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● *Technical Note*

ON THE ADVANTAGES OF IMAGING THE AXIAL-SHEAR STRAIN COMPONENT OF THE TOTAL SHEAR STRAIN IN BREAST TUMORS

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Abstract—Axial-shear strain elastography was described recently as a method to visualize the state of bonding at an inclusion boundary. Although total shear strain elastography was initially proposed for this purpose, it did not evolve beyond the initial reported finite element model (FEM) and simulation studies. One of the major reasons for this was the practical limitation in estimating the tissue motion perpendicular (lateral) to the ultrasound (US) beam as accurately as the motion along the US beam (axial). Nevertheless, there has been a sustained effort in developing methods to improve the lateral motion tracking accuracy and thereby obtain better quality total shear strain elastogram (TSSE). We hypothesize that in some cases, even if good quality TSSE becomes possible, it may still be advantageous to utilize only the axial-shear strain (one of the components of the total shear strain) elastogram (ASSE). Specifically, we show through FEM and corroborating tissue-mimicking gelatin phantom experiments that the unique "*fill-in*" discriminant feature that was introduced recently for asymmetric breast lesion classification is depicted *only* in the ASSE and not in the TSSE. Note that the presence or conspicuous absence of this feature in ASSE was shown to characterize asymmetric inclusions' boundaries as either loosely-bonded or firmly-bonded to the surrounding, respectively. This might be an important observation because the literature suggests that benign breast lesions tend to be loosely-bonded, while malignant tumors are usually firmly-bonded. The results from the current study demonstrate that the use of shear strain lesion "*fill-in*" as a discriminant feature in the differentiation between asymmetric malignant and benign breast lesions is only possible when using the ASSEs and not the TSSEs. (E-mail: Arun.K.Thittai@uth.tmc.edu) © 2012 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Axial-shear strain, Asymmetric lesion, Benign, Bonding, Breast cancer, Discriminant feature, Elastography, Elliptical, FEM, Fibroadenoma, Malignant, Orientation, Shear strain fill-in, Sonogram, Total shear strain, Ultrasound.**

INTRODUCTION

Ultrasound (US) elastography (Ophir et al. 1991) is now a well-established technique, which has been incorporated into many commercial ultrasound scanners used in clinical practice. This technique involves acquiring US (radio-frequency [RF]/envelope) signals from an imaging plane in tissue before and after a small applied quasi-static compression and computing all the local axial displacements in the imaging plane. The gradients of these displacements are then used to generate a map of the local axial strains in the tissue. This strain map is referred to as an *axial strain elastogram* (Ophir et al. 1999).

Based on the axial strain elastograms alone, elastography has been shown to be helpful in a wide variety of clinical applications such as in detecting tumors in breast and prostate tissues (Céspedes et al. 1993; Garra et al. 1997; Hiltawski et al. 2001; Lorenz et al. 1999), monitoring HIFU therapy in the prostate (Souchon et al. 2003), thyroid tumor classification (Lyshchik et al. 2005; Bae et al. 2007), lymph node characterization (Săftoiu et al. 2006), monitoring thermal ablation (Kallel et al. 1999; Righetti et al. 1999; Bharat et al. 2005; Souchon et al. 2005) and in intravascular plaque characterization (de Korte et al. 2000). The utility of elastography for the reduction of the rate of unnecessary breast biopsies has recently been demonstrated by Regner et al. (2006), Svensson et al. (2005), Barr (2006) and

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Burnside et al. (2007). It is reasonable to assume that any additional independent mechanical tissue parameters that can be imaged with elastography may either improve current elastographic performance and/or find utility in newer applications.

