KEY PARAMETERS FOR PRECISE LATERAL DISPLACEMENT ESTIMATION IN ULTRASOUND ELASTOGRAPHY

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ABSTRACT

Complementary to axial, lateral and elevational displacement and strain can provide important information on the mechanical properties of biological soft tissues. In this paper, the effects of key parameters on the lateral displacement estimation were investigated in simulations and validated in phantom experiments. The performance of the lateral estimator was evaluated by measuring its associated bias, and jitter (i.e., standard deviation). Simulation results showed that the bias and jitter undergo periodic variations depending on the lateral displacement, with a period equal to the pitch (i.e., adjacent element distance). The performance of the lateral estimation was improved, when a smaller pitch, or a larger beamwidth, was used. The effects of the pitch were found to be greater than those of the beamwidth. The results of the phantom experiments were shown in good agreement with the simulation findings, including the periodic variation of the performance with lateral displacement, effects of pitch and beamwidth. In conclusion, smaller pitches and wider beamwidths were found to be key in reducing the jitter error in the lateral displacement estimation. The same results also hold for tracking in the elevational direction.

Index Terms—Beamwidth, Bias, Jitter, Pitch, Ultrasound elastography

I. INTRODUCTION

Ultrasound elastography has been developed into an effective imaging method of estimating the local elastic properties of biological tissues [1]. This technique has been successfully applied to the diagnosis of breast lesions and is currently clinically used.

Typically, only the axial displacement and strain are estimated in ultrasound elastography. However, most biological tissues are nearly incompressible [2], i.e., the axial compression leads to equivalent expansion in the lateral (in plane, orthogonal) and elevational (out of plane, orthogonal) directions. Estimation of the displacement and strain in the orthogonal directions may provide important additional information on the tissue mechanical properties.

Elastography has been shown capable of obtaining lateral displacements and strains [3]. By taking advantage of the lateral estimation technique, lateral strains, shear strains and the Poisson's ratio have been imaged successfully [3, 4].

In cardiac applications, the axial and lateral strain estimation of myocardium were used to calculate the radial, circumferential, or principal strains, which are angle-independent and centroid-independent [5].

Previously reported efforts have concentrated on the performance analysis of the axial displacement and strain estimation using different parameters. However, there are only a few fundamental studies on the performance of the lateral displacement and strain estimation [6]. In particular, the effects of lateral displacement magnitude, pitch (i.e., adjacent element distance) and beamwidth on the lateral estimation have not been studied thoroughly.

In this paper, we studied the effects of different parameters (i.e., pitch, beamwidth and beam overlap) on the lateral displacement estimation under well-controlled simulation and experimental conditions, which only considered lateral rigid motion. In the simulations, a homogeneous phantom was displaced in the lateral direction without any axial displacement, axial strain or lateral strain. Phantom experiments using lateral rigid motion were also performed to validate the simulation findings.

II. METHODS

A. Simulation

In the linear array simulation, the pre- and post-displaced RF signals were generated using a 2-D convolution-based linear scattering model [7]. The transducer PSF had a 60% -6-dB bandwidth, a 3.3 MHz center frequency and a -6dB beamwidth varying between 1 and 6 mm. The sampling frequency of the RF signals was 20 MHz. The speed of sound in tissues was assumed to be equal to 1540 m/s.

The scattering function consisted of point scatterers uniformly distributed in a space of 100×50 mm^2 (width $\times$ depth). The scatterer density was equal to 12 scatterers / wavelength. The 2-D PSF was convolved with the scattering function to obtain the pre-displaced RF signals. The scatterers were then moved in the lateral direction at a specific lateral displacement steps. Post-displaced RF signals were obtained by convolving the 2-D PSF with the post-displaced scattering function. Gaussian white noise was subsequently added to the RF signals. The sonographic signal-to-noise ratio (SNRs) was set to be 60 dB.

The method developed by Konofagou and Ophir [3] was used to estimate the lateral displacements. The window size was equal to 3.85 mm with a 90% overlap. The average estimated lateral displacement was calculated in a region of interest (ROI) of 50×50 mm^2 located at the center of the simulated phantom. The bias of the estimation was obtained as the simulated lateral motion subtracted from the average estimates, while the jitter was calculated to be equal to the standard deviation (SD) of the estimates.

B. Experimental phantom

A polyacrylamide tissue-mimicking phantom was constructed. The phantom was placed in a water tank and subsequently immersed in degassed water. A linear-array transducer (model 10L5, Terason Ultrasound, Burlington, MA) was attached to a computer-controlled positioner (Velmex Inc., Bloomfield, NY) and placed below the water surface but without any contact with the phantom. Efforts were made to align the lateral and axial directions of the transducer with the horizontal and vertical directions of the positioner, respectively. The 128-element linear array had a center frequency of 7 MHz. The pitch, defined as spacing between adjacent array elements in a linear array, was approximately equal to 0.30 mm. A Terason 2000 ultrasound system (Teratech Corp., Burlington, MA) was used to drive the transducer. The transmit focus was at a depth of 2.8 cm while dynamic focusing was used on the receive. The RF signals were acquired at a sampling frequency of 30 MHz. Each RF frame had 256 beams, which were twice the number of elements.

The transducer was then moved by the positioner in the horizontal (or approximately, lateral) direction at a step of 0.015 mm. Forty steps were performed to reach a maximum lateral motion of 0.6 mm. Five seconds after the transducer was moved to each position, the RF signals were acquired at a sampling frequency of 30 MHz.

The axial and lateral displacements relative to the first RF frame were estimated [3]. A window size of 2.57 mm and a 90% overlap were used. A 2-D cosine interpolation was used to obtain 2-D subsample displacement [8]. In order to study the effects of the pitch on the lateral displacement estimation, the acquired RF signals were decimated by a factor of 4 or 2 (i.e., from 256 to 128, or 64, beams) in the lateral direction. When 256 or 128 beams were used, the pitch was kept the same, i.e., at 0.3 mm. When 64 beams were used, the pitch was increased from 0.3 to 0.6 mm. In order to compare the performance of different beamwidths, three 5×5 mm^2 ROI's were selected, one near the focal zone and the other two 6.5 mm away from the focal zone. The centers of the ROI's were at depths of 2.15, 2.8 and 3.45 cm, respectively. For ROI's I, II and III, the beamwidth was equal to 0.9, 1.3 and 1.7 mm, respectively, as measured using the backscattered signals from a 5-0 (1.0 metric) braided thread (Ethicon Inc., Somerville, NJ).

III. RESULTS

A. Simulation results

Figure 1 shows the effects of the lateral displacement magnitude on the lateral displacement estimation at a fixed pitch (0.625 mm) and beamwidth (2 mm). Figure 2 compares the estimator performance at different pitches at a fixed beamwidth (2 mm). Figure 3 depicts the beamwidth effects on lateral displacement estimation at a fixed pitch (0.625 mm). Figure 4 illustrates the performance of the lateral displacement estimation at the same beam overlap (defined as 1–pitch/beamwidth) of 68.75%.

As shown in Fig. 2, both the bias and jitter undergo a periodic variation with the period equal to the pitch. When the displacement is equal to half-integer pitch multiples (e.g., 0, 0.5, 1, 1.5 or 2 pitches), the bias is the lowest and nearly zero. The jitter reaches minimum at integer pitch multiples (e.g., 0, 1 or 2 pitches) and maximum at odd half-integer pitch multiples (e.g., 0.5, 1.5 or 2.5 pitches), respectively.
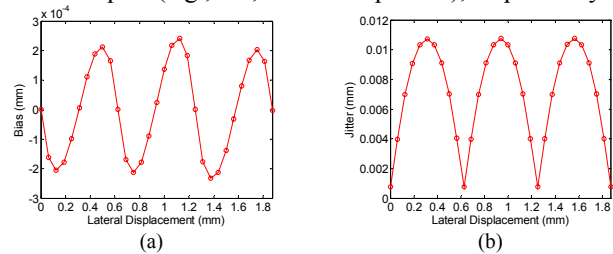

Figure 1. Effects of lateral displacement in the simulation study. (a) bias and (b) jitter as a function of the applied lateral displacement.

