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ORIGINAL RESEARCH

Ultrasonic agar phantom experiment for comparison of the measurement accuracy of tissue elasticity obtained by displacement vector measurement using lateral modulation with multidimensional autocorrelation and Doppler methods and corresponding one-dimensional methods

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Abstract: Comparison of the measurement accuracy of elasticity was performed through agar phantom experiments, ie, two-dimensional (2D) strain tensor components and 2D shear modulus reconstruction obtained by previously developed multidimensional displacement vector measurement methods on the basis of autocorrelation and Doppler methods (2D AM and 2D DM) and the corresponding 1D methods. The multidimensional methods yield more accurate and stable results than the corresponding 1D methods. As is shown, however, such 1D methods can also be used when the echo signal-to-noise ratio is high, eg, obtainable by previously developed lateral modulation with parabolic apodizations.

Keywords: ultrasound, lateral modulation, displacement vector measurement, accuracy, multidimensional methods, one-dimensional methods, tissue elasticity, strain tensor, shear modulus, agar phantom experiment

Introduction

We have been maximizing beamforming[1–5] by using beam steering and apodization for accurately measuring tissue (eg, breast, liver, and heart) or blood displacement vectors or strain tensors using the multidimensional cross-spectrum phase gradient method (MCSPGM)[6,7] or multidimensional autocorrelation or Doppler methods (MAM and MDM).[1,8,9] For instance, we have reported[1–3,9] several lateral modulation (LM) methods in addition to other beamforming methods, ie, the multidirectional synthetic aperture method (MDSAM) and multiple transmitting method (MTM). Our developed LM is achieved by the coherent superimposition of crossed, steered beams (LM).[1–3,9] The LM has a higher potential for realizing a more accurate measurement of a displacement vector in real-time than the synthesis of the displacement vector using the accurately measured axial displacements obtained by MDSAM or MTM.[9] The instantaneous frequencies of respective directions are determined mainly by the steering angles. The measurement accuracy of displacement components increases with higher instantaneous frequencies.[9] Such an LM can also be obtained by Fraun-

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hofer approximation,[10–12] and Hilbert transform is achieved in an analog manner[11,12] but with more beam generation and signal processing than are achieved only with digital processing in our method.[1–3,9] Our developed LM can also be used for B-mode imaging simultaneously.[1,2] If necessary, plural transducers are also used.[1–3,9] We also reported another beamforming technique that requires less beam generation and signal processing, ie, ASTA,[3–5] which involves the steering of beams through a steering angle. However, ASTA yields less accurate displacement vector measurements than LM, although the applications of displacement measurement increase.

In this study, for LM, an agar phantom experiment was performed to compare the measurement accuracy of elasticity obtained using such multidimensional displacement vector measurement methods with that obtained with the corresponding one-dimensional (1D) displacement measurement methods. That is, similarly to the studies by Sumi and Tanuma[1] and Sumi et al,[2] the correspondingly obtained strain tensor components and 2D shear modulus reconstructions (2D stress assumption) are evaluated. Although measurement accuracy is significantly lower, some conventional 1D displacement measurement methods can also be used (eg, references 13 and 14) instead of the multidimensional displacement vector measurement methods, ie, those originally used only for an axial displacement measurement along the beam direction. Here, 2D autocorrelation and Doppler methods (2D AM and 2D DM)[1,2,8,9] and 1D AM and 1D DM[13,14] were used. In the 1D methods, however, the 2D moving average was used[15] to calculate the instantaneous axial frequency and phase change in the slow-time axis instead of the 1D moving average in the original 1D AM.[16]

