Elastographic Imaging Using Staggered Strain Estimates

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Conventional techniques in elastography estimate strain as the gradient of the displacement estimates obtained through crosscorrelation of pre- and postcompression rf A-lines. In these techniques, the displacements are estimated over overlapping windows and the strains are estimated as the gradient of the displacement estimates over adjacent windows. The large amount of noise at high window overlaps may result in poor quality elastograms, thus restricting the applicability of conventional strain estimation techniques to low window overlaps, which, in turn, results in a small number of pixels in the image. To overcome this restriction, we propose a multistep strain estimation technique. It computes the first elastogram using nonoverlapped windows. In the next step, the data windows are shifted by a small distance (small fraction of window size) and another elastogram is produced. This is repeated until the cumulative shift equals/exceeds the window size and all the elastograms are staggered to produce the final elastogram.

Simulations and experiments were performed using this technique to demonstrate significant improvement in the elastographic signal-to-noise ratio (SNR) and the contrast-to-noise ratio (CNR) at high window overlaps over conventional strain estimation techniques, without noticeable loss of spatial resolution. This technique might be suitable for reducing the algorithmic noise in the elastograms at high window overlaps.

KEY WORDS: CNR; correlation; elastogram; elastography; resolution; segmentation; SNR; strain; stress; ultrasonic imaging; ultrasound.

INTRODUCTION

Elastography has been well established in the literature as a strain imaging technique of soft tissues.1-5 Conventional techniques in elastography estimate the local axial strains as the gradients of the displacements of the tissue elements under compression. These displacement estimates are obtained through cross-correlation of the precompression and postcompression (temporally stretched) rf A-lines.6 The rf A-lines are segmented into overlapping windows and strain is estimated as the gradient of the displacement estimates computed over adjacent windows.

For these conventional strain estimation techniques (CSE), the size of the windows (W) and the spatial separation of adjacent windows (ΔW) are algorithmic parameters that influence the quality of the strain estimates. For example, the strain estimates computed over windows that are separated by small distances (i.e., high window overlaps) are noisier than
those that are computed over windows separated by large distances (i.e., low window overlaps). This is because the noise variance due to the gradient operation is inversely proportional to $\Delta W$. Some of the parameters that quantify the quality of the elastograms are the signal-to-noise ratio (SNR), the contrast-to-noise ratio (CNR), and the spatial resolution.

The dependence of the elastographic signal-to-noise ratio (SNR) on the algorithmic parameters ($W$ and $\Delta W$), the sonographic parameters (such as the echo signal SNR, the transducer center frequency and bandwidth) and the physical parameters (such as the applied strain and the boundary conditions) has been established in reference 8. The SNR was shown to be proportional to $\Delta W^{1/2}$. It has been shown that the upper bound on the CNR can be obtained directly from the upper bounds of the SNR at different strain contrast levels. Hence, the CNR too shows a half-power dependence on $\Delta W$. Regarding the axial resolution in elastography, empirical and simulation studies have shown that $W$ and $\Delta W$ determine the practically-achievable axial resolution of the elastogram (the axial resolution was shown to
be a linear function of $W$ and $\Delta W$ in references 10 and 11), while the lower bound on the axial resolution is controlled by the system bandwidth.\(^{12}\) Smaller values of $\Delta W$ result in finer axial resolution than larger values of $\Delta W$, favoring the use of small values of $\Delta W$. Hence, for CSE, a tradeoff between $\text{SNR}_e$ and resolution exists.\(^{11}\)

We hypothesize that the $\text{SNR}_e$ (and $\text{CNR}$) values can be improved without affecting the axial resolution by using segmentation schemes. A multistep strain estimation scheme that can improve the $\text{SNR}_e$ (and $\text{CNR}$) is briefly explained as follows. For the first step, strains are estimated using nonoverlapped windows. The data windows are shifted by a small distance (smaller than the window size) and the strains are estimated again. This process is repeated until the cumulative shift equals/exceeds the window size. The strain estimates of all the steps are staggered (i.e., ordered according to the location of the data window) to produce the final elastogram. For such a scheme, the loss of the axial resolution due to the use of large values of $\Delta W$ is overcome by computing strain estimates that are separated by small distances.

