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Original Contribution

REDUCTION OF STRESS NONUNIFORMITIES BY APODIZATION OF COMPRESSOR DISPLACEMENT IN ELASTOGRAPHY

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Abstract—Elastography is a method for imaging the elastic properties of compliant tissues that produces gray-scale strain or elasticity images called elastograms. The method is based on external tissue compression, with ultrasonic detection of local target displacements and subsequent computation of strain profiles along the compression axis. The internal strain variations are a result of the tissue elasticity variations and the applied deformation or compression. A number of mechanical artifacts that appear in elastograms have been identified. One such artifact appears as the result of a nonuniform stress distribution under the compressors used, including darkening (low stress) of the central region and brightening (high stress) of the peripheral regions under the compressor. On an elastogram, these areas may be misinterpreted as being respectively harder and softer than the rest of the target. In this article, a displacement apodization method for the minimization of this artifact is discussed, and its effects are studied using finite element simulations. When the isometric compression of standard elastography was replaced by an apodized displacement profile calculated from reciprocity conditions, a significant improvement in stress uniformity under the compressor was achieved.

Key Words: **Apodization, Artifact, Elasticity, Elastogram, Elastography, Imaging, Reciprocity, Strain, Stress, Ultrasound.**

INTRODUCTION

Elastography is a technique capable of producing images of internal strain or, alternatively, Young's modulus of soft tissues (Ophir et al. 1991). It involves the steps of obtaining an ultrasonic scan of the target, subjecting it to a small mechanical compression and obtaining a second scan of the same region. The RF A-lines from the two scans are then analyzed using cross-correlation techniques for time delay (related to the mechanical displacement) estimations between congruent data segments. The displacement estimations are then converted to axial strain information using a gradient operation. If the applied axial stresses are known or assumed constant in the target, these strain values can be directly converted to elastic modulus values, and the gray levels on the resulting image will ulitmately correspond to tissue elasticity. This image is called an elastogram.

Any kind of nonuniformity (due to internal or external causes) in the target may result in an increase of the dynamic range of strain and, therefore, of the decorrelation noise in the high strain areas. Elastography is always performed by uniformly displacing the target surface through a small distance, which results in a nonuniform stress under the compressor (Fig. 1). This stress nonuniformity is significant near the compressor and is progressively smaller in deeper regions in the target. However, the uniformity of appearance of the elastogram greatly depends on the uniformity of the stress distribution throughout the homogeneous target. Therefore, the nonuniformities of stress caused by the compressors in elastography should be reduced before the elastic moduli at each point in the target are estimated.

In this article, this correction is accomplished by apodization; the compression profile (or the compres-

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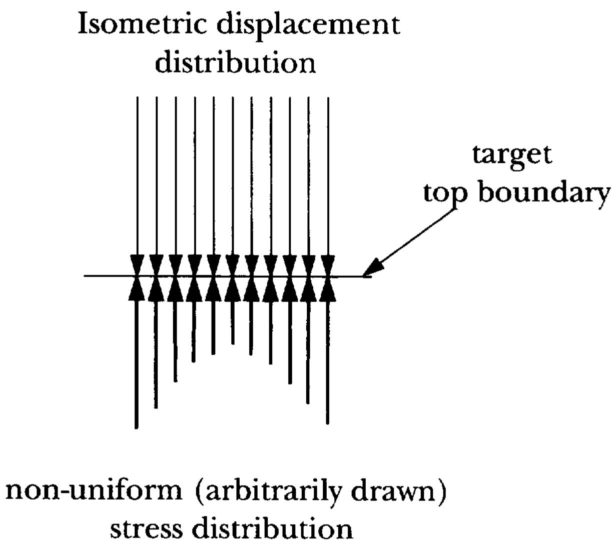

Fig. 1. Isometric compression. Uniform displacement resulting in nonuniform stress distributions.

sor displacement distribution) is weighted in such a way as to produce uniform stress distribution along the compressor and at different depths in the target. However, the stress distribution in the target will also decay with depth, and this effect will not be corrected. The apodization concept has been used in the biomechanics field to avoid high shear stress generation (Candadai et al. 1992).

The present apodization method is based on the hypothesis of reciprocity: if the target displacement distribution that results from the application of uniform pressure on a target is imparted to the displacement of the compressor (or the displacement profile of the compression), the resulting stress distribution in the target will be uniform (Fig. 2). The experimental implementation of this modified applied displacement profile will probably include a spherically shaped compressor. This effect would result in a reduction of the artifactual darkening and brightening of elastograms near and under the compressor, which are due to local stress concentrations and dilutions.

THEORY

The displacement profile that results from a uniformly distributed vertical pressure on part of the boundary of a semi-infinite elastic solid has been analytically described by Johnson (1985), for regions inside and outside the loaded area. The equation was developed for a plane–strain model. The area examined in the medical applications is always under the combined transducer-compressor (ranging from −b to b, Fig. 3), and the resulting displacement in that region is:

$$u(a) = \frac{-Q(1-v)^2}{\pi E}\left[(b+a)\ln\left(\frac{b+a}{b}\right)^2 + (b-a)\ln\left(\frac{b-a}{b}\right)^2\right] + C, \quad (1)$$

where Q = uniformly distributed applied vertical pressure, $2b$ = size of the compressor, v = Poisson's ratio, E = Young's modulus, a = distance along and directly under the compressor (ranging from 0–2b) and C = constant of integration. The leading negative sign denotes downward displacement.

Multiplying and dividing eqn (1) by b, we get:

$$u(a) = -\frac{2bQ(1-v)^2}{\pi E}\left[\left(1+\frac{a}{b}\right)\ln\left(1+\frac{a}{b}\right)^2 + \left(1-\frac{a}{b}\right)\ln\left(1-\frac{a}{b}\right)^2\right] + C \quad (2)$$

and expressing the distance variable a in terms of the compressor half-width b, the displacement can be

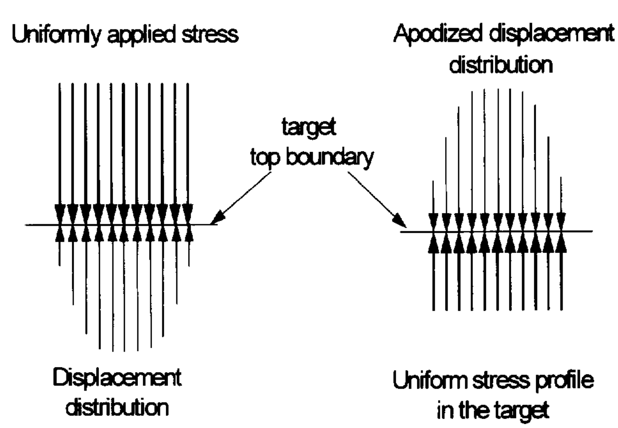

Fig. 2. Apodization of the isometric displacement distribution via reciprocity. Using as the compression profile the displacement distribution resulting from applied uniform pressure should cause a more uniform stress profile under the compressor.

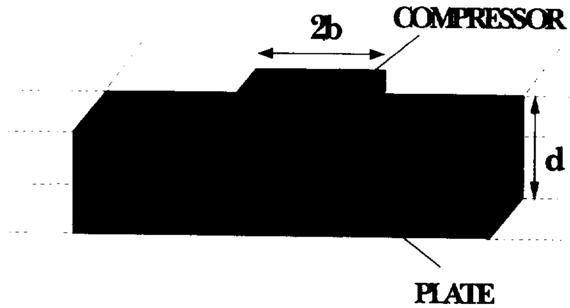

Fig. 3. Geometrical representation of the target and compressor parameters used in the theoretical model.

written as a function of the ratio $x = \frac{a}{b}$ (varying from -1 to 1):

$$u(x) = -\frac{2bQ(1-v)^2}{\pi E}[(1+x)\ln(1+x)^2 + (1-x)\ln(1-x)^2] + C \quad (3)$$

Evidently, the basic functional shape of the apodization function $u(x)$ depends only on the geometrical parameters a and b. Since the load Q and the compressor size have fixed values for every point under the compressor, the product $2bQ$ in eqn (3) is constant. Moreover, since the target was assumed to be isotropic and homogeneous with a Young's modulus equal to 21 kPa (representing normal tissue), the product $2bQ$ was attributed a value equal to 20 kPa (normalized spatial pressure). This is because the mechanical properties of the model will also define the applied (apodized) displacement profile. The target was also assumed incomressible, *i.e.*, with a Poisson's ratio equal to 0.495.

