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Evaluation of Reconstruction Parameters for Two-Dimensional Comb-push Ultrasound Shear Wave Elastography

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Abstract

Shear wave elastography (SWE) is a noninvasive ultrasound imaging modality used in the assessment of the mechanical properties of tissues such as the liver, kidney, skeletal muscle, thyroid and the breast. Among the methods used to perform SWE is the comb-push ultrasound shear elastography (CUSE) method. This method uses multiple focused ultrasound beams to generate push beams with acoustic radiation force. Applying these push beams generates propagating shear waves. The propagation motion is measured with ultrafast ultrasound imaging. The shear wave motion data is directionally filtered, and a two-dimensional shear wave velocity algorithm is applied to create group velocity maps. This algorithm uses a moving window and a specified patch for performing cross-correlations of time-domain signals. We performed a parametric study of how the choice of the patch and window size affected the reconstruction of the shear wave velocity in homogeneous and inclusion phantoms. We quantified the mean velocity and coefficient of variation in the homogeneous phantoms. We measured the contrast-to-noise ratio and bias in the inclusion phantoms. In each of these cases, we found that particular combinations of the patch and window provided optimal values of these evaluation metrics for the phantoms tested. This study provides a basis to construct algorithms to produce optimal shear wave velocity reconstructions for various clinical applications.

I. INTRODUCTION

Shear wave elastography (SWE) is a noninvasive ultrasound imaging modality used in the assessment of the mechanical properties of tissues. This method assesses the tissue stiffness by inducing shear waves with acoustic radiation forces (ARF) and measuring the wave propagation velocity [1–3]. There are numerous research studies that have demonstrated the feasibility and diagnostic performance in different organs such as the liver, kidney, skeletal muscle, breast, and thyroid [2, 4–7].

SWE techniques include point-shear wave elastography (pSWE), and two-dimensional (2D) SWE as technical approaches for elasticity imaging. In pSWE, a small region-of-interest (ROI) with limited axial and lateral extent typically on the order of 5–10 mm is used for measurement. Additionally, in pSWE methods only shear wave propagation lateral to the push is utilized for the shear wave velocity (SWV) calculation. A single value is given from this ROI [8, 9]. Two-dimensional SWE has the advantages of measuring the SWV over a large area ranging from 10–40 mm in the axial and lateral directions within the same field-of-view as a 2D B-mode image and providing visualization of a quantitative elastogram, and enabling the operator to select the ROI guided by stiffness and anatomical structures [10–16]. Introducing 2D SWE in the clinical setting has been shown to reduce the use of biopsy with the advantage of allowing the operator to define an ROI and make real-time mechanical estimations avoiding inadvertent focal lesions and anatomical structures as large blood vessels [17].

Rapid SWE data acquisition and SWV reconstruction are highly desired for monitoring tissue stiffness in real-time and minimizing motion artifacts [18]. Therefore, the Comb-push Ultrasound Shear wave Elastography (CUSE) technique has been recently developed and has the ability to reconstruct a full field-of-view (FOV) SWV map in only one rapid data acquisition (< 35 ms) using multiple simultaneous focused or unfocused spaced acoustic radiation force (ARF) push beams. Other methods such as supersonic shear imaging (SSI) and acoustic radiation force impulse (ARFI) which use a single push beam need to be repeated across the FOV to reconstruct the SWV map. With CUSE, the entire FOV is filled with shear waves traveling in both lateral directions, left-to-right (LR) and right-to-left (RL). A directional filter is applied to separate the LR and RL waves. A previously described algorithm is applied to measure the 2D SWV distribution [19]. This algorithm uses a moving window and a specified patch for performing cross-correlations of time-domain signals. A final SWV map is then constructed by combining the SWV maps from the LR and RL wave propagation [1, 18–20].

In this report, we describe a parametric study of how the choice of patch and window affects the reconstruction of the shear wave velocity in homogeneous and inclusion phantoms. We evaluated different image quality metrics and found that certain combinations of the patch and window produced optimal reconstructions. These optimal configurations were identified and analyzed.

