Electromechanical imaging of the myocardium at normal and pathological states

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Abstract—The motion of the myocardium is mainly due to the contraction and the relaxation of the cardiac muscle. However besides this slow and large motion component, more rapid displacements occur at several periods of the cardiac cycle. Indeed, the contraction of the myocardium is induced by electrical waves that propagate very fast (about 1 m/s) in the cardiac tissue. Due to the electrical excitation, the fibers’ contraction results in a strong mechanical wave that propagates in the myocardium. We propose here a method for measuring the electromechanical coupling properties in the myocardium. Our method is based on imaging and analyzing the delay in small tissue displacements resulting from the propagation of this contraction wave. In-vivo experiments are performed in anesthetized normal and ischemic animals. The contraction wave is first observed in dogs using a commercial clinical scanner. The displacement maps are estimated using a 1D cross-correlation-based technique. The displacement maps clearly show the propagation of a strong mechanical wave along the circumference of the myocardium. The speed of the wave is found to be lower in the ischemic region. Then, thanks to the high frame rate capability of an ultrasound scanner for small animals (Vevo 770, visualsonics), some sequences of approximately three cardiac cycles are acquired at a frame rate of 4000 images/s in mice. The wave velocity is found to be approximately 0.87 m/s in the posterior wall. Temporary regional ischemia is then induced by coronary artery ligation. The velocity of the electromechanical wave is found to decrease to approximately 0.66 m/s in the ischemic region.

I. INTRODUCTION

The heart is a complex electromechanical pump. Therefore, accurate diagnosis of a number of heart diseases would potentially take advantage of quantitative and complete analysis of the electromechanical coupling mechanisms. However, this is currently limited by the lack of non-invasive imaging techniques of the global electromechanical function of the heart.

In order to image the motion of the myocardium several techniques have been introduced recently such as tissue doppler imaging [1] strain rate imaging [2], elastography [3] in the field of ultrasound imaging, or cardiac tagging [4] in the field of magnetic resonance imaging. In these techniques the local deformations of the myocardium are quantified over a complete cardiac cycle in order to provide information on the myocardial viability. Using these techniques, the evaluation of the heart function is based on the mechanical interpretation of the global heart contraction (systole) and relaxation (diastole).

However, the contraction of the cardiac muscle is an active process that results from electrical excitations. During the cardiac cycle, electrical waves propagate in the myocardium in order to initiate the contraction and relaxation of the myocardium. The fibers’ contraction induces a strong mechanical wave that propagates in the myocardium. Since this wave results from coupling of the electrical excitation and the mechanical response of the tissue, it is hereby named ‘electromechanical wave’. This electrical activation occurs in a very short time compared to the following contraction or relaxation of the muscle and therefore cannot be detected in most of the conventional imaging devices.

Moreover, some evidences of mechanical vibrations have been shown by Kanai et al. [5],[6], in human patients. They demonstrated that several pulsive low frequency mechanical vibrations were obtained around end-systole and end-diastole in the frequency range of 25 to 100 Hz. These waves propagate in the myocardium with high velocities up to 5m/s.

We propose here a new approach to image the local mechanical properties of the myocardium. Our method is based on imaging small displacements of the myocardium at high frame rate. This method allows imaging the propagation of the mechanical waves induced both by electrical excitations and mechanical excitation. The wave speed is a function of both electrical and mechanical properties of the myocardium, i.e., the electrical conductivity and the shear modulus, this method could potentially be used for early, noninvasive and simultaneous detection of electrical and mechanical dysfunctions in the heart.

The goal of this paper is to present preliminary results demonstrating the feasibility of imaging in vivo the electromechanical coupling mechanisms in the heart.

II. DOGS EXPERIMENTS

The experiments were performed in an anesthetized open-chested dog. The left descending artery (LAD) was ligated during surgery in order to induce ischemia. The ultrasound images were acquired using a commercial scanner (Terason 2000, Teratech, Inc.) with RF-data storage capability. The
The transducer was placed on the anterior wall of the left ventricle of the heart, to obtain a short axis view. Approximately every two minutes, a sequence of three cardiac cycles was acquired during the experiment, with a frame rate of 56 fps.

The motion detection technique was based on detecting the small displacements of the myocardium that occurs between two consecutive frames. Only axial displacements (in the direction of the transducer) were computed. The time-shifts in the backscattered signals are determined between the two consecutive frames through cross-correlation of small sliding windows (correlation windows of 3 mm, overlapping 90%) over the entire ultrasound image. This technique allows the detection of very small displacements on the order of 50 µm.

On the movie of the displacements, a strong contraction wave is clearly detected (Fig.1). The negative (blue) displacement indicating contraction of the myocardium propagates in the posterior wall from the septum (left side of the images) to the lateral wall (right side). The speed of the propagation was measured by tracking the contraction wavefront in the sequence. An average speed of 1.2m/s was found for the normal part of the heart, and 0.7 m/s for the ischemic region.

