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Minimization of Displacement Estimation Bias due to High Amplitude Reflections using Envelope-Weighted Normalization

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Abstract

In elastography, displacement estimation is often performed using cross-correlation based techniques, assuming fully-developed, homogeneous speckle. In the presence of a local, large variation in echo amplitude, such as a reflection from a vessel wall, this assumption does not hold true, resulting in a biased displacement estimate. Normalizing the echo by its envelope before displacement estimation reduces this effect at the cost of larger jitter errors. An algorithm is proposed to reduce amplitude-dependent bias in displacement estimates while avoiding a large increase in the jitter error magnitude. The algorithm involves “Envelope-Weighted Normalization” (EWN) of echo data before displacement estimation. A parametric analysis was conducted to find the optimum parameters with which this technique could be implemented. The EWN technique was found to significantly reduce the RMS error of the displacement estimates showing the greatest improvements when utilizing longer window lengths and higher ultrasonic frequencies.

Keywords

Cross-correlation; normalization; bias; displacement estimation; reflection; envelope

INTRODUCTION

Elastography allows for the quantification of changes in tissue mechanical properties that are often observed secondary to pathological processes or during therapeutic interventions. One particular property of interest is the displacement and ultrasonic tracking of tissue when subjected to acoustic radiation forces.^{1–6} Current techniques are very effective at estimating displacement with fully developed, homogeneous speckle. When high amplitude reflections exist within the region of interest (ROI) these bright reflections are tracked to the exclusion of other, lesser amplitude reflections. In this study, a novel pre-processing algorithm named “Envelope-Weighted Normalization” (EWN) is described and is shown to be a robust solution for the high amplitude reflection problem.

A number of groups have recently developed methods for elastographic imaging of blood vessels,⁷⁻¹¹ and in these applications accurate displacement estimation can prove to be difficult where reflection amplitude is high at the vessel-tissue boundary. In the presence of significant acoustic impedance mismatches, strong reflections occur at the vessel wall. 1D cross correlation-based techniques are commonly employed to estimate displacement with a defined signal window. The estimated displacement is considered to be the average of the displacements within that window with the assumption that the underlying speckle is fully developed without large variations in reflection amplitude. However, local high-amplitude signals tend to dominate the displacement estimate. The result is displacement bias that spatially corresponds to the high amplitude region of the echo in the vicinity of the reflective boundary.

To minimize displacement estimation bias, several authors developed log compression methods to reduce the relative amplitude of the bright reflections.^{12, 13} Logarithmic compression reduces the fluctuation in the echo signal before displacement estimation, thereby reducing the relative weighting of the correlation function. Bias was successfully reduced while improving the jitter of the displacement estimates. Further investigation by Alam et al.¹³ found that the signal waveform approached that of a square wave with greater log compression, and the autocorrelation of a square wave is a triangular wave. Typically, continuous functions (e.g., parabolic and cosine) are used to estimate the correlation peak for sub-sample displacement estimation. Attempting to estimate a “triangularized”, discontinuous function with a continuous function was shown to result in a cyclic bias in the displacement estimate.¹³

One method to minimize displacement estimation bias without drastically changing the sinusoidal shape of the waveform is the process of normalization. Soft limiting, as proposed by Alam et al.,¹³ normalized signal amplitude every half cycle. Signal normalization can also be achieved by dividing a signal by its envelope, preserving the phase content of the signal while reducing amplitude modulation. A drawback of signal normalization is the increase in jitter magnitude (a measure of the precision of the displacement estimation). Local signal-to-noise ratio (SNR) is diminished because of a relative increase in amplitude of low amplitude, low SNR portions of the signal, and a relative decrease in amplitude of initially high amplitude, high SNR portions of the signal. A decrease in SNR results in an increase in jitter magnitude.¹⁴

In this study, a novel envelope-weighted normalization (EWN) technique is used to lessen the high-amplitude reflections without critically affecting the quality of the rest of the signal. If the echo's envelope is used to weight the normalization, then the larger amplitude values within the echo are reduced more than smaller amplitude values, minimizing the local drops in SNR. To verify the utility of this technique, a parametric analysis was performed to quantify the improvement in the displacement estimation bias and the jitter magnitude.

THEORY

Normalized cross-correlation based displacement estimation is widely employed in the field of elastography.^{1, 2, 6, 15–17} The standard form of the cross-correlation between two echoes is given below:

$$\rho(\tau) = \int_{-T/2}^{T/2} f(t)g(t+\tau)dt \quad (1)$$

where T is the correlation window length. When the reflection amplitudes of scattering sources in the medium are equal, the populated echo amplitudes result in a Rayleigh distribution (Fig. 1a), and displacement estimates generally represent the average displacement that occurs within a correlation window.