II. METHODS

A. Shear Wave Elastography Data Acquisition

Focused push beams were generated using a Verasonics V-1 ultrasound system (Verasonics, Inc., Kirkland, WA, USA) equipped with a linear array transducer L7-4 (Philips Healthcare, Andover, MA, USA). The elements of the linear array transducer were divided into four subapertures of 32 elements to create four push beams (teeth in the CUSE parlance) into three configurations with different numbers of pushes. All the subgroups transmitted focused ultrasound beams simultaneously with a center frequency set to 4.09 MHz and push beam duration of 400 μ s. The focal depth of the focused push beams was 29.88 mm.

After the push beam transmission, the Verasonics system was immediately switched to plane wave imaging mode using all the transducer elements with a center frequency set to 5 MHz [21]. We used three different steering angles (-4° , 0° , 4°) to obtain each imaging frame with a spatial resolution 0.154 mm and an effective frame rate of 3.33 kHz [14]. The FOV was 55.13 mm axially and 39.42 mm laterally

In-phase/quadrature (IQ) data from consecutive frames were obtained by the Verasonics ultrasound system. A 1D- autocorrelation method was used to calculate the particle velocity generated by the shear wave propagation [22]. A median filter (3×3 pixels or 0.462×0.462 mm) was used to reduce the noise from shear wave motion [18, 20]. A directional filter was used to separate the left-to-right and right-to-left propagating shear waves [18, 23, 24].

B. Shear Wave Velocity Calculation

A 2D calculation is needed to measure the correct SWV. Axial (V_z) and lateral (V_x) shear wave velocities were computed for both LR and RL directions using correlations of particle velocity waveforms [19]. The local SWV, V , is given by

$$V = \frac{V_x V_z}{\sqrt{V_x^2 + V_z^2}} \quad (1)$$

The SWV was estimated using a robust approach introduced by Anderssen and Hegland in 1999 [25] and incorporated by Song, *et al.* [19] to calculate the shear wave velocities along the x and z directions. In these methods, one-dimensional correlations are performed to measure time-of-flight of a shear wave between two spatial locations. For these correlations, a patch (in units of pixels) is defined which separates the two locations used for the correlations. The approach proposed by Anderssen and Hegland uses a window within which the results from each patch are averaged. A sliding patch of size, p , that is smaller than the window size, w , to calculate normalized cross-correlations (CC) between each pair of shear wave signals at spatial locations that are p pixels apart as depicted in one-dimension in Fig. 1 where $p = 8$ and $w = 12$ and the square is the point which is being defined for the calculation [19].

Using this approach for 2D-processing window as was thoroughly described in [19], the final SWV at the center pixel, $V(m,n)$, is then given by calculating V_x and V_z with the following equations and then using these maps in Eq. (1)

$$\begin{aligned}
 V_x(m, n) &= \sum_{i=m-h'}^{m+h'} \sum_{j=n-h'}^{n+h'} \left\{ V_x(i, j) \cdot \frac{\frac{CC_x(i, j)^2}{r(i, j)}}{\sum_{i=m-h'}^{m+h'} \sum_{j=n-h'}^{n+h'} \frac{CC_x(i, j)^2}{r(i, j)}} \right\}, \\
 V_z(m, n) &= \sum_{i=m-h'}^{m+h'} \sum_{j=n-h'}^{n+h'} \left\{ V_z(i, j) \cdot \frac{\frac{CC_z(i, j)^2}{r(i, j)}}{\sum_{i=m-h'}^{m+h'} \sum_{j=n-h'}^{n+h'} \frac{CC_z(i, j)^2}{r(i, j)}} \right\},
 \end{aligned} \tag{2}$$

where h' and $r(i, j)$ are defined by:

$$h' = \frac{w-p}{2},$$

$$r(i, j) = \begin{cases} 1, & i = m \text{ and } j = n \\ \sqrt{(i-m)^2 + (j-n)^2}, & \text{else} \end{cases},$$

and m is the pixel lateral dimension, n is the pixel axial dimension, CC_x and CC_z are the normalized cross-correlation coefficient along the x - and z -directions [19]. The values of CC_x and CC_z range from 0.0–1.0 and can be considered as confidence metrics reflecting how similar the two signals that are used for the cross-correlation as the value trends towards unity. The $r(i, j)$ is the distance from the reconstructed pixel (m, n) where data closer to the reconstructed pixel is weighted higher. Equations (2) were used along both V_x and V_z for both LR and RL directions obtaining two shear wave velocity maps.

