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● *Original Contribution*

SYSTEMATIC PERFORMANCE EVALUATION OF A CROSS-CORRELATION-BASED ULTRASOUND STRAIN IMAGING METHOD

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Abstract—Estimation of tissue motion in the lateral direction remains a major challenge in 2-D ultrasound strain imaging (USI). Although various methodologies have been proposed to improve the accuracy of estimation of in-plane displacements and strains, the fundamental limitations of 2-D USI and how to choose optimal algorithmic parameters in various tissue deformation paradigms to retrieve the full strain tensor of acceptable accuracy are scattered throughout the literature. Thus, this study attempts to provide a systematic investigation of a 2-D cross-correlation-based USI method in a theoretical framework. Our previously developed cross-correlation-based USI method was revisited, and additional estimation strategies were incorporated to improve in-plane displacement and strain estimation. The performance of the presented method using different matching kernel sizes (axial: from 1λ to 14λ, where λ = wavelength; lateral: from 1 to 13 pitches) and two data formats (radiofrequency and envelope) in various kinematic scenarios (normal, shear or hybrid deformation) was investigated using Field II simulations, in which coherent plane wave compounding with 64 steered angles was realized. For radiofrequency-based USI, smaller axial and larger lateral kernel sizes were preferred in scenarios with normal strains, whereas larger kernel sizes along the shearing direction and smaller ones orthogonal to the shearing direction were more suitable in scenarios with shear strains. For envelope-based USI, in contrast, the kernel size requirement was relatively relaxed. A compromise between optimal kernel sizes and estimation accuracy of various strain components was required in complex kinematic scenarios. These practical strategies for accurate motion estimation using 2-D cross-correlation-based USI were further tested in a tissue-mimicking phantom under quasi-static compression and in a preliminary *in vivo* examination of a normal human median nerve at the wrist during active finger motion. (E-mail: wnlee@eee.hku.hk) © 2016 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Coherent plane wave compounding, Envelope, Lateral, Radiofrequency, Shear, Speckle tracking, Strain, Ultrasound.**

INTRODUCTION

Ultrasound strain imaging (USI) has been established in past decades as a non-invasive technique providing kinematic parameters of biological soft tissues, such as the breast (Burnside et al. 2007; Cespedes et al. 1993; Garra et al. 1997; Thitaikumar et al. 2008), heart (D'hooge et al. 2002a; Jia et al. 2009; Konofagou et al. 2002; Lee et al. 2007; Li et al. 2007; Lopata et al. 2011; Luo et al. 2007), liver (Emelianov et al. 1998; Varghese et al. 2002; Yeh et al. 2002), kidney (Emelianov et al. 1995, 2000), vessel (de Korte et al. 2000; Hansen et al. 2009; Idzenga et al. 2012; Larsson et al. 2011; Ribbers et al. 2007) and carpal tunnel (Liao et al. 2015). Among the wide applications of USI, a 1-D array probe is typically used to acquire ultrasound signals in a 2-D view, so the tissue motion can be estimated in both the axial and lateral directions. Various 2-D USI methods have been proposed and can be categorized into two main groups: optical flow and block matching. Optical flow assumes the preservation of image brightness before and after the tissue deformation and calculates motion fields by minimizing the error in the rate of change of brightness (Hein and O'Brien 1993; Mailloux et al. 1987; Suhling et al. 2005; Zakaria et al. 2010). Block matching typically searches specific brightness patterns between a 2-D window in the pre-deformed frame and candidate 2-D windows in a defined search region in the post-deformed frame to estimate local

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tissue motion (Basarab et al. 2008; Bohs and Trahey 1991; Li et al. 2007). Some block matching methods also use both brightness and phase of ultrasonic raw signals and can be further divided into frequency-domain (phase tracking) and time-domain techniques. Frequency-domain methods typically process complex or analytical ultrasonic signals and estimate the phase shift reflecting the underlying tissue motion from the complex similarity function (*e.g.,* normalized cross correlation) (Lubinski et al. 1999b; Pesavento et al. 1999). Time-domain methods estimate the time delay between pre- and post-deformed radiofrequency (RF) ultrasonic signals through real-valued similarity function (*e.g.,* normalized cross-correlation, sum of absolute/squared difference) (D'hooge et al. 2002b; Konofagou and Ophir 1998; Ophir et al. 1991).