A strain estimation technique that performs such a multistep window shifting involves staggering the strain estimates computed over several steps and is henceforth called the staggered strain estimation technique (SSE). In SSE, the strain estimates at all steps are obtained using nonoverlapped windows (i.e., $\Delta W = W$). The data windows are shifted sequentially by small distance in successive steps and the shifted distance corresponds to the desired axial pixel size on the elastogram (for CSE, the axial pixel size equals $\Delta W$). For example, for a $W$ of 2 mm and a desired axial pixel size of 0.4 mm (i.e., $\Delta W = 0.4$ mm in CSE), five steps in SSE (i.e., a 5x staggering) are to be used. The strain estimates are then staggered according to the location of the window as explained in the next section.

It is to be noted that the SSE technique is a limiting case of CSE, when the window separation equals the window size (i.e., a fractional window overlap of 0%). Yet, there is no significant loss of spatial resolution as explained in the subsequent sections. The next section describes a schematic of this technique. Details of the performance of SSE and a comparison with CSE are reported in the subsequent sections of this paper.

**TECHNIQUE**

Sequential windowed rf A-lines segments that are not overlapped (or with low overlaps) are used to estimate the strain. Strain estimation is done in a series of steps as detailed below. First, nonoverlapping windows of length $W$ (shown as the boxes in step 1 in figure 1) are used to obtain a set of strain estimates (shown as the estimates $s^1_1, s^1_2, s^2_2$,... in step 1 of figure 1). The strain estimates are obtained as the gradients of the displacement estimates $d^1_{w_1}, d^1_{w_2}, d^1_{w_1},..., as shown in step 1 of figure 1. Next, the windows are shifted by lengths that equal the desired axial pixel size on the elastogram (this equals the value of $\Delta W$ in CSE) and a set of strain estimates (shown as the estimates $s^2_1, s^2_2, s^2_2$,... in step 2 of figure 1) are obtained. This process is repeated until the total shifted distance of each window equals/exceeds $W - \Delta W$ (step $n$ in figure 1). The strain estimates for all such shifts are staggered (i.e., ordered as $s^1_1, s^2_1, ..., s^n_1$ followed by $s^1_2, s^2_2, ..., s^n_2$ and so on) to produce the elastogram shown as the last step in figure 1.

We can increase the number of pixels in elastograms by a simple interpolation (or upsampling) of strain estimates obtained using CSE with nonoverlapping windows (henceforth called CSE). This is different from SSE because interpolation does not add new information to the elastogram. On the other hand, SSE estimates displacements over shifted windows that span many locations in the A-line (Fig. 1) and hence provides the unused infor-
mation of the rf A-lines. Moreover, CSE, could result in a loss of contrast for small targets depending on how the windows are aligned with respect to the target edges. To demonstrate such a case, consider a medium with a square wave type strain profile as shown in figure 2a. Figure 2b shows the strain profiles computed using SSE and CSE, when the windows are aligned with the square wave such that the strain is constant within each window. Figure 2c shows the strain profiles when the windows are shifted by distance that is equal to a quarter-cycle of the square wave (i.e., each window has a nonuniform strain). The loss of contrast using CSE, is clearly evident from figure 2c. Such a loss of contrast for CSE, is expected, since for windows containing parts of the medium that undergo different strains, the estimated strain values are intermediate between the differing strain levels. Therefore, interpolating the strain does not recover the loss of contrast. For SSE, some steps of strain estimation result in intermediate strains, while the rest of the steps produce the correct strains. This results in a triangular-shaped waveform, as can be seen in figure 2b and 2c. Thus, there is no significant loss of contrast.

SSE produces an improvement in the values of $SNR_e$ over CSE and a $W/\Delta W$ improvement in the $CNR_e$ values over CSE (see Appendix A for details). It is to be noted that if the values of $\Delta W$ are greater than $W$, then there is an expected degradation of the $SNR_e$ and $CNR_e$ values using SSE. However, strain estimation is performed over closely-separated windows to prevent loss of contrast and to utilize all the information in the A-lines. For example, for the square-wave strain profile (Fig. 2), if strain estimation is performed over largely-separated
windows, it can be seen that a severe loss of contrast may occur. The performance of SSE and a comparison with that of CSE are given in the next section. Note that CSE produces the same improvement of $SNR_e$ and $CNR_e$ as does SSE, but at the loss of spatial resolution and strain contrast.