To evaluate the optimal window and patch combination for local SWV estimation, we used a window range between 8 and 40 pixels with increments of 4 pixels, and a patch range between 4 and 36 with increments of 4 pixels where the pixels were 0.154×0.154 mm. Rouze, *et al.*, investigated reconstruction parameters for creating SWV maps, but in this case only the lateral propagation (V_x) was used [26] as opposed to using both the axial and lateral shear wave velocities in this study.

C. Shear Wave Speed Map Reconstruction

To obtain a full FOV SWV map, the LR and RL field were combined. Previously the final FOV was constructed by combining the computed average shear wave speed from both LR and RL directions as was introduced by Song, *et al.* [19]. In these previous methods the middle of the image was the average of the LR and RL maps. The left edge was taken from the RL map and the right edge was taken from the LR map. The edges were chosen as such because there is not adequate data to be used due to the push locations and the absence of sufficient shear wave propagation. These transitions were previously modeled as sharp transitions. In this work we present a sigmoid-based weighting to smooth these edges.

The sigmoid is a function that is defined for all the real input values and has a positive derivative at each point of the curve [27, 28].

$$f(x, a, c) = \frac{1}{1 + e^{-a(x-c)}} \quad (3)$$

Equation (3) corresponds to the sigmoid function where a corresponds to the steepness of the curve and c is the cut-off that determines the midpoint of the input curve and the value of a controls the amount of blending [29]. We used this method to combine the SWV maps from the LR and RL motion fields into a final SWV map. For this work, we performed this calculation in the x -direction. For the formulation for the LR weighting, we consider N_x pixels

$$y_{LR} = \begin{cases} 0.5/(1 + e^{-a(x+c)}), & x = [-1, 0] \\ 0.5 + 0.5/(1 + e^{-a(x-c)}), & x = [0, 1] \end{cases} \quad (4)$$

$$x = [-N_x/2, N_x/2]/(N_x/2)$$

For the RL field we use a different version

$$y_{RL} = \begin{cases} 1 - 0.5/(1 + e^{-a(x+c)}), & x = [-1, 0] \\ 0.5 - 0.5/(1 + e^{-a(x-c)}), & x = [0, 1] \end{cases} \quad (5)$$

The weighting curves, y_{LR} and y_{RL} , range from values of 0 to 1. The a value was set to 30 after numerous tests. The tests conducted varied the value of a and qualitatively evaluated the presence of vertical artifacts. This value may change based on the number of push beams and locations for the push beams, but the value of $a = 30$ was determined for the four push beams used in this study. The value of $c = 1 - L_w/(N_x/2)$ where $L_w = 75$, which makes $c = 0.40$ for this work. The value of c would need to be changed depending on the locations of the pushes with respect to the edge of the FOV. The weighting functions are shown in Fig. 2 and compared to ones that would be conventionally used in CUSE reconstructions.

D. Phantom Experiments

To explore the effects of the patch and window values on the SWV reconstructions, we performed experiments in four homogeneous elasticity imaging phantoms (Model 039 CIRS Inc., Norfolk, VA) with nominal Young's moduli of 3.50, 10.00, 24.70 and 44.60 kPa which are meant to model the range of healthy to cirrhotic-like liver stiffness. The mean ultrasound attenuation was 0.47 dB/cm/MHz. In an elastic, homogeneous, isotropic, incompressible material Young's modulus, E , is given by

$$E = 3\rho c_s^2, \quad (6)$$

where ρ is tissue density (1000 kg/m³) and c_s is the shear wave velocity [18]. The expected shear wave speeds calculated using (6) were 1.08, 1.82, 2.86 and 3.85 m/s, respectively. To evaluate the performance of the parametric processing, the mean value of the SWV was calculated for each combination of p and w . Additionally, the coefficient of variation was calculated as

$$CV = \sigma_c / \mu_c, \quad (7)$$

where μ_c is the mean speed and σ_c is the standard deviation in the defined ROI.

