Published in final edited form as:

Ultrason Imaging. 2005 October ; 27(4): 256–270.

Spatial Angular Compounding for Elastography without the Incompressibility Assumption

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Abstract

Spatial-angular compounding is a new technique that enables the reduction of noise artifacts in ultrasound elastography. Previous results using spatial angular compounding, however, were based on the use of the tissue incompressibility assumption. Compounded elastograms were obtained from a spatially-weighted average of local strain estimated from radiofrequency echo signals acquired at different insonification angles. In this paper, we present a new method for reducing the noise artifacts in the axial strain elastogram utilizing a least-squares approach on the angular displacement estimates that does not use the incompressibility assumption. This method produces axial strain elastograms with higher image quality, compared to noncompounded axial strain elastograms, and is referred to as the least-squares angular-compounding approach for elastography. To distinguish between these two angular compounding methods, the spatial-angular compounding with angular weighting based on the tissue incompressibility assumption is referred to as weighted compounding. In this paper, we compare the performance of the two angular-compounding techniques for elastography using beam steering on a linear-array transducer. Quantitative experimental results demonstrate that least-squares compounding provides comparable but smaller improvements in both the elastographic signal-to-noise ratio and the contrast-to-noise ratio, as compared to the weighted-compounding method. Ultrasound simulation results suggest that the least-squares compounding method performs better and provide accurate and robust results when compared to the weighted compounding method, in the case where the incompressibility assumption does not hold.

Keywords

Angled beams; angular compounding; compounding; elasticity; elastogram; elastography; imaging; strain; signal-to-noise; ultrasound

INTRODUCTION

Elastography is an imaging modality that is capable of mapping local internal strains that a tissue experiences after a quasistatic compression.^{1–14} In this technique, local displacements are typically computed by applying a cross-correlation analysis to the pre- and postcompression ultrasonic radiofrequency (rf) echo signals. Strains are then estimated as the gradient of the displacements along the beam axis and displayed as a local strain image, referred to as an elastogram. Many algorithms have been developed to improve the image quality of elastograms, such as temporal stretching,^{15–17} multicompression averaging,¹⁸ wavelet denoising¹⁹ and other compounding approaches.^{20,21} Temporal stretching of the postcompression signal by the appropriate factor can compensate for axial decorrelation effects.^{15–17} Multicompression averaging reduces decorrelation by averaging elastograms generated using successive small compressions. Wavelet denoising smoothes the displacement estimates in the wavelet domain without losing edge information.¹⁹ Most of these algorithms can be used in conjunction with each other for artifact reduction in elastography.

In this paper, we compare two spatial angular compounding techniques used to reduce noise artifacts in axial strain images: spatial-angular compounding using angular weighting,^{22–24} referred to as weighted compounding, and compounding based on a least-squares approach previously used to obtain the normal and shear strain components,²⁵ referred to as least-squares compounding. For weighted compounding, the compounded axial strain image is obtained by weighted averaging of multiple strain estimates around the same region-of-interest (ROI) acquired from different insonification angles. This technique utilizes the same concept utilized to reduce speckle noise²⁶ in conventional ultrasound imaging with angular compounding of the B-mode signals.^{27–29} The least-squares compounding was previously used by Techavipoo et al²⁵ to estimate lateral and shear strains images. However, this method also can be used to improve image quality of estimated axial strains. In this technique, displacements at each spatial location in the compressed medium are measured along each beam direction using time-delay estimation techniques.³⁰ A linear model of the relationship between these directional displacements and components of the actual displacement vector is then constructed. Orthogonal components of the displacement vector are then estimated using a least squares solution.²⁵ The compounded axial strain image is then estimated from the gradient of the axial component of the displacement vector.

The performance of weighted compounding and least-squares compounding for elastographic imaging is compared using phantom experiments. We present qualitative and quantitative results obtained using a single inclusion phantom that demonstrates the improvements in the elastographic signal-to-noise ratio (SNR_e) and contrast-to-noise ratio (CNR_e), compared to noncompounded elastograms. Simulation results presented in this paper also illustrate the conditions where the least squares compounding method provides accurate results when compared to the weighted compounding approach.