**METHODS**

To evaluate the performance of SSE and to compare it with that of CSE, simulations and experiments were conducted. The $SNR_e$, the $CNR_e$ and the axial resolution were used as quantitative performance criteria for these techniques.

**Simulations**

2-D displacement and echo generation models were used to generate displacement and rf A-lines of three types of phantoms. These phantoms were (1) a uniformly elastic phantom (for the $SNR_e$ study), (2) a uniformly elastic phantom with a stiff inclusion at the center (for the $CNR_e$ study), and (3) a uniformly-elastic phantom with two axially positioned stiff inclusions (for the axial resolution study). The displacement models for the simulations that involved a single inclusion and the uniformly elastic medium utilized analytical solutions. For the axial resolution study, the displacement fields were generated using finite-element techniques (Linear Stress, ALGOR Inc., Pittsburgh, PA). The medium was simulated as a set of uniformly distributed point scatterers (with randomly distributed strengths on a uniform grid corresponding to a density of at least 40 scatterers per resolution-cell) in the inclusions and the background. Simulations in MATLAB (Mathworks. Inc., Natick, MA) were used to generate pre- and postcompression rf signals. The speed of sound was assumed to be constant at 1540 m/s. The point-spread function (PSF) of the system was simulated using a Gaussian modulated cosine pulse with a 5-MHz center frequency, a 50% 3-dB fractional bandwidth and a 1 mm full-width half-maximum Gaussian beamwidth. The PSF was convolved with the scattering distribution to obtain the precompression rf signal. A sampling frequency of 50 MHz was used in the simulations. The postcompression signals were generated after applying a small uniform compression to the target and convolving the perturbed scatterer distribution with the original PSF. The sonographic $SNR (SNR_s)$ was set to 40 dB by adding other in-band uncorrelated rf A-lines to both the pre- and postcompression A-lines. The quantization errors were negligible in the simulations. The applied strain was varied from 0.25% to 10%.

Conventional strain estimation (CSE) was performed by stretching the postcompression A-line, followed by windowing of the pre- and stretched postcompression A-lines. The time delay for each window was obtained as the location of the cross-correlation peak between congruent pre- and postcompression A-lines. A parabolic interpolation was used for identifying the subsample location of the peak. Strain was estimated as the gradient of the time delay estimates and was added to the strain value that was used to stretch the postcompression A-line. Window lengths of 2 mm were used unless stated otherwise. For SSE, adjacent nonoverlapping windows were used to estimate the strain for each step. The distance shifted between successive steps was equal to the value of $\Delta W$ used in CSE.

For the $SNR_e$ study, the phantom was simulated as a $40 \times 40$ mm² region of constant Young's modulus. The $SNR_e$ was indirectly estimated from the value of the correlation coefficient. For the CSE, overlaps of 50% and 80% of the window length were used.
For the CNR study, the background was simulated as a 40 x 40 mm$^2$ region of uniform Young’s modulus. The radius of the inclusion was fixed at 5 mm and the modulus contrast ratio between the inclusion and the background was varied between 1.5 and 10.

For the resolution study, the background was simulated as a 40 x 40 mm$^2$ region of uniform Young’s modulus. Two axially positioned, uniformly elastic inclusions of 1 mm radius each, which were three times stiffer than the background were placed in the center of the phantom and were moved toward each other until they were not spatially resolvable. The minimum spatial separation that corresponded to the actual separation of the inclusions was chosen as the upper bound on the spatial resolution. This technique required setting a strain threshold of half the strain difference between the background and the inclusion and finding the number of pixels between the inclusions that exceeded this threshold. It was used to determine the upper bounds on the axial resolution in elastography$^{12}$ at an applied strain of 1%.

Experiments

Experiments were performed on a 90 x 90 x 90 mm$^3$ gelatin phantom with a 10 mm radius cylindrical inclusion located 40 mm below the transducer. The strain contrast (as measured from the elastogram) between the inclusion and the background was approximately 2.5. A 5 MHz, 60% fractional bandwidth 128 element HDI 1000 array transducer (Philips–ATL corporation, Bothel, WA) was used for the study. The phantom (prepared using the method described in reference 21) was imaged across the cylindrical axis and the rf A-lines were sampled at a frequency of 20 MHz. For the SNR$e$ study, experiments were performed on a 50 x 50 x 50 mm$^3$ uniformly elastic gelatin phantom that was imaged with the same ultrasound system.