It is essential to normalize the isometric and apodized displacement profiles to guarantee accurate comparison. The isometric displacement was fixed at -1, the negative sign denoting downward movement. For comparison reasons, the constant C in eqn (3) was also fixed at -1. The final form of the apodized displacement profile then becomes:

$$u(x) \cong 0.23[(1+x)\ln(1+x)^2 + (1-x)\ln(1-x)^2] - 1 \quad (4)$$

This function is plotted in Fig. 4. As described in the next section, this function is used to apodize the applied displacement, and the results as well as the standard isometric compression results are observed and compared on targets simulated by finite element models.

FINITE ELEMENT SIMULATION

Finite element analysis (FEA) allows total control over the mechanical properties, composition and boundary conditions, which were extremely important in this study. Homogeneous and isotropic targets were simulated using a commercially available FEA software (Pal2, MacNeal-Schwendler Corporation, Los Angeles, CA, USA). For all the targets generated, the nodes were restricted to movement solely in the axial and lateral directions. The boundary conditions were set only at the base of the target and restricted the motion of these nodes in all directions while the sides were left free. These boundary conditions were used to simulate a clinical situation where a breast is placed on a large flat mammography table while being examined by a small rectangular linear array transducer (Ponnekanti et al. 1995). It should be noted that the compressor is attached to the transducer and during the compression they are displaced together.

In elastography, all dimensions may be calibrated with respect to the compressor lateral size. Therefore, the distances were calibrated in terms of an arbitrary constant called a ''unit'' so that all dimensions were scalable in terms of the compressor lateral size. The compressor had a lateral dimension of 80 units. An area of 80 × 240 units representing the region directly under the compressor was chosen as the region of interest. The nodal density was twice as high in this area compared to the rest of the target, and five times higher near the edges of the compressor. These values were chosen according to the degree of stress variations expected in those regions.

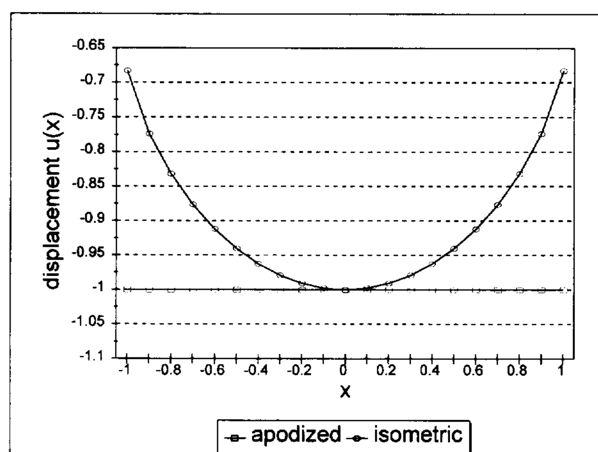

Fig. 4. Plots of isometric (squares, uniform value = -1) and (normalized) apodized displacement (circles) vs. $x = \frac{a}{b}$.