ANGULAR COMPOUNDING ALGORITHMS FOR ELASTOGRAPHY

The two angular compounding algorithms for elastography that are compared in this paper are described in the following section. The weighted compounding algorithm that uses the incompressibility assumption can be described in four steps:²³

1. After data acquisition, each of the angular rf pre- and postcompression frame pairs were analyzed separately to determine angular tissue displacements at the specified beam angle. These are referred to as angular displacement frames.
2. The gradient of the angular displacements was obtained using a least-squares strain estimator to generate local strain estimates or angular elastograms at each beam angle.
3. Linear interpolation was then applied for image registration of the angular elastograms onto the elastogram obtained for the zero-angle grid.
4. Compound elastograms were obtained by a weighted averaging of the strain estimates over the multiple angular elastograms.^{22,23}

$$C(\Delta\theta, N) = \frac{1}{N} \sum_{i=-n}^n w_x(v, i\Delta\theta) A(i\Delta\theta) \quad (1)$$

where $C(\Delta\theta, N)$ represents a compound elastogram. N is the number of angular elastograms used for compounding, which equals $2n + 1$, where n is the number of angular elastograms in either the positive or negative angular direction. $A(\theta)$ and $w_x(v, \theta)$ are the angular elastogram and the weighting factor for axial strains at angle θ , respectively. The weighting factor is given by^{22,23}

$$w_x(v, \theta) = 1 / (\cos^2 \theta - v \sin^2 \theta) \quad (2)$$

where ν is the Poisson's ratio, which is assumed to be 0.495 for incompressible soft tissue.³² The least-square based spatial angular compounding algorithm is summarized as follows:²⁵

1. After data acquisition, each of the angular rf pre- and postcompression frame pairs was analyzed separately to determine tissue displacements at the specified beam angle. These are referred to as angular displacement frames.
2. Linear interpolation was then applied for image registration of the angular displacement data to a Cartesian spatial grid obtained for the zero-angle data.
3. The displacement vector components at each pixel on the zero-angle grid are then estimated using a least-squares approach on the angular displacement estimates at each pixel
4. The compounded elastogram is obtained from the gradient of the axial component of the displacement vector using the least squares strain estimator.³¹

The relationship between the actual displacement vectors and the measured angular displacement is given by:²⁵

$$q = A\bar{d} + n \quad (3)$$

where

$$q = \begin{bmatrix} q_{\theta_1} \\ q_{\theta_2} \\ \vdots \\ q_{\theta_m} \end{bmatrix} \quad A = \begin{bmatrix} \cos \theta_1 & \sin \theta_1 \\ \cos \theta_2 & \sin \theta_2 \\ \vdots & \vdots \\ \cos \theta_m & \sin \theta_m \end{bmatrix} \quad \bar{d} = \begin{bmatrix} d_z \\ d_x \end{bmatrix} \quad n = \begin{bmatrix} n_{\theta_1} \\ n_{\theta_2} \\ \vdots \\ n_{\theta_m} \end{bmatrix}$$

q_{θ_i} represents an observation of the displacement vector $\bar{d}$ at beam angle θ_i for $i = 1, \dots, m$, where m is the total number of beam steering angles; n_{θ_i} is the noise in the observation at angle θ_i . The terms d_z and d_x denote, respectively, the orthogonal axial and lateral components of the displacement vector. We can minimize the squared error between the measurement $\bar{q}$ and the linear model $A\bar{d}$ with respect to $\bar{d}$ to estimate the value of $\bar{d}$. The solution is the least-squares solution,³³ which is given by:

$$\tilde{\bar{d}} = (A^T A)^{-1} A^T q \quad (4)$$

In this paper, for both weighted compounding and least-squares compounding approaches, we consider the case where the compounding of both symmetrical positive and negative angles, as shown in the summation index of Eq (1) is performed.

