between operators and across different shear wave imaging platforms when evaluating shallow structures (4 cm in depth), such as might be performed in the pediatric population, in general, or for superficial small parts in adults.

The purpose of our investigation was to assess the repeatability and reproducibility of superficial SWS measurements acquired from soft and hard elasticity phantoms at varying imaging depths using multiple operators, two different ultrasound systems, and three shear wave imaging methods.

Methods and Materials

“Soft” and “hard” (similar to normal and cirrhotic (fibrotic) liver in stiffness) cylindrical (10 cm depth, 10 cm diameter) ultrasound elasticity phantoms manufactured by Computerized Imaging Reference Systems, Inc. (CIRS; Norfolk, VA) and donated to the Quantitative Imaging Biomarker Alliance (QIBA) were utilized for the current investigation [13,14]. These phantoms were determined to be adequately homogenous based on testing performed by the Nightingale Laboratory at Duke University (Department of Biomedical Engineering) [13,14].

For each elasticity phantom (soft and hard), ultrasound shear wave imaging was performed at two separate institutions (BLINDED). At each site, imaging was performed by four operators (operators #1 and #2 performed “initial” phantom imaging and data collection, while after a period of time greater than 24 hours operators #3 and #4 performed “replicate” phantom imaging and data collection). Imaging was performed at three shallow phantom depths (1.0, 2.5, and 4.0 cm) to simulate imaging of the pediatric patient.

Shear wave imaging at institution #1 (BLINDED) was performed using an Acuson S3000 ultrasound system (Siemens Medical Solutions USA, Inc.; Mountain View, CA), 9L4 linear array and 4C1 curved array transducers, and two distinctive shear wave elastography methods (Virtual Touch Quantification [VTQ] and Virtual Touch IQ [VTIQ]). VTQ shear wave elastography was performed using both the 9L4 and 4C1 transducers, while VTIQ shear wave elastography was performed using only the 9L4 transducer (the 4C1 transducer currently does not support the VTIQ shear wave elastography technology) (Fig. 1). Thus, the Acuson S3000 system provided *three* unique sets of shear wave imaging data.

Shear wave imaging at institution #2 (BLINDED) was performed using an Aixplorer ultrasound system (Supersonic Imagine [SSI]; Bothell, WA) in Shear Wave Elastography mode and both SL10-2 and SL15-4 linear array transducers. Thus, the Aixplorer system provided *two* additional unique sets of shear wave imaging data (Fig. 2).

In total, *five* different sets of shear wave data (from five shear wave imaging method/transducer combinations) from *two* different imaging platforms and *three* unique shear wave imaging methods were acquired for the current study.

For each operator, elasticity phantom, and imaging depth, a series of 10 consecutive stiffness shear wave speed measurements (m/s) were acquired. Two separate measurements were acquired perpendicular to the phantom's round surface at the 12, three, six, and nine o'clock positions as well as in the isocenter of the phantom (a mark was made on the outside of the phantom to signify the 12 o'clock position). Transducers were lifted from the phantoms between individual measurements (i.e., simulated "coffee break"), and a single measurement was obtained per image acquisition for all shear wave imaging methods except VTIQ (for VTIQ imaging, two SWS measurements separated by at least 1 cm were obtained from a single image acquired at each phantom position and imaging depth) (Fig. 1a).

Water was used to couple transducers and phantoms, and any air bubbles observed along the transducer surface were removed. Operators were instructed to use the minimum amount of transducer force required to generate diagnostic gray-scale imaging. Default region-of-interest (ROI) shapes and sizes were used for the various shear wave imaging methods. Shear wave imaging using the Aixplorer system and SL15-4 transducer (institution #2) was not possible at an imaging depth of 4 cm due to technical limitations (this transducer only allows SWS measurement at superficial depths); therefore, no data was acquired for this shear wave imaging method/transducer combination at this imaging depth.

Shear Wave Imaging Methods

Virtual Touch IQ (VTIQ; Acuson S3000 ultrasound system) uses multiple acoustic radiation force impulses (ARFIs), or "push pulses", applied across the span of the transducer and at multiple depths to remotely generate shear waves that can be tracked and create a color image (elastogram) of material (tissue) stiffness. As unique SWSs are assigned different colors, the elastogram provides a visual assessment of material/tissue (e.g., liver) stiffness over a several cm by several cm area (the exact area can be adjusted by the operator) and can be used to evaluate material heterogeneity. VTIQ push pulses range in frequency from 4.00–5.71 MHz. VTIQ allows placement of fixed 1.5 mm² square regions of interest (ROIs) on the elastogram image to obtain SWS estimates; multiple ROIs can be placed on a single VTIQ image.

Virtual Touch Quantification (VTQ; Acuson S3000 ultrasound system) utilizes a "push pulse" (4.00 MHz when using the 9L4 transducer and 2.67 MHz when using the 4C1 transducer) at a single location to remotely generate shear waves that can be tracked and provide an estimate of SWS. VTQ–9L4 employs a fixed 5 mm² square ROI to measure SWS, while VTQ–4C1 uses a fixed 6 x 10 mm ROI. Only a single SWS measurement can be obtained per image acquisition when using the VTQ shear wave imaging technique; there is no associated color elastogram.

The SSI Aixplorer ultrasound system in Shear Wave Elastography (SWE) mode also uses multiple acoustic radiation force impulses to remotely generate shear waves that can then be monitored in real-time. This shear wave imaging method, also known as supersonic shear imaging [15], produces constructively interfering shear waves that create a single shear wave front. Multiple push beam locations are used to obtain shear wave data [16]. Like VTIQ, the SSI shear wave imaging method provides a color elastogram of tissue stiffness. The "push pulses" for the SL10-2 and SL15-4 transducers were transmitted at 4.00 and 6.00

MHz, respectively. Circular ROIs can be placed on the elastogram image to obtain estimates of Young's modulus; default circular ROI sizes were used (diameters of 8.3 mm and 9.1 mm for SSI-SL10-2 and SSI-SL15-4, respectively).

Statistical Analysis

All analyses were performed using SWS as the primary outcome. Estimates of tissue stiffness can be converted between Young's modulus (kPa) and SWS using the following formula:

$$SWS (m/s) = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{3\rho}},$$

where μ is the shear modulus in units of Pa, ρ is the mass density of the medium, E is the Young's modulus in units of kPa, where $\mu = E/(2(1+\nu)) \approx E/3$, and ν is the Poisson's ratio which is assumed to be 0.5 to account for tissue incompressibility [1].

SWS measurements were summarized as means and standard deviations for each shear wave imaging method/transducer combination, elasticity phantom, and imaging depth (data for all operators at a given institution combined). Coefficients of variation were calculated. Box plots of SWS measurements were used to visually demonstrate the dispersion in the data, both within and between the various shear wave imaging method/transducer combinations. Unpaired student's t-tests (unequal variance assumption) were used to compare SWS measurements between shear wave imaging technologies. Inter-reader agreement between operators at each institution for each shear wave imaging method/transducer combination and imaging depth was assessed with single-measure intra-class correlation coefficients (ICCs) using a two-way random effects model.

Mixed model regression analysis was performed for each ultrasound imaging system (Acuson S3000 and Aixplorer, respectively) and elasticity phantom (soft and hard) to identify the predictor variables that affect the primary outcome (measured SWS). The following predictor variables were included in the model: shear wave imaging method (e.g., for this analysis, VTIQ, VTQ-9L4, VTQ-4C1, SSI-SL10-2, and SSI-SL15-4 were considered unique shear wave imaging methods), day of imaging ("initial" imaging by operators #1 and #2 vs. "replicate" imaging by operators #3 and #4), phantom position, and imaging depth. A variable taking into account multiple operators was nested within the "day of imaging" variable. A duplicate measurements variable (two stiffness measurements were acquired at each phantom position by each operator) was nested within the "phantom position" variable. Interaction terms were also assessed. A stepwise forward regression based on the Akaike information criterion (AIC) was used for model selection.

A p value <0.05 was considered statistically significant for inference testing. Statistical analyses were performed using SAS, version 9.3 (SAS Institute, Inc.; Cary, NC).