RESULTS

Simulation results

SNR$e$ results

The improvement in the values of the SNR$e$ using SSE is shown in figure 3a. A 2 mm window length and an overlap of 80% of the window length were used here. This corresponds to
five iterative steps (i.e., a 5x staggering) for SSE. Neither lateral correction\textsuperscript{22} nor 2-D companding schemes\textsuperscript{23} were used. Hence, only the values of $SNR_e$ at the axis of no lateral motion are reported. Derating the $SNR_e$ to account for the lateral motion\textsuperscript{24} could be used to account for the $SNR_e$ values at other lateral positions and are not applicable here. The ratios between the mean values of the $SNR_e$ of the SSE and the CSE for overlaps of 50% and 80% of the window length are shown in figure 3b. Note the constancy to these ratios as a function of strain for given overlap values as evident from an examination of Eq. (A9). An improvement of $\sqrt{W/\Delta W}$ can be seen for both overlaps. Such an improvement is theoretically expected since for SSE the individual strain estimates are obtained using values of window separations that equal the window lengths ($\sqrt{W/\Delta W}>1$).

$CNR_e$ results

Figure 4a shows a typical elastogram using CSE and figure 4b shows a typical elastogram using SSE of a simulated 5 mm radius inclusion inside a uniformly elastic phantom, with a modulus contrast of 3 and an applied strain of 1%. The darker shades represent stiff areas. Figure 4c shows the theoretical elastogram\textsuperscript{14} and figure 4d shows the strain profiles at the axis of zero lateral motion. The smooth appearance of the elastogram (shown in figure 4c using the analytical form) is represented clearly by SSE than by CSE. This demonstrates that higher window overlaps (80% overlap in this case) introduce algorithmic noise that does not reflect real structure. Figure 4d shows the strain profiles along the axis of lateral motion symmetry for SSE and CSE. Improvement in the $CNR_e$ can be inferred from figure 4d. It is
to be noted that spatial filtering of the displacement or the strain images can be performed to reduce the noise in figure 4a at the expense of lower spatial resolution. Figure 4d shows one such filtered profile (using a 1.5 \( \times \) 1.5 mm\(^2\) 2-D median filter) of CSE. It can be seen that for the filtered profile, the transition at the edge occurs over a large distance (as opposed to SSE) resulting in a loss of the spatial resolution as was also observed in reference 25. However, the \( \text{CNR}_e \) improves significantly. A comprehensive comparison of the spatial resolution of SSE with filtered CSE is beyond the scope of this work.

Quantitative improvement in the \( \text{CNR}_e \) using SSE is shown in figure 5. Figure 5a shows the \( \text{CNR}_e \) as a function of the modulus contrast at a strain of 2%. Significant improvement in the \( \text{CNR}_e \) can be seen. It is to be noted that filtering was deliberately not used in the computation of the strain estimates and, hence, the \( \text{CNR}_e \) values for CSE at a high (80%) overlap is close to zero. Figure 5b shows the \( \text{CNR}_e \) as a function of strain at a modulus contrast of 3. A statistical analysis (ANOVA) over 50 independent realizations was performed to show that the mean values of \( \text{CNR}_e \) due to SSE and CSE differed from each other at a 95% level of significance (\( p \)-values less than 0.05) for strains ranging between 0.5% and 3%.

Axial resolution results

Figure 6 shows a set of ideal elastograms of two inclusions in a homogenous background (generated using ALGOR models), those generated using SSE (figure 6c) and those generated using CSE at two separations (Figs. 6a, b). In figure 6, the elastograms were generated using CSE at an overlap of 95% (Fig. 6a), CSE\(_i\) (interpolated to produce the same pixel size as CSE at 95% overlap (Fig. 6b)), and SSE (at the same pixel size as the CSE). The images shown were averaged over five realizations. Spatial filtering was not performed on any of the images. It can be seen that the inclusions are clearly separated with the use of SSE unlike CSE due to significant noise reduction by SSE. Also notice the loss of contrast in CSE, (the second column in figure 6b) that could result in incorrect measures of spatial resolution. To appreciate the loss of spatial resolution due to CSE, in comparison with SSE, figure 7 shows the regions in figures 6b and 6c in the regions around the inclusions. The distance corresponding to the separation of the inclusions was measured from the strain profiles as the number of pixels in the strain profile (between the pixels corresponding to the inclusion) whose strain value exceeded half the difference between the strain value in the background and the strain value in the inclusion. The presence of ‘zebras and worm artifacts’ due to
the use of parabolic interpolation (to estimate the displacements) and the use of large segment overlaps can be seen in figure 6a. Moreover stretching artifacts due to the use of a global stretch factor can be seen below the inclusions. The range of strains displayed in figure 6 varied from 0.7% to 1.1% as indicated by the colorbar. Therefore, the stretching artifacts appear to be enhanced in the elastograms (Figs. 6a-c). For the CSE, large overlaps like 95% resulted in high noise as is evident from figures 4a and 6a. The values of $W$ used in figure 6 were equal to the separation distance between the two inclusions.

Prior work on the use of two inclusion models to study spatial resolution incorporated truncated-Gaussian modulus distributions of the inclusions and median filtering of both the displacement and strain profiles to overcome some of the effects due to noise. We do not perform such a filtering for consistency, and for facilitating quantitative comparison of SSE and CSE. Yet, results similar to those obtained in that work are reported here. A quantitative comparison of the measured axial resolution of these two methods is reported below.

Figure 8a shows the spatial resolution as a function of $W$ and figure 8b shows the spatial resolution as a function of the pixel size (i.e., $\Delta W$) expressed as a percentage of the window length. A statistical analysis over 50 independent realizations was performed to test if the mean values of the measured resolutions of the two techniques were different for several window lengths and pixel sizes. No significant difference between the mean values was
FIG. 7 Enlarged portions of the simulated axial elastograms shown in figure 6 obtained using (a) interpolated CSE and (b) SSE for the resolution phantom, where the two inclusions are separated by 0.9 mm (upper panel) and 2 mm (lower panel). The applied strain was 1% and the window length for the two cases was the same as the separation distance. An overlap of 95% the window length was used for CSE. A 5 MHz, 50% fractional bandwidth array transducer was simulated. The elastograms were obtained as the gradient of the displacements and spatial filtering was not used.
found (p-values >0.05 over 50 independent realizations) indicating no significant loss of spatial resolution in using SSE. It is to be noted that the lower bounds on the axial resolution are smaller than the values shown in figure 8. The estimated separation between the inclusions on the elastogram exceeded the actual separation between the inclusions by a factor between 5% and 20% using SSE and between 0% and 10% using CSE at an overlap of 95%. This range increases for lower overlaps as can also be seen in figure 8b.

Experimental results

The elastograms from the inclusion phantom (imaged across the cylinder axis and with the compressor plate) using CSE and SSE are shown in figures 9a and 9b respectively. The corresponding sonogram is shown in figure 9c.

The strain contrast measured was approximately 2.5. For such a contrast, the CNR as a function of strain is shown in figure 10. Here the CNR was computed by taking rectangular strips of pixels from the background and the inclusion of the strain image. The rectangular strips were chosen close to the center of the inclusion and in the background region that was at least two diameters away from the inclusion as indicated by the square boxes in figure 9c. Ten independent realizations of a multicompression experiment (20 successive compressional steps of 0.25% strain for each compression step) were used to compute the statistics. Multicompression was preferred over single compression schemes in order to reduce the data acquisition time since 10 realizations over 20 different strains were acquired. The stress-strain curves for tissue and gelatin samples for strains less than 3% are nearly linear. Hence, the loss of contrast due to changes in the precompression is insignificant.

The improvement in CNR is evident from figure 10. It is to be noted that the CNR values are significantly lower than those corresponding to the simulations (at the same contrast) due to several reasons, some of which include nonuniform compression, frequency dependent attenuation, lower SNR, nonuniform strain distribution within the inclusion and in the background and lower digitization rates (both sampling frequency and quantization).

