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Assessing the atrial electromechanical coupling during atrial focal tachycardia, flutter, and fibrillation using electromechanical wave imaging in humans

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ABSTRACT

Minimally-invasive treatments of cardiac arrhythmias such as radio-frequency ablation are gradually gaining importance in clinical practice but still lack a noninvasive imaging modality which provides insight into the source or focus of an arrhythmia. Cardiac deformations imaged at high temporal and spatial resolution can be used to elucidate the electrical activation sequence in normal and paced human subjects non-invasively and could potentially aid to better plan and monitor ablation-based arrhythmia treatments. In this study, a novel ultrasound-based method is presented that can be used to quantitatively characterize focal and reentrant arrhythmias. Spatio-temporal maps of the full-view of the atrial and ventricular mechanics were obtained in a single heartbeat, revealing with otherwise unobtainable detail the electromechanical patterns of atrial flutter, fibrillation, and tachycardia in humans. During focal arrhythmias such as premature ventricular complex and focal atrial tachycardia, the previously developed electromechanical wave imaging methodology is hereby shown capable of identifying the location of the focal zone and the subsequent propagation of cardiac activation. During reentrant arrhythmias such as atrial flutter and fibrillation, Fourier analysis of the strains revealed highly correlated mechanical and electrical cycle lengths and propagation patterns. High frame rate ultrasound imaging of the heart can be used non-invasively and in real time, to characterize the lesser-known mechanical aspects of atrial and ventricular arrhythmias, also potentially assisting treatment planning for intraoperative and longitudinal monitoring of arrhythmias.

1. Introduction

Atrial arrhythmias are a major cause of morbidity and mortality worldwide. Extensive research underscores the important role of mechanical factors such as fiber orientation [18], chamber size and wall tension in the onset and perpetuation of atrial arrhythmia (see [6] for a review) and how existing echocardiographic measurements can be used to characterize atrial arrhythmias [19,3,7]. Yet, there is little information on the 2-D spatio-temporal evolution of the local deformations of the atria during e.g., focal tachycardia, flutter, and fibrillation.

Over the last few years, ultrasound imaging has been undergoing important technical improvements with the advent of software-based systems that allow ultra-high frame rates: 2000–5000 frames/s are achieved by using defocused transmissions, as opposed to 50–200 frames/s used in commercial clinical systems, for the depths needed in transthoracic cardiac applications [1,13,14,2,4,5,8]. Such high frame rates allow unprecedented temporal resolution, and, perhaps most importantly, a five-fold improvement in the signal-to-noise ratio of cardiac motion and deformation mapping [15]. Using such techniques, we have recently shown that mapping the transient strains occurring in response to the electrical activation, i.e., the electromechanical wave, can be used to map the transmural activation sequence of the normal and abnormal heart ([10–12]) and to locate pacing sites in patients undergoing cardiac resynchronization therapy [9].

Expanding on this approach, for the purposes of this study, we have developed novel methodologies applied to the study of the mechanical behavior of the atria during four specific types of

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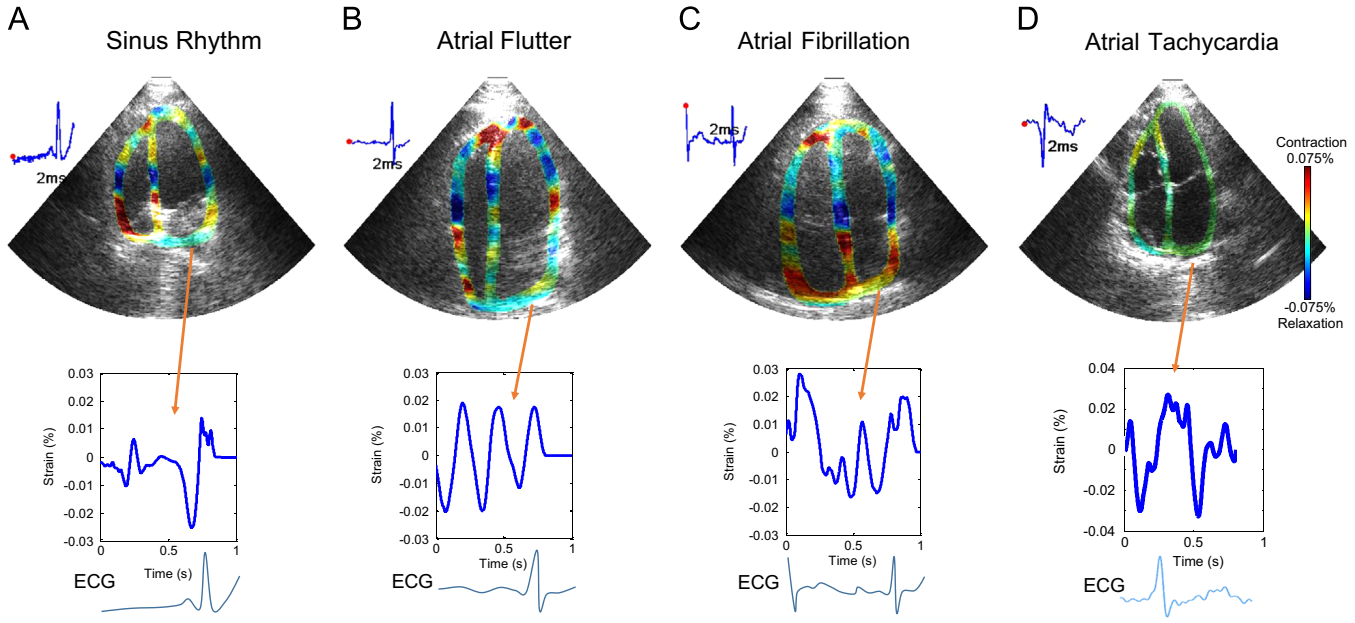

Fig. 1. Representative examples of high temporal resolution strains during different types of arrhythmia. A. During sinus rhythm in a healthy volunteer, two main events can be observed during the cardiac cycle: end-systole, and end-diastole. By tracking the propagation front of the end-diastole electromechanