Published in final edited form as:

Ultrason Imaging. 2013 April ; 35(2): 109–125. doi:10.1177/0161734612474159.

Single Tracking Location Methods Suppress Speckle Noise in Shear Wave Velocity Estimation

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Abstract

In ultrasound-based elastography methods, the estimation of shear wave velocity typically involves the tracking of speckle motion due to an applied force. The errors in the estimates of tissue displacement, and thus shear wave velocity, are generally attributed to electronic noise and decorrelation due to physical processes. We present our preliminary findings on another source of error, namely, speckle-induced bias in phase estimation. We find that methods that involve tracking in a single location, as opposed to multiple locations, are less sensitive to this source of error since the measurement is differential in nature and cancels out speckle-induced phase errors.

Keywords

acoustic radiation force; elastography; shear modulus; speckle-induced bias; SMURF; MTL; STL

Introduction

The measurement of shear wave velocity, particularly in soft tissue, is of interest to several groups.^{1–10} Assuming a linear elastic material of constant density, the shear wave velocity is proportional to the square root of the tissue stiffness, which in turn has been shown to be a useful parameter in the detection of disease. In ultrasound-based elastography methods, the process of estimating the shear wave velocity usually involves the tracking of scatterer displacements due to an applied force. Errors in this displacement estimation are propagated through the process and ultimately affect the estimates of the shear wave velocity and thus the estimates of shear stiffness. These errors are often attributed to electronic noise and decorrelation due to physical processes.¹¹ Some of the results in our earlier work indicate that there exists another source of error, namely, a speckle-induced bias. This bias was discovered on closer inspection of the estimates of shear modulus within a linear elastic phantom, using two different elastographic methods (spatially modulated ultrasound radiation force [SMURF] imaging and sonoelastography). In the following sections, we first present the relevant portions of our findings from that earlier study,¹² and then our methods and results from our investigation on this speckle-induced bias.

SMURF imaging was validated¹³ using standard mechanical testing (MTS) and sonoelastography in uniform gelatin and Zerdine™ (CIRS Inc., Norfolk, Virginia) phantoms. The results showed good agreement between all three methods. In the SMURF

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Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Stephen A. McAleavey is the inventor of U.S. Patent No. 8,225,666, assigned to the University of Rochester, titled *Shear modulus estimation by application of spatially modulated impulse acoustic radiation force approximation*.

method, a spatially varying acoustic radiation force impulse (ARFI) was generated by a linear array transducer. The resulting shear wave of known wavelength was generated within a homogeneous phantom. By tracking the speckle at a single location and using cross-correlation techniques, the temporal frequency of the shear wave was estimated and used to calculate the shear modulus.

In the sonoelastography measurements, an electromagnetic shaker was used to vibrate a phantom at a known frequency. This motion generated a forward traveling shear wave. At two locations, a known distance apart, the same linear array transducer was used to measure the shear-wave-induced displacements, which differ by only a phase shift if attenuation is neglected. The shear wavelength was estimated using the phase shift between the two signals, and this was in turn used to calculate the shear modulus.

In both methods, several echoes were acquired at the tracking locations within a homogeneous phantom. To create estimates of shear modulus as a function of depth, the phase shift (sonoelastography) or temporal frequency (SMURF) was calculated for each sample of the RF echo signal and then converted to a shear modulus.

In the sonoelastography case, it was found that the trial-to-trial variation was insignificant compared with the variation within the depth of field in the estimates. This indicated that the variation was not due to random noise, as it would have been minimized when the data from the various echo lines were averaged, but rather it was due to a correlated noise source. In contrast, the trial-to-trial variation in the SMURF estimates was comparable with the variation within the depth of field and thus indicated that the estimates were limited by random noise.

One explanation for the correlated noise in the sonoelastography experiment is the effect of shearing. Shearing can cause variations in the shear modulus estimates because it creates a range of displacements within the tracking beam, and the resulting displacement estimate is an average of these displacements.¹⁴ As portrayed in Figure 1,¹⁵ higher excitation frequencies result in a greater amount of shearing since all the scatterers are not displaced uniformly as the shear wave propagates through.

However, in a sonoelastography experiment performed in a gelatin phantom, phase shifts were measured and plotted for three different distances between the lateral tracking locations (shown in Figure 2). Beam spacing values of 0 mm, 0.885 mm, and 1.77 mm were used. The intertrial standard deviations associated with the beam spacing values were 0.0026, 0.0040, and 0.0043 radians, respectively. The intratrial standard deviations, which represent the standard deviation of the phase shift estimates over a total depth of 1.9 cm, were 0.0021, 0.3328, and 0.281 radians, respectively. The $\Delta x = 0$ mm case is not exactly the same as the autocorrelation. Here, the correlation can be thought of as being between the even samples and the odd samples, each with some random noise component. This is consistent with the other cases as the echoes from the two tracking locations were not collected simultaneously, and the time between echoes collected at one location was twice the pulse repetition period. When $\Delta x = 0$ mm, that is, the same speckle was used in the calculation, the phase estimates had a standard deviation in the region of interest that was comparable with the random error. The other two lateral tracking distances were greater than the tracking beam width and yielded repeatable measurements with much higher variation over the region of interest. These results suggested that random noise and shearing were not the main reasons why the trial-to-trial variation was insignificant compared with the variation in the phase difference estimates.

An important difference between the SMURF method and other elastography methods such as sonoelastography, lateral time-to-peak (TTP), and supersonic shear wave imaging is that they determine the shear wave arrival time difference or phase shift by tracking speckle in two different locations, while SMURF determines the arrival time information by tracking speckle in a single location. We hypothesize that the displacement tracking along an A-line is biased by strong speckle because scatterers whose echoes interfere constructively at a point slightly off the beam axis will be tracked in preference to a weaker on-axis speckle. Consequently, at different depths, there is a speckle-induced variation in the path length, and there is thus a location-dependent underestimation or overestimation of the phase shift. SMURF, however, is a differential measurement because the same speckle is being used in calculating the arrival time difference. This suggests that using the same set of scatterers during tracking to determine the shear wave velocity could potentially reduce the variation in the estimates because the speckle-induced bias is circumvented.

The amount of variation due to this bias has not been examined until now. In this preliminary work, we examine the effect of speckle-induced bias on the estimates of shear wave velocity and thus shear modulus. We examine the effect of echo signal-to-noise ratio (SNR) and the choice of beam spacing on the variation in shear modulus estimates using both single tracking location (STL) and multiple tracking location (MTL) algorithms. Shear modulus estimation methods that track the displacement of speckle in different lateral locations will be termed *multiple tracking location* methods, while those that track the shear-wave-induced displacements from a fixed point will be referred to as *single tracking location* methods.

Method

Simulation

The STL and MTL algorithms were compared using one-dimensional (1-D) and 2-D simulations. The 1-D simulations (FIELD II¹⁵) were performed to show the effect of the position of a single scatterer within a tracking beam, on the estimates of shear modulus. The 2-D simulations were performed using a finite-element model (FEM; COMSOL Multiphysics), and included potential effects associated with the pushing beam shape and choice of material properties. The 2-D simulation was used to explore the effect of the distance between the pushing beams (STL) or tracking beams (MTL), as well as the effect of SNR, on the shear modulus estimates.

1-D Simulation—The shear wave is modeled as a 1-D-struck string problem, wherein the resulting velocity wave is a replica of the impulsive forcing function.¹² The forcing function is proportional to the pushing beam intensity, which is modeled as having a Gaussian profile. Consequently, the velocity wave as a function of time (t) and the lateral location (x) of the scatterer at a fixed depth can be expressed as follows:

$$v(x, t) = Ae^{-\frac{\left(t - \frac{\Delta x}{c_s} - \frac{x}{c_s}\right)^2}{\sigma^2}}, \quad (1)$$

where A is the peak velocity amplitude, Δx is the distance from the push location to the track location, and σ is the push beam width. The material shear modulus is determined by the choice of shear wave speed c_s . The displacement function is the integral of this velocity,

$d(x, t) = \int_{-\infty}^t v(x, t) dt$. The STL ARFI algorithm is simulated by applying the displacements $D(x, t)$ and $D(x + \Delta P, t)$ to the same collection of randomly distributed scatterers, while in the MTL ARFI case $D(x, t)$ is applied to two different, random sets of scatterers. The input displacements are independent of scatterer depth. The resulting displacements are tracked by

simulating a VF7-3 Antares Scanner with 192 elements and 5.33 MHz center frequency in the FIELD II program.¹⁵

The velocity data are derived from the finite-time difference of the tracked displacement waveform from each “push.” The arrival time difference, ΔT , is estimated using the cross-correlation of the velocity data. Since the distance between the two pushing (or tracking) locations, ΔP , is known, the shear wave speed can then be calculated, and assuming a linear elastic model, the shear modulus of the region between the pushes (or track locations) is simply,

$$G = \rho c_s^2 = \rho \left(\frac{\Delta P}{\Delta T} \right)^2, \quad (2)$$

where G is the shear modulus, c_s is the shear wave speed, ΔP is the distance between the pushing locations (STL) or tracking locations (MTL), ΔT is the difference in the arrival time of the shear waves, and ρ is the material density that is assumed to be 1 g/cm³. The flowchart of the 1-D simulation process can be seen in Figure 3.