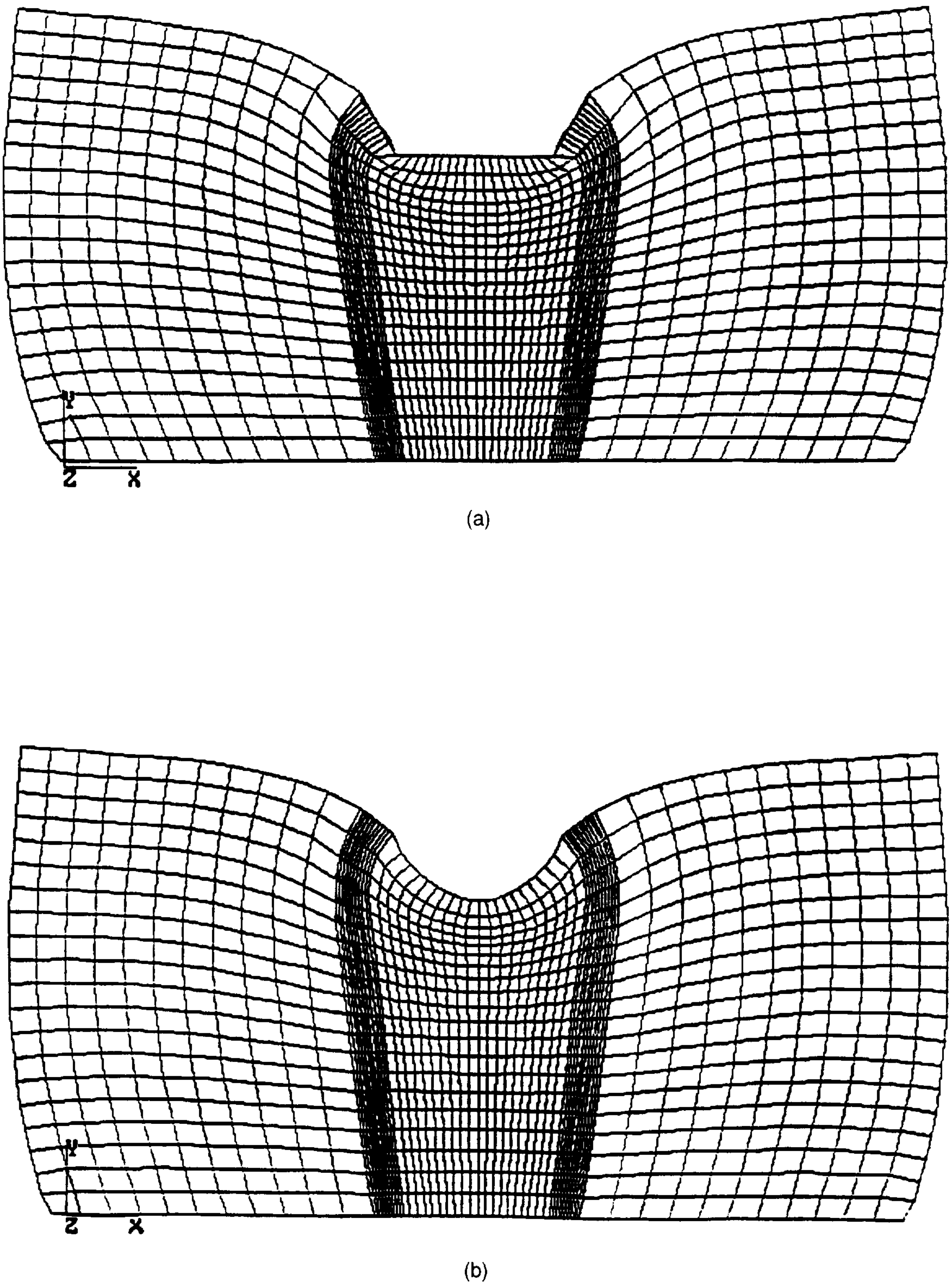

Fig. 5. Finite element meshes showing an (a) isometric and (b) apodized displacement distribution.

As specified earlier, the target is isotropic with a Young's modulus of 21 kPa, which was arbitrarily chosen to represent normal tissue, and a Poisson's ratio of 0.495 (virtually incompressible). The nonapodized compression was represented by an isometric displacement equal to -1 unit (or $\frac{1}{240} = 0.4\%$ compressive strain), and the apodized displacement distribution is normalized by taking the absolute maximum displacement value equal to 1 unit.

The mesh, into which the target is arbitrarily subdivided, is shown in Fig. 5a and b after isometric (nonapodized) and isobaric (apodized) displacement, respectively (exaggerated display). These FEA models were used for two different purposes. First, the results of the apodized displacement are obtained for five different lateral dimensions of the target while its depth as well as the compressor size were kept constant. This is because the theoretical description (Johnson 1985) is strictly valid for semi-infinite targets. The lateral dimension of the target was taken to be equal to 1, 2, 3, 4, 5, 6 and 7 times the compressor lateral size ($2b$), and the depth of the target was kept equal to three times the lateral dimension (or length) of the compressor, to study the departure from the theory due to finite lateral target dimensions. The stress distribution of the apodized compression, which satisfies the theoretical conditions, was then compared to the stress distribution resulting from the isometric compression. The latter was represented by a small constant deformation of -1 unit (0.4% compressive strain).

In both studies, the comparison among the results of different finite element models is made using the parameter SNR, defined here as the lateral gray level signal-to-noise ratio. This value represented the degree of stress uniformity in the area under the compressor.

After compression, the finite element program computes the resulting nodal displacements in the target. This displacement information is used to compute the local axial strains that are taken as the vertical gradient of the displacement, or as the ratios of the finite differences in the displacements of two consecutive nodes along the direction of the applied load to the original distance between the nodes (Ophir et al. 1991). Thus, a two-dimensional matrix of axial strain values is obtained in the plane of interest. It is important to note that, since the target is assumed to have a uniform Young's modulus, strain distribution is indicative of the distribution of stress.