The use of 1D methods is enabled for LM using our developed demodulation method.[3] The respective measurements of displacement components are achieved by realizing point spread functions that oscillate only in the respective directions through the demodulation. Although our developed demodulation method with digital signal processing only[3] yields more accurate measurements than other analog demodulation methods,[17,18] all the measurements suffer from the decorrelation of echo signals due to displacement orthogonal to the oscillation direction, even if multidimensional phase matching (spatial shifting using spatial intervals of echo data) is performed (non-LM case[6,7,13,14] [phantom experiments]; LM case[9] [simulations]). For such phase matching, multidimensional cross-correlation (MCCM) or MCSPGM with digitization of measured displacements can be used as a coarse estimator[6,7,9] (also recall that MCSPGM requires fewer calculations than MCCM). After the coarse estimation, the local window can

Table 1 For echo data obtained on agar phantom using listed methods, means and standard deviations (SDs) were evaluated for two-dimensional (2D) strain tensor measurement and 2D relative shear modulus reconstruction in a central square region with 5.5 mm-long sides in stiff inclusion (relative modulus 3.29)

Lateral modulation frequency (MHz)	Focus	Method (figures in Figure 1)	Strains (10–1%)			Relative shear modulus
			Lateral	Axial	Shear	
Designed 3.75 Obtained 2.97	Tr/Re	2D auto (1A)	–1.96 (2.77)	0.10 (0.97)	0.67 (2.21)	3.28 (0.35)
		1D auto (1B)	–1.85 (3.08)	0.06 (1.06)	0.73 (2.34)	3.37 (0.38)
		2D Doppler (1C)	–1.85 (3.50)	0.07 (1.09)	0.89 (3.36)	3.23 (0.35)
		1D Doppler (1D)	–2.06 (7.64)	0.20 (3.38)	–0.51 (6.20)	2.94 (0.29)
		2D CSPGM	–1.76 (3.50)	0.09 (1.47)	1.02 (3.93)	3.26 (0.36)
Designed 0.00 Obtained 1.00	Tr/Re	2D auto (1E)	–1.23 (17.57)	0.15 (1.83)	–0.95 (15.10)	3.38 (0.32)
		1D auto (1F)	–2.15 (17.89)	0.20 (2.40)	–0.16 (15.76)	3.59 (0.42)
		2D Doppler (1G)	–1.39 (9.38)	0.03 (2.29)	1.01 (8.03)	3.42 (0.40)
		1D Doppler (1H)	–2.19 (17.34)	0.16 (2.33)	0.23 (13.61)	3.19 (0.32)
		2D CSPGM	–2.87 (18.69)	0.09 (1.83)	0.60 (9.32)	2.60 (0.35)
Designed 1.88 Obtained 1.62	Re	2D auto	–17.83 (13.44)	0.07 (1.70)	3.70 (6.95)	5.25 (2.27)
		1D auto	–17.63 (13.76)	0.06 (1.98)	3.90 (7.95)	4.98 (2.20)
		2D Doppler (1I)	–18.17 (12.75)	0.07 (1.70)	3.84 (8.22)	3.81 (1.17)
		1D Doppler	–17.23 (15.98)	0.08 (4.31)	3.20 (10.82)	3.67 (0.92)
Designed 0.00 Obtained 0.67	Re	2D auto	–13.55 (43.08)	0.22 (3.42)	2.42 (44.23)	2.30 (0.46)
		1D auto	–10.12 (58.77)	0.16 (3.98)	3.43 (53.42)	2.13 (0.30)
		2D Doppler (1J)	–12.86 (41.38)	0.28 (3.63)	3.03 (31.02)	1.89 (0.34)
		1D Doppler	–9.78 (64.95)	–0.04 (7.57)	1.61 (53.20)	1.72 (0.28)

Abbreviations: auto, autocorrelation method; CSPGM, cross-spectrum phase gradient method; Re, reception; Tr, transmission.

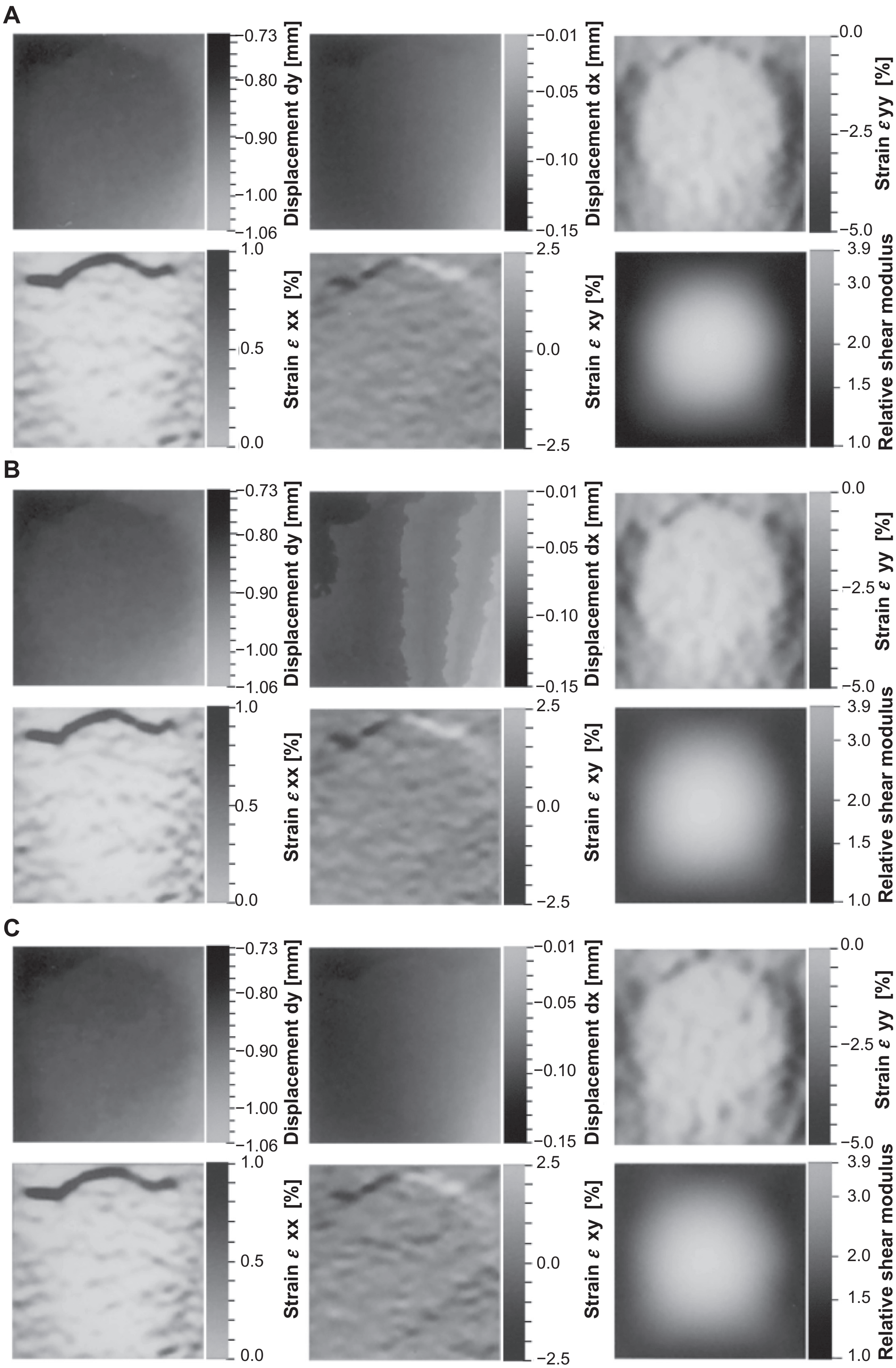

Figure 1 (*Continued*)