Typically, for displacement estimation, a search region is defined over which a correlation window is shifted for one of the two signals, while the window is stationary on the “reference” signal. The shift at which the largest correlation coefficient occurs is used to estimate the displacement. However, this may result in higher correlation between a portion of a signal and an indiscriminate bright spot. The reason for this is that Equation 1 is maximized by the total energy of the product of the two functions involved. To combat this artifact, normalized cross correlation is commonly implemented:¹⁴

$$NCC(\tau) = \frac{\int_{-T/2}^{T/2} f(t)g(t+\tau)dt}{\sqrt{\int_{-T/2}^{T/2} (f(t))^2 dt \int_{-T/2}^{T/2} (g(t+\tau))^2 dt}} \quad (2)$$

This expression normalizes the result of cross correlation by the product of signal squared, thereby accounting for any large changes in amplitude. Normalized cross-correlation is most useful when the search region is large relative to the window length, allowing for the comparison of windows with very different brightness profiles. Nevertheless, when there is a local bright region within a correlation window, this definition still implies that the value of the correlation coefficient, albeit normalized, is still weighted by the high amplitude portions of the signal.

One approach to minimize the bias is to pre-normalize the echoes by dividing the echo by its envelope before performing standard normalized cross-correlation. Unfortunately, the normalization process increases the relative magnitude of the low amplitude portions of the echo, decreasing signal SNR and therefore increasing jitter error. A second option is to weight the signal after signal normalization as a function of signal amplitude. For low amplitude values, the weighting is proportional to the amplitude. For high amplitude values, the weighting function approaches a limiting value. As a result, low amplitude signals remain minimally affected, while higher amplitude signals are more normalized. The hyperbolic tangent is a function that has this quality, given in Eq. (3) below:

$$n = \tanh(A_e/C) \quad (3)$$

where A_e is the envelope of echo signal A , and C (the “normalization coefficient”) affects the values at which n approaches unity (Fig. 1b). In this study, the default value used for C is a multiple of the median of the echo envelope. The median of a Rayleigh distribution is proportional to the standard deviation of the echo.¹⁸ The median was used rather than a constant because this would adjust the convergence of the n function according to the relative magnitude of the high amplitude region. The second step of the algorithm requires the normalization and then scaling of the signal by n :

$$A_n = n \frac{A}{A_e} \quad (4)$$

By using these EWN echoes (A_n), increases in jitter error as well as amplitude-dependent bias are reduced. Figure 2 illustrates the advantage of using the EWN technique before displacement estimation. Notice, the EWN technique avoids the bias seen in the image created using the original echo signals, and the jitter generated when normalized echoes are employed.

METHODS

Two simulations were developed, one to estimate the ability to accurately represent the displacement between two bright regions (and in turn quantify displacement estimation bias), and the second to estimate jitter error before and after echo normalization. Simulations followed the procedure detailed in the simulation study.¹⁹ All calculations were performed in Matlab (Mathworks Inc., Natick, MA). Signals were generated by convolving white noise with sinc-enveloped sinusoids given by:

$$psf(t) = \frac{\sin(\pi B f_0 t)}{\pi B f_0 t} \sin(2\pi f_0 t) \quad (5)$$

where B is the fractional bandwidth and f_0 is the center frequency. This particular point spread function was chosen to match the conditions used to determine the Cramer-Rao lower bound (CRLB) that is used to calculate the minimum achievable jitter error magnitude:¹⁴

$$\sigma(\Delta t - \hat{\Delta t}) \geq \sqrt{\frac{3}{2f_0^3 \pi^2 T (B^3 + 12B)} \left(\frac{1}{\rho^2} \left(1 + \frac{1}{SNR^2} \right) - 1 \right)} \quad (6)$$

where T is the correlation window length, and ρ is the density. The default parameters used in this study were a 6.67 MHz center frequency, a 40 MHz sampling frequency, a 0.5 fractional bandwidth, 0.77 mm correlation window length, a normalization coefficient of 0.6 times the median values, and a 2:1 ratio between the echo amplitude of the simulated reflective boundaries and the remaining scatterers. These value ranges are typical of those used in ARFI imaging correlation-based displacement estimation.

Simulations were employed to investigate the effect of correlation window length from 0.4 mm-1.2 mm, brightness contrast range of 1 (no contrast) to 8, normalization level from 0.2

to 0.8 (in multiples of the echo envelope median), and center frequencies from 3 MHz to 8 MHz on the displacement estimation bias and jitter errors.