As shown in Fig. 2, the estimator performance improves as the pitch decreases, i.e., the jitter and bias drop. As evident in Fig. 3, both the bias and jitter decrease when the beamwidth increases.
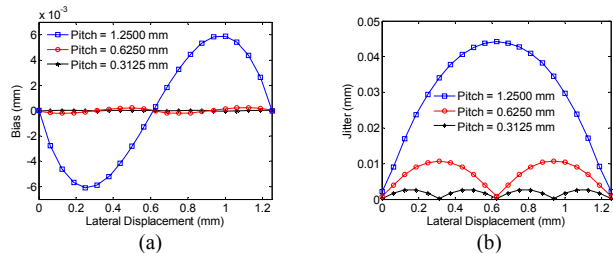

Figure 2. Effects of pitch in simulations. (a) bias and (b) jitter.

If the beam overlap is fixed, the bias and jitter increase with the pitch (Figs. 4(a) and (b)). At a fixed beam overlap, a larger pitch also denotes a larger beamwidth. These two parameter changes have opposite effects, as shown in Figs. 2 and 3. Results in Figs. 4(a) and (b) indicate that the effects of the pitch on the lateral displacement estimation are significantly larger than those of the beamwidth. On the other hand, when the bias and jitter are normalized by the pitch and plotted against the lateral displacement, also

normalized by the pitch, they become relatively independent of the pitch (or, the beamwidth) (Figs. 4(c) and (d)). Results in Figs. 4(a) and (b) can be explained by the fact that the lateral displacement estimation is first measured in sub-pitch multiples and then converted into millimeters by multiplying by the pitch.
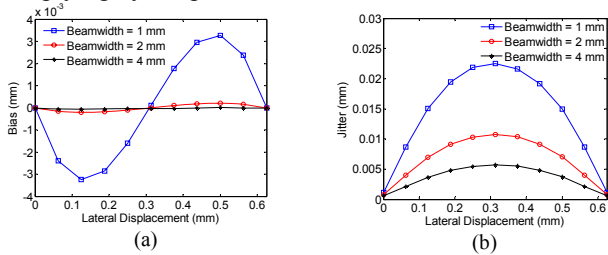

(a)   (b)

Figure 3. Effects of beamwidth in simulations. (a) bias and (b) jitter.

(a)   (b)
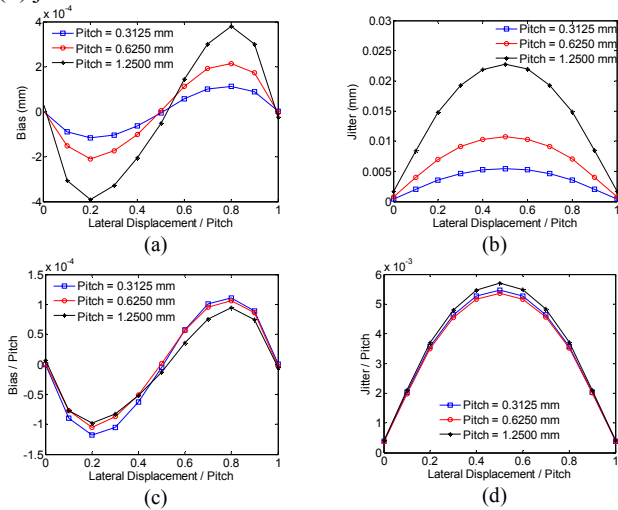
(c)   (d)

Figure 4. Effects of beam overlap in simulations. (a) bias, (b) jitter, (c) normalized bias and (d) jitter.