The SNR was shown in figure 11a as a function of the window length and in figure 11b as a function of the pixel size for the uniformly elastic phantom. The SNR was computed by taking rectangular strips of pixels close to the center of the phantom where there was little lateral motion. The SNR was estimated as the ratio of the mean over the standard deviations of the
strain in those rectangular strips. Five independent realizations of a multicompression experiment (five successive compressional steps of 1% strain) were used to compute the statistics. From figure 11a, it can be seen that as the pixel size increases (lower window overlaps for CSE), the $SNR_e$ values using CSE are closer to those obtained using SSE. Both the schemes show improvements with the window size as predicted by the theory. Figure 11b shows the improvement of $SNR_e$ with increasing pixel size using CSE. Since SSE uses nonoverlapped windows to compute the strain estimates, SSE does not show any improvement with the window overlap. The $SNR_e$ values obtained using SSE and CSE are significantly lower than those predicted by the simulations as can also be seen from figures 3, 5, 10 and 11. This is because some undesired experimental conditions such as nonuniform and/or nonslip boundary conditions, elevational motion, orientation of the transducers relative to the direction of compression (resulting in depth-dependent decorrelation), nonhomogeneities in the tissue-mimicking phantoms, frequency-dependent attenuation and other beam related effects are not accounted for in the simulations.

**FIG. 9** Axial elastograms obtained using (a) CSE and (b) SSE for displacements of a uniformly elastic phantom (90 x 90 x 90 mm) with a cylindrical inclusion (7 mm radius) located roughly 40 mm below the top compressor plate. The phantom was compressed 1% axially and imaged to a depth of 57 mm across the cylindrical axis with a 5 MHz, 50% fractional bandwidth array transducer. The sampling frequency was 20 MHz and the processing parameters were a 2 mm window at a pixel size of 0.4 mm for SSE and a 50% overlap and 80% overlap for CSE. (c)
DISCUSSION

The improvement in the SNR and CNR using SSE is due to the use of lower window overlaps. Concurrently with improvements in these quantities, the results presented above show that the use of lower window overlaps does not produce a statistically-significant deterioration in the axial resolution of the elastogram compared to CSE (Fig. 7). Such a result is expected since, the use of staggered window locations utilize several portions of the rf A-lines for the strain estimation and thereby compensates for using higher window overlaps. Hence, the dependence of elastographic image quality on the window overlap can be reduced. Similarly, multiresolution methods that utilize strain estimation at several window lengths and overlaps could also be used to reduce the dependence of the elastographic quality on the window overlap.

It is to be noted that using large nonoverlapped window lengths worsen the spatial resolution of the elastogram. However, for resolution and lesion-detectability studies, the window

FIG. 10 CNR plotted as a function of strain for both CSE and SSE. A uniformly elastic phantom (90 x 90 x 90 mm³) with a circular inclusion (7 mm radius) located roughly 40 mm below the compressor plate was used, imaged to a depth of 57 mm across the cylindrical axis with a 5 MHz, 60% fractional bandwidth array transducer, sampled at a frequency of 20 MHz and processed using a 2 mm window at a pixel size of 0.4 mm for SSE and a 50% overlap and 80% overlap for CSE.

FIG. 11 SNR plotted as a function of (a) window length and (b) pixel size (as a percentage of W) for both SSE and CSE. A 5 MHz, 60% fractional bandwidth transducer, a sampling frequency of 20 MHz and an applied strain of 1% was used in these experiments.
lengths needed to obtain a particular resolution are smaller than or equal to the value of the resolution (or to detect a particular lesion size, the window length needs to be smaller than the size of the lesion). The use of window lengths larger than the resolution reduces the contrast since the time delay estimate for a given window length is the average value over that window length. Hence, no statistically-significant differences between SSE and CSE can be seen for the resolution study.

The use of large window overlaps produces significant amount of noise in the elastograms that could be mistaken for elastographic ‘texture.’ For example, figure 3a shows the elastograms at an overlap of 95% of the window length and figure 3c shows the analytical strain profiles. Clearly, the use of high window overlaps for the purpose of studying elastographic texture is not easily justifiable. Statistical analysis of the elastographic texture of experimental phantoms that is suitable for texture measurements needs to be performed. A correspondence between the actual modulus map of the phantom (obtained using mechanical measurements of the phantom moduli) and the elastographic map has to be established.

Adaptive stretching schemes have been used\textsuperscript{26, 29-31} to improve the $\text{CNR}_e$ and $\text{SNR}_e$. These schemes are not expected to corrupt the spatial resolution since they do not perform any spatial filtering. One of these techniques that involves a gradient-based strain estimation\textsuperscript{26} could be combined with SSE and thereby result in significant improvements in the quality of elastograms. Using SSE, the improvement in $\text{SNR}_e$ and $\text{CNR}_e$ over CSE is significant only at high overlaps (>50%). For low overlaps, the improvement in $\text{SNR}_e$ and $\text{CNR}_e$ over CSE is minimal. However, the alignment of windows at strain edges using CSE (at low overlaps) could result in loss of strain contrast as well as the spatial resolution as explained earlier (Fig. 2).