Results

Mean Shear Wave Speed Measurements

Mean SWS measurements and standard deviations acquired from both the soft and hard elasticity phantoms at the three specified imaging depths are presented for both ultrasound systems and all five shear wave imaging method/transducer combinations in Tables 1 and 2 and Figs. 3 and 4.

For the soft phantom, mean SWS measurements ranged from 0.80 m/s (VTQ–9L4 at both 1.0 and 4.0 cm imaging depths) to 0.93 m/s (SSI–SL10-2 at 4.0 cm imaging depth). The average of the mean SWS measurements across the various shear wave imaging method/transducer combinations and imaging depths for the soft phantom was 0.86 ± 0.05 m/s (overall, N=14), 0.84 ± 0.04 m/s (Acuson S3000, N=9), and 0.90 ± 0.02 m/s (Aixplorer, N=5). The SWS measurements obtained in the soft phantom by the Acuson S3000 system were significantly different from those obtained by the Aixplorer system ($p=0.003$).

For the hard phantom, mean SWS measurements ranged from 2.00 m/s (VTIQ at 4.0 cm imaging depth) to 2.29 m/s (VTQ–4C1 at 1.0 cm imaging depth). The average of the mean SWS measurements across the various shear wave imaging method/transducer combinations and imaging depths for the hard phantom was 2.11 ± 0.07 m/s (overall, N=14), 2.14 ± 0.08 m/s (Acuson S3000, N=9), and 2.07 ± 0.03 (Aixplorer, N=5). The SWS measurements obtained in the hard phantom by the Acuson S3000 system were not significantly different from those obtained by the Aixplorer system ($p>0.05$).

Coefficients of Variation and Inter-Operator Agreement

The coefficients of variation were greater for the Acuson S3000 ultrasound system (range: 1.1–6.8%) than the Aixplorer ultrasound system (range: 0.5–3.8%), but were small in magnitude for both systems. Inter-operator agreement was near-perfect for all shear wave imaging method/transducer combinations and all imaging depths (Table 3).

Effects of Predictor Variables

Mixed model regression analysis was performed to determine how a variety of predictor variables affect SWS measurements (Tables 4 and 5).

Acuson S3000 – Soft Phantom—Shear wave imaging method (VTIQ vs. VTQ–9L4 vs. VTQ–4C1; $p<0.0001$) and imaging depth (1.0 vs. 2.5 vs. 4.0 cm; $p<0.0001$) significantly affected SWS measurements in the soft phantom with the Acuson S3000 system. Operator had no significant effect.

The VTQ–4C1 and VTQ–9L4 methods reduced the SWS measurements by an estimated 0.071 and 0.082 m/s, respectively, when compared to the VTIQ method. The 1.0 and 2.5 cm imaging depths increased the SWS measurements by an estimated 0.007 and 0.026 m/s, respectively, when compared to the 4.0 cm imaging depth.

Acuson S3000 – Hard Phantom—Shear wave imaging method (VTIQ vs. VTQ–9L4 vs. VTQ–4C1; $p<0.0001$), imaging depth (1.0 vs. 2.5 vs. 4.0 cm; $p<0.0001$), and the

interaction term “shear wave imaging method x imaging depth” ($p<0.0001$) significantly affected SWS measurements in the hard phantom with the Acuson S3000 system, implying that the effect of shear wave imaging method varied by imaging depth. Operator had no significant effect.

The VTQ-4C1 and VTQ-9L4 methods increased the SWS measurements by an estimated 0.168 and 0.080 m/s, respectively, compared to the VTIQ method. The 1.0 and 2.5 cm imaging depths increased the SWS measurements by an estimated 0.125 and 0.093 m/s, respectively, compared to the 4.0 cm imaging depth.

Aixplorer – Soft Phantom—Imaging depth (1.0 vs. 2.5 vs. 4.0 cm; $p<0.0001$) significantly affected SWS measurements. The main effect of shear wave imaging method (SSI-SL10-2 vs. SSI-SL15-4) on SWS measurements was not significant ($p=0.17$), although the interaction term “shear wave imaging method x imaging depth” ($p<0.0001$) significantly affected SWS measurements in the soft phantom using the Aixplorer system. Operator did not significantly affect SWS measurements. The 1.0 and 2.5 cm imaging depths reduced the SWS measurements by an estimated 0.058 and 0.055 m/s, respectively, compared to the 4.0 cm imaging depth.