Estimation of SNR_e , CNR_e and strain contrast

The values of elastographic SNR_e , CNR_e , and the strain contrast C_0 were analyzed for compounded elastograms of the single-inclusion phantom. The SNR_e is defined as:

$$SNR_e = \frac{\bar{s}}{\sigma_s} \quad (5)$$

where $\bar{s}$ and σ_s are, respectively, the mean and standard deviation of the strains over pixels in the selected ROI. The strain contrast C_0 and the elastographic CNR_e are defined as follows:³⁴

$$C_0 = s_2 / s_1. \quad (6)$$

$$CNR_e = \frac{2(\bar{s}_1 - \bar{s}_2)^2}{(\sigma_1^2 + \sigma_2^2)} \quad (7)$$

where $\bar{s}$ and σ^2 denote the mean and variance of the strains in the selected ROI. The subscripts 1 and 2 refer to the regions inside and outside the inclusion, respectively. In our experimental data acquisition, we acquired eight sets of pre- and postcompression rf data along the same imaging plane of the phantom using different precompression levels ranging from 0 to 4% of the phantom height, to obtain statistically-independent results for the SNR_e , strain contrast and CNR_e estimates.

EXPERIMENTAL RESULTS

Method

The performance of the two angular-compounding techniques are evaluated using rf data acquired using a TM phantom. A single-inclusion TM phantom of size $9 \times 9 \times 9 \text{ cm}^3$ was used to evaluate the two compounding methods. The inclusion phantom contains a 1 cm diameter cylindrical inclusion encased within a uniform background. The inclusion is three times stiffer than the background. The phantom was scanned using an Ultrasonix 500RP (Ultrasonix Medical Corporation, Bothell, WA, USA and Vancouver, BC, Canada) real-time scanner equipped with a 5 MHz linear-array transducer with an approximately 60% band width. In order to acquire rf data at different beam angles, we developed a client program, to communicate with the Ultrasonix Ultrasound Research Interface (URI) and software server and to control the beam steering algorithm. The URI client program enables the operator to input the maximum angle and the angular increment and the system will automatically scan the phantom along the specified angular sweep. In our experiment, the phantoms were scanned from -15° to 15° with a minimum angular increment of 0.75° . A schematic illustration of the angular data acquisition is shown in Figure 1.

A compression plate with a rectangular slot for the transducer face was mounted on a linear stage driven by a stepper motor. The compression plate is larger than the phantom surface, to provide a uniform compression of the phantom as shown in Figure 1. The compression was applied along the axial direction i.e., angle 0° , the nonsteered case. Echo signals were acquired over a total depth of 4 cm centered about the inclusion imaged, before and after a compression of 0.5% of the phantom height. The stepper motor controlled compression process is controlled by the URI program on the Ultrasonix 500RP system, enabling synchronized acquisition of both the pre- and postcompression rf data sets. We implemented an automated beam-steering and data acquisition algorithm on the system. The algorithm first acquires the precompression data along the specified angular sweep (-15° to 15° in 0.75° increments). The stepper motor is then activated to compress the phantom to a specified compression increment, following which the postcompression rf data are acquired following the same angular sequence.

Results

Figure 2 presents a typical example of the angular displacement (a) to (c) and angular elastograms (d) to (f), before appropriate weighting, obtained from the single-inclusion phantom, for angles of 0° , 7.5° , and 15° , respectively. As expected, we observe increased noise artifacts in the displacement and strain images at the larger insonification or beam angles. This is due to the fact that angular elastograms obtained where the beam angle relative to the direction of compression is large, suffer from significant decorrelation of the pre- and postcompression rf echo signals due to the increased movement of the scatterers. Note also that the angular elastograms become darker as the insonification angle increases, suggesting that the strains measured at larger angles are biased lower than those measured at smaller

angles. This bias is compensated by appropriate angular weighting of the angular strain estimates.