In addition to the homogeneous phantoms, we performed tests in phantoms with simulated lesions with clinically relevant sizes. For this a stepped cylinder inclusion phantom (Model 049 CIRS Inc., Norfolk, VA) was used. The inclusions are located in four areas with nominal Young's moduli of 11 (Type I), 16 (Type II), 48 (Type III) and 80 (Type IV) kPa. All inclusions studied were centered at $z = 30$ mm. The Type III and IV inclusions were used in this study as they were stiffer than the background. The mean ultrasound attenuation is 0.50 dB/cm/MHz. Using (6), the nominal shear wave speeds are 4.00 and 5.16 m/s for the Type III and IV inclusions, respectively. Each inclusion type consists of stepped cylinders with different diameters (16.67, 10.40, 6.49, and 4.05 mm). The background material has Young's modulus of 29.00 kPa and a nominal shear wave speed of 2.88 m/s. To evaluate the performance of the parametric study, the contrast-to-noise ratio (CNR) and bias were calculated. For ROI-based analyses, the inclusion location was identified on the B-mode data and a circle was defined for calculating means of the inclusion. A rectangle of equal width as that of the inclusion was situated above the inclusions to provide estimates of background parameters.

The CNR was calculated using [18]

$$\text{CNR} = \frac{|V_L - V_B|}{\sigma_B}, \quad (8)$$

where V_L is the mean of the inclusion, V_B is the mean of the background and σ_B is the standard deviation of the background. The background ROI is approximately the same size as the inclusion for each case and is situated above the inclusion. The bias of the inclusion is expressed as a percentage using

$$\text{Bias} = \frac{|V_L - V_N|}{V_N} \times 100\%, \quad (9)$$

where V_N is the nominal speed of the inclusion.

III. RESULTS

One of the changes made to the algorithm in this paper was the use of the sigmoid weighting for combining the SWV maps reconstructed from the LR and RL shear wave motion data. An illustration of the differences is shown in Fig. 3 for homogeneous phantoms, where the conventional weighting is used in the top row and the sigmoid weighting is used in the bottom row for the same acquisitions. There are noticeable vertical streaks near $x = 11$ and $x = 26$ mm, particularly in the first and third columns.

The SWV reconstructions for the homogeneous phantom with a $V = 1.82$ m/s for different combinations of p and w values are shown in Fig. 4. As the value of w increases, there is a border that extends around the image that is proportional to the value of w . For a small value of p and an increasing value of w , there are noticeable regions of higher than expected SWV at the top and bottom of the image. As the value of p is increased, the SWV map becomes more homogeneous.

The mean SWV values and CV values for the four homogeneous phantoms for the different combinations of p and w values are shown in Figs. 5 and 6, respectively. In the homogeneous phantoms, the mean SWV values did not vary greatly with the p and w values though there was a slight downward shift with larger values of p and w . The CV is higher for smaller values of p and w and decreases as they both increase. The CV is lowest for the combinations (p, w) for the four homogeneous phantoms shown in Table I. In the cases for the lowest CV values, the measured values were lower than the nominal values, possibly due to some spatial averaging which decreases the CV but also decreases the SWV value.

We also identified the median frequency of the shear waves propagating in the phantom using the medfreq function in MATLAB (Mathworks, Natick, MA) for each spatial location and then calculating an average over the reconstructed field. The frequencies, f_m , were listed in Table I and using the measured SWV, we calculated the shear wavelength, λ_m , for each phantom. The median frequency increased along with the stiffness of the phantom, which has been shown previously in simulation-based work [30]. The shear wavelength also increased with the stiffness as expected. Finally, we calculated the values of p and w as fractions of the shear wavelengths to explore whether there was a relationship between lowest CV and shear wavelength. For minimizing the CV in the homogeneous phantoms, the ratio p/λ_m ranged between 0.38–0.58, and the ratio w/λ_m ranged between 0.65–0.76. There was not a clear pattern with respect to the shear wavelength that was observed. The w/λ_m occupied a fairly narrow range.