The general assumption with the MTL methods is that the path length between the scatterers in the two tracking beams is the distance from the middle of one tracking beam to the middle of the next. Essentially, it is as if the scatterers being tracked are located in the middle of their respective beams. If the scatterers within both tracking beams are exactly offset to the left or right of their respective beam centers, the assumed path length is still accurate. However, this is not the case in reality.

The effect of this speckle-induced change in path length was investigated in a 1-D simulation by placing a single scatterer within each tracking beam (no shearing present) and then offsetting the scatterers in the beams by varying amounts. The full-width half-maximum (FWHM) of the tracking beam in both methods was 0.7 mm. In the MTL method, the scatterer in one beam was placed in the middle of its corresponding beam while translating the scatterer within the other beam in steps of 0.1 mm to the left or right of its beam axis. The distance between the tracking beam centers was 3 mm.

In the STL method, only one tracking beam was employed, and the scatterer within this beam was also translated in steps of 0.1 mm to the left or right of its beam axis. The distance between the pushing beams was 3 mm.

In both methods, each scatterer was displaced by 10 μ m using a single-frequency sine wave at 500 Hz. The tracking of the induced displacements was simulated using FIELD II. The finite-time difference of the displacement data was used to derive the velocity-time waveforms. The arrival time difference was estimated using cross-correlation techniques. The shear modulus estimate was then derived from (2), where the beam spacing is assumed to be 3 mm. The shear modulus was set at 2 kPa by choosing a shear wave speed of 2 m/s (Equation 2).

Finite-Element Simulation—Using COMSOL Multiphysics (COMSOL Inc., Burlington, Massachusetts), a 2-D plane strain, FEM of a linear elastic material was created. The material had an elastic modulus of 6 kPa, density of 1 g/cm³, and a Poisson’s ratio of 0.499. The acoustic radiation force, $F(x,z)$, was proportional to the pushing beam intensity. The push beam was generated in FIELD II by simulating a 4.2 MHz VF7-3 linear array transducer with F/2.7 and a 200-cycle-long pushing pulse. The push beam was then imported into COMSOL as a forcing function. The force amplitude was scaled and applied to the mesh for 50 μ s. The push beam was focused at 3 cm, and the radiation force was

scaled to result in a 20 μs peak displacement at the point of application in the FEM. The resulting displacements in a 2-mm-wide-by-1-cm-tall region centered around the focus, at distances 3 mm and 5 mm away from the push (i.e., $\Delta P = 2$ mm), were applied to a corresponding 2 mm by 1 cm set of random scatterers. To mimic the STL ARFI method, the displacements generated at the two locations are applied to the same set of random scatterers. For the MTL ARFI method, the displacements were simply applied to different random scatterer sets to mimic the differing speckle between the two tracking locations. The shear modulus was then estimated as outlined in Figure 3. This FEM included Rayleigh damping with a stiffness damping parameter, $\beta = 10^{-6}$ s, and a mass damping parameter $\alpha = 1$ s $^{-1}$. The pulse repetition frequency (PRF) was 7.5 kHz. The FEM, unlike the 1-D simulations, included potential effects associated with the pushing beam shape and choice of material properties.

To explore the effect of the distance between the pushing beams (STL) or tracking beams (MTL), the separation between the locations at which the displacements were extracted from the mesh was varied from 1 mm to 4 mm. The same process outlined above was used to estimate the shear modulus. White Gaussian noise was band-passed to match the bandwidth of the VF7-3 transducer, and then added to the simulated tracked RF data. The noise was added to generate simulated RF echo data with SNR levels of 10 dB (low) and 30 dB (average).