The echoes generated were left unmodified in their original form, normalized by the signal envelope, or processed using the EWN algorithm. The resulting original, normalized and EWN echoes were then used to estimate the applied echo shift using normalized cross-correlation displacement tracking. Following up-sampling by a factor of 8, normalized cross-correlation was performed using a 0.77 mm window length with a search region size of 19 μm in both directions. A single sample (19 μm) window shift was used after each estimate. The location of the peak in the correlation function was used to estimate axial displacement. Sub-sample peak estimation was achieved using parabolic interpolation.

RMS Error Estimation and Bias

For each condition analyzed, 500 scatterers were defined at random locations along a line that represented a distance of 2 cm ($c = 1540$ m/s, $f_0 = 6.67$ MHz, $f_s = 40$ MHz). The amplitude of the scatterers was set to unity, and a uniform 10 μm shift was applied except for the center 2 mm of the echo and no shift was applied to the scatterers. In this center 2 mm, and the scatter amplitude was set to 2 (unless otherwise defined) before convolution with the PSF. The RMS error was calculated between the applied and tracked displacements in a 5 mm window at the center of the echo, a window long enough to include the biasing effect that are a function of window length and tracking pulse width. Each RMS error calculation was repeated for 1000 echo realizations, and the 95% confidence intervals of the means were computed assuming a normal distribution:²⁰

$$x - 1.96 \frac{\sigma}{\sqrt{n}} \leq \mu \leq x + 1.96 \frac{\sigma}{\sqrt{n}}$$

where x is the sample mean, μ is the true mean, σ is the standard deviation, and n is the number of samples.

Bias was quantified by subtracting the applied displacement from the tracked displacement as shown in Figure 3. To reduce jitter, 10 displacement profiles were averaged from 10 independent speckle realizations. For each set of conditions, the bias was plotted as a function of position (Fig. 3b).

Jitter Error Estimation

500 scatterers were created to generate speckle along a line that represented a distance of 2 cm. The default SNR was 30 dB and the correlation coefficient of 0.998 was defined using Cholesky factorization of the cross correlation matrix, following the protocol described by Walker et al.¹⁴ The signal in the final 2 mm of the echo were defined to have a reflection amplitude of 2. The jitter error was estimated by calculating the standard deviation of the displacement estimates at the beginning of each of 1000 realizations of echo signals, with 0 μm displacement. The 95% confidence intervals of the standard deviation of jitter errors were computed assuming a normal distribution:²⁰

$$\frac{s}{1+1.96/\sqrt{2 \cdot (n-1)}} \leq \sigma \leq \frac{s}{1-1.96/\sqrt{2 \cdot (n-1)}}$$

where s is the sample standard deviation, σ is the true standard deviation, and n is the number of samples.

Tissue Imaging *Ex Vivo*

A porcine hepatic artery was imaged to demonstrate the performance of EWN as compared to unmodified echoes *ex vivo*. Imaging was performed with a Siemens Sonoline Antares Ultrasound Scanner (Siemens Medical Solutions USA, Inc., Issaquah, WA, USA). A VF10–5 linear array transducer with a 2 cm lateral focal depth and 6.67 MHz excitation frequency was used for the pushing and tracking pulses. Beam sequences included a 0.30 μ s reference pulse, followed by a 30 μ s pushing pulse, and 30 – 0.3 μ s tracking pulses (at a pulse repetition frequency (PRF) of 12.7 kHz) and data was acquired at a 40 MHz sampling rate.

The tissue was imaged while submerged in 0.9% saline and the brightness ratio between the artery wall and the surrounding liver was approximately 6. A lumen mask was applied by using a threshold of the correlation coefficient in which the value of 0 was defined for the lumen pixel. The empirically derived threshold of 0.997 was used. At this threshold level, values in the center of the vessel fell under the threshold, while those geometrically outside of the vessel remained above the threshold. Displacement estimates were compared with and without using the EWN technique. The widths of the vessels of in both ARFI images were then compared to the width of the vessel measured from the B-mode image.

RESULTS

The results are presented for displacement estimates using original (unmodified), EWN, and normalized echoes. Jitter and RMS errors are presented for all three sets of displacement estimates as functions of correlation window length, center frequency, amplitude contrast, normalization coefficient, and SNR. In the case of jitter error, the CRLB was plotted. In addition, bias was plotted as a function of position for two parameters values under each parameter investigated.

