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Velocity estimation of naturally occurring mechanical waves in the left ventricle in healthy persons

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***Abstract*— The propagation velocities of three naturally occurring mechanical waves in the left ventricle were investigated for this study for seven healthy volunteers. Ultrasound images were acquired at high frame rates and analyzed with a novel signal processing method called clutter filter wave imaging, designed to detect mechanical waves propagating in tissue. Six ventricular walls were investigated per subject and the velocities were compared wall by wall, and for increasing frame rates. The aim of this study was to contribute to measurements of velocities of naturally occurring mechanical waves in healthy persons, to possibly be able to use these velocities to distinguish between healthy and pathologic cardiac tissue. Additionally, we wanted to investigate changes in the velocities based on acquisition frame rates and on locations in the left ventricle. The study found that the lower frame rate intervals led to fewer exclusions of estimates due to quality and lower ranges of average velocities between subjects. No pattern was found for increased or decreased velocities in different parts of the LV.**

Keywords*— *Mechanical wave velocity estimation, high frame rate ultrasound

I. Introduction

Detecting and characterizing waves propagating in tissue has the potential to give information about the characteristics of the tissue and to aid in detecting pathology [1]. This has been shown in ultrasound shear wave imaging [2], where artificially produced or naturally occurring waves have been used to estimate the stiffness of tissue in animals [3] and humans [4]. Artificially produced waves, from an externally vibrating source or an ultrasound transducer, have high frequency and low penetration, and are therefore suitable for investigating shallow tissues such as the liver [5]. Naturally occurring mechanical waves (MWs), produced by the body itself, have a lower frequency and thus a higher penetration, which make them suitable for heart applications where propagation along the walls is necessary. During the cardiac cycle, several mechanical events, such as the closure of the valves, cause perturbations, or MWs, in the tissue. Studies have shown that it is possible to detect and estimate the velocity of these waves [6], and have linked the change in propagation velocities to pathology [4]. Thus, changes in propagation velocities of MWs could possibly be a useful tool for diagnosing cardiac diseases associated with change in tissue characteristics, such as cardiac fibrosis [7]. To find abnormal MW propagation velocities, we need to know the normal propagation velocities, and to establish these waves as trustworthy and stable phenomena. Studies reporting normal MW propagation velocities in healthy humans are currently few, and studies investigating the velocities at different locations in the left ventricle (LV) are fewer. Thus, there is a need for more contributions to increase the knowledge on normal MW propagation velocities in the LV.

Previous studies have used a conventional tissue velocity estimator, such as Tissue Doppler Imaging (TDI), to estimate the MW velocities. For this study we have used a novel signal processing method called clutter filter wave imaging (CFWI). CFWI was designed to detect MWs propagating through tissue by using a high pass clutter filter to suppress tissue velocities of interest [8]. This method has previously been shown to have a higher signal-to-noise ratio (SNR) than TDI, especially in apical regions [8], and it has previously been used to map the mechanical activation wave in an animal study [9].

For this study, we would like to assess the feasibility of using CFWI and high frame rate (HFR) ultrasound imaging to estimate the velocities of three MWs occurring during the cardiac cycle; after mitral valve closure (MVC) - the MVC wave, after aortic valve closure (AVC) - the AVC wave, and after the atrial kick (AK) - the AK wave. Furthermore, we aim to contribute to increasing the knowledge of normal MW velocities; including whether the estimated velocities are

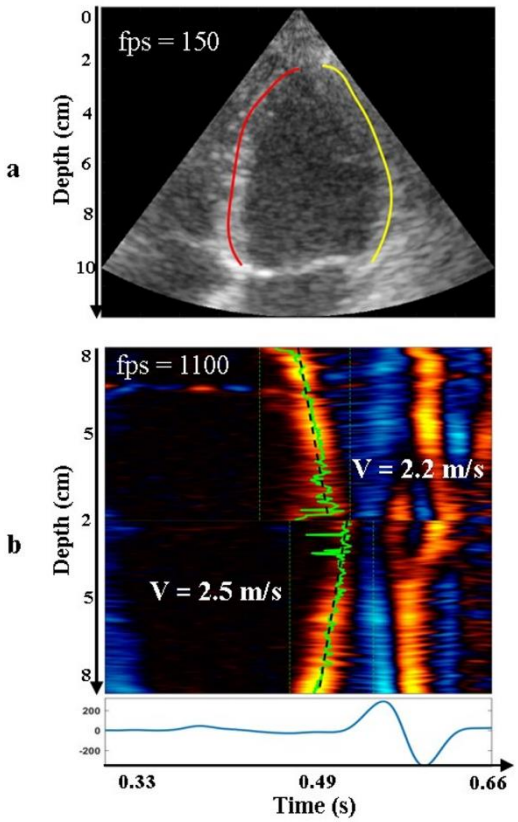

Fig. 1: (a) Manually drawn traces following the septum (red) and lateral wall (yellow). (b) A spatiotemporal M-mode CFWI acceleration map for the septum (top) and the lateral wall (bottom), and the estimated propagation path (dashed line) and corresponding velocities of an AK wave.

affected by the acquisition frame rate, if there is a detectable pattern of naturally stiffer regions in the LV, and finally, describe the variation of velocities between healthy persons.