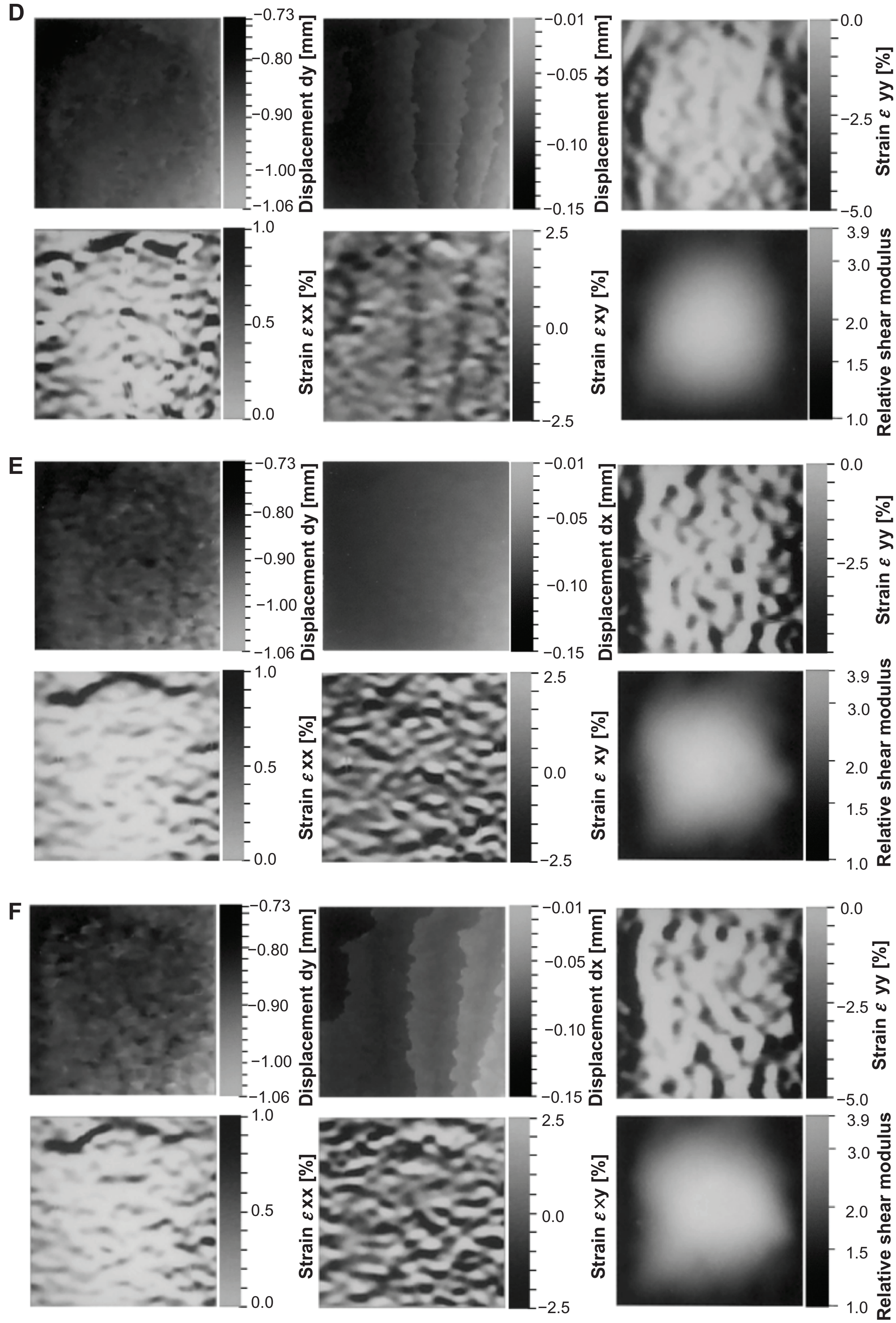

Figure 1 (*Continued*)