The effect of correlation window length on the standard deviation of jitter errors, RMS error, and bias are presented in Figure 4 and Figure 5. Displacements estimates from original, EWN, and normalized echoes all show a decrease in jitter errors with increasing correlation window length within a range of window lengths from 0.4 mm to 1.12 mm (Fig. 4a). The increase in jitter magnitude when using normalized echoes was 25%. In contrast, when the EWN algorithm is employed, the increases in jitter magnitude were only 5% (<0.1 μ m). The RMS error showed an increasing trend as a function of correlation window length under all three conditions, as shown in Figure 4b. Displacement estimation using EWN echoes resulted in the least RMS error as compared to original, and normalized conditions. Bias is plotted in Figure 5 as a function of position for correlation window lengths of 0.4 mm and 1.2 mm. While the profiles for all three conditions closely match when using the short, 0.4

mm window, when a longer 1.2 mm window is employed, increases in bias magnitude and the spatial extent of the bias is observed.

Figure 6 depicts the standard deviation of jitter errors and RMS error, while Figure 7 shows bias, as functions of amplitude contrast. Amplitude contrast is defined as the ratio of the average amplitude of the signal in the higher amplitude region of the signal to that of the lower amplitude region of the signal. Under all three conditions tested, no significant change in jitter errors was measured within the amplitude contrast range of 1 (no contrast) to 8 (Fig. 6a). RMS error increased with amplitude contrast for all three sets of signals, but was consistently lower in the normalized and EWN cases than when using the original signals (Fig. 6b). The bias is shown in Figure 7 for amplitude contrasts of 1 and 8 as functions of position. Under all three conditions the difference between the displacement estimates are minimal.

The standard deviation of jitter errors and RMS errors are presented in Figure 8, and bias in Figure 9, as functions of the normalization coefficient (C , Eq. (3)). As C increases, the jitter magnitude decreases. The increase in jitter magnitude after using the EWN algorithm is significant but when C is greater than 0.3 times the median (M , Eq. (3)), the increase in jitter error is less than 20%. The increase in jitter magnitude as a result of complete normalization is nearly 40%. RMS error using the EWN algorithm is approximately 25% lower than that measured when using the original echoes at all values of C from 0.3–0.9. The difference in RMS error when using normalized and EWN echoes was small at all values of C ($< 0.1 \mu\text{m}$), and fall within their 95% confidence intervals for normalization coefficients greater than 0.6 times the median of the echo amplitudes. The bias is given in Figure 9 for normalization coefficients of 0.3 and 0.9. Notice although there a negligible difference in the bias between the normalized and EWN conditions when the normalization coefficient is 0.3, at a value of 0.8, the bias profile for the EWN echo falls between the profiles of bias using normalized and original echoes.

Figures 10 and 11 show the standard deviation of jitter errors, RMS error and bias as functions of center frequency. The jitter magnitude decreases with an increase in frequency when original, EWN, and normalized echoes are employed. The increase in the jitter magnitude due to EWN remains small, less than $1 \mu\text{m}$ for frequencies greater than 3 MHz, and is approximately 50% (in all cases $> 0.1 \mu\text{m}$) when normalized echoes are utilized. A decreasing trend was observed in RMS error with an increase in frequency in all three cases. The decrease in RMS error when using the EWN echoes ranged from 10% to 15%. Bias was plotted for signals with center frequencies of 3 MHz and 8 MHz. Although the bias profiles showed little variation between the three profiles when a center frequency of 3 MHz was used, the bias was noticeably greater when original echoes were employed with a center frequency of 8 MHz.

The standard deviation of jitter errors is presented as a function of SNR in Figure 12. The increase in the jitter magnitude due to EWN is small for SNR values above 11 dB ($< 0.1 \mu\text{m}$). When echoes are normalized, increases in jitter magnitude range from 25% to 30% ($> 0.1 \mu\text{m}$).

A porcine hepatic artery was imaged *ex vivo* to demonstrate the utility of the EWN method in tissue. Figure 12 shows B-mode and displacement images of porcine hepatic arteries before and after using the EWN algorithm. Notice the artifact in the displacement image in Fig. 12c, in which the walls appear thicker than in the B-mode images. This artifact is diminished in Fig. 12d, where the width of the lumen more accurately depicts the size of the lumen represented in the corresponding B-mode image. The average differences between the widths of the blood vessels as measured from the masked ARFI images and the B-mode image (-6 dB drop in intensity approaching the lumen) were 0.81 ± 0.39 mm when using the original echoes and 0.46 ± 0.40 mm when EWN echoes are employed. Figure 13 shows a representative echo signal and corresponding correlation coefficient profiles

DISCUSSION

The use of correlation-based displacement estimation in ultrasonic elastography is quite common, but it is used under the assumption that the underlying speckle is relatively homogeneous in amplitude. When this assumption is not true, a bias in the estimated displacement may result. The goal of this study was to minimize this “echo amplitude dependent” bias without significantly increasing the jitter magnitude. Bias reduction was quantified using an estimate of RMS error.