Experimental Methods

Data Acquisition—A Siemens Antares VF7-3 linear array was used to image gelatin phantoms and excised porcine liver tissue. The STL and MTL configurations were implemented using custom software that allows for the modification of the transducer transmit and receive beam-forming sequences. The same linear array transducer was used to generate the pushing beams, as well as to track the induced displacements. The beam-formed RF echo data was sampled at 40 MHz and digitized with 16-bit resolution. The probe has 192 elements of 0.2-mm pitch and 7.5-mm height. The elevation focus is fixed at 3.75 cm. The center frequency of both the push and track pulses was 4.21 MHz. The push pulses were 200 cycles long, while the track pulses were 2 cycles long. A Hanning apodization geometrically focused at 2 cm was used on transmit. Dynamic focusing and apodization were used on receive. The pushing beam width is chosen to be twice that of the tracking beam width to mimic a more uniform displacement of the scatterers and thus minimize shearing effects within the beam.

In the STL ARFI algorithm, the acoustic radiation force was applied at two locations, P_1 and P_2 , 2.1 mm apart, and the induced shear waves were tracked at a location, T , 1.8 mm from P_1 as shown in Figure 4a. The shear modulus estimate is associated with the region between the two pushing pulses. This sequence of pushing and tracking is known as an ensemble. To map out the shear modulus of a region of interest, the entire ensemble is simply translated laterally. The shear modulus of the region between the pushing pulses is estimated by cross-correlating the velocity data to attain the arrival time difference.

For the MTL ARFI algorithm, the acoustic radiation force is applied to the material at a location P , and the induced shear waves are tracked at the force application point and then at increasing lateral distances from that pushing location as portrayed by Figure 4b. The distance from the pushing location to first tracking location is 1.8 mm, and the distance from the first tracking location (T_1) and the last tracking location (T_N) is 2.1 mm. The shear wave is thus tracked over a lateral region that is 2.1 mm wide, with each track location placed approximately 0.35 mm from the previous one.

Data Processing—The post-push tracking echoes were received at a PRF of 7.5 kHz. The received echoes were up-sampled to 320 MHz using a low-pass interpolation filter. The displacements were estimated using a windowed normalized cross-correlation on the reference and post-push echoes. A window length of 1.5 mm was used along with a 39 μm search region. Subsample precision in finding the location of the peak of the cross-correlation function was achieved by applying a parabolic fit to the peak sample and its neighbors. The data used in estimating the shear wave speed was confined to the depth of field and was calculated to be approximately 7 mm.

In the STL ARFI algorithm, the finite-time difference of the slow-time displacement was calculated to get the velocity data. The velocity data associated with the two pushes were first up-sampled by a factor of 10 using linear low-pass interpolation, and then cross-correlated to extract the arrival time difference between both waves. This was repeated for every axial sample and lateral ensemble. In calculating the average shear modulus over depth or within a region, the cross-correlated velocity waveforms with a correlation coefficient less than 0.5 were ignored.

Two methods were used to process the MTL data. In the first method, the same data-processing algorithm described for the STL case was used in acquiring the shear wave arrival time difference at each axial sample and lateral ensemble, but in this case, the displacement data was from the first and last tracking locations (T_1 and T_N). This method was used in the FEMs. In the second method, the displacement over time as tracked by the beams at T_1 through T_N , are used to calculate the shear wave speed as outlined by Palmeri et al.¹⁶ For each lateral location, the time it took to reach the peak displacement is recorded and plotted against the distance of that lateral location from the pushing location. A linear regression is performed on the Time-to-Peak (TTP) data. The inverse slope of the regression line represents the shear wave speed in the tracked region. This was repeated for every axial sample and lateral ensemble. In calculating the average shear modulus over depth or within a region, a goodness-of-fit threshold ($R^2 > 0.8$) was applied. This lateral TTP method was used for the phantom and excised porcine liver experiments.

Tissue-Mimicking Phantoms—Two tissue-mimicking phantoms were made from deionized (DI) water, gelatin and cornstarch. The softer phantom was made from 100-bloom gelatin, while the stiffer phantom was made from 200-bloom gelatin. Cornstarch powder was added to provide ultrasound scattering and attenuation. Glutaraldehyde was added to the mixture to accelerate the gelatin cross-linking process. The mixture was poured into a mold, which was then sealed and rotated for at least 12 hours. On solidification, the phantom was removed from the mold and stored in mineral oil. The phantoms are cylindrical in shape. Each phantom has a radius of 4 cm and is 7 cm in height. The phantoms were imaged using a Siemens Antares VF7-3 (linear array) transducer.