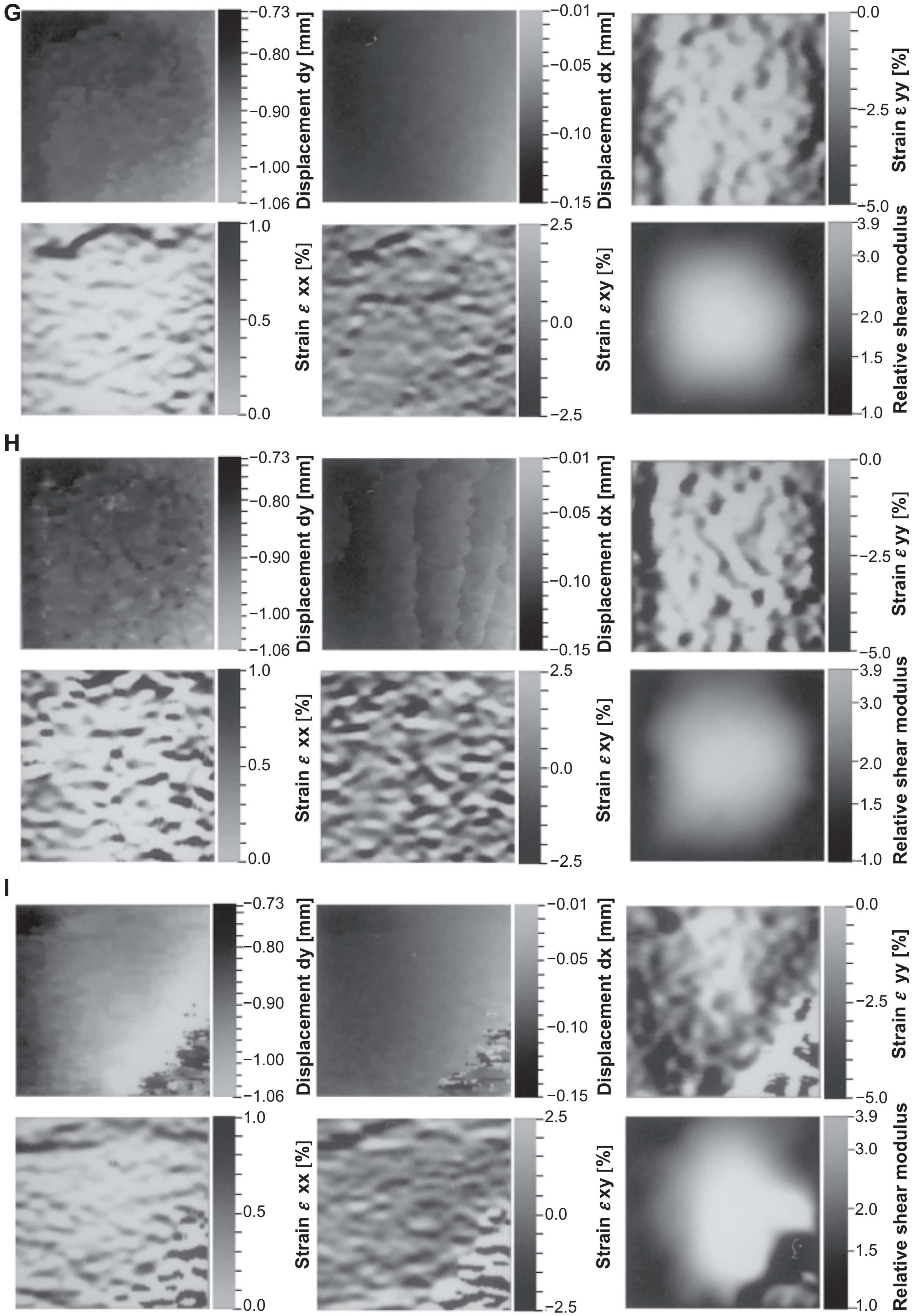

Figure 1 (*Continued*)

J

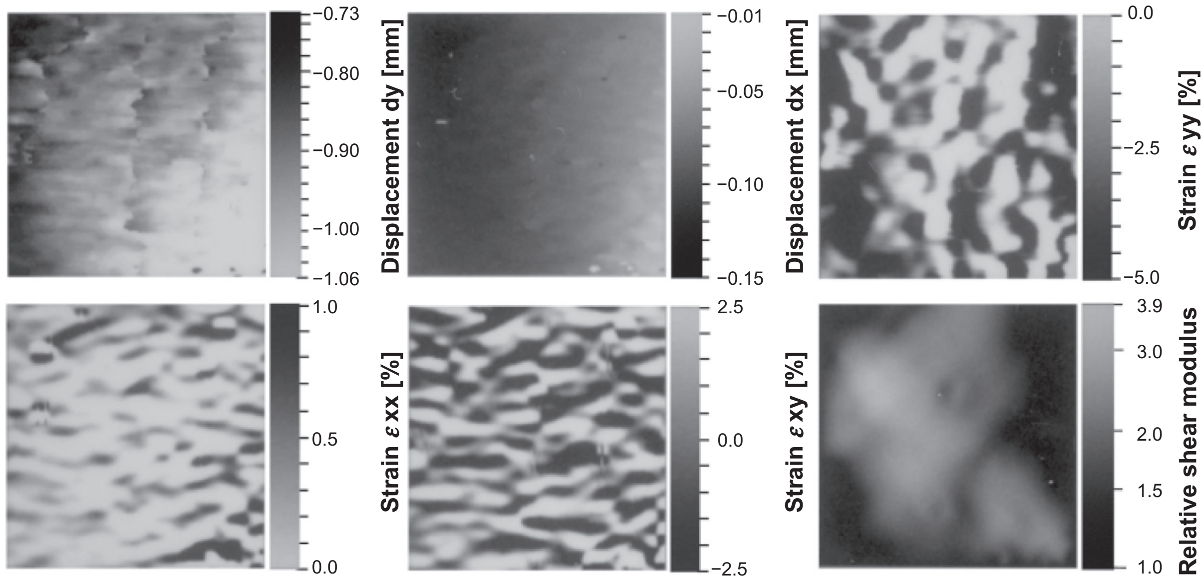

Figure 1 Grayscale images of measured lateral and axial displacements dy and dx; lateral, axial, and shear strains ε_{yy}, ε_{xx}, and ε_{xy}; and reconstructed relative shear modulus in the central plane (see Table 1).

be made small.[7,9] Thus, the higher accuracy in measuring target motions can be achieved by the combined use of LM and our developed displacement vector measurement methods that enable simultaneous axial and lateral displacement measurements.[6,7,9]

Agar phantom experiment

The 2D experiments were performed using the same agar phantom as that used by Sumi and Tanuma[1] and Sumi et al.[2] The target agar phantom (40 [axial, x] × 96 [lateral, y] × 40 [elevational] mm^3) had a central circular cylindrical inclusion (diameter 10 mm; depth 19 mm) with a shear modulus that was different from that of the surrounding region, and shear moduli of 2.63 and 0.80 × 10^6 N/m^2 in the inclusion and surrounding regions, respectively (ie, relative shear modulus 3.29). Manually, the phantom was compressed by 2 mm in the lateral direction. The contact surfaces of the linear array-type transducer (7.5 MHz, 0.2 mm US element pitch) and phantom were separated by less than 0.3 mm by immersing them in water in a tank. A rectangular region of interest 13.7 (axial, x) × 13.2 (lateral, y) mm^2 was centered on the inclusion (depths from 12.2 mm to 25.9 mm). For both 2D and 1D methods, local windows used were 0.51 (axial, x) × 0.50 (lateral, y) mm^2.

For the apodizations, the same parabolic functions were used as those described in Sumi and Tanuma[1] and Sumi et al[2] (equation with σ_y 0.4 mm). As has already been shown,[1] the use of parabolic functions yields a larger bandwidth and a higher signal-to-noise ratio (SNR) than those of Gaussian functions. For both transmission (Tr) and reception (Re) focusing, spherical focus[1,2,9] was achieved with MDSAM. For LM, the lateral modulation frequencies designed and achieved were, respectively, 3.75 MHz and 2.97 MHz (center frequency estimated using power spectra as weights). For comparison, nonmodulation realized by nonsteering of one beam[8,14,19] was also performed with the same apodizations (lateral modulation obtained was 1.00 MHz). For LM and non-LM, a plane wave with a rectangular apodization was also used for Tr. Although such beamforming achieves rapid processing even with a 2D array transducer,[1,2,9] less accurate measurements are obtained due to lower lateral frequency and/or smaller bandwidth generations. For LM about half lateral frequency was achieved[1,2,9] (1.62 MHz), whereas for non-LM a lateral frequency of 0.67 MHz was obtained.