In the case of echo normalization, a large increase in the jitter magnitude was also observed. Echo signals include a certain level of system noise. During the normalization process the local echo SNR decreases around higher amplitude, higher SNR regions and around lower amplitude, lower SNR regions. The result is an increase in the jitter magnitude. In order to avoid this artifact, an algorithm was developed that would more strongly weight the normalization in regions of higher amplitude, minimizing the augmentation of system noise in regions of lesser amplitude.

Figures 4 and 5 showed little increase in the standard deviation of jitter errors for all correlation window lengths (< 0.05 μm) and a significant decrease in RMS error ranging from 0.1 μm to 0.4 μm (6% to 18%) for window lengths of 0.4 mm to 1.2 mm, and the bias shows noticeable differences in the profiles when using EWN echoes and the original echoes when using a 1.2 mm window length. When echoes were normalized, the increase in jitter was greater than 0.1 μm for all window lengths ($> 25\%$), and the decrease in RMS was less than that observed when using EWN echoes, especially at lower window lengths in which the jitter errors presumably begin to dominate the RMS errors. The EWN algorithm results in little augmentation of noise in the regions of lesser brightness because it does not flatten the low amplitude regions and therefore generates smaller jitter errors. The increase in RMS with window length is greatest when using the original echoes, suggesting that when the original echoes are used, RMS error is more greatly dependent on the correlation window length. This greater dependence is a result of amplitude-dependent bias, as illustrated in Figure 5. Once a higher-amplitude region of a signal falls within a correlation window, the displacement that corresponds to that region will dominate the estimate, causing bias. In other words, as the window length increases, the local, high amplitude region will bias more of the displacement profile, resulting in greater bias in the region corresponding to the low

amplitude echo region, and a slightly lower bias in the region of higher echo amplitude. The net result is a lower overall bias when using the EWN algorithm.

In Figure 6 and Figure 7, as echo amplitude contrast increased from 1 to 8, no significant change was noticed in jitter errors when original, EWN and normalized echoes were used, a decrease in RMS error was observed when EWN echoes were utilized, and only small differences in bias were observed for the higher amplitude contrast value of 8. Although jitter errors were not found to be strongly dependent on amplitude contrast, there remains a significant $0.2\ \mu\text{m}$ increase in jitter with normalization, and only a small increase of less than $0.1\ \mu\text{m}$ when EWN echoes are used. RMS generally increased from $1.5\ \mu\text{m}$ to $3.5\ \mu\text{m}$ for all three sets of echoes. The greatest decrease between profiles using original and EWN echoes was found to occur for an amplitude contrast of 4. When the amplitude contrast value is small, little biasing occurs. When the amplitude contrast is too high, the sidelobes of the echo response of the bright scatterers dominate the surrounding signal. This reduces the effectiveness of EWN. In Figure 7, notice the larger bias values are generated when the amplitude contrast equal to 8, as is expected because a greater echo amplitude is expected to result in greater biasing of the displacement estimates, especially in the absence of normalization or EWN. These algorithms serve to reduce the relative amplitude of these high amplitude regions, thereby limiting displacement bias.

Standard deviation of jitter errors decreases and RMS error increases as a functions of normalization coefficient (C , Eq. (3)), are shown in Fig. 8, and the associated bias is illustrated in Figure 9. The magnitude of the jitter errors decreased by 13% with an increase in the normalization coefficient from 0.3 to 0.9. The RMS error, on the other hand, showed a small increase with normalization coefficient of less than 3%. As a value of 0.3 is approached, the RMS error approaches that of the fully normalized condition, as expected. A decrease in C also results in an increase in the standard deviation of the jitter errors. For this range of C values (0.3–0.9) the difference in the jitter magnitude between the original data and the EWN data is significant, and ranges from less than 10% when C is 0.9 to 25% when C is 0.3. The jitter magnitude is 40% larger when the echoes are fully normalized, which is significantly higher than both the original and EWN conditions. The results here suggest that under these conditions, a C value of 0.6 is appropriate for an improvement in RMS error while avoiding a large increase in the jitter magnitude, for this set of common parameters. In Figure 9, with an increase in C , we see the EWN echo displacement profile shows bias that approaches that of the original echoes.