Spatial filtering of the strain or displacement images was not used in any studies in this paper. This enabled a reliable quantitative comparison of the algorithms especially for the resolution study. Spatial filtering of the elastogram computed at large overlaps can improve the $\text{SNR}_e$ (CNR$_e$) of the elastogram at the expense of spatial resolution as demonstrated in figure 4d. Though SSE computes strains at several window locations, the number of computations for a given pixel resolution is the same as that due to CSE.

**CONCLUSION**

A new staggered strain estimation technique for elastography was developed. This technique resulted in significant improvements in the elastographic image quality over the conventional strain estimation techniques at high window overlaps. We developed theoretical expressions for the expected improvement in the noise performance and in the contrast-to-noise performance of staggered strain estimation over conventional strain estimation, based on previously published theory. Simulations were used to quantify the improvement in quality of the elastograms in terms of the elastographic $\text{SNR}$ ($\text{SNR}_e$), contrast-to-noise ratio ($\text{CNR}_e$) and axial resolution. Experiments on a phantom with a stiff inclusion and a uniformly elastic phantom were performed to illustrate and quantify the improvement in the $\text{CNR}_e$ and $\text{SNR}_e$, respectively. This technique showed improvement over conventional strain estimation techniques in the $\text{SNR}_e$ and $\text{CNR}_e$ without any statistically-significant compromise in spatial resolution.

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APPENDIX 1

Derivation of the SNR and CNR Expressions for SSE

The expression for the SNR e is given by

\[
SNR_e = \frac{s}{\sigma_s}
\]  

(A1)

where \(s\) is the applied strain and \(\sigma_s\) is the standard deviation of the strain estimate. The expression for the CNR e is given in reference 10 as

\[
CNR_e = \frac{2(s_t - s_b)^2}{\sigma_i^2 + \sigma_b^2}
\]  

(A2)

where \(s_t\) and \(s_b\) are the estimated strain values in the target and the background, respectively, and \(\sigma_i\) and \(\sigma_b\) are the standard deviations of the estimates. The lower bound on the variance of the strain estimate for strains in the Cramér-Rao-lower bound is given by combining Eqs. (2) and (6) in reference 8 to yield

\[
\sigma^2_{CRLB} \approx \frac{3c^2}{4\pi^2W^2\Delta Wf_c^3(B^3 + 12B)^2} \left(1 + \frac{1}{SNR_c}\right)^2 - 1
\]  

(A3)

where \(c\) is the speed of sound, \(B\) is the fractional bandwidth and \(f_c\) is the center frequency. \(SNR_c\) is the effective SNR that is a combination of the sonographic SNR (\(SNR_s\)) and the SNR contributed by the value of the correlation coefficient (\(SNR_r\)). Details on these parameters can be found in references 8 and 13. Combining Eqs. (A1) and (A3), we find that

\[
SNR_{CSE}^c \propto W\sqrt{\Delta W}
\]  

(A4)

and from Eqs. (A1), (A2) and (A3) we observe that

\[
CNR_{CSE}^c \propto W^2\Delta W
\]  

(A5)

The values of \(\Delta W\) in CSE are typically smaller than the values of \(W\). Since SSE uses nonoverlapped windows to compute the strain (i.e. \(\Delta W = W\)), the expressions for \(SNR_c\) and \(CNR_e\) for SSE become

\[
SNR_{SSE}^c \propto W^3
\]  

(A6)

and

\[
CNR_{SSE}^c \propto W^3
\]  

(A7)
From Eqs. (A6) and (A4), it can be seen that using SSE, the improvement in SNR, over CSE equals $\sqrt{W/\Delta W}$ (which is greater than unity), i.e.,

$$\frac{SNR_{e}^{SSE}}{SNR_{e}^{CSE}} \propto \sqrt{\frac{W}{\Delta W}} \quad (A8)$$

Similarly, from Eqs. (A7) and (A5), it can be seen that SSE produces a $W/\Delta W$ improvement in the CNR, values, i.e.,

$$\frac{CNR_{e}^{SSE}}{CNR_{e}^{CSE}} \propto \frac{W}{\Delta W} \quad (A9)$$

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