Porcine Liver Tissue—Porcine liver was obtained from a local butcher and stored in cold saline. B-mode scans of the excised tissue were done to find sections that appeared relatively homogeneous. Such sections were excised, placed in a separate container of saline, and degassed in a vacuum bell jar for two hours. The sections were then imaged with the VF7-3 linear array transducer using the STL and MTL algorithms.

Results

1-D Simulation

The effect of the speckle-induced change in path length was investigated in a 1-D simulation by placing a single scatterer within each tracking beam (no shearing present) and then offsetting the scatterers in the beams by varying amounts. The FWHM of the tracking beam

in both methods was 0.7 mm. In the MTL method, the scatterer in one beam was placed in the middle of its corresponding beam, while translating the scatterer within the other beam in steps of 0.1 mm to the left or right of its beam axis.

In the STL method, only one tracking beam was employed, and the scatterer within this beam was also translated in steps of 0.1 mm to the left or right of its beam axis.

The distance between the tracking beams was 3 mm in the MTL method, and the distance between the pushing beams was 3 mm in the STL method.

Figure 5 shows the consequence of assuming that the distance between the tracked scatterers is a fixed 3-mm distance.

Estimates of Shear Modulus versus Depth of Field

The shear moduli in a FEM and two gelatin phantoms were estimated using both algorithms. The finite-element simulations were repeated 10 times with different scatterers each time. Figure 6a shows the shear modulus estimates over the 1-cm depth around the focus for both methods, as well as the correlation coefficients of the velocity waves used in estimating the arrival time difference. The error bars represent the intertrial variation in the estimates of shear modulus. Figures 6b and 6c show the distribution of the arrival time and shear modulus estimates for both methods over the 10 trials.

Using both methods, the shear modulus of a soft gelatin phantom was estimated with a VF7-3 linear array. The beams were focused at 2 cm, and the echoes corresponding to a 1-cm axial region around the focus were used to calculate the shear modulus over depth ("Experimental Methods" section). Each measurement was repeated 10 times in the same location. There are approximately 500 axial samples within that region, but only the points from every 20th sample are shown to prevent overcrowding of the plot. Figure 7 shows the estimates for both algorithms as a function of depth. The RF echo SNR was measured in this phantom to be approximately 51 dB. The results are consistent with the results from the simulations. Figure 8 shows the amount of variation at four different lateral locations within two gelatin phantoms with shear modulus values of ~1 kPa and ~4.5 kPa, using both methods. The shear modulus estimates over the 1-cm depth of field for all the different trials are used to calculate the mean shear modulus value and the standard deviation (shown as the error bars).

Figure 9 shows the estimates as a function of depth in an excised porcine liver sample using both algorithms.

Effect of Beam Spacing and Echo SNR

The amount of variation in the modulus estimates is affected by the relationship between the size of the error in the estimates of the arrival time difference and the true arrival time difference. Specifically, the error in the estimates of the arrival time difference relative to the true arrival time difference decreases as the push beam distance (STL) or track beam distance (MTL) increases. The error in the shear modulus estimates is expected to be inversely proportional to the push beam spacing. Figure 10 and Table 1 show the data for both algorithms. Table 1 contains the average shear modulus estimate for both methods with different beam spacings, as well as the standard deviation of the measurements. The standard deviation of the estimates over the axial depth of field for 10 trials is plotted as a function of beam spacing for both methods in Figure 10.

The echo SNR also affects the error in the shear modulus estimates. The same simulation from Table 1 was repeated with band-passed white noise added to the RF echo data to attain

10-dB and 30-dB SNR levels. Figure 11 and Table 2 show the effect of added noise and beam spacing on the amount of variation in the estimates.

Discussion

Speckle-Induced Bias versus Jitter

Errors in shear wave velocity estimation using transient elastography methods are a function of jitter,¹¹ shearing,¹⁴ variation in the intensity field/out-of-plane propagations,¹⁷ motion artifacts, and dispersion. The results presented thus far are consistent with the hypothesis that in addition to these other sources of variation, there is a correlated noise source that is associated with transient elastography methods that track displacements at multiple locations to estimate shear wave velocity. This noise source is due to the fact that stronger speckle are tracked preferentially, and they may be located off the axis of the tracking beam. The consequence is that the propagation path length, which is often approximated as the distance from one tracking axis to the next, is a variable.