B. Phantom results

Using a total beam number of 64, the bias is minimum when the displacement is 0, 0.5 or 1 pitch multiples (i.e., 0, 0.3 or 0.6 mm) (Fig. 5(a)), i.e., when the interpolation or RF signals is not required or adjacent beams contribute to the interpolated, sub-beams equally. The bias for the 0.30-mm pitch (i.e., 256 or 128 beams) is very small (< 0.005 mm) and does not clearly exhibit a periodic variation with the lateral displacement. For both 0.30- and 0.60-mm pitches, the jitter is the lowest (or, the highest) when the displacement is equal to integer pitch multiples (or, at odd half-integer pitch multiples) (Fig. 5(b)). As is evident in Fig. 5, a pitch of 0.3 mm could result in significantly lower bias and jitter, demonstrating the importance of a smaller pitch in the lateral displacement estimation. The maximum jitter is approximately equal to 10 μm when a pitch of 0.3 mm is used.

Figure 5(b) also shows that, when 256 beams are used, the jitter is also slightly lower, except at lateral displacements around 0.15 or 0.45 mm. The bias remains

similar in both cases (Fig. 5(a)). The variation period is also identical in both cases because the pitch is the same (0.3 mm).

Figure 6 compares the performance of the estimation in ROI's I, II and III. The same periodic variation can be observed in the jitter of three ROI's. In addition, the jitter is the lowest in region III and highest in region I, except for displacements between 0.5 and 0.6 mm. These results can be explained by the largest beamwidth in region III (1.7 mm) and smallest beamwidth in region I (0.9 mm). Although similar across the three ROI's, the magnitude of bias appears slightly lower in region III than in regions I and II (Fig. 6(a)), because of the wider beamwidth, similar to the simulation results (Fig. 3). These experimental results obtained in different regions and beamwidths are thus in good agreement with the simulation results.
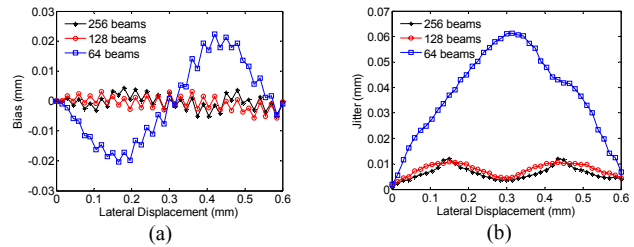

(a)   (b)

Figure 5. Effects of lateral displacements and pitch in experiments. (a) bias and (b) jitter.`

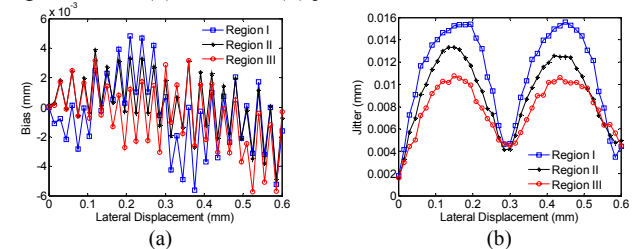(a)   (b)

Figure 6. Effects of beamwidth in experiments. (a) bias and (b) jitter.

Simulations results show that the pitch effects on the lateral estimation performance are larger than the beamwidth effects. The phantom experimental findings are consistent with the simulation results. Greater effects of the pitch are shown in Figs. 5 and 6. The jitter increases by a six-fold when the pitch increases from 0.3 to 0.6 mm, but less than twice when the beamwidth decreases from 1.7 to 0.9 mm.

IV. DISCUSSION

The results of the simulation and phantom experiments clearly demonstrate a periodic variation in the performance of the lateral displacement estimation (i.e., bias and jitter) at different lateral displacements, with the period equal to the pitch.

