Ultrasonics 49 (2009) 98–111

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Ultrasound frame rate requirements for cardiac elastography: Experimental and *in vivo* results

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ARTICLE INFO

Article history:
Received 28 February 2008
Received in revised form 15 May 2008
Accepted 31 May 2008
Available online 20 June 2008

Keywords:
Cardiac imaging
Displacement
Echocardiography
Elastography
Elastogram
Elasticity
Elasticity imaging
Strain
Cardiac deformation
Ultrasound

ABSTRACT

Cardiac elastography using radiofrequency echo signals can provide improved 2D strain information compared to B-mode image data, provided data are acquired at sufficient frame rates. In this paper, we evaluate ultrasound frame rate requirements for unbiased and robust estimation of tissue displacements and strain. Both tissue-mimicking phantoms under cyclic compressions at rates that mimic the contractions of the heart and *in vivo* results are presented. Sinusoidal compressions were applied to the phantom at frequencies ranging from 0.5 to 3.5 cycles/sec, with a maximum deformation of 5% of the phantom height. Local displacements and strains were estimated using both a two-step one-dimensional and hybrid two-dimensional cross-correlation method. Accuracy and repeatability of local strains were assessed as a function of the ultrasound frame rate based on signal-to-noise ratio values.

The maximum signal-to-noise ratio obtained in a uniformly elastic phantom is 20 dB for both a 1.26 Hz and a 2 Hz compression frequency when the radiofrequency echo acquisition is at least 12 Hz and 20 Hz respectively. However, for compression frequencies of 2.8 Hz and 4 Hz the maximum signal-to-noise ratio obtained is around 16 dB even for a 40 Hz frame rate. Our results indicate that unbiased estimation of displacements and strain require ultrasound frame rates greater than ten times the compression frequency, although a frame rate of about two times the compression frequency is sufficient to estimate the compression frequency imparted to the tissue-mimicking phantom. *In vivo* results derived from short-axis views of the heart acquired from normal human volunteers also demonstrate this frame rate requirement for elastography.

1. Introduction

Echocardiography has been routinely used for assessment of regional myocardial function, left ventricular size, and ventricular structure since it provides real-time information, is portable, and is readily available. Conventional two-dimensional (2D) B-mode imaging along with M-mode recordings are well suited to define global and regional functional changes in left ventricular performance. However, this type of analysis is limited because it provides semi-quantitative information on cardiac wall movement abnormalities. As a consequence, there is considerable variation among interpreters of echocardiograms, limiting the usefulness of such evaluations [1].

During systole short-axis echo images of the left ventricle (LV) show wall thickening in the radial direction and shortening in the circumferential direction, while in the long-axis view thickening is observed in the lateral direction and shortening is observed as the base moves towards the apex. Thickening and shortening of the wall muscle during the cardiac cycle may be characterized by local tissue displacements and accompanying wall strain, suggesting that strain imaging could be a very useful indicator of myocardial performance [2].

Doppler techniques, originally applied to analysis of blood flow across valves, have evolved to provide information about global and regional left ventricular and right ventricular performance. Tissue Doppler imaging (TDI), also called tissue velocity imaging, estimates local tissue velocities and tracks heart wall motion. [3,4]. TDI is most commonly derived from pulsed Doppler imaging of localized regions. Resultant signals may be displayed by color-coding and superimposing TDI velocity estimates on a B-scan image, similar to color-flow imaging. However, TDI does not differentiate between active contraction and simple rotation or translation of the heart wall, nor does it differentiate passively following tissue from active contraction. Fleming et al. [5] used the spatial gradient of the TDI derived velocities to measure relative changes in wall thickness, or strain-rate (definitions of the strain and strain-rate are

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doi:10.1016/j.ultras.2008.05.007

provided in Appendix A), to overcome this problem. However, as velocities decrease toward the apex, the Doppler signal-to-noise ratio decreases, limiting TDI's usefulness in the apical part of the ventricle. Strain-rate plots using cross-correlation also have been reported on M-mode data [6]. Strain and strain-rate measurements based on TDI have been compared to three-dimensional myocardial strain using tagged magnetic resonance imaging methods [7].

Because of limitations in Doppler-derived velocity and strain indices, there has been renewed interest in B-mode based strain and strain-rate measurements for assessing cardiac muscle performance [8–11]. B-mode based calculations of strain have the considerable advantage of not being directionally limited. Thus, limitations from Doppler imaging, such as an inability to differentiate between active contraction, simple rotation, and translational motion of the heart wall are no longer significant issues. Furthermore, B-mode related techniques such as speckle tracking have allowed new strain methodologies to be used in the left ventricle. Local strain along the long-axis is now being estimated, along with rotational and radial indices of strain and strain-rate.