The results from the 1-D simulation (Figure 5) show the effect of the speckle-induced path length changes by tracking a single scatterer. Specifically, when the scatterer is offset in such a way that the true path length is shorter than the assumed path length, the arrival time difference is smaller and the shear modulus is estimated as being larger than it actually is

since $G = \rho \left(\frac{\Delta P}{\Delta T} \right)^2$ and the beam spacing was assumed to be fixed. Inversely, when the scatterer is offset in such way that the true path length is longer than the assumed path length, the arrival time difference is larger and the shear modulus is estimated as being smaller than it actually is. The use of a single scatterer, in addition to making it easier to visualize the changes in path length, also eliminates the shearing component.

One way to circumvent this problem is to use the same set of speckle when performing the shear wave velocity estimation as is the case with STL methods. Using the same set of speckle makes the calculation a differential one, so that an identical bias is present in both sets of the estimated displacement data and is subtracted out. Averaging the results from multiple iterations of the experiment can reduce the random error component. The speckle-induced bias, however, cannot be removed this way. It can, however, be reduced by spatial averaging, but doing this detracts from the resolution. The implication of a significant reduction in the variation of the shear modulus estimates is that the precision of the estimates will be improved, which would then enhance the elastographic image quality and the diagnostic value of the estimates.

Figure 6 shows the intertrial variation in a 10-iteration finite-element simulation using both algorithms in the same model. Interestingly, while it is true that the STL algorithm has consistently better correlation coefficients, both algorithms have good correlation coefficients (greater than 0.94), which suggests that the estimates are likely of good quality and that there is actually a variation in the arrival time difference. In other words, even in a simulation where the correlation coefficients are relatively high in both methods, the variation of the estimates is still seen to be greater in the MTL method than in the STL method. As illustrated by Figure 6c, the arrival time differences of the different depth samples over the 10 trials is almost symmetrically distributed, but since the calculation of

the shear modulus involves the inversion of the arrival time difference, $G = \rho \left(\frac{\Delta P}{\Delta T} \right)^2$ the resulting shear moduli do not have a symmetric distribution. In addition, the MTL method has larger variations in the arrival time estimates than in the STL method, and these variations are further magnified with the inversion (Figure 6b). For these reasons, there is

often a bias in the MTL measurements in addition to the variation within the estimates, as shown in Figure 6a.

The variation in the shear wave velocity estimates due to this speckle-induced bias can be quite significant as Figures 7, 8, and 9 demonstrate. In Figures 7 and 9, the estimates are found at a single location within a gelatin phantom (~ 0.9 -kPa shear modulus) and an excised porcine liver tissue sample, respectively, over the depth of field of the ultrasound pushing beam. Repeated measurements in the same location using both methods result in different amounts of variation in the estimates. In both a relatively nondispersive material (the gelatin phantom) as well as in a viscoelastic medium (the excised liver tissue), the variation in the shear modulus values is larger when multiple tracking lines are used than when a STL is employed. We expect that the more viscous a material is, the greater the distortion (amplitude loss and spreading) of the tracked shear wave displacement waveform. The greater the distortion, the harder it becomes to accurately extract the arrival time difference between the induced shear waves. This will affect both STL and MTL methods, and presumably, the variation in the estimates of shear modulus as a result of this distortion will eventually become comparable with the speckle-induced bias. So far, however, in the experiments in excised porcine liver—which is known to have a viscous component—the improvement in the estimates from the STL method is still clear.

In cases where motion, whether physiologic or otherwise, is present, it is expected that the degradation of the STL method performance will be determined by the degree to which the motion results in a decorrelation of echoes collected along a single track line.

In the phantom and liver experiments, the lateral TTP MTL algorithm was used in the estimation of the shear moduli. The use of additional tracking lines within the region of interest improved the variation within the estimates, but this variation was still greater than that found in the STL measurements.

In Figure 8, the estimates from all the trials over the depth of field are used to calculate the mean and standard deviation at different lateral locations within two gelatin phantoms of shear modulus values of ~ 0.9 kPa and ~ 4.5 kPa. The phantoms are fabricated in-house, and great care was taken to make the phantoms as homogeneous as possible. The choice of shear modulus values for the gelatin phantoms represents the lower and higher end of shear modulus values reported in normal to cirrhotic human liver tissue. The standard deviation of shear modulus estimates within different regions of two phantoms is significantly larger in the MTL case than in the STL case.

Echo SNR and Beam Spacing

The benefit of tracking in a single location is decreased at low echo SNR. In Figure 10 and in Table 1, the SNR was infinite, representing the ideal scenario. Figure 11 and Table 2, show the effect of reduced SNR on both methods. A smaller improvement in the STL estimates over the MTL estimates is seen when significant noise is present in the simulation data. This is intuitive, as one would expect a significant amount of variation in the estimates as the noise level increases. Comparing the data from the 30-dB noise level and the infinite SNR case suggests that beyond a certain point, increases in SNR will not result in a significant reduction of the variation in the estimates.