Figure 3 presents compounded elastograms for the single inclusion phantom obtained with the least-squares compounding method (top) and weighted compounding method (bottom). An angular increment of 0.75° and maximum angles of 1.5° , 7.5° and 15° were used during compounding for the elastograms shown in the first to third columns, respectively. These compounded elastograms demonstrate the significant reduction in noise artifacts and subsequent improvement in the detectability of the inclusion.

Plots of the SNR_e versus the maximum angle used for compounding are shown in Figure 4. The error bars denote the standard deviation of the SNR_e estimates over eight independent experiments. For each data set, the value of SNR_e was calculated using the rectangular region within the inclusion shown in Figure 2(d). Observe that the improvement in the SNR_e of the compounded elastograms obtained with weighted compounding is larger than those obtained with least-squares compounding.

Quantitative variations in the CNR_e and strain contrast were calculated using the rectangular ROI within the inclusion and in the background region, as shown in Figure 2(d). The CNR_e curves are plotted versus the maximum angle used in the compounding process, as shown in Figure 5. The weighted compounding method provides a higher CNR_e in the compounded elastograms when compared to the least-squares compounding method. Note also that the CNR_e curve for the weighted compounding method decreases slightly after a maximum angle of around 6° . This is due to the increased strain variance of elastograms obtained for the larger beam insonification angles. The CNR_e curve for the least-squares compounding method also saturates around a maximum angle of 6° , providing an improvement of 18 dB over the maximum angle from 0 to 6° .

The strain contrast plotted versus the maximum angle used for compounding is shown in Figure 6. The error bars denote the standard deviation of the mean contrast obtained over eight sets of compounded elastograms. Note that angular compounding has little effect on the strain contrast.

Figures 7 and 8 show the effect of the angular increment on the compounding performance. The SNR_e plotted versus the angular increment is given in Figure 7, with a maximum angle of (a) 6° and (b) 9° used in compounding. In our data set, the smallest angular increment was 0.75° . Therefore, we could use this angular increment value or a multiple of 0.75° . Figure 8 presents the CNR_e curves plotted against the angular increment with a maximum angle of (a) 6° and (b) 9° used in compounding. For small angular increments (0.75 to 3°), the SNR_e and CNR_e is almost constant with increases of the angular increment. For angular increment greater than 3° , the SNR_e and CNR_e decreases faster for weighted compounding compared to least-squares compounding.

ULTRASOUND SIMULATION RESULTS

This section illustrates conditions where the least-squares compounding method would provide more accurate and robust estimations of the compounded elastograms. Since the weighted compounding algorithm is based on the incompressibility assumption where the Poisson's ratio is $\cong 0.495$, we will compare the performance of the two compounding methods where the underlying material would have a different value of the Poisson's ratio. For example lung tissue has a Poisson's ratio of 0.3,³⁶ while cartilage has a Poisson's ratio of 0.17.³⁷

Method

A simulated single inclusion phantom of dimensions $4 \times 4 \times 4 \text{ cm}^3$ was constructed using Finite Element Analysis (FEA) software (ANSYS Inc., Canonsburg, USA), with a Poisson's ratio of 0.3 assumed for both the inclusion and the background. The inclusion was three times stiffer than the background. The incompressibility assumption is not satisfied in this simulated phantom and the ability of least-squares angular compounding to provide robust results under these conditions is evaluated in this section.

Axial and lateral displacements generated, using FEA of the plane-strain elasticity problem described above, were used to displace the point scatterers utilized in a frequency-domain ultrasound simulation program.³⁸ A linear-array transducer was modeled, which consist of $0.1 \times 10 \text{ mm}$ elements with a 0.1 mm center-to-center element separation. Each beam line was formed using 128 consecutive elements. The incident pulses were modeled to be Gaussian shaped with an 8 MHz center frequency and a 60% bandwidth. The simulations were performed assuming the sound speed in the phantom to be constant at $1,540 \text{ m/s}$ and attenuation to be negligible. The scatterers were randomly distributed with an average concentration of $40/\text{mm}^3$. The sampling frequency utilized was 52 MHz . In our simulation, the phantom was scanned over an insonification angle range from -15° to 15° in 3° increments using beam steering, which was implemented in the ultrasound simulation program by applying appropriate time delay to each element in the beam forming procedure.