II. Material and Method

All data analysis was performed off-line using MATLAB (The Mathworks, Natick, MA, USA).

A. Data Acquisition

The studied group consisted of seven healthy volunteers (age from 24 to 45 years old). HFR ultrasound images were acquired with a 2.8-MHz center frequency phased array probe connected to a modified GE Vivid E95 ultrasound system. A weakly focused beam was used to achieve high frame rate and four to six transmit beams per image were used. Data was acquired at 3 frame rate intervals (800-1000, 1100-1500 and >1500 fps) from three standard apical views in 2D; 4-chamber, 2-chamber and long axis. This led to six imaged walls per subject (the septum and lateral wall, the anterior and inferior walls, and the anteroseptal and inferolateral walls). Surface ECG was acquired simultaneously with ultrasound imaging and was monitored from limb lead. The acquisition sequence lasted for about two seconds, which resulted in at least 2 heart cycles per acquisition.

B. Data Analysis

1) Clutter Filter Wave Imaging: The method consists of applying a high pass filter to ultrasound signal data (IQ-data) to suppress tissue velocities of interest. Then, the output from the filter is converted to B-mode images where the propagating velocities of interest are represented by a black void [8]. The steps of the method are first to apply the high pass filter to the IQ data with a normalized cutoff frequency suitable for the velocity of interest. The normalized cutoff velocity is defined as

$$fc_n = Vc \big/ vNyq, \quad (1)$$

with

$$vNyq = \frac{c_0 \times FPS}{4 f_0}, \quad (2)$$

and

$$fc = fc_n \times FPS \big/ 2, \quad (3)$$

where Vc is the cutoff velocity, c_0 is the speed of sound, FPS is the frame rate, f_0 the transmit frequency, v_{Nyq} the Nyquist velocity and f_c the cutoff frequency in Hz. Second, the output from the filter is log compressed to obtain filtered B-mode images. Third, the time derivative of the filtered B-mode signals gives the CFWI acceleration data that is used for MW velocity estimation.

2) Mechanical Wave Velocity Estimation: IQ-data was extracted from the ultrasound scanner and a filter was applied with a normalized cutoff frequency of 0.2 for the AK-wave, corresponding to a cutoff frequency ranging from 80 to 150 Hz depending on the frame rate (from low to high), and 0.25 for the MVC and AVC waves, corresponding to a range of 100 to 187 Hz. The output from the filter was log compressed and derived in time to obtain CFWI acceleration. A low pass smoothing filter was applied to the CFWI acceleration data with a normalized cutoff frequency of 0.05.

For the MW velocity estimation, the walls of the LV were manually traced in the B-mode images for every acquisition (Fig. 1a). The coordinates were used to create an anatomical M-mode trace of CFWI acceleration, creating a spatiotemporal CFWI acceleration map (Fig. 1b). The maximum of the MW for each spatial point was found automatically within a search window in time, defined in the electrocardiogram (ECG) for each MW. A line was fitted to the maximum points of the waves by linear regression analysis and the slope was used to calculate the MW velocity (Fig. 1b). For each linear regression a correlation value was estimated to assess the quality of the velocity estimate. All estimates with a correlation value below 0.4 were excluded. Two velocity estimates were obtained per acquisition and averaged to give one MW velocity value for each LV wall and for each frame rate interval and each MW.