Another parameter that can be altered to control the amount of variation in the estimates is the beam spacing. Larger distances imply longer arrival times. Since the error in the estimates of the arrival time difference falls within a relatively small range, the size of that error relative to the true arrival time difference will decrease as the push beam distance (STL) or track beam distance (MTL) increases.

This effect can also be visualized using simple error propagation methods:

In general, if $G = G(x)$ is some function of x , then the error in G , ε_G , as a function of the error in x , ε_x , is given by,

$$\partial G = \left| \frac{dG}{dx} \right| \partial x. \quad (3)$$

Similarly, given the shear modulus,

$$G = \rho \left(\frac{\Delta P}{\Delta T} \right)^2 = \rho c_s^2, \quad (4)$$

where ρ is the material density, ΔP is the push beam spacing, ΔT is the arrival time difference and c_s is the shear wave speed. The error in G , ε_G , in terms of the error in arrival time difference, ε_T , can be written as follows:

$$\varepsilon_G = 2\rho \left(\frac{(\Delta P)^2}{(\Delta T)^3} \right) \varepsilon_T \quad (5)$$

This is equivalent to

$$\varepsilon_G = 2\rho c_s^3 \left(\frac{1}{\Delta P} \right) \varepsilon_T \quad (6)$$

The error in the shear modulus estimates is thus seen to be inversely proportional to the push (track) beam spacing. This beam spacing dependence can be seen in Figure 8. It is harder to see the dependence in the case of the STL method because both methods were plotted on the same scale. Selecting an arbitrarily large spacing, however, is not practical. Furthermore, dispersion can distort the shear wave before it arrives at the tracking location, and the distortion of the shear waves can ultimately result in inaccurate estimates of the shear modulus.

Conclusion

We have shown that phase-shift/arrival time errors due to speckle can be a significant source of jitter in transient elastography methods that involve displacement estimation. Our results are consistent with the hypothesis that slightly off-center speckle with a strong signal will be tracked in favor of weaker on-axis speckle, and that this results in a variation in the propagation path length that is dependent on the location of the speckle within the tracking beam. Tracking at a single location subtracts out this speckle noise in shear wave velocity estimates because the same scatterers are being used.

The greatest benefit in using a STL is derived when the echo SNR is good (>20 dB), and when there is minimal distortion of the shear wave shape and minimal transducer motion.

Acknowledgments

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Institutes of Health Grant 1R21 EB008724.

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Figure 1.

A narrow set of random scatterers was displaced using a single-frequency sine wave (1 Hz, 250 Hz, 500 Hz) in a one-dimensional simulation.

The resulting displacements were tracked using FIELD II.

Figure 2.

Sonoelastographic measurements of phase shifts in a gelatin phantom.

(a) Sonoelastography setup. (b) Sonoelastographic phase difference estimates in the compliant gelatin phantom for three track beam spacings. The mean phase estimates are 0.3816 ($\Delta x = 0$ mm), 2.328 ($\Delta x = 0.885$ mm), and 4.342 ($\Delta x = 1.77$ mm) radians. The intertrial standard deviations were 0.0026, 0.0040, and 0.0043 radians, respectively. The intratrial standard deviation—the standard deviation of the phase shift estimates over depth (total of 1.9 cm)—was much smaller for the $\Delta x = 0$ case (0.0021) than for $\Delta x = 0.886$ mm (0.3328) and $\Delta x = 1.77$ mm (0.2810). The small trial-to-trial variation in phase estimate compared with the overall variation in the estimates suggests the variation is not due to inadequate signal-to-noise ratio.¹³ The mean phase shift is not zero for the case when $\Delta x = 0$ mm because the tracking echo signals were not acquired simultaneously. The time between echoes collected at one location was twice the pulse repetition period.

Figure 3.

Flowchart of the simulation process.

Scatterers are displaced by functions D_1 and D_2 to mimic the radiation force application.

The resulting scatterer displacement is then tracked over time using an ultrasound field simulator. The measured displacements are used to estimate the arrival time difference and then the shear modulus.

Figure 4.

STL versus MTL ARFI Algorithm.