The strain matrix is then converted into a grayscale image. An image processing program (Image Pro Plus, Media Cybernetics, Silver Spring, MD, USA) is used to display and analyze the images. All images were displayed using gray level equalization to allow for a valid comparison among images. Once the images were displayed, the gray level uniformity was measured along the lateral direction under the compressor, at different depths in the target model.

RESULTS

The first step involved building different finite element target models to assess the minimum lateral target size/compressor size ratio needed for the theoretical semi-infinite condition to be well approximated. The SNR was used as the parameter to represent the gray level (and stress) uniformity and, thus, the adequacy of the model.

Approximation to infinite case

A typical lateral SNR variation is plotted in Fig. 6 for a depth $d = \frac{2b}{3}$ ($2b$ = size of the compressor). From Fig. 6, it becomes obvious that the increase of the lateral dimension of the target to more than five times the compressor size does not have an important effect on the SNR of the image and, hence, on the stress distribution under the compressor. Therefore, the target used for the comparison with the isometric displacement results has a lateral dimension $>$ 4 times the compressor size.

Comparison of stress images resulting from nonapodized and apodized displacement

The elastograms of the homogeneous target obtained by using the isometric (nonapodized) and isobaric (apodized) load conditions are shown in Fig. 7. The isometric load case gives an elastogram with a clearly nonuniform gray level distribution near the

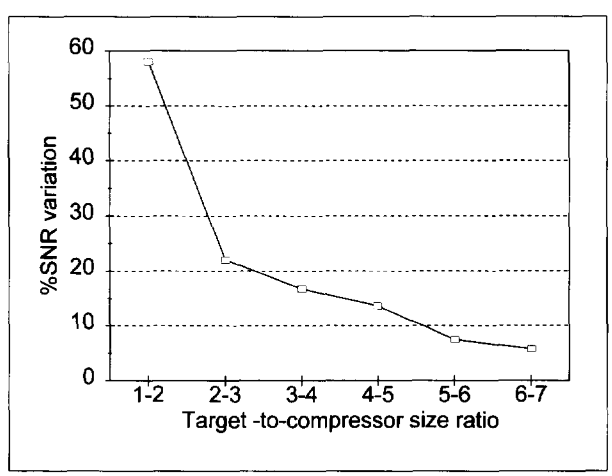

Fig. 6. Typical %SNR variation vs. change in size of the target relative to the compressor (taken here at a depth $2b/3$ from the face of the compressor).