Aixplorer – Hard Phantom—Shear wave imaging method (SSI-SL10-2 vs. SSI-SL15-4; $p<0.0001$), imaging depth (1.0 vs. 2.5 vs. 4.0 cm; $p<0.0001$), and the interaction term “shear wave imaging method x imaging depth” ($p<0.0001$) significantly affected SWS measurements in the hard phantom with the Aixplorer system. Operator had no significant effect.

The SSI-SL10-2 method increased SWS measurements by an estimated 0.005 m/s compared to the SSI-SL15-4 method. The 1.0 and 2.5 cm imaging depths reduced SWS measurements by an estimated 0.001 and 0.049 m/s, respectively, compared to the 4.0 cm imaging depth.

Discussion

Our study builds on findings from a recent QIBA investigation [13,14] of SWS repeatability by specifically focusing on SWS measurements at imaging depths most relevant for superficial small parts (e.g., thyroid gland) and the general pediatric population. The QIBA study [13,14] assessed imaging depths commonly encountered in adult populations (3.0–7.0 cm) on a heterogeneous collection of elasticity phantoms that varied across study sites (mean shear wave speed of soft phantoms ≈ 0.95 m/s; mean shear wave speed of hard phantoms ≈ 2.09 m/s), while we evaluated the repeatability and reproducibility of SWS measurements in the very shallow portions (1.0–4.0 cm in depth) of two homogeneous elasticity phantoms. Both phantoms in our study were used by both imaging sites for all SWS measurements in our study, regardless of operator and shear wave imaging method/transducer combination. This allowed us to eliminate any variability or systematic bias that may be introduced by using different phantoms at different imaging sites.

Mean SWS measurements obtained from the soft elasticity phantom ranged from 0.80 to 0.93 m/s across the various imaging depths using three different shear wave imaging methods (five different shear wave imaging method/transducer combinations) on two ultrasound systems (N=40 measurements/depth for VTIQ, VTQ-9L4, VTQ-4C1, SSI-SL10-2, and SSI-15-4, respectively). Close inspection of our data shows that the small 0.06 m/s difference in mean SWS measurements noted between the Acuson S3000 and Aixplorer ultrasound systems was primarily due to lower SWS measurements acquired when using the VTQ-9L4 and VTQ-4C1 imaging techniques. SWS measurements acquired using other shear wave imaging method/transducer combinations were similar.

The greatest variability in SWS measurements in the soft phantom occurred when using the VTIQ method at 1.0 and 2.5 cm imaging depths, although this variation was minor (coefficients of variation: 6.5–6.8%, respectively). We suspect this variability is at least in part (if not mostly) due to the small size of the VTIQ ROI in comparison to the ROIs used for the other shear wave imaging methods. The fixed VTIQ 1.5 mm² ROI has an area of 2.25 mm² which is approximately 24 times smaller than the smallest Aixplorer system default ROI (SSI-10.2, circular ROI with diameter of 8.3 mm and area of 54.1 mm²). In essence, VTIQ is providing a point estimate of SWS while other shear wave imaging methods are providing an estimate over an area, which results in less variability between measurements. SWS measurements obtained using shear wave imaging methods other than VTIQ had minimal variability at given imaging depths (standard deviations = 0.1–0.3 m/s).

Mean SWS measurements obtained from the hard elasticity phantom ranged from 2.00 to 2.29 m/s across the various imaging depths using three different shear wave imaging methods (five different shear wave imaging method/transducer combinations) on two ultrasound systems (N=40 measurements/depth for VTIQ, VTQ-9L4, VTQ-4C1, SSI-SL10-2, and SSI-15-4, respectively). SWS measurements of the hard phantom acquired using the VTQ imaging method and 4C1 transducer demonstrated minimally higher SWS measurements at all three imaging depths. SWS measurements acquired using other shear wave imaging method/transducer combinations were similar. All three Acuson S3000 shear wave imaging techniques (VTIQ, VTQ-9L4, and VTQ-4C1) displayed greater SWS measurement variability at all three imaging depths when compared to measurements obtained using the Aixplorer system (coefficients of variation: 1.4–3.8% vs. 0.5–1.0%, respectively). However, these differences in variability between the two ultrasound systems are of small magnitude and of doubtful clinical significance.