The SWV reconstructions for the Type III and IV inclusions of different sizes centered at $z = 30$ mm are shown in Figs. 7 and 8, respectively, for $p = 8$ and $w = 12$, $p = 16$ and $w = 20$, and $p = 28$ and $w = 40$. The larger inclusions are detected rather easily even down to a diameter of 4.05 mm. The smallest inclusion is difficult to detect for the Type III, but is visible for the Type IV.

Results of reconstruction of phantoms with inclusions of different shear moduli were evaluated using the CNR and bias. The CNR was calculated for the inclusions shown in Fig. 9 for different combinations of p and w . We found that the larger inclusions provided higher levels of CNR than smaller ones, and the CNR was higher for the Type IV inclusions as compared to the Type III as would be expected because the Type IV inclusions have higher shear moduli. The CNR was generally maximized at large w size but the p value varied with the inclusion.

The bias was also calculated for the different combinations of p and w for the Type III and IV inclusions and the results are shown in Fig. 10. In general, the bias is lowest for smaller p and w values. The absolute bias increases as the size of the inclusion decreases and this has been demonstrated previously [15].

The optimal p and w values for maximizing CNR were summarized in Tables II and III for the Types III and IV inclusions, respectively. A similar analysis to that for the homogeneous phantoms to find the median frequency and shear wavelength of the inclusion material was conducted. For maximizing the CNR in Type III inclusions, the ratio p/λ_m ranged between 0.24–0.58, and the ratio w/λ_m ranged between 0.61–0.68. The value of p/λ_m did tend to decrease with inclusion size while the range for w/λ_m was rather narrow. For maximizing the CNR in Type IV inclusions, the ratio p/λ_m ranged between 0.11–0.24, and the ratio w/λ_m ranged between 0.38–0.48. The ratios for these inclusions did not have obvious trends, but the w/λ_m occupied a narrow range.

For the bias, it was lowest for smaller values of p and w . The bias magnitude increased with the size of the inclusion. The bias magnitude was larger for the Type IV inclusions, particularly for the inclusions with diameters 10.40 mm and smaller. Again, the p and w combinations were identified that minimized the absolute bias and those values are summarized for Type III and IV inclusions in Tables IV and V, respectively. For minimizing bias in the Type III inclusions, the ratio p/λ_m ranged between 0.07–0.12, and the ratio w/λ_m ranged between 0.13–0.25. Both ratios decreased with decreasing inclusion size. For minimizing bias in the Type IV inclusions, the ratio p/λ_m ranged between 0.08–0.19, and the ratio w/λ_m ranged between 0.12–0.31. The ratios decreased with decreasing inclusion size, with a strong decline from the 16.67 to the 10.40 mm.

Horizontal profiles at $z = 30$ mm are shown in Fig. 11 for the Type III and Type IV for different combinations of patch and window sizes. When smaller values of p and w are used the edges of the inclusion are sharper and the width of the inclusions are increased, but there is more variation in background and in the inclusion. The sizes of the Type III and Type IV inclusions were under- and overestimated, respectively, with respect to the sizes evaluated using B-mode images (dashed vertical lines in Fig. 11).

IV. DISCUSSION

This study systematically examined the effects of changing the patch and window for reconstruction of SWV maps using a 2D SWV time-of-flight analysis [19]. A previous study by Rouze, *et al.*, explored parameters affecting 2D SWV map reconstruction examining

different time-of-flight algorithms and reconstruction kernel sizes [26]. However, only lateral shear wave propagation was used as opposed to both axial and lateral shear wave velocity components in this study. We used different evaluation metrics in homogeneous and inclusion phantoms to evaluate optimal parameters for reconstructing the SWV.