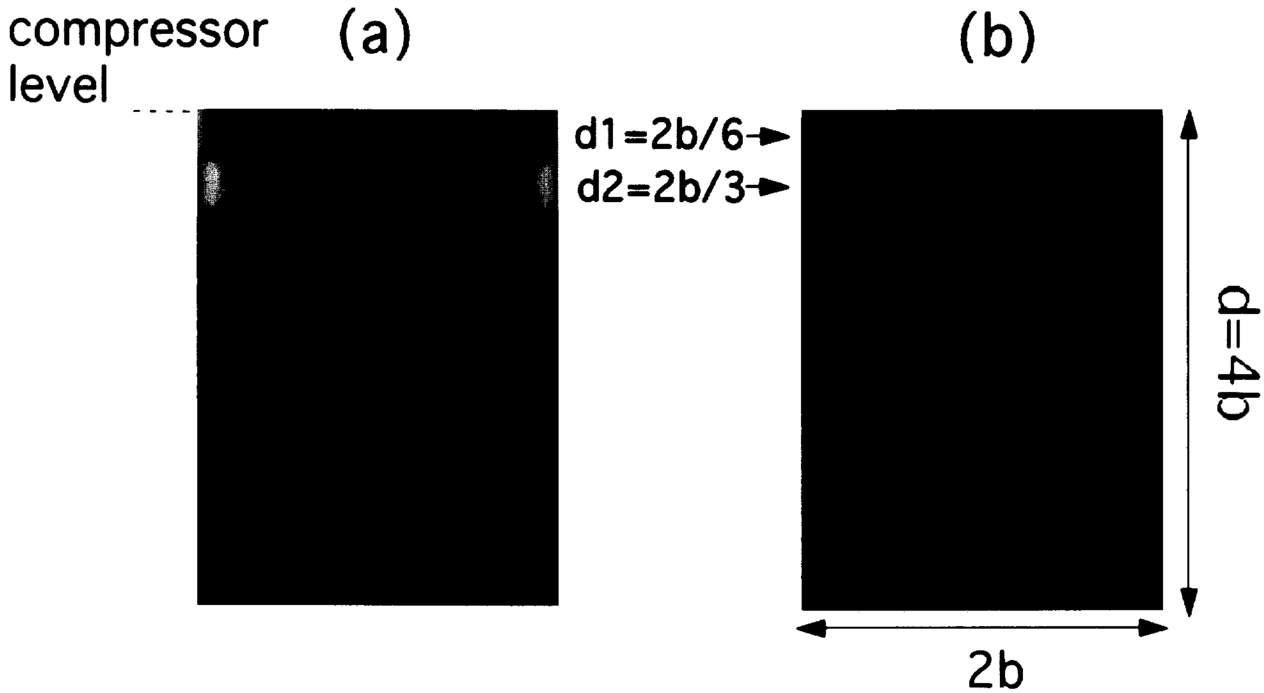

Fig. 7. Gray level (or relative stress) images up to a depth 1.5 times the lateral compressor size (*3b*) for (a) isometric and (b) apodized compression. Note the resulting decrease of the gray level excursion due to the apodization (white denotes high stress and black denotes low stress).

compressor, including a dark central area and two bright spots at the edges of the compressor (Fig. 7b). In the apodized load case, these nonuniformities are significantly reduced, resulting in a more accurate image of the homogeneous modulus properties of the target (Fig. 7a).

Two specific results to be compared were taken at two different depths in the target, both proximal to the face of the compressor. This is because in breast imaging, the region of interest is generally found in the proximity of the compressor, usually up to a depth equal to the size of the latter (Cespedes et al. 1993). Figures 8 and 9 show the gray level vs. normalized distance along the compressor for both the isometric and the apodized displacement distribution at depths equal to $d = \frac{2b}{6}$ and $\frac{2b}{3}$ from the face of the compressor.

At a distance of $\frac{2b}{6}$ from the compressor, an isometric compression results in large variations in gray level as shown in Fig. 8. The gray level uniformity, as measured by the SNR, is 3.4 times greater for the apodized displacement as compared to the isometric case. At a distance of $\frac{2b}{3}$ from the compressor, the case of isometric compression is shown in Fig. 9. The apodized displacement exhibits 3.6 times more uniform gray level than that associated with the isometric compression. As expected, the improvement in gray level uniformity diminishes as the distance from the compressor increases. These figures clearly illustrate that the artifact due to the stress nonuniformity near the face of the compressor is significantly reduced.

Looking at the rest of the target, it is seen that the apodization results in a global improvement (Fig.

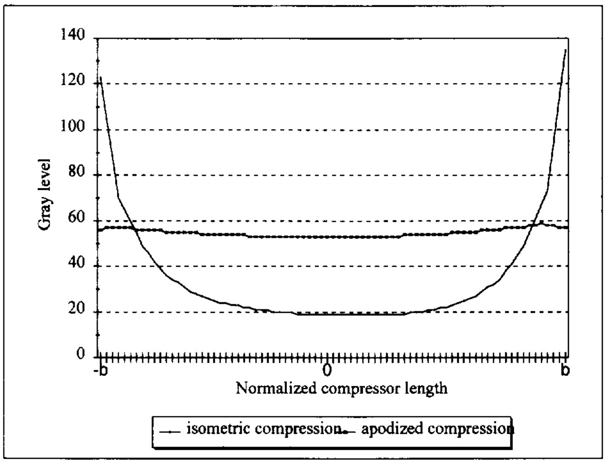

Fig. 8. Lateral gray level (or relative stress) vs. normalized distance along the compressor (at a depth $\frac{2b}{6}$ from the compressor) for isometric and apodized displacement.

