CARDIAC ELASTOGRAPHY – A FEASIBILITY STUDY
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Abstract - Early detection of cardiovascular diseases has been a very active research area in the medical imaging field. Assessment of the local and global mechanical functions is one of the major goals for accurate diagnosis. In this paper, we studied the use of elastography for estimation and imaging of the local cardiac muscle displacement and strain in vivo. In its noninvasive applications, elastography has been typically used to determine local tissue strain through the use of an externally applied compression. For our study, we utilized the cardiac muscle motion, i.e., contraction and relaxation, as the mechanical stimulus, and acquired successive RF data frames over a few cardiac cycles in parastemal and apical views. Best quality cine-loop elastograms were obtained at higher frame rates due to the relatively lower decorrelation noise while the expected tradeoff between signal-to-noise ratio and spatial resolution was also observed. Furthermore, the strain contrast was higher in the parastemal case, when solely the posterior wall was imaged while strain estimation was more robust in the apical case. High repeatability of the results was observed through elastographic measurements over several cardiac cycles. Finally, an M-mode version of elastography was used in order to follow a particular segment of the image in the course of two cardiac cycles. Not only do these preliminary results show that elastography is feasible in cardiac applications in vivo, but also that it can provide new information regarding the cardiac motion and mechanical function. Future prospects include the assessment of the role of elastography in the detection of ischemia as well as infarction.

I. INTRODUCTION
Detection of cardiac dysfunction through assessment of the mechanical properties of the heart muscle has been the long-term goal in diagnostic cardiology. Ischemia and infarction can successfully be determined through characterization of the regional cardiac function. Despite the fact that Magnetic Resonance Imaging (MRI) has been shown capable of generating high quality images of the cardiac deformation with methods such as cardiac tagging and HARP MRI, in echocardiography, techniques for mapping the mechanical response of the cardiac muscle are still in their infancy. However, echocardiography remains the main dominant imaging modality in diagnostic cardiology due to its real-time feedback, high temporal resolution and a multitude of complementary methods that can be used for a complete and accurate diagnosis. The two main areas of investigation are motion estimation techniques and tissue characterization methods. Motion estimation methods include Doppler Myocardial Imaging (DMI) and Strain Rate Imaging (SRI), which use Doppler techniques to obtain regional velocity estimates and velocity gradients of the myocardium, respectively. The field of tissue characterization, a complement to the motion estimation techniques, measures acoustic parameters, such as attenuation, speed of sound and Integrated Backscatter (IB) to determine such myocardial attributes as thickening and thinning (cyclic variation), and anisotropy. A brief but thorough overview of the tissue characterization methods is given in Miller et al. [1]. Despite it being their main goal and unlike their MRI counterparts, all of the aforementioned methods, measure parameters that are only indirectly dependent on the mechanical attributes of the cardiac muscle. For example, SRI calculates the strain rate curve through the velocity gradient [2] while the method of speed of sound estimation provides indirect measures of the regional Young’s modulus [1].

Elastography is a technique that estimates local tissue strain through crosscorrelation of RF segments before and after a small (external or internal) deformation. Based on the principle of palpation, elastography was initially designed for the detection of stiffer masses (i.e., tumors) inside normal tissue and shown to have successful results in muscle, prostate and breast in vitro and in vivo applications [3]. Recently, however, elastography has been shown to have an important impact on several other
applications, such as normal tissue strain and poroelasticity imaging [3]. Since assessment of the myocardial mechanical parameters has proven to be a crucial step in the detection of cardiac abnormalities, elastography could also have a significant impact in this field. In this preliminary study, we concentrated on a normal volunteer case to mainly determine the feasibility of elastography on cardiac muscle and subsequently design the optimal ultrasound system parameters for cardiac elastographic measurements. The examples of left-ventricular muscle considered were the posterior wall and intraventricular septum, a muscular wall, which separates the left ventricle from the right ventricle. Below we start by providing the methods used for the generation of cardiac elastograms and proceed to showing and discussing the results.

II.METHODS
The septal and posterior walls of a 28-year-old normal male volunteer were scanned in apical four-chamber (A4C) and parasternal long-axis (LAx) views, respectively, using a Vingmed System FiVe (GE Vingmed, Horten, Norway) with a 2.5 MHz phased array. The apical view was particularly chosen because the data set could be acquired in such a way so that the septum moves along each A-line, i.e., minimizing the lateral motion. IQ (in-phase quadrature) data was acquired and transferred to a workstation for off-line analysis and converted back to RF. The sampling frequency was equal to 20 MHz and the depths and widths scanned were equal to 90 mm and 10 mm over an angle of 10 degrees, respectively.

In order to obtain axial displacement and axial strain estimates, the crosscorrelation method of temporally successive RF segments was applied using a window equal to 2 mm and a window overlap of 80% to assure high elastographic resolution [3]. The method was initially applied on RF segments that were acquired in the same direction but using different pulses (PRF = 1 kHz), i.e., the pairs 1-2 (i.e., RF signals from pulse 1 and pulse 2), 2-3 and 1-3 were considered. From a preliminary analysis (not shown here), it was concluded that immediately successive frames (i.e., 1-2 or 2-3) should be used, since decorrelation corrupts the elastographic estimation otherwise. The 1-2 pair was used for each elastographic frame. The frame rate was also varied between 60 and 710 Hz and the corresponding lateral resolution varied in the range of 0.5 to 5 mm. The axial resolution was not compromised. Best quality cine-loop elastograms were obtained at higher frame rates (and, thus, lower lateral resolution). In order to assure high temporal resolution, and, thereby, low decorrelation between frames, only eight (10 degree angle) and ten (15 degree angle) A-lines per frame were acquired in the parasternal and apical cases respectively.