Figure 4 showed the results of using different combinations of p and w . With small values of p and w , the levels of variation in the images are quite high. However, as the value of w increases, the SWV map becomes smoother. If p is very low, the SWV is high at the top and bottom of the map. When the value of p is increased, the entire SWV map becomes very homogeneous as expected. As the distance between correlation locations (p) is increased, the SWV is estimated more robustly due to a longer propagation distance. As a result, errors in estimation are reduced. The artifacts at the top and bottom of the SWV map are related to areas where the shear wave motion amplitude is reduced. The focus of the push beams used in this study was near 30 mm. If only the patch is used without the averaging with the window as described using the algorithm described in Eq. (2), there is significantly more variation in the results which affects the CV and CNR values.

The mean SWV reconstructed in the homogeneous phantoms (Fig. 5) does not change appreciably, but the CV shown in Fig. 6, changes widely over the range of p and w values. Table I provides the optimal parameters for minimizing CV. The optimal values were found when the p and w values were slightly larger than half the shear wavelength. It was found that when CV was minimized, there was an underestimation of the SWV based on comparison with nominal values from the manufacturer. This is not completely unexpected as larger windows provide lower values of CV due to averaging effects. The change is more considerable in the phantoms with lower SWV as compared to those with higher SWVs, which may be due to the lower value of SWV used in Eq. (7).

For the inclusion phantoms, we evaluated optimal reconstructions based on the CNR and bias. The CNR was generally optimized by large values of w and the p value changed based on the size and stiffness of the inclusion. However, to minimize bias, lower values of p and w need to be used. The CNR is optimized when the patch and window are slightly larger than half the shear wavelength. This is likely due to the reduction of the noise component using larger p and w values. The bias is optimized with smaller patch and window sizes, and this is because using large p and w values will cause some level of averaging and reduction of the reconstructed SWV values.

The inclusion phantom that was used has four types of materials for the simulated lesions, two of which are softer than the background and two which are stiffer than the background. We chose to evaluate only those that were stiffer as in most clinical cases of breast, thyroid, and liver cancers the lesions are stiffer than the surrounding tissue despite whether they are benign or malignant [16, 31–33].

One goal of this work was to evaluate how the different parameters in the 2D SWV reconstruction algorithm affect the results in homogeneous and heterogeneous materials. This will guide evaluations for specific clinical applications. Depending on the application such as in homogeneous tissues such as liver and skeletal muscle (given a consistent

orientation), the CV may be the optimal metric. In the case of heterogeneous cases such as thyroid, breast, or liver cancer, the CNR may be the best metric. In this case, a zone would need to be identified in the lesion and outside in the surrounding tissue. An approach that could be used is one that varies the p and w values to optimize a particular metric within a region or pre-defined inclusion by an iterative reconstruction. A scout SWV map could be produced by a generic choice of p and w and then different p and w values could be used to generate reconstructions that have less noise, better CNR, or lower bias for instance. In addition, these types of metrics could be weighted in a particular way to contribute to the optimization of the SWV maps.

The linear array transducer used in this study produces shear waves that primarily propagate in a lateral direction. In this case, the V_x component may only be necessary, but in the inclusion phantoms, interactions of the shear wave with the inclusion can cause reflection and refraction of the wave and in this case the axial and lateral components are needed.

There were a few limitations of this study. To make comparisons of measurements made in the optimal reconstructions specifically bias in the inclusion phantoms, we used the nominal values provided by the phantom manufacturer CIRS, Inc. Each batch of materials is tested by the manufacturer using compression mechanical testing. This is the most reliable independent test that we have without destroying the phantom tested and performing mechanical testing or some other independent test. Only a few phantoms were tested, but the results and framework for this type of analysis could be generalized for other phantoms or *in vivo* datasets. The advantage of using phantoms is the high level of experimental control and comparison to nominal values from the manufacturer. To obtain more data for evaluation of these reconstructions, simulations such as those from finite element modeling could be used [34].