Additionally, we have demonstrated near-perfect inter-operator agreement in both the soft and hard elasticity phantoms across the various shear wave imaging method/transducer combinations and imaging depths (ICCs = 0.99–1.00). This shows the potential for excellent repeatability of SWS measurements for shallow structures *in vivo* (i.e., tissues located within 4 cm of the skin surface [e.g., pediatric liver or adult thyroid gland]). A recent study by Cosgrove et al. [17] assessing the intra- and interobserver reproducibility of shear wave elastography in more than 700 breast masses also concluded that shear wave elastography is highly reproducible. In their study, intraobserver reliability for *in vivo* breast mass mean elasticity was very good (ICC = 0.87). A study by D'Onofrio et al. [18] performed in healthy adult volunteers and using two ultrasound operators found that hepatic SWS measurements

obtained from the deep portion of the right hepatic lobe were very reliable with an ICC of 0.87. Hanquinet et al. [19] measured liver SWS values in 103 children (including infants and adolescents) without known liver disease and found no difference in measurements based on age; ICC was 0.77 in their study.

Imaging depth significantly affected SWS measurements in both ultrasound systems across both phantoms, an observation that was also noted by the QIBA study [13,14]. In our study, this effect was very small and inconsistent across the two ultrasound systems. It is important to note that phantom position did not significantly affect SWS measurements; this provides corroborative evidence that the elasticity phantoms are homogeneous in construction. The interaction term “shear wave imaging method x imaging depth” was also significant for the Acuson S3000 system in the hard phantom and the Aixplorer system in both phantoms. This interaction term indicates that the effect of shear wave imaging method (e.g., Acuson S3000 VTIQ vs. VTQ-9L4 vs. VTQ-4C1) on SWS varies by imaging depth. These depth-related differences in SWS measurement are very small, however, and of questionable clinical significance.

Our study has limitations. First, we are assessing the variability and inter-operator agreement of SWS measurements in soft and hard elasticity phantoms and not in human subjects. While our results are encouraging, they must be validated *in vivo* in children. Additionally, we intentionally imaged only the shallow portions of the elasticity phantoms. We did not collect data deeper than 4.0 cm from the phantom surface. As mentioned above, SWS measurements were unable to be acquired at an imaging depth of 4.0 cm using the SSI-15-4 shear wave imaging method due to technical limitations.

In conclusion, we have systematically assessed SWS measurement repeatability and reproducibility for three different shear wave elastography methods on two ultrasound systems in soft and hard elasticity phantoms at imaging depths that are specifically relevant to the pediatric population. Superficial SWS measurements obtained from both phantoms demonstrated minimal variability across the various shear wave imaging methods and imaging depths that we assessed.

This variability, which was slightly greater for the Acuson S3000 system in both phantoms, was quite small in magnitude and is currently of unknown clinical significance (it is conceivable that the clinical significance of SWS variability may vary by organ and the specific disease state being assessed). While mixed model regression analysis demonstrated that imaging depth significantly affected SWS measurements, the size of this effect was small and inconsistent. Finally, our results establish near-perfect inter-operator agreement, an observation that is promising and needs to be confirmed *in vivo*.

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This work is an extension of a study performed by the Quantitative Imaging Biomarker Alliance (QIBA) of the Radiological Society of North America (RSNA) that is directed toward unifying the quantification of shear wave speed and tissue elastic modulus across different US and MRI platforms [13]. The elasticity phantoms used in this study were manufactured and donated by Computerized Imaging Reference Systems Inc. (Norfolk, VA) for the QIBA study through the efforts of Ted Lynch, PhD.

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Figure 1a

Figure 1b

Figure 1c

Fig 1.