As shown in Figs. 2 and 3, in order to reduce the bias and jitter of the lateral displacement estimation, a smaller pitch and a larger beamwidth are preferred. At smaller pitch,

the beam density is higher, with reliable data instead of the post-interpolated, reconstructed beams. However, small pitch may complicate the design of the transducer. At larger beamwidth, the adjacent beams share more ultrasound scatterers and the RF signals of these beams are more statistically dependent. Therefore, it may be more accurate to interpolate the RF signals between adjacent beams. As a result, increasing the beamwidth reduces the jitter and bias. However, the trade-off is the reduced lateral resolution and will thus be dictated by the specific application.

When a phased-array transducer is used, the beam spacing increases with depth and is not equal to the pitch [9]. A phased array simulation was also performed, using the Field II program and methods described in [9]. A lateral rigid motion from 0 to 1 beam spacing was simulated in the phased array. As shown in Fig. 7(a), the jitter (normalized by the beam spacing) increased as the lateral displacement increased from 0 to 0.5 beam spacing, and decreased as the lateral displacement increased from 0.5 to 1 beam spacing. In addition, the jitter significantly decreased when the beam density increased from 64 to 128 beams / 90°. After multiplied by the beam spacing, the jitter at a lower beam density would be further amplified. These were in agreement with previous results obtained using a linear array. In Fig. 7(b), the normalized jitters at different depth were in the same order of 0.05 beam spacing when the lateral displacement is equal to 0.5 beam spacing (at a beam density of 128 beams / 90°). The jitter of normalized displacements was similar at different depths (Fig. 7(c)).
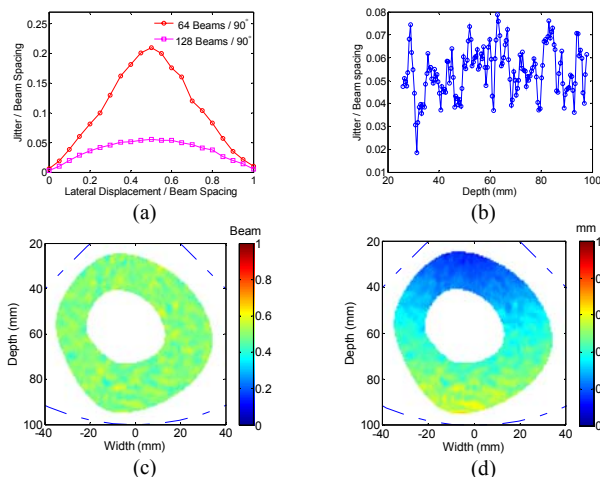

Figure 7. The jitter as function as (a) lateral displacement and (b) depth in a phased-array simulation, and lateral displacement images (c) before and (d) after normalization.

After the jitter is converted into millimeters by multiplying by the beam spacing, a shallow depth obtains lower jitter than a deeper region in a phased array configuration (Fig. 7(d)), because the beam spacing is smaller. In addition, both the beamwidths and displacements vary spatially. The combined effects of all these factors on the lateral displacement estimation in elastography using a phased array will be explored in future studies.

V. CONCLUSION

Simulation and phantom experiments were performed to investigate the effects of various parameters on reliable lateral displacement estimation in ultrasound elastography. A lateral rigid motion configuration was applied in order to eliminate the effects of axial displacement / strain and lateral strain on lateral displacement estimation. The estimator performance, as indicated by the bias and jitter, showed a periodic variation with the lateral displacement, with a period equal to the pitch. Due to the periodic variation, a larger lateral displacement might be preferred to improve the SNR of the estimation. The performance was found to improve with smaller pitched and/or larger beamwidths. A smaller pitch was preferred at the same beam overlap, because the effects of the pitch on lateral displacement estimation quality were larger than those of the beamwidth. In summary, smaller pitches and wider beamwidths are required in order to reduce the jitter error of the lateral displacement estimation. At a pitch of 0.3 mm and a beamwidth of 1.7 mm and using linear interpolation, the maximum jitter was about 10 microns in experiments. Preliminary results in a phased-array configuration were in agreement with the linear-array results. Our recent study also showed that the use of cubic spline, instead of linear, interpolation decreases the jitter (e.g., to 5 microns), with the trade-off of slightly increased bias [10].

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