Figure 10 shows the effects of varying the frequency from 3 MHz to 8 MHz on the standard deviation of jitter errors, and RMS error, and Figure 11 depicts bias as a function of for frequencies of 3 MHz and 8 MHz. For all frequencies tested, the increase in the standard deviation of jitter error was approximately 50% when the echoes were normalized, and 5% ($< 0.1\ \mu\text{m}$) when the EWN algorithm was employed. This suggests that percentage increase in the jitter magnitude is independent of frequency. This result is intuitive because although frequency effects jitter, that effect would affect all three conditions equally. As the frequency increases, the difference between the RMS error using EWN echoes and the original echoes increases from 5% to 20% ($0.1\ \mu\text{m}$ to $0.4\ \mu\text{m}$). Greater decreases in RMS error suggest that the EWN algorithm performs better at higher frequencies. The reason for

greater success of the EWN algorithm at higher frequencies is that the wavelength is shorter. As a result, the reflections from the high amplitude region of the signal only impact the local speckle. As the wavelength increases, the region over which the high amplitude reflections contribute to the surround speckle increases. Even after normalization, this contribution results in an increase in the RMS error. The bias plots in Figure 11 also corroborate that at the higher frequency of 8 MHz, the original profile shows visibly more bias than the EWN profile.

Since the normalization process tends to augment noise in the echo signal, the jitter magnitude was measured for the original, EWN and normalized echoes over a range of SNR values (Fig. 12). The absolute value of the SNR decreases with an increase in SNR between 11 dB and 41 dB. In the case of the normalized echoes, the difference in the jitter magnitude from that of the original echoes decreases from 0.7 μm to 0.2 μm between 11 dB and 41 dB SNR. When the EWN algorithm was applied the difference in the jitter magnitude decreases from 0.2 μm to less than 0.1 μm in the same range. These results imply that the EWN algorithm does not increase the standard deviation of jitter error by a large amount, even when using signals with low SNR.

Figures 12 and 13 illustrate the result of using this algorithm when imaging tissue. In our porcine hepatic artery experiment, a luminal mask was applied because in an ARFI image the lumen appears as noise due to radiation force induced streaming of the fluid. As expected, the walls of the vessel seem thicker in the displacement image (Fig. 12c), and these thicker regions correspond to the strong reflection at the vessel wall that result in amplitude-dependent displacement estimation bias. When this EWN algorithm is applied, this bias is diminished by approximately 50%. After normalization, when applying the luminal mask, the apparent width of the vessel in the normalized case matches the width of the lumen in the B-mode image, while the original ARFI Images shows appreciable narrowing. In Figure 13, a representative echo signal is plotted along with correlation coefficient as a function of depth. The decrease in correlation coefficient using EWN echoes is local to the walls of the vessel, outlined by the two high amplitude regions of the echo signal. The spatial extent of the decrease in correlation coefficient is greater for distal artery wall due to the higher amplitude signal. The 0.997 correlation coefficient cut-off value for luminal masking is indicated. A value was chosen that masks the lumen without eliminating displacement estimates in the surrounding tissue. A change in the cut-off value would result in little relative change in the apparent lumen diameter, as can be seen by the steep decreases in correlation coefficients when original and EWN echoes were employed.

CONCLUSIONS

An algorithm has been successfully developed to reduce amplitude-dependent bias in displacement estimates while avoiding a large increase in the jitter magnitude. The algorithm involves an envelope-weighted normalization of an echo. A parametric analysis was conducted in order to find the optimum conditions in which this partial normalization technique could be implemented. The results were also compared to the unmodified case, and the case in which the echoes were first fully normalized. It was found that under these conditions, application of this particular EWN algorithm resulted in an improvement in

RMS error of at least 10% when longer correlation window lengths (> 0.6 mm) and higher frequencies (> 3 MHz) are used. Echo amplitude contrast had little impact on the relative improvement of separation distance. When a normalization level of 0.6 times the median was used, the increase in the standard deviation of the jitter errors was negligible ($<5\%$). It was demonstrated that the EWN technique reduces displacement estimation bias under conditions typical of ARFI imaging without a large increase in jitter errors. This algorithm shows promise in imaging of blood vessels, and the monitoring of ablation treatments, in which strong reflections are prevalent.