Shear wave elastography images showing shear wave speed measurements acquired from soft elasticity phantom using three different shear wave imaging method/transducer combinations (Acuson S3000 ultrasound system; Siemens Medical Solutions USA, Inc.). **A**,

Virtual Touch IQ (VTIQ); **B**, Virtual Touch Quantification using 9L4 transducer (VTQ – 9L4); and **C**, Virtual Touch Quantification using 4C1 transducer (VTQ –4C1). Shear wave speed measurements at 2.5 cm imaging depth range from 0.82–0.91 m/s on the images shown.

Fig 2. Shear Wave Elastography mode image showing Young's modulus measured in kilopascals (kPa) acquired from hard elasticity phantom using Aixplorer ultrasound system (Supersonic Imagine) and SL10-2 transducer. Mean stiffness within the circular region-of-interest is estimated to be 12.2 kPa (shear wave speed = 2.02 m/s).

Figure 3a

Figure 3c

Fig 3.

Box plots showing shear wave speed measurements acquired in a soft elasticity phantom using 5 different shear wave imaging method/transducer combinations (N=40 measurements for each combination). **A**, 1 cm imaging depth; **B**, 2.5 cm imaging depth; **C**, 4 cm imaging depth. Dots represent statistical outliers (greater than 1.5 interquartile ranges above Quartile 3 or below Quartile 1).

Figure 4a

Figure 4b

Figure 4c

Fig 4.

Box plots showing shear wave speed measurements acquired in a hard elasticity phantom using 5 different shear wave imaging method/transducer combinations (N=40 measurements for each imaging combination). **A**, 1 cm imaging depth; **B**, 2.5 cm imaging depth; **C**, 4 cm imaging depth. Dots represent statistical outliers (greater than 1.5 interquartile ranges above Quartile 3 or below Quartile 1).

Table 1

Shear wave speed measurements using soft elasticity phantom at three shallow imaging depths. Results for five different shear wave imaging method/transducer combinations are presented.*

Ultrasound System	Shear Wave Imaging Method	Transducer	Phantom	Depth (cm)	Mean SWS (m/s)	Standard Deviation (m/s)	COV
Acuson S3000 (Siemens)	VTIQ	9L4	Soft	1	0.88	0.06	6.8%
Acuson S3000 (Siemens)	VTIQ	9L4	Soft	2.5	0.92	0.06	6.5%
Acuson S3000 (Siemens)	VTIQ	9L4	Soft	4	0.86	0.02	2.3%
Acuson S3000 (Siemens)	VTQ	9L4	Soft	1	0.80	0.01	1.3%
Acuson S3000 (Siemens)	VTQ	9L4	Soft	2.5	0.81	0.02	2.5%
Acuson S3000 (Siemens)	VTQ	9L4	Soft	4	0.80	0.01	1.3%
Acuson S3000 (Siemens)	VTQ	4C1	Soft	1	0.82	0.03	3.7%
Acuson S3000 (Siemens)	VTQ	4C1	Soft	2.5	0.82	0.02	2.4%
Acuson S3000 (Siemens)	VTQ	4C1	Soft	4	0.81	0.02	2.5%
Aixplorer (SSI)	SWE	SL10-2	Soft	1	0.92	0.01	1.1%
Aixplorer (SSI)	SWE	SL10-2	Soft	2.5	0.87	0.01	1.2%
Aixplorer (SSI)	SWE	SL10-2	Soft	4	0.93	0.01	1.1%
Aixplorer (SSI)	SWE	SL15-4	Soft	1	0.89	0.01	1.1%
Aixplorer (SSI)	SWE	SL15-4	Soft	2.5	0.89	0.02	2.3%

SWS = shear wave speed; COV = coefficient of variation; VTIQ = Virtual Touch IQ; VTQ = Virtual Touch Quantification; Siemens = Siemens Medical Solutions, Inc.; SSI = Supersonic Imagine; SWE = Shear Wave Elastography mode.

* N=40 measurements for each SWS mean and standard deviation (measurements for all four operators at each institution combined).