Both General Electric Medical Systems (GEMS) (GE Healthcare, Milwaukee, WI, USA) and Siemens (Siemens Ultrasound, Mountain View, CA, USA) have introduced 2D speckle tracking for strain imaging on their cardiac ultrasound systems. GEMS's strain imaging is based on processing ultrasound B-mode data loops. [8–10]. Reisner et al. [10] utilized the entire U-shaped length of the LV to estimate global peak longitudinal strain (GLS) and strain-rate (GLSR) in 4 patients after myocardial infarction (MI) and 3 controls. Their results show that the average GLS and GLSR differ significantly between patients who have suffered myocardial infarction (MI) and normal control subjects. Korinek et al. [8] compared strains measured *in vitro* using sonomicrometry and *in vivo* using the GEMS EchoPAC software package. Becker et al. [9] collected data over 64 patients and showed that tracking strain and strain-rate using B-mode image data enables improved analysis of regional systolic LV function. Their study provides an excellent analysis of regional strain for wall motion.

Cardiac elastography using radiofrequency echo signals can provide improved 2D strain information over that obtained from B-mode image data [12], provided data are acquired at sufficient frame rates. The frame rate of current medical ultrasound systems, though high, may not be sufficient to characterize the quasi-periodic compression, relaxation, and rotation of the myocardium during the cardiac cycle for unbiased and robust cardiac displacement and strain imaging.

In this paper, we present a relationship between the frame rate of an ultrasound system and the quality of computed strain images for a uniformly elastic tissue-mimicking phantom undergoing cyclic compressions. Image quality is quantified using the strain signal-to-noise ratio (SNR_e) for various ratios of the compression frequency to the ultrasound system frame rate. In addition, displacement and strain estimates are obtained from *in vivo* strain images for short-axis views of the heart. The relative phase between strains measured in different locations of the myocardium is determined as a function of ultrasound system frame rates, which is varied by skipping radiofrequency (RF) data frames for which strains are computed.

2. Materials and method

2.1. Cyclic compression system

Since LV wall movements and velocities during the cardiac cycle can be assumed to vary in a quasi-periodic manner, a combined tissue-mimicking (TM) phantom and cyclic compression system was developed to evaluate tradeoffs between frame rate and strain imaging performance. A TM phantom was subjected to cyclic compressions using the apparatus shown in Fig. 1. The phantom is supported between two plates, which are mounted on cylindrical slides as shown in the figure. The top plate is held stationary but its location can be adjusted to accommodate different sized phantoms. This plate has a fixture and a rectangular channel that holds an ultrasound transducer. The transducer can be translated linearly within the channel. The bottom of the channel is sealed using a poly-methyl pentene (PMP) strip that is flush with the bottom surface of the plate. Madsen et al. [13] have described this material and shown that ultrasound can be transmitted readily through the PMP material. This enables the use of a coupling medium such as water or ultrasound gel within the translation channel.

The bottom compression plate is connected using ball bearings to cylindrical slides to minimize friction during applied compressions. This plate is driven by a variable speed direct current (DC) motor (Cole-Parmer Instruments, Chicago IL) whose shaft rotates between 1 and 10 cycles/s. The motor speed is adjusted using an analog controller to vary the current. The shaft is connected to the plate in a slightly eccentric manner, with multiple connectors to enable the introduction of variations in the stroke amplitude. The moving compression plate supports the TM phantom and is larger than the phantom surface, providing a uniform compression. The phantom is placed in a small concave groove in the compression plate to minimize horizontal slippage. The US transducer placed on the top plate is utilized to collect RF data during compressions. In this study, echo data were acquired for different strain-rates by varying the amplitude and frequency of the cyclic compressions. The maximum compressional displacement applied by the DC motor was approximately 4 mm. Compression frequencies in the range of 0.6 Hz to 4 Hz were used as these are similar to the human heart beat frequency.

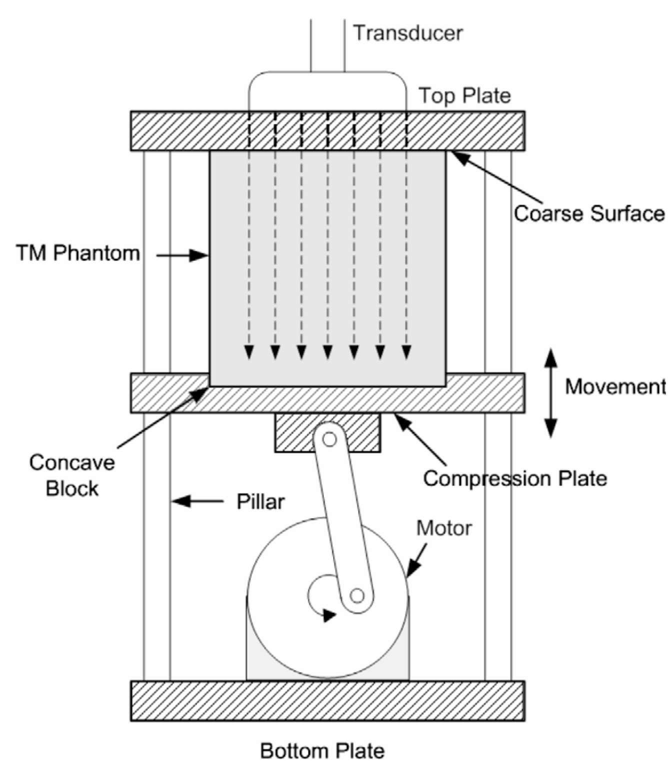

Fig. 1. Schematic diagram of the cyclic compression apparatus used to apply the sinusoidal compression force to the uniform TM phantom.