Results

Figure 9 shows the noncompounded and compounded elastograms of the simulated inclusion phantom obtained with least-squares compounding and weighted compounding respectively. An angular increment of 3° and maximum angles of 15° were used during the compounding. The strain contrast and the CNR_e were calculated using the rectangular ROI within the inclusion and in the background region, as shown in Figure 9(a). Plots of the strain contrast and the CNR_e versus the maximum angle used for compounding are shown in figures 10 and 11, respectively. The error bars denote the standard deviation of the strain contrast and the CNR_e estimates over eight independent simulations. Note that the least squares compounding has little effect on the strain contrast but weighted compounding leads to an erroneous increase of the strain contrast due to the use of the incompressibility assumption. Although this increase is not significant at lower maximum insonification angles, it suggests that the weighted compounding approach may provide incorrect information about the strain contrast when the incompressibility assumption is not satisfied. Figure 11 shows that the least-square compounding provides better results than weighted compounding in this simulated case where the incompressibility assumption does not hold. Observe that the improvement in the CNR_e , of the compounded elastograms obtained with least-squares compounding is significantly larger than those obtained with weighted compounding as seen from the increased separation of the error bars with the increased maximum angle utilized for the compounding.

DISCUSSION

Experimental results demonstrate that weighted compounding provides an improvement in the SNR_e and CNR_e of around 15 and 17 dB, respectively, with a maximum angle of around 6° , using a single-inclusion phantom model, when compared with an elastogram obtained without compounding. The improvement in the SNR_e and CNR_e obtained with the least-squares compounding approach is around 11 and 15 dB, respectively, with a maximum angle ranging from 6 to 7.5° . Both of these compounding techniques do not significantly affect the strain contrast. However, the results for the simulated phantom with a Poisson ratio of 0.3, suggest that the least-squares compounding method performs better and provides accurate and robust results when compared to the weighted compounding method.

The different results obtained from the experiment and simulation can be explained by the assumptions behind the two different compounding methods. For the weighted compounding technique, tissue is assumed to be incompressible with a Poisson's ratio of 0.495, as shown in Eqn. (2). The angular elastograms can be averaged using a weighting factor to generate compounded elastograms only when the Poisson's ratio is a constant over the entire imaged object. While in the least-squares compounding method, compounded elastograms are obtained by estimating displacement vectors from angular displacement data. No assumptions are made regarding compressibility of the object in this method. Note that the incompressibility assumption may not hold in some tissues, for example, lung tissue with a Poisson's ratio of 0.3³⁶ and cartilage with a Poisson's ratio of 0.17.³⁷ The simulation results demonstrate that the weighted-compounding method provides erroneous results when the incompressibility assumption is not satisfied. In addition, the Poisson's ratio may not be constant, such as for poroelastic tissue when edema is present.^{39,40} Although weighted compounding provides better compounding results under certain situation, it cannot be applied to all types of tissues to be imaged. It is safer to use the least-squares compounding approach when the compressibility of the tissue is unknown.

Both weighted compounding and least-squares compounding require the acquisition of angular rf frames from different beam angles, which increases the computational time and also reduces the frame rate of the ultrasound system. The maximum angle and angular increment are two important parameters that affect the efficiency of compounding. The SNR_e and CNR_e curves presented in Figures 4 and 5 indicate saturation around an insonification angle between 4° to 6° for both weighted compounding and least-squares compounding methods. For the weighted-compounding method, the CNR_e values obtained even decrease slightly after a maximum angle of 9°, as shown in Figure 5. For our experimental setup, the optimum value of the maximum angle is therefore around 6° beyond which no appreciable increases in the SNR_e or CNR_e are obtained. This can be explained by the significant increase in the decorrelation of the pre- and postcompression rf echo signals at larger angles, as shown in Figure 2.