III.RESULTS
The transducer (at the apex) and the base are respectively located on the top and bottom of all images shown in this paper. A series of displacement images from the apical view (taken at regular intervals from the ciné-loop) is first shown in Fig. 1 at different intervals of the cardiac cycle. Steps (b) and (c) show high positive displacement, i.e., motion of the septal muscle towards the transducer at the apex. They correspond, thus, to the ejection phase of the left ventricle, when the septum wall shrinks from the base towards the apex. Fig. 1d shows highest negative displacement of the muscle close to the base, signifying muscle relaxation. This occurs at the early or fast filling phase of the left ventricle, when the septum gradually relaxes. Figs. 1e, f and g correspond to diastasis (accounting for ~40% of the cardiac cycle in this case), with step (g) closely resembling the displacement mapping of step (a).

In Fig. 2 an M-mode version and a plot of the loci displacement variation over two cardiac cycles allow for further identification of several cardiac events. During ejection (E) the base is moving closer to the apex (positive displacement rising), then starts to

Figure 1: Displacement images in the A4C view at a) 8%, b) 23%, c) 38%, d) 53%, e) 67%, f) 75% and g) 97% of the cardiac cycle. White and black denote displacement towards and away from the transducer (or, apex), respectively.

In Fig. 2 an M-mode version and a plot of the local displacement variation over two cardiac cycles allow for further identification of several cardiac events. During ejection (E) the base is moving closer to the apex (positive displacement rising), then starts to
slowly move away again (positive displacement decreasing) approaching isovolumetric relaxation (IVR), when the displacement follows an initial drop (short black region close to 40% in the M-mode image). During fast filling (FF) the muscle stretches from apex to base and the displacement progressively decreases (or, muscle moves towards the base). It then levels off during diastasis (D) (grey area in M-mode) and momentarily drops to negative levels during late (or, atrial) filling (AC). In the second cycle the displacement follows an almost identical pattern. The conventional elastograms (Fig. 3) and the M-mode elastogram and plot (Fig. 4) show the same trend. During ventricular systole (or ejection), the septum experiences compressive (positive) strain (Fig. 3b), and during diastole (or, ventricular filling) the muscle undergoes tensile (negative) strain (Fig. 3d). During diastasis the strain is practically zero (Figs. 3e, f and g). The temporal strain profile of Fig. 4 also shows the compression (E), tension (FF) and virtually no strain (D) of the septum over two cardiac cycles. The M-mode results of Figs. 2 and 4 compare to those obtained with DMI techniques showing the displacement and strain gradient from base to apex (that stays practically fixed during a cycle) [4].

Figures 5, 6, 7 and 8 are the exact equivalents of Figs. 1, 2, 3 and 4 in the parasternal long-axis view case. In this case, a higher displacement contrast was observed with a distinct horizontal structure (particularly seen in Figs. 5a, e and g) that corresponds to the part of the posterior wall undergoing motion. The area above it mainly consists of blood while the epicardium lies below it.

Figure 2: Top: M-mode images of an axial line segment through the displacement image (20% off the right end of the images in Fig. 1; same scale used). Depth of 0 mm and 90 mm are closer to the apex and base, respectively; Bottom: temporal profile of displacement at 45 mm depth. E: ejection, AVC: aortic valve closure, IVR: isovolumic relaxation, MVO: mitral valve opening, FF: fast filling, D: diastasis, AC: atrial contraction. The ECG is merely used here as reference.

Figure 3: Elastograms in the A4C view at a) 8%, b) 23%, c) 38%, d) 53%, e) 67%, f) 75% and g) 97% of the cardiac cycle. White denotes highest compressive strain and black denotes highest tensile strain.

Figure 4: Top: M-mode images of an axial line segment through the elastogram (20% off the right end of the images in Fig. 3; same scale used); Bottom: temporal strain profile at 45 mm depth. Labeling same as in Fig. 2.

In the series of elastograms (particularly Figs. 7a, b, c, e and g) a duality of compressive and tensile strain appears around the posterior wall and the muscle seems to be split into two areas experiencing opposite strains. This may relate to the efficiency of the muscle throughout the cardiac cycle. The time-dependences
of the displacement and strain in the parasternal case are also very close to that observed in the apical case.

Figure 5: Displacement images in the LAx view at a) 8%, b) 23%, c) 38%, d) 53%, e) 67%, f) 75% and g) 97% of the cardiac cycle.

Figure 6: Top: M-mode images of an axial line segment through the displacement image (20% off the right end of the images in Fig. 5; same scale used). Bottom: temporal displacement profile at 35 mm depth. The scale is the same as that in Fig. 5.

Figure 7: Elastograms in the LAx view at a) 8%, b) 23%, c) 38%, d) 53%, e) 67%, f) 75% and g) 97% of the cardiac cycle.

IV. DISCUSSION
Assessment of the mechanical properties of the cardiac muscle has proven to be an important element in the detection of myocardial abnormalities. Most current methods estimate the strain parameter using an indirect measure. In this paper, we applied elastographic techniques in an in vivo case in order to estimate the local displacement and local strain resulting from ventricular muscle deformation throughout several cardiac cycles. RF signals were acquired from the septal and posterior walls in parasternal and apical views, respectively. Elastograms provided the highest contrast compared to displacement images, especially in the parasternal view case, where a compressive/tensile strain duality around the muscle could be observed throughout most of the cardiac cycle, assumed to regulate the deformation of the muscle. The results were judged highly repeatable over a few cardiac cycles and several cardiac events could be identified. In conclusion, elastography was shown feasible in cardiac applications in vivo and to provide significant information on the mechanical time-dependent properties of the ventricular wall. Future investigations should determine its role in the diagnosis of ischemia and infarction.

V. REFERENCES