Ultrasound in Med. & Biol., Vol. 42, No. 11, pp. 2606–2615, 2016

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2016.07.009

● *Original Contribution*

HIGH-FRAME-RATE DEFORMATION IMAGING IN TWO DIMENSIONS USING CONTINUOUS SPECKLE-FEATURE TRACKING

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(*Received* 26 *October* 2015; *revised* 8 *July* 2016; *in final form* 9 *July* 2016)

Abstract—The study describes a novel algorithm for deriving myocardial strain from an entire cardiac cycle using high-frame-rate ultrasound images. Validation of the tracking algorithm was conducted *in vitro* prior to the application to patient images. High-frame-rate ultrasound images were acquired *in vivo* from 10 patients, and strain curves were derived in six myocardial regions around the left ventricle from the apical four-chamber view. Strain curves derived from high-frame-rate images had a higher frequency content than those derived using conventional methods, reflecting improved temporal sampling. (E-mail: mvan@hst.aau.dk)

Key Words: **Deformation imaging, Strain, Algorithm, Speckle tracking, Feature, Speckle, Ultrasound, Echocardiology, High frame rate, Feature tracking.**

INTRODUCTION

Cardiac disease is the leading cause of morbidity and mortality in the population over the age of 40. For example, heart failure is common in the United States, occurring in 6% to 10% of the adult population above the age of 65 (Roger et al. 2011). Heart failure can be the result of either electrical or mechanical abnormalities. The effects of both mechanical and electrical abnormalities are difficult to distinguish in early stages of heart failure, making accurate diagnosis and effective treatment difficult (Bristow et al. 2004; Risum et al. 2012, 2013; Vernooy et al. 2005).

Detection and measurement of rapid mechanical phenomena, such as the propagation of mechanical contraction and relaxation subsequent to depolarization, could have great clinical significance. Depolarization propagates with a velocity between 0.5 and 2 m/s depending on whether the electrical excitation is through the myocardial tissue or the Purkinje fibers (Durrer et al. 1970). It is unlikely that these events will be detected using conventional ultrasound scanners, which operate at 50 to 110 fps (Teske et al. 2007). A frame rate of ≥500 fps is necessary to record information about mechanical activation sequences and correlate them to electrical measurements acquired by electrocardiography (EKG) (Cikes et al. 2014).

If these mechanical phenomena are similar in speed and duration to the propagation of the electrical excitation wave through the left ventricle, they will last 30 ms (Durrer et al. 1970). These rapid mechanical phenomena are currently undetected because of the low image acquisition rates of conventional clinical ultrasound imaging (Teske et al. 2007).

A common method for automating measurements in ultrasound images is speckle or feature tracking. The most commonly used commercial speckle tracking algorithms, such as GE Healthcare's Automated Function Imaging software and TomTec's 2-D Cardiac Performance Analysis software, use Optical Flow methods for frame-to-frame myocardial motion tracking (Geyer et al. 2010; Hor et al. 2011; Teske et al. 2007). Optical Flow has a lower limit of detectable velocities that depends on the algorithm's ability to detect sub-pixel variations between frames. If the movement of a target between two sequential images is smaller than that between adjoining spatial samples, and the tracking method does not implement sub-pixel variation detection, the frame-to-frame Optical

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Flow approach will not be able to detect the movement (Hor et al. 2011). Multiple studies on speckle tracking state that the best tracking accuracy is achieved using frame rates between 40 and 110 fps, as this gives the best trade-off between image quality and frame rate (Dandel and Hetzer 2009; Kawagishi 2008; Teske et al. 2007). This finding reflects the performance of currently available commercial diagnostic machines, which increase frame rate by reducing spatial sampling (Dandel and Hetzer 2009; Gorcsan and Tanaka 2011; Kawagishi 2008; Teske et al. 2007). Any measurement or observation derived from ultrasound images with inadequate spatial sampling may suffer from artifacts not indicative of actual myocardial motion. Currently there are no commercial diagnostic machines capable of capturing B-mode ultrasound images with the same temporal resolution as tissue Doppler imaging (TDI, ≥180 fps) or ordinary EKG sampling rate (≥ 500 Hz) while maintaining adequate spatial sampling (Kligfield et al. 2007; Teske et al. 2007). If temporal resolution were to be increased without affecting spatial sampling, then clinicians would have a better tool to investigate myocardial motion and its relationship to electrical events in the heart (Dandel and Hetzer 2009; Teske et al. 2007).