Another important factor that affects the efficiency of the compounding is the angular increment used in compounding. An optimum angular increment whereby fewer angular data are required to obtain similar improvements in the SNR_e or CNR_e can significantly improve the entire compounding procedure. Angular increments of 0.75° to 3° provide similar improvements in the SNR_e and CNR_e for a fixed maximum angle (see Figures 7 and 8). This is because rf data from a tissue volume viewed with beams separated by a small angular increment are highly correlated. However, for a smaller angular increment (0.75° to 3°), the compounding efficiency is low since a larger number of angular data are required to achieve a given SNR_e or CNR_e level. For a very large angular increment (greater than 4.5°), on the other hand, the improvement in image quality is lower than that obtained for the smaller angular increment, due to the fewer number of angular data available for compounding. In our experiment, the optimum angular increment lies between 3 to 4.5° for both weighted compounding and the least-squares compounding methods. The use of this optimum angular increment could reduce the number of angular elastograms that have to be utilized in the compounding process, and hence reduce the computation time and improve the frame rate.

CONCLUSION

In summary, weighted compounding provides greater improvement in both the SNR_e and the CNR_e when compared to least-squares compounding. However, weighted compounding is based on the incompressibility assumption, which makes this method only suitable for tissues with a Poisson's ratio of around 0.495. The least-squares compounding technique can be applied to any tissue without regard to whether the incompressibility assumption would hold. For both

compounding methods, the maximum angle and angular increment used for compounding are two important factors that affect the efficiency of the compounding algorithm.

Acknowledgements

This work is supported in part by NIH grants R21 EB003853 and R21-EB002722. The authors would also like to thank Dr. Laurent Pelissier for the loan of the Ultrasonix 500 RP system used on this research.

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FIG 1.

A schematic diagram depicting elastographic imaging using a linear array transducer with beam steering. The z and x directions are defined as the axial and lateral direction of the displacement vector.

FIG 2.

Angular displacements (top) and angular elastograms (bottom) of the single-inclusion phantom. The first, second and third columns show displacement and elastograms obtained at 0° , 7.5° and 15° insonification angles, respectively. The grey scale bar for displacements image denotes axial displacement in mm and the grey scale bar for elastograms denotes strain, where a 1% strain is displayed as 0.01.

FIG 3.

Compound elastograms obtained with least-squares compounding (a to c) and with weighted compounding (d to f). An angular increment of 0.75° was used over a maximum angle of 1.5° (a & d), 7.5° (b & e) and 15° (c & f), respectively.

FIG 4. Plots of mean SNR_e and standard deviation shown as the error bars over eight independent realizations of the compound elastograms vs. maximum angle used for compounding.

FIG 5.

Plots of mean CNR_e with standard deviation shown as the error bars over eight independent realizations of the compound elastograms vs. maximum angle used for compounding.

FIG 6. Plots of mean strain contrast with standard deviation shown as the error bars over eight independent realizations of the compounded elastograms vs. maximum angle used for compounding.

FIG. 7.

Plots of mean SNR_e and standard deviation shown as the error bars over eight independent realizations of the compound elastograms vs. angular increment, with a maximum angle of (a) 6° and (b) 9° used for compounding.

FIG 8. Plots of mean CNR_e and standard deviation shown as the error bars over eight independent realizations of the compound elastograms vs. angular increment, with a maximum angle of (a) 6° and (b) 9° used for compounding.

FIG 9. Noncompounded elastogram (a) and compounded elastograms obtained with least-squares compounding (b) and with weighted compounding (c) of the simulated inclusion phantom. An angular increment of 3° was used over a maximum angle of 15° .

FIG 10.

Plots of mean strain contrast with the standard deviation shown as the error bars over eight independent simulations of the compounded elastograms vs. maximum angle used for compounding.

FIG 11.

Plots of mean CNR_e with the standard deviation shown as the error bars over eight independent simulations of the compounded elastograms vs. maximum angle used for compounding