We only used one implementation of CUSE with focused beams, but similar work could be done with CUSE configurations with unfocused beams or focused beams at different depths [18, 20]. Additionally, multi-source ARF beam profiles could also be used [15]. Using CUSE allows for acquisition of the necessary shear wave motion in one transmission. Other methods that use a single push beam (supersonic shear imaging, ARFI [8, 35]) need to be repeated across the FOV to avoid high shear wave attenuation and because the SWV cannot be estimated in region of the push. CUSE alleviates the issue with reconstructing in the push region of one push with shear waves produced at other locations and the distributed sources also address the shear wave attenuation problem.

Other advanced approaches for SWV velocity have also been presented in the literature that could be used for future comparisons. A multiresolution method of analysis of time-of-flight data has also been proposed by Hollender, *et al* [36], which could be compared to the type of analysis that was described in this article. Additionally, this study used the CUSE approach that maintains the ARF pushes in a single location and used coherent plane wave imaging to measure the shear wave motion. Alternative approaches include measuring the shear waves at a fixed location, termed single track location, which reduces speckle bias and can improve SWV image contrast and resolution [37–40]. The resolution was not systematically analyzed in this study, but that could be undertaken in more detail in future

studies. However, based on images in Figs. 7 and 8, the edges of the inclusions are well-defined despite changing the reconstruction parameters. We did analyze how the different values of p and w affect the transition length from the background to the lesion in Fig. 11. Additionally, the sizes of the Type III and IV inclusions were under- and overestimated, respectively with respect to the sizes identified on the B-mode ultrasound images.

V. CONCLUSION

This study presented a systematic evaluation of a 2D SWV analysis to determine effects of varying patch (p) and window (w) size has on various image evaluation metrics. This was evaluated in homogeneous phantoms and phantoms with simulated inclusions of different sizes and Young's moduli. It was found that large values for p and w provided reliable measurements of SWV in homogeneous phantoms with low coefficient of variation. For the inclusion phantoms, different trends for the p and w values for optimizing CNR and bias. This type of study provides a framework for constructing optimal images that could be reconstruction using an iterative or multi-scale approach.

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Index Terms

(ARF)	Acoustic radiation force
(CUSE)	comb-push ultrasound shear wave elastography
(SWE)	shear wave elastography
(SWV)	shear wave velocity

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Fig. 1.

Depiction of correlation pairs for $w = 12$ and $p = 8$. In this case, 5 patches were identified for averaging, and the average value would be placed at the square location on the one-dimensional line.

Fig. 2.

Weighting of wave velocity maps reconstructed from LR and RL motion fields. The solid lines are the conventional weighting used previously for CUSE, and the dashed lines are the proposed sigmoid-based weighting curves.

Fig. 3.

Shear wave velocity reconstructions in homogeneous phantom with nominal SWV values of 1.82, 2.86, and 3.85 m/s for the different columns, respectively. The conventional weighting was used in the top row and sigmoid weighting for the bottom row. (a) $V = 1.82$ m/s, $p = 4$, $w = 40$, (b) $V = 2.86$ m/s, $p = 20$, $w = 40$, (c) $V = 3.85$ m/s, $p = 20$, $w = 40$.

Fig. 4.

Shear wave velocity reconstructions in homogeneous phantom with nominal SWV of 1.82 m/s. The images are reconstructed with different values of p and w . The ROI (23.1×38.5 mm) depicted on the upper left image was used for all calculations of means and standard deviations.

Fig. 5. Mean shear wave velocity for four homogeneous phantoms with different Young's moduli. The reconstructions are performed with different values of p and w .

Fig. 6. Coefficients of variation (CVs) for SWV reconstructions in homogeneous phantoms with different Young's moduli. The reconstructions are performed with different values of p and w .

Fig. 7.

Shear wave velocity reconstructions stepped cylinder phantom for the Type III inclusions with values of $p = 8$, $w = 12$ (top row), $p = 16$, $w = 20$ (middle row), $p = 28$, $w = 40$ (bottom row). ROIs for calculation of CNR are depicted in the first row.

Fig. 8.

Shear wave velocity reconstructions stepped cylinder phantom for the Type IV inclusions with values of $p=8$, $w=12$ (top row), $p=16$, $w=20$ (middle row), $p=28$, $w=40$ (bottom row). ROIs depicted in the first row of Fig. 7 are also used for this figure.

Fig. 9. Contrast-to-noise ratio (CNR) values for Type III (top row) and Type IV (bottom row) inclusions of different sizes. The CNR values were evaluated from SWV reconstructions with different values of p and w .

Fig. 10.

Bias values for Type III (top row) and Type IV (bottom row) inclusions of different sizes.

The bias values were evaluated from SWV reconstructions with different values of p and w .

Fig. 11.

Horizontal profiles through the middle of the Type III (left column) and Type IV (right column) inclusions at $z = 30$ mm for different combinations patch and window sizes.

TABLE I

RECONSTRUCTION PARAMETERS FOR HOMOGENEOUS PHANTOMS FOR LOWEST CV

Parameter	Phantom SWV			
	1.08 m/s	1.82 m/s	2.86 m/s	3.85 m/s
$V, m/s$	0.90	1.60	2.42	3.46
p, mm	4.93	4.93	3.08	4.93
w, mm	6.16	6.16	6.16	6.16
f_m, Hz	105.3	186.8	300.3	367.8
λ_m, mm	8.55	8.57	8.06	9.41
p/λ_m	0.58	0.58	0.38	0.52
w/λ_m	0.72	0.72	0.76	0.65

TABLE II

OPTIMAL RECONSTRUCTION PARAMETERS FOR TYPE III INCLUSIONS FOR CNR

Parameter	Inclusion Diameter, mm			
	16.67	10.40	6.49	4.05
V_B , m/s	2.81	2.76	2.78	2.71
V_L , m/s	3.55	3.45	3.14	2.80
p , mm	5.54	3.08	2.46	4.31
w , mm	6.16	6.16	6.16	6.16
f_m , Hz	372.0	345.7	311.2	310.8
λ_m , mm	9.54	9.98	10.09	9.01
p/λ_m	0.58	0.31	0.24	0.48
w/λ_m	0.65	0.62	0.61	0.68

TABLE III

OPTIMAL RECONSTRUCTION PARAMETERS For TYPE IV INCLUSIONS For CNR

Parameter	Inclusion Diameter, mm			
	16.67	10.40	6.49	4.05
V_B , m/s	2.89	2.78	2.79	2.83
V_L , m/s	5.22	4.53	3.97	3.51
p , mm	1.85	3.70	3.08	1.85
w , mm	6.16	6.16	6.16	6.16
f_m , Hz	319.3	298.8	275.6	274.9
λ_m , mm	16.35	15.16	14.40	12.77
p/λ_m	0.11	0.24	0.21	0.14
w/λ_m	0.38	0.41	0.43	0.48

TABLE IV

OPTIMAL RECONSTRUCTION PARAMETERS FOR TYPE III INCLUSIONS FOR BIAS

Parameter	Inclusion Diameter, mm			
	16.67	10.40	6.49	4.05
V_B , m/s	2.87	2.79	2.81	2.75
V_L , m/s	3.73	3.57	3.25	2.90
p , mm	1.23	1.23	1.23	0.62
w , mm	2.46	1.85	1.85	1.23
f_m , Hz	372.0	345.7	311.2	310.8
λ_m , mm	10.03	10.32	10.44	9.33
p/λ_m	0.12	0.12	0.12	0.07
w/λ_m	0.25	0.18	0.18	0.13

TABLE V

OPTIMAL RECONSTRUCTION PARAMETERS FOR TYPE IV INCLUSIONS FOR BIAS

Parameter	Inclusion Diameter, mm			
	16.67	10.40	6.49	4.05
V_B , m/s	2.86	2.82	2.82	2.85
V_L , m/s	5.16	4.77	4.22	3.79
p , mm	3.08	1.23	1.23	1.23
w , mm	4.93	1.85	1.85	1.85
f_m , Hz	319.3	298.8	275.6	274.9
λ_m , mm	16.16	15.96	15.31	13.79
p/λ_m	0.19	0.08	0.08	0.09
w/λ_m	0.31	0.12	0.12	0.13