Brekke et al. (2014) presented strain rate curves derived from TDI at 1200 samples per second. However, as TDI is a 1-D technique, it cannot discriminate between motion in different directions in the myocardium (Brekke et al. 2014; Teske et al. 2007). Nevertheless, systolic and diastolic performance assessed using higher-temporal-resolution TDI has provided additional information not available with conventional frame rate B-mode ultrasound imaging (Brekke et al. 2014; Teske et al. 2007). Using TDI with a sample rate of 350 and 560 Hz, Pislaru et al. (2014) and Kanai (2009) described wave propagation in the inter-ventricular septum with spatial origins, temporal onsets and a propagation velocity similar to those of the electrical excitation from Purkinje fibers (Durrer et al. 1970; Kanai 2009; Pislaru et al. 2014). Increasing temporal resolution of B-mode ultrasound images may therefore allow capture of these rapid events that otherwise would remain unappreciated (Teske et al. 2007).

Several methods exist to increase the temporal resolution of ultrasound scanners without significantly decreasing spatial resolution, field of view (FOV) or depth. Retrospective gating is a method in which multiple ultrasound images recorded at high frame rate and narrow FOV are reconstructed into a single normal FOV image. However, prolonged acquisition time and movement artifacts cause the method to fail in many circumstances (Cikes et al. 2014). Another method for increasing frame rate is multi-line transmit imaging, in which multiple focused beams are transmitted simultaneously, but artifacts occur because of crosstalk between the transmit beams (Cikes et al. 2014; Tong et al. 2014). Widening the transmit beam by using an either unfocused or negatively focused transmit beam allows for the acquisition of multiple received image lines simultaneously, increasing frame rate. Moore et al. (2015) presented live B-mode ultrasound images using a negatively focused transmit beam at up to 2500 fps for general applications and 1000 fps for images of the adult human heart. For a fixed amount of transmitted energy, an unfocused or negatively focused transmit beam will, however, have lower acoustic pressure across the image field than a focused transmit beam, resulting in lower signal to noise in the resulting images (Cikes et al. 2014). Although we did not find any derived strain curves from high-frame-rate B-mode ultrasound images (≥500 fps), velocity curves from areas with strong myocardial signal in ultrasound sequences recorded at 900 fps have been derived (Papadacci et al. 2014).

Papadacci et al. (2014) used coherent spatial compounding to reduce noise in their velocity measurements. This effectively reduced the frame rate to 180 fps. Coherent spatial compounding does have the potential to create high-quality ultrasound images at more than 300 fps (Papadacci et al. 2014). Another method for improving image quality is harmonic imaging, which exploits oscillation that produces harmonics in the ultrasound field stronger than the fundamental waves. A significant improvement in image quality with less clutter and better blood contrast can be achieved, but it requires high acoustic pressure, which can be an issue for phased array ultrasound systems (Kornbluth et al. 1998; Spencer et al. 1998).

Here, a novel algorithm is presented for speckle-feature tracking and strain estimation in high-frame-rate B-mode ultrasound images acquired using the Duke University's experimental phased array ultrasound scanner, T5. *In vitro* validation of the tracking algorithm is performed and applied to limited patient studies.

METHODS

Data acquisition

Image acquisition rate in ultrasound is limited by the number of transmit–receive (Tx-Rx) operations and the speed of sound in tissue. Parallelism in receive, also known as explososcanning, increased frame rate while maintaining adequate spatial sampling (Moore et al. 2015; Shattuck et al. 1984). This study used ultrasound images acquired using Duke University's experimental phased array ultrasound scanner, T5 (T5, Duke University, Durham, NC, USA). A 96-element, 1-D phased array (Volumetrics, Durham, NC, USA) was