Table 1 summarizes the means and standard deviations (SDs) evaluated in a central square region with 5.5 mm-long sides in the inclusion for axial, lateral, and shear strain measurements and 2D relative shear modulus reconstruction. For comparison, the results obtained by a 2D cross-spectrum phase gradient method (2D CSPGM) are also shown for both Tr and Re focusing. Except for the Re focusing and the use of 2D CSPGM, all grayscale images obtained are shown in Figure 1. For Re focusing, only images obtained using 2D Doppler are shown. Regarding the strain tensor measurement, for all the beamformings, 2D methods yield more accurate and stable results than the corresponding 1D methods, ie, accurate means and small SDs. When LM was performed, 2D and 1D AMs were more accurate than the corresponding dimensional DMs, whereas when LM was not performed, the opposite was the case (eg, Figures 1A compared with 1C and 1E compared with 1G). MAM and MDM, respectively, yielded accurate and stable results when the echo SNR was high (≈20 dB) and low.[9] For both LM and non-LM, solo Re focusing yields less accurate results than both Tr and Re focusing due to the generation of a lower lateral frequency. Moreover, images of the inclusion obtained are significantly distorted (see Figures 1I and 1J). Regarding the shear modulus reconstruction, the more accurate stain tensor measurements yielded the more accurate results, eg, for 2D AM with 3.75 MHz modulation, mean was 3.28 and SD was 0.35.

Discussion

Comparison of measurement accuracy of elasticity was performed through agar phantom experiments. The multidimensional displacement vector measurement methods yielded the more accurate and stable results than the corresponding 1D methods. However, such 1D methods can also be used when the echo SNR is high, although large numbers of calculations are required in comparision with the corresponding multidimensional methods. The use of 1D methods also requires geometrically symmetric beamforming to obtain the same axial, lateral, and elevational frequencies with a different sign, respectively, although the multidimensional methods do not require such a condition. If symmetric beams cannot be obtained, eg, due to the existence of obstacles such as a bone, the rotation of coordinate system is effective.[3–5] The rotation is also effective for controlling the instantaneous frequencies for the multidimensional methods.[3–5] To achieve a high measurement accuracy by the synthesis of the displacement vector using the accurately measured axial displacements obtained by MDSAM or MTM, a spatial resolution in beam angles generated is also required, ie, obtainable by using the arctangent of the ratio of the instantaneous frequencies or the first moments of a local spectra,[3] which makes it impossible to accomplish the measurement in real-time.[20] The frequency division method with MAM or MDM[3,8,9] as well as the multidimensional moving average with 1D AM[15] or 1D DM[8,9] can be used.[20] However, the division of the instantaneous phase change by the synthesized frequency in the estimated beam direction without the coordinate rotation makes the synthesis of the displacement vector the same as MAM or MDM with LM.[20] The method can also be used for ASTA to measure a lateral displacement.[20] Disregarding low frequency spectra is also effective for increasing a displacement measurement accuracy, particularly when nonsteering or lateral sine-modulation is performed with rectangular apodizations.[21] Reversibility of lateral cosine and sine modulations in a frequency domain is also effective for achieving the LM displacement vector measurements and new LM echo imaging simultaneously.[21] Superimposition of incoherent echo signals obtained through the spectra frequency division is also effective for speckle reduction.[21] Such measurements will also be reported elsewhere.

Disclosure

The authors report no conflicts of interest in this work.

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