References

1. Fatemi M, Greenleaf JF. Ultrasound-stimulated vibro-acoustic spectrography. *Science*. 1998; 280(5360):82–85. [PubMed: 9525861]
2. McAleavey SA, Menon M, Orszulak J. Shear-modulus estimation by application of Spatially Modulated impulsive acoustic radiation force. *Ultrasonic Imaging*. 2007; 29(2):87–104. [PubMed: 17679324]
3. Nightingale K, Nightingale R, Stutz D, Trahey G. Acoustic radiation force impulse imaging of in vivo vastus medialis muscle under varying isometric load. *Ultrason Imaging*. 2002; 24(2):100–8. [PubMed: 12199416]
4. Nightingale K, Soo MS, Nightingale R, Trahey G. Acoustic radiation force impulse imaging: in vivo demonstration of clinical feasibility. *Ultrasound Med Biol*. 2002; 28(2):227–35. [PubMed: 11937286]
5. Bercoff J, Tanter M, Fink M. Supersonic shear imaging: A new technique for soft tissue elasticity mapping. *Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control*. 2004; 51(4):396–409.
6. Sarvazyan AP, Rudenko OV, Swanson SD, Fowlkes JB, Emelianov SY. Shear wave elasticity imaging: A new ultrasonic technology of medical diagnostics. *Ultrasound in Medicine and Biology*. 1998; 24(9):1419–1435. [PubMed: 10385964]
7. Behler RH, Nichols TC, Zhu HT, Merricks EP, Gallippi CM. Arfi Imaging for Noninvasive Material Characterization of Atherosclerosis Part II: Toward in Vivo Characterization. *Ultrasound in Medicine and Biology*. 2009; 35(2):278–295. [PubMed: 19026483]
8. Dumont D, Behler RH, Nichols TC, Merricks EP, Gallippi CM. ARFI imaging for noninvasive material characterization of atherosclerosis. *Ultrasound in Medicine and Biology*. 2006; 32(11):1703–1711. [PubMed: 17112956]
9. Dumont D, Dahl J, Miller E, Allen J, Fahey B, Trahey G. Lower-Limb Vascular Imaging with Acoustic Radiation Force Elastography: Demonstration of In Vivo Feasibility. *Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control*. 2009; 56(5):931–944.
10. Trahey GE, Palmeri ML, Bentley RC, Nightingale KR. Acoustic radiation force impulse imaging of the mechanical properties of arteries: In vivo and ex vivo results. *Ultrasound in Medicine and Biology*. 2004; 30(9):1163–1171. [PubMed: 15550320]
11. Couade M, Pernot M, Tanter M, Prada C, Szymanski C, Bruneval P, Emmerich J, Fink M, Messes E. Real time Non-Invasive Quantitative Imaging of arterial wall elasticity using Supersonic Shear Imaging. *Circulation*. 2008; 118(18):S1008–S1008.
12. Cespedes I, Ophir J. Reduction of image noise in elastography. *Ultrason Imaging*. 1993; 15(2):89–102. [PubMed: 8346613]
13. Alam SK, Ophir J. The effect of nonlinear signal transformations on bias errors in elastography. *IEEE Trans Ultrason Ferroelectr Freq Control*. 2000; 47(1):297–303. [PubMed: 18238543]
14. Walker WF, Trahey GE. A Fundamental Limit on Delay Estimation Using Partially Correlated Speckle Signals. *Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control*. 1995; 42(2):301–308.
15. Parker KJ, Fu DS, Graceswki SM, Yeung F, Levinson SF. Vibration F and the detectability of lesions. *Ultrasound in Medicine and Biology*. 1998; 24(9):1437–1447. [PubMed: 10385965]

16. Nightingale KR, Palmeri ML, Nightingale RW, Trahey GE. On the feasibility of remote palpation using acoustic radiation force. *J Acoust Soc Am*. 2001; 110(1):625–34. [PubMed: 11508987]
17. Varghese T, Zagzebski JA, Frank G, Madsen EL. Elastographic imaging using a handheld compressor. *Ultrasonic Imaging*. 2002; 24(1):25–35. [PubMed: 12102226]
18. Crocker, MJ. *Handbook of acoustics*. Wiley; New York: 1998.
19. Viola F, Walker WF. A comparison of the performance of time-delay estimators in medical ultrasound. *Ieee Transactions on Ultrasonics Ferroelectrics and Frequency Control*. 2003; 50(4): 392–401.
20. Crow, EL.; Davis, FA.; Maxfield, MW. *Statistics*. Coles; Toronto: 1978.

FIG. 1.

Rayleigh distribution (a) of echo amplitudes in a homogeneous medium with fully developed speckle and the weighting of the normalization algorithm (b). Sigma is the standard deviation of the echo amplitudes.

FIG. 2.

B-mode (log-compressed) and ARFI images using cross-correlation (a) without normalization, (b) EWN, and (c) full normalization. The center frequency is 5.33 MHz, the correlation window length was 0.77 mm, and the tracking pulse length was 2λ .

FIG. 3.

Bias is measured by subtracting the applied displacement profile (a) from the tracked displacement profile and is plotted in (b). In this example, a 6.67 MHz center frequency, a fractional bandwidth of 0.5, and a normalization level of 0.6 times the median were used for both estimates and a correlation coefficient of 0.998, an amplitude contrast of 2. Jitter errors were reduced by averaging 10 displacement profiles from independent speckle realizations.