III. HIGH FRAME RATE ACQUISITIONS

The goal of these high frame rate acquisitions was to understand better the wave propagation mechanisms taking advantage of the high-frame rate capability available at a high-frequency (35 Hz) scanner for small animals (Vevo 770, Visualsonics). On this system, 2D ultrasound images of the mouse heart are acquired thanks to a high frequency ultrasound probe (30MHz central frequency) composed of a single focused transducer mechanically rotated. The RF signals are then digitized and stored in real-time.

The normal B-mode acquisition frame rate is limited by the mechanical rotation of the probe. However, in order to obtain a high frame rate up to 8000 images/s, the acquisition can be triggered on the mouse electrocardiogram (ECG). For each position of the transducer, on the ECG peak, a set of RF-signals is acquired with a high pulse repetition frequency (PRF) of 8000Hz. Thus, 1D RF signals are recorded in real-time, one line after the other, by the digitizer during several heart beats. Then, the RF data are transferred on a computer and processed off-line. The sequence of 2D ultrasound images is reconstructed at the desired frame rate up to 8000 Hz, based on the ECG signal.

Finally, the axial displacements were computed (correlation windows of 60 µm, overlapping 90%) and a complete movie of the myocardium displacements was processed at a frame rate up to 8000Hz.

These experiments were performed on an anesthetized mouse. The transducer was placed on the chest in parasternal position to obtain a long axis view of the left ventricle. Axial displacements of the myocardium were processed for a complete heart cycle at a high frame. In order to keep large displacements, the frame rate was adjusted at 4000 Hz. In this experiment the duration of a complete heart cycle was about 150ms.

A. Normal mouse

The strong contraction wave was also found in this experiment. A sequence of images, selected around the QRS peak of the ECG shows the contraction of the myocardium (Fig. 2). The contraction starts right on the ECG peak at the apex (right side of the first image) and then propagates in the septum and the posterior wall of the ventricle. It is particularly clear on these images for the posterior wall (bottom wall of the image). In this region the propagation speed of the wave was found to be about 0.87m/s.

B. Ischemic Mouse

The left anterior descending (LAD) artery was then ligated in order to induce ischemia in the left ventricle. One hour after the ligation, the heart was scanned again. Due to ischemia, the displacements are very small and noisy, but it was still possible to follow the contraction and to observe the wave that starts on the QRS peak. However, as for the dog, the contraction wave propagates at a lower speed than in the normal heart. The speed was found to be about 0.66 m/s.
C. Shear waves

Finally, a temporal analysis of the displacement was performed on the previous experiments. The axial displacement along one RF-line of the ultrasound image is shown on the fig 2. with the corresponding ECG signal as a function of time. This image shows clearly the main phases of the heart cycle: the contraction of the myocardium (systole) that started on the QRS peak of the ECG, followed by the relaxation (diastole). These components of the displacement are the “slow” and large components of the motion and are shown by the long blue and red traces. However, some much more rapid variations in the displacements are also visible on this image. The direction of the displacements changes briefly at two different times: at end-systole and end-diastole (see red arrows on Fig.2). A frequency analysis of this variation shows that these rapid displacements are in the frequency range of 70Hz and 200Hz. The middle plot of fig. 4 shows the displacement of a small part of the septum in this bandwidth after a bandpass filtering. It confirms that a first rapid motion occurs at end-diastole right on the QRS peak, and a second one at end-systole. This is very similar to what was found by previous investigators [5-6]. However, it is important to note that the strong contraction wave is not visible on this plot, which indicates its distinct nature.

Fig. 4: Top: displacement of the tissue along a single line of the ultrasound image as a function of time. Red displacements are in the direction of the transducer (located at top of the image) and blue displacements are in the opposite direction. The displacements are shown between -4µm and 4µm. Middle: High frequency component of the displacement as a function of time (between 70Hz and 200Hz). Bottom: ECG signal as a function of time.

The sequence of 2D images corresponding to the end-systolic rapid motion is shown on Fig. 5. On these images, it is clearly visible that this rapid motion, is actually a mechanical wave (shear wave) that propagates in the septum from the left side of the image to the right side. The speed of this shear wave is found to be 1.2m/s.
Fig. 5: Sequence showing the propagation of a shear wave at end-systole. Red displacements are in the direction of the transducer (located at top of the image), and blue displacements in the opposite direction. The shear wave propagates from the base (left side of the image) to the apex (right side), in the septum, the papillary muscle and the posterior wall. The four images were taken every 1.5ms. A large shadowing effect is caused by the ribs on the left half of the image. The red point shows the temporal position on the ECG signal.

IV. CONCLUSION

The motion of the myocardium was imaged in animals using an ultrasound imaging-based technique. We found that a strong contraction wave propagates in the myocardium at the beginning of the ventricular contraction. The speed of this wave decreases in ischemic myocardium. Contrary to the pure mechanical shear waves that propagate in the myocardium, some evidences indicate here that the origin of the contraction wave could be the propagation of the electrical excitation. It will be confirmed in further electrical conduction mapping experiments. This technique could have some important applications in the early detection of heart diseases.

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VI. REFERENCES