(a) STL ARFI algorithm: the acoustic radiation force is applied at two locations, P_1 and P_2 , a known distance apart, and the induced shear waves were tracked at a location, T , a known distance from P_1 while in (b) MTL ARFI algorithm: the acoustic radiation force is applied to the material at a location P and the induced shear waves are tracked at locations T_1 and T_N a known distance apart. ARFI = acoustic radiation force impulse; STL = single tracking location; MTL = multiple tracking location.

Figure 5.

One-dimensional simulation using a single scatterer.

The scatterer is placed at different lateral locations within the tracking beam. (a) STL: The arrival time difference estimate is unaffected by the location of the scatterer within the tracking beam. (b) MTL: As indicated by the estimates of arrival time difference, the shear wave path length changes with the location of the scatterer. This affects the estimates of shear modulus since the path length was assumed to be constant (3 mm). The region being interrogated to determine shear modulus is between the pushing pulses in STL methods but is between the tracking lines in MTL methods. STL = single tracking location; MTL = multiple tracking location.

Figure 6.

Representative examples of FEM simulation data: 2-mm lateral spacing of track (MTL) or push (STL) beams, no noise added to simulated RF data; 20 μm peak displacement.

(a) Mean and standard deviation of the shear modulus estimates (top) and the correlation coefficients of the cross-correlated velocity waveforms (bottom). The error bars represent the standard deviation of the 10 trials. (b) Box plot of all the arrival time difference estimates (top) and shear modulus estimates (bottom) over the 10 trials. (c) Histogram of all the arrival time difference estimates (top) and shear modulus estimates (bottom) over the 10 trials. STL = single tracking location; MTL = multiple tracking location; FEM = finite-element model.

Figure 7.
100-bloom gelatin phantom at high echo signal-to-noise ratio show results consistent with simulations.
The error bars represent the intertrial variation over 10 trials.

Figure 8. Variation in the estimates of shear modulus in two phantoms with shear moduli of roughly 0.9-kPa (left) and 4.5-kPa (right) phantom, using the STL (top) and MTL (bottom) methods. The error bars represent the standard deviation of the estimates from all 10 trials over a 1-cm axial depth around the focus, as a function of lateral location. STL = single tracking location; MTL = multiple tracking location.

Figure 9.

STL and MTL ARFI measurements in an excised porcine liver sample.

Top panel: B-mode image and STL ARFI image of the ROI within the excised porcine liver sample. Bottom panel: Variation in the estimates of shear modulus in an excised porcine liver sample using the STL method (left) and MTL method (right). The error bars represent the intertrial variation over 10 trials. STL = single tracking location; MTL = multiple tracking location; ARFI = acoustic radiation force impulse; ROI = region-of-interest.

Figure 10.

Variation in the estimates of shear modulus for both the MTL and STL methods as a function of beam spacing.

MTL = multiple tracking location; STL = single tracking location.

Figure 11.

Simulated data showing the effect of SNR and beam spacing on the variation in the estimates of shear modulus.

SNR = signal-to-noise ratio.

Table 1

Simulated Data of the Mean and Standard Deviation of the Estimates for Both MTL and STL Methods as a Function of Beam Spacing. Infinite Echo SNR.

	STL				MTL			
	Beam Spacing	1 mm	2 mm	4 mm	Beam Spacing	1 mm	2 mm	4 mm
M (kPa)		2.005	1.997	2.013	M (kPa)	2.590	2.203	2.071
SD (kPa)		0.068	0.032	0.022	SD (kPa)	1.869	0.796	0.311

SNR = signal-to-noise ratio; STL = single tracking location; MTL = multiple tracking location. Shear modulus as a function of beam spacing; Infinite SNR.

Table 2

Simulated Data of the Mean and Standard Deviation of the Estimates for Both MTL and STL Methods as a Function of Beam Spacing.

STL				MTL			
Beam Spacing	1 mm	2 mm	4 mm	Beam Spacing	1 mm	2 mm	4 mm
Echo SNR = 10 dB							
M (kPa)	2.302	2.081	2.013	M (kPa)	2.777	2.267	2.103
SD (kPa)	1.361	0.573	0.178	SD (kPa)	2.344	1.054	0.431
Echo SNR = 30 dB							
M (kPa)	2.009	1.996	2.012	M (kPa)	2.586	2.204	2.071
SD (kPa)	0.096	0.040	0.023	SD (kPa)	1.858	0.813	0.307

STL = single tracking location; MTL = multiple tracking location; SNR = signal-to-noise ratio.