FIG. 4.

Jitter magnitude (a) and RMS error (b) as a function of correlation window length. The error bars represent the 95% confidence intervals ($n = 1000$). A 6.67 MHz center frequency, a fractional bandwidth of 0.5, and a normalization level of 0.6 times the median were used for both estimates and a correlation coefficient of 0.998, an amplitude contrast of 2 and an SNR of 30 dB were used for jitter error estimates.

FIG. 5.

Bias as a function of position for a correlation window length of (a) 0.39 mm and (b) 1.16 mm. A 6.67 MHz center frequency, a fractional bandwidth of 0.5, a normalization level of 0.6 times the median, and an amplitude contrast of 2 were used for both estimates.

FIG. 6.

Jitter magnitude (a) and RMS error (b) as a function of amplitude contrast; defined as amplitude of the bright region (the amplitude of the surrounding region is unity). The error bars represent the 95% confidence intervals ($n = 1000$). A center frequency of 6.67 MHz center frequency, a correlation window length of 0.77 mm, and a fractional bandwidth of 0.5 were used for both estimates and a correlation coefficient of 0.998, and an SNR of 30 dB were used for jitter error estimates.

FIG. 7.

Bias for amplitude contrast values of (a) 1 and (b) 8 defined as amplitude of the bright region (the amplitude of the surrounding region is unity). A 6.67 MHz center frequency, a fractional bandwidth of 0.5, correlation window length of 0.77 mm, and a normalization level of 0.6 times the median.

FIG. 8.

Jitter magnitude (a) and RMS error (b) as a function of normalization coefficient C , or a fraction of the median amplitude value (Eqn. 1). The error bars represent the 95% confidence intervals ($n = 1000$). A center frequency of 6.67 MHz center frequency, a correlation window length of 0.77 mm, and a fractional bandwidth of 0.5 were used for both estimates and a correlation coefficient of 0.998, an amplitude contrast of 2, and an SNR of 30 dB were used for jitter error estimates.

FIG. 9. Bias for normalization coefficients (C in Eqn. 1), of (a) 0.3 and (b) 0.9 (in fractions of the median echo amplitude value). A 6.67 MHz center frequency, a fractional bandwidth of 0.5, correlation window length of 0.77 mm, and an amplitude contrast of 2 were used.

FIG. 10.

Jitter magnitude (a) and RMS error (b) as a function of center frequency. The error bars represent the 95% confidence intervals ($n = 1000$). A correlation window length of 0.77 mm, a fractional bandwidth of 0.5, a correlation coefficient of 0.998, a brightness contrast of 2 and an SNR of 30 dB were used.

FIG. 11. Bias for central frequencies of (a) 3 MHz and (b) 8 MHz. A fractional bandwidth of 0.5, correlation window length of 0.77 mm, a normalization level of 0.6 times the median, and a brightness contrast of 2.

FIG. 12.

Jitter magnitude as a function of SNR. The error bars represent the 95% confidence intervals ($n = 1000$). A center frequency of 6.67 MHz center frequency, a correlation window length of 0.77 mm, a fractional bandwidth of 0.5, a brightness contrast of 2, and a correlation coefficient of 0.998 was used.

FIG. 13.

Images of porcine hepatic arteries *ex vivo*. The B-mode image is given in (a). A representative profile of the cross-correlation coefficients at a lateral position of 1.4 cm is plotted in (b), with the cut-off value of 0.997 that was used for luminal masking. In the bottom row are the displacement images 0.6 ms after an ARFI pushing pulse using the original (c) and EWN normalized (d) echoes. The frequency was 6.67 MHz, the correlation window length was 0.77 mm, the fractional bandwidth was 0.5, and the B-mode brightness contrast between the artery wall and the surrounding liver was approximately 6:1. The grayscale corresponds to displacement amplitude (μm) in the ARFI images (c and d). The average differences between the widths of the blood vessels as measured from the masked ARFI images and the B-mode image (-6 dB drop in intensity approaching the lumen) were 0.81 ± 0.39 mm when using the original echoes and 0.46 ± 0.40 mm when EWN echoes are employed.

FIG. 14.

Representative (a) original echo signal and (b) correlation coefficient values as functions of depth of a porcine hepatic artery *ex vivo*. In (b), correlation coefficient is plotted for displacement estimates using both original and EWN echoes. The 0.997 correlation coefficient used for luminal masking is also marked. The frequency was 6.67 MHz, the correlation window length was 0.77 mm, the fractional bandwidth was 0.5, and the brightness contrast between the artery wall and the surrounding liver was approximately 6:1. A lumen mask was used in which a correlation threshold of 0.997 was implemented.