III. Results

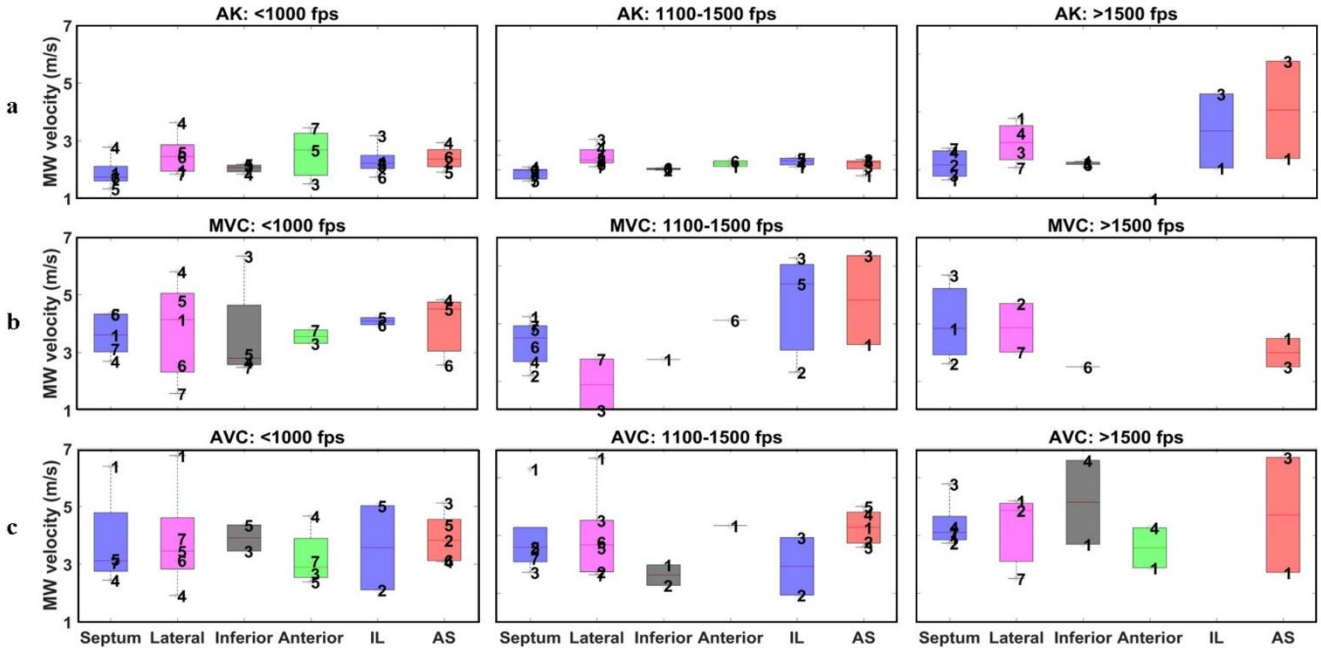

Fig.2: MW velocities for all subjects and for all imaged LV walls for frame rate intervals 800-1000 fps (left), 1100-1500 fps (middle) and > 1500 fps (right). (a) shows the velocities from the AK wave, (b) shows the velocities from the MVC wave, and (c) shows the velocities from the AVC wave. The numbers in the box plots represent each of the 7 subjects, and one color is used for the same wall in all plots. IL = inferolateral, AS = anteroseptal.

A. Mechanical Wave Velocities

The results from the MW velocity estimation are shown in Fig. 2 and Table I. Fig. 2 shows the MW velocities per imaged LV wall for all subjects for the AK wave (a), the MVC wave (b) and the AVC wave (c) for each frame rate interval (800-1000 fps on the left, 1100-1500 fps in the middle and >1500 fps on the right). The estimates are represented by box plots where each box corresponded to one imaged LV wall and each subject was numbered from 1 to 7. The same color was used for each wall throughout the figure. Table I shows the velocity values for each wave and for each frame rate interval averaged for all subjects and LV walls, as well as the number of estimates the average was based on. In common for all three MWs was that for the higher frame rate interval (>1500 fps), the number of excluded estimates and the variation of velocities between subjects increased. For the two lower frame rate intervals, the variation between subjects and number of excluded subjects were fairly similar, especially for the AK and AVC waves.

For the AK wave (Fig. 2a), the result with the highest number of estimates and the lowest variation between subjects was the middle frame rate interval. The velocities ranged from 1.6 to 3.0 m/s, and the average was found to be 2.2±0.2 m/s. An average velocity of 2.5±0.6 m/s was found for all subjects at all frame rates. Slightly higher velocities were observed for the lateral and the anteroseptal walls for the middle frame rate interval, while for the low and high frame rate intervals, higher velocities were observed in the lateral and anterior walls, and the anteroseptal and inferolateral walls, respectively.

The result with the highest number of estimates and lowest range of velocities for the MVC wave (Fig. 2b) was the low fps interval, where the velocities ranged from 1.6 to 6.3 m/s and the average velocity was found to be 3.7±0.2 m/s. For this wave, a slightly decreasing average velocity was observed for increasing frame rate. For all frame rate intervals an average of 3.8±0.5 m/s was found. Higher velocities were observed in the anteroseptal and inferolateral walls for the middle fps interval.

Furthermore, for the AVC wave (Fig. 2c), the result with the lowest range of velocities and the lowest number of excluded estimates was the lower frame rate interval with an average velocity of 3.7±0.3 m/s. The average velocity for all frame rates was found to be 4.0±0.8 m/s for the AVC wave. Higher velocities were observed for the septum and lateral wall for the lower fps intervals, but for the inferior and inferolateral walls for the high fps interval.