We have shown that in addition to the axial strain, which is one of the strain tensors that describe the target deformation, it is feasible to image another strain tensor in the form of the axial-shear strain (ThitaiKumar et al. 2007b). We have demonstrated that the axial-shear strain distribution pattern around an inclusion is directly influenced by the bonding at the inclusion-background boundary using simulations, gelatin-phantom experiments and breast lesions *in vivo* (ThitaiKumar et al. 2007b). Results from an initial study to evaluate the potential of axial-shear strain elastograms (ASSEs) to differentiate between fibroadenomas (reported to be loosely-bonded to their host tissue [cf. Fry 1951]) and cancers (reported to be firmly-bonded to the surrounding tissue [cf. Fry 1951]) in the breast have been very promising (ThitaiKumar et al. 2008; Thittai et al. 2011). [*Please note that ThitaiKumar and Thittai refer to the same author who had a name change recently.] The earlier work on ASSEs had assumed a simple, circularly-symmetric inclusions. More recent papers have corroborated our original reports on the utility of ASSE for breast lesion classification using this inclusion model (Xu et al. 2010; Varghese 2011).

Recently, we extended the simple circularly-symmetric inclusion model to a more general elliptical geometry with an arbitrary orientation with respect to the axis of compression. For ease of description, we will refer to this more general model as “asymmetric inclusion model.” With this generalization, we have shown that finite, non-zero, interior axial-shear strains were present only in “loosely-bonded” asymmetric inclusions. This phenomenon was referred to as “*fill-in*” (Galaz et al. 2009, Thittai et al. 2010). The presence or absence of this “*fill-in*” was shown as a potential easily-recognizable feature that could distinguish benign fibroadenomas from malignant breast lesions (Thittai et al. 2010). Our original observation on the presence of “*fill-in”* only in the loosely-bonded, asymmetric inclusion model, and its conspicuous absence in the firmly-bonded asymmetric inclusion was independently corroborated and reported recently (Fig. 3 in Xu et al. 2011).

It should be noted that almost all of the work discussed in the preceding paragraph focuses on estimating and imaging the local distribution of axial-shear strain (the first term of eqn [1] below) in an elastically inhomogeneous material. The total shear strain is defined as the sum of the axial- and lateral-shear strain components (both terms in eqn [1]), where (*u, v*) are the lateral and axial displacement components along the *x*- and *y*-axes, respectively (Timoshenko and Goodier 1970).

$$\varepsilon_{x,y} = \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right) \tag{1}$$

The ability to use the total shear strain ($\varepsilon_{x,y}$) for assessing the inclusion bonding properties was first shown through finite element simulation and US simulation studies more than a decade ago (Konofagou et al. 2000). Later, it was shown that using only the axial component ($\frac{\partial v}{\partial x}$) of the total shear strain had a practical advantage in terms of superior image quality (ThitaiKumar et al. 2005). This is due to the well-known US limitation that the estimation of motion *along* the direction of the US beam axis is significantly more precise than estimation of the motion *across* the US beam axis. Therefore, the relatively inferior image quality of the lateral component estimate ($\frac{\partial u}{\partial y}$) was seen as the primary *practical* reason for developing ASSE (ThitaiKumar et al. 2006, 2007a, 2007b, 2008; Thittai et al. 2011; Chen et al. 2010; Garcia et al. 2011; Xu et al. 2010; Varghese 2011).

Moreover, we report in this article that in certain cases it may be *necessary* to use the axial shear strain image for *fundamental* reasons. This is because important unambiguous features that are present in the shear strain components (axial- or lateral-component alone) may be completely absent in the total shear strain image. Specifically, we demonstrate below through simple finite element modeling (FEM) and tissue-mimicking gelatin phantom experiments that the “*fill-in*” discriminant feature (Galaz et al. 2009; Thittai et al. 2010) can be imaged and utilized only by using the ASSE and not the total shear strain elastogram (TSSE).

In addition to the above demonstration, we also show in this article that the inclusion “*fill-in*” that is visualized in ASSE can be interpreted effectively as an image of rotation, which is defined by Timoshenko and Goodier (1970) as

$$\omega_{x,y}(rotation) = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \tag{2}$$

Note that unlike the total shear strain defined in eqn (1), the difference between the two components defines the rotation.

MATERIALS AND METHODS

Finite element modeling

A two-dimensional (2-D) plane strain model was built by using the finite-element modeling (FEM)