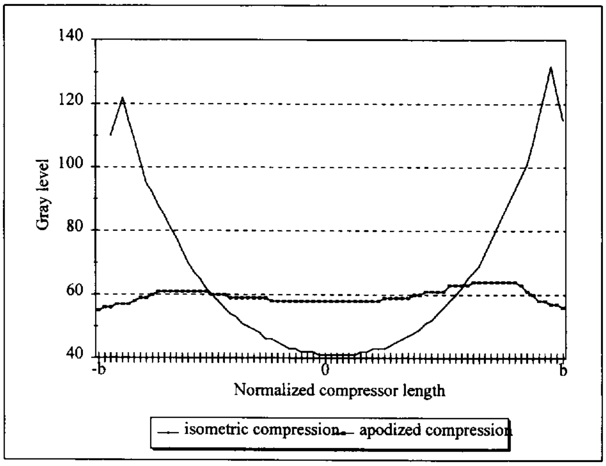

Fig. 9. Lateral gray level (or relative stress) vs. normalized distance along the compressor (at a depth $\frac{2b}{3}$ from the compressor) for isometric and apodized displacement.

10), except in the case where the depth is approximately equal to half the compressor size, and the isometric displacement case has a slightly higher SNR than the apodized one. However, it should be noted that, even at this depth, the apodized SNR is still relatively high ($\cong 6$). These results resemble the stress field pattern produced by application of normal loading with a spherically shaped compressor (Saaf 1991). Moreover, it has been observed (although not shown here) that, regardless of the lateral dimension of the target, there is always a significant improvement of the SNR in the area near the compressor.

SUMMARY AND CONCLUSION

In elastography, isometric compressions produce a highly nonuniform stress distribution in areas close to the compressor. Concentrated stress levels appear under the edges of the compressor, and diluted stress levels appear under the center of the compressor. The standard elastograms clearly show this artifact as a nonuniform gray level distribution near the compressor. In elastography, any nonuniformity, whether real or artifactual, results in an increase of the dynamic range of strain in the target, which may cause an increase in the decorrelation noise in the high strain areas. The proposed technique applies a specific apodized (or weighted) compressor displacement in such a way as to produce a nearly uniform stress distribution in the area under the compressor. The simulations presented in this article demonstrate the improvement in the uniformity of the elastograms obtained by using apodized displacement of the compressor as compared with the conventional isometric compression.

The proposed apodizing function was the theoretical displacement distribution caused by application of uniform pressure on the boundary of a semi-infinite solid. The studies used a finite size target. However, the results showed that the semi-infinite nature of the theoretical model could be well approximated by a finite element target that has a lateral dimension of at least five times the compressor size. This finding is important in the mechanical aspect of elastography, as the finite element models used are always finite (Kallel and Bertrand 1996; Ponnekanti et al. 1995), while the theoretical models tend to be infinite or semi-infinite.

Unlike the isometric displacement, the apodized displacement restores uniformity of appearance to the strain image, which is expected for a homogeneous target. However, while the apodization improves the lateral uniformity of the target, it has no effect on the axial uniformity. Therefore, a significant improvement in the lateral gray level SNR is observed in the apodized case. The greatest improvement is observed in the area directly under the compressor, which is also the area most strongly affected by this mechanical artifact. Moreover, the only relative decrease of the SNR was observed at a distance equal to the size of the compressor, but this decrease is relatively negligible.

In conclusion, the initial assumption made that apodized displacement produces near-isobaric conditions was corroborated. Taking into account the limitations of the finite element model (2000 nodes maxi-

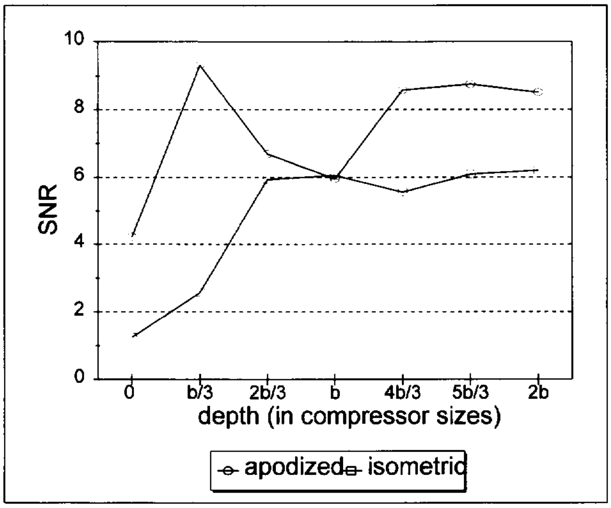

Fig. 10. Comparison of SNRs at different depths (in compressor sizes) from the face of the compressor.

mum) and the finite size of the target, these results demonstrate that the uniformity of the elastograms may be significantly increased by proper apodization of the compressor displacement.

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