IV. Discussion

The propagation velocities for three MWs were investigated for healthy individuals. The aim of the study was to assess the feasibility of using CFWI for MW velocity estimation, and to investigate how velocities were affected by increasing frame rates and how they varied for different persons and regions of the LV. The results with the lower number of exclusions and lower variability were the mid fps interval for the AK-wave and the low fps interval for the MVC and AVC waves. However, results from low and middle fps intervals were similar in quality and the average velocities were fairly consistent. For all MWs, the highest frame rate interval gave estimates with poor correlation values which led to many exclusions. Furthermore, the variation of velocities increased between subjects, shown in Fig. 2 and by increasing standard deviations of the average velocities in Table I. A possible reason for this was the poor spatial resolution inevitable for increasing frame rates for this imaging modality.

TABLE I. AVERAGE MW VELOCITIES

MW	*All (m/s)*	*Low (m/s)*	*n*	*Mid (m/s)*	*n*	*High (m/s)*	*n*
AK	2.5±0.6	2.3±0.3	26	2.2±0.2	28	2.6±1.0	17
MVC	3.8±0.5	3.7±0.2	22	3.6±1.1	16	3.3±0.7	10
AVC	4.0±0.8	3.7±0.3	22	3.7±0.7	22	4.4±0.6	14

The velocities are averaged over all six LV walls and all subjects. Low means the lower frame rate interval 800-1000 fps, Mid means the middle frame rate interval 1100-1550 fps, and High the higher frame rate interval >1500 fps. n represents the number of samples used for each estimate.

The average value for the best result for the AK wave was 2.2±0.2 m/s (Table I). Previous studies have shown MWs occurring at this time in the cardiac cycle with velocities ranging from 1 to 4 m/s [1], and more specific of 1.8 m/s [8], which is within our average when considering the standard deviation. The average velocity for the most reliable result for the MVC wave was 3.7±0.2 m/s. Velocities for healthy persons for this wave have previously been reported for the septum, and found to be 3.2±0.6 m/s [6], and 3.1±0.5 m/s [4]. This fits well with our findings of average velocities per frame rate interval. The velocity for the AVC wave was found to be slightly higher than that of the MVC wave, at 3.7±0.3 m/s for the lower fps interval, and 4.0±0.8 m/s for all frame rates. Other studies have found similar results, of an increased AVC over MVC wave velocity in the septum, at 3.5±0.6 m/s [4, 6]. This result was consistent with how the wall stress varies throughout the cardiac cycle [10]. The pressure of the LV is known to be slightly lower at the time of the AK than the time of MVC, and much higher at the time of AVC. Thus, MW velocities were expected to increase for the AVC wave as higher pressure leads to stiffer tissue.

Previous studies have investigated MW velocities of the septum [4, 6]. For this study, we looked at MW velocities in six different LV walls in the attempt to detect naturally stiffer regions in the LV. For the AK wave (Fig. 2a), higher average velocities (between subjects) were observed for the lateral and the anterior wall, for the lower fps intervals. Higher velocities were found for the MVC wave (Fig. 2b) in the anteroseptal and the inferolateral walls, while higher velocities for the AVC wave (Fig. 2c) were found in the inferior and the inferolateral walls. Thus, there was no detectable pattern between MWs of naturally stiffer regions of the LV for this data set and this method.

Another aim of this study was to investigate the variation of velocities between healthy subjects. A small variation would mean that differentiating between healthy tissue and stiffer, possibly pathologic tissue would be simple. The standard deviations from the most reliable average velocities found from this study (Table I) ranged from a small variation of 0.2 m/s, to a quite large variation of 1.1 m/s. If these variations are significant remains to be evaluated against velocity estimates from patients with known stiffer tissue.

There were several limitations in this study. Most importantly, the sample size was very low which makes it difficult to draw conclusions. However, we still believe that it is valuable to have more contributions on this subject. Additionally, the HFR imaging made the data acquisition more vulnerable. Ensuring that the exact same tissue was imaged between subjects was difficult because obtaining the exact desired view is more challenging with poorer image quality. Further work includes studying a larger group of subjects and comparing this new method to TDI.

V. CONCLUSIONS

We have estimated the MW propagation velocities for three naturally occurring mechanical waves in the LV in healthy volunteers. The study found that the lower frame rate intervals led to more reliable results and fewer excluded samples, in addition to lower variation of velocities between subjects. No pattern of naturally increased stiffness depending on location in the LV was found. Average MW velocities were found to be consistent with literature, but there was also a quite large variation of velocities between subjects. This study had a major limitation in the limited number of studied subjects, thus, a larger group of healthy individuals should be studied, and the MW velocities compared to patients with known elevated tissue stiffness.

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