Table 2

Shear wave speed measurements using hard elasticity phantom at three shallow imaging depths. Results for five different shear wave imaging method/transducer combinations are presented.*

Ultrasound System	Shear Wave Imaging Method	Transducer	Phantom	Depth (cm)	Mean SWS (m/s)	Standard Deviation (m/s)	COV
Acuson S3000 (Siemens)	VTIQ	9L4	Hard	1	2.13	0.07	3.3%
Acuson S3000 (Siemens)	VTIQ	9L4	Hard	2.5	2.10	0.08	3.8%
Acuson S3000 (Siemens)	VTIQ	9L4	Hard	4	2.00	0.05	2.5%
Acuson S3000 (Siemens)	VTQ	9L4	Hard	1	2.12	0.03	1.4%
Acuson S3000 (Siemens)	VTQ	9L4	Hard	2.5	2.13	0.04	1.9%
Acuson S3000 (Siemens)	VTQ	9L4	Hard	4	2.08	0.05	2.4%
Acuson S3000 (Siemens)	VTQ	4C1	Hard	1	2.29	0.07	3.1%
Acuson S3000 (Siemens)	VTQ	4C1	Hard	2.5	2.21	0.08	3.6%
Acuson S3000 (Siemens)	VTQ	4C1	Hard	4	2.17	0.08	3.7%
Aixplorer (SSI)	SWE	SL10-2	Hard	1	2.12	0.01	0.5%
Aixplorer (SSI)	SWE	SL10-2	Hard	2.5	2.04	0.01	0.5%
Aixplorer (SSI)	SWE	SL10-2	Hard	4	2.09	0.02	1.0%
Aixplorer (SSI)	SWE	SL15-4	Hard	1	2.08	0.02	1.0%
Aixplorer (SSI)	SWE	SL15-4	Hard	2.5	2.04	0.01	0.5%

SWS = shear wave speed; COV = coefficient of variation; VTIQ = Virtual Touch IQ; VTQ = Virtual Touch Quantification; Siemens = Siemens Medical Solutions, Inc.; SSI = Supersonic Imagine; SWE = Shear Wave Elastography mode.

* N=40 measurements for each SWS mean and standard deviation (measurements for all four operators at each institution combined).

Table 3

Intra-class correlation coefficients (ICCs) from each site (institution) using a single-measure two-way random effects model calculated to assess inter-operator agreement for each shear wave imaging method/transducer combination and imaging depth (N=4 readers per category).

	ICCs
Site #1 (BLINDED institution) overall	0.99 [0.99–1.00]
1.0-cm depth	0.99 [0.99–1.00]
2.5-cm depth	0.99 [0.99–1.00]
4.0-cm depth	0.99 [0.99–1.00]
VTIQ(Acuson S3000/Siemens)	0.99 [0.99–1.00]
VTQ-9L4 (Acuson S3000/Siemens)	0.99 [0.99–1.00]
VTQ-4C1 (Acuson S3000/Siemens)	0.99 [0.99–1.00]
Site #2 (BLINDED institution) overall	0.99 [0.99–1.00]
1.0-cm depth	1.00 [0.99–1.00]
2.5-cm depth	0.99 [0.99–1.00]
4.0-cm depth	0.99 [0.99–1.00]
SL10-2 (Aixplorer/SSI)	0.99 [0.99–1.00]
SL15-4 (Aixplorer/SSI)	0.99 [0.99–1.00]

ICCs = intra-class correlation coefficients; Siemens = Siemens Medical Solutions USA, Inc.; SSI = Supersonic Imagine.

Table 4

Table of factor importance based on mixed model regression analysis performed to determine how a variety of predictor variables affect shear wave speed measurements.

Factor(Predictor Variable)	Elasticity Phantom			
	Soft		Hard	
	Ultrasound System			
	Acuson S3000 (Siemens)	Aixplorer(SSI)	Acuson S3000 (Siemens)	Aixplorer (SSI)
Shear Wave Imaging Method	Yes	No	Yes	Yes
Imaging Depth	Yes	Yes	Yes	Yes
Phantom Position	No	No	No	No
Shear Wave Imaging Method x Imaging Depth	No	Yes	Yes	Yes
Shear Wave Imaging Method x Phantom Position	No	No	No	No
Imaging Depth x Phantom Position	No	No	No	No
Shear Wave Imaging Method x Imaging Depth*Phantom Position	No	No	No	No
Operator	No	No	No	No

Siemens Medical Solutions USA, Inc.; SSI = Supersonic Imagine.