Despite the aforementioned exemplary USI methods and their extensive applications, only the axial displacement/strain component can currently be accurately estimated. Ultrasound lateral motion estimation remains a major challenge owing to the lack of phase information and lower spatial resolution in the lateral direction (Hein and O'Brien 1993; Lubinski et al. 1996). This fundamental limitation hinders USI from being a truly reliable diagnostic tool for some tissues, for example, the heart (D'hooge et al. 2002a), in which tissue kinematics depicted in the cardiac coordinate system (*i.e.,* radial and circumferential) require both the axial and lateral strain components. Tremendous efforts have been made to improve the estimation accuracy of displacements/strains in the lateral or both directions using various methodologies. Some methods have taken advantage of the more accurate axial displacement. Lubinski et al. (1996) used the assumption of tissue incompressibility and obtained less noisy lateral displacements from accurate axial strain estimates, but the practical use of this method might be limited when the relationship between the axial and lateral strain components is unknown in anisotropic tissues. Rao et al. (2007) derived both in-plane displacement components from axial displacements estimated using multiple beam steering angles; this is also known as "spatial compounding." A similar approach was proposed by Hansen et al. (2010), with fewer but larger steering angles to further improve the accuracy of lateral estimates. An adaptive low-pass filter was used to address the grating lobe issue at large steering angles. Some methods have proposed interpolation of RF lines to increase the lateral sampling rate (Konofagou and Ophir 1998; Luo and Konofagou 2009), which improved the lateral estimation accuracy to the sub-pitch level. Motion compensation strategies were also used to alleviate lateral displacement estimation from signal decorrelation induced by axial deformation (Alam and Ophir 1997; Chaturvedi et al. 1998; Lee et al. 2007; Lopata et al. 2009; Maurice and Bertrand 1999). In some other studies, regularization approaches were used to improve in-plane motion estimation. In Langeland et al. (2004), regularization was imposed on the estimated cardiac velocity field to follow a linear gradient through the heart wall, but this assumption might be inappropriate in diseased hearts with abnormal motion patterns. In Brusseau et al. (2008), local continuity was imposed within displacement and strain fields using the similarity metric—normalized cross-correlation (NCC)—as an indicator of estimation accuracy. The motions of samples with low NCC values were re-estimated from neighboring samples with high NCC values, thus improving estimation accuracy and robustness. In Jiang and Hall (2015), in-plane displacements were initially estimated by imposing continuity on motion fields to avoid large tracking errors at the integer level, followed by signal shifting and stretching to maximize the correlation between the pre- and post-deformed signals. Subsample displacements were then obtained by determining an iso-contour of the correlation function to find the true NCC peak at the contour centroid. These exemplary works are summarized in Table 1 for readers' convenience.

In addition to the efforts with respect to methodology, theoretical studies in system and algorithm parameters concerning the optimization of ultrasound motion estimation were also reported. The effect of system parameters (*e.g.,* center frequency, bandwidth, sonographic signal-to-noise ratio) on the performance of USI has been examined (Cespedes et al. 1997; Luo and Konofagou 2009; Walker and Trahey 1995). One key parameter in block-matching techniques is the matching kernel size, which has an obvious influence on ultrasound motion estimation (Lopata et al. 2009; Walker and Trahey 1995). However, distinct optimal kernel sizes were reported in different studies. For axial kernel size, for example, a 1-D kernel of 10 wavelengths was used in the cross-correlation (CC)-based myocardial elastography technique in Lee et al. (2008), whereas in Lubinski et al. (1999b), the optimal axial kernel size was equal to the autocorrelation length of the ultrasound pulse. For lateral kernel size, Lopata et al. (2009) measured the root-mean-square error (RMSE) of displacement estimates with varying kernel sizes in a quasi-static compressional experiment and validated the superiority of the 2-D kernel over the 1-D kernel in estimating lateral displacement; however, no significant difference in estimated cardiac strains between 1-D and 2-D kernels was reported in another study (Langeland et al. 2005). These discrepancies in the matching kernel size necessitate further systematic assessment to derive the proper kernel setting for hybrid tissue motion estimation.

The data format also has an impact on the performance of USI. RF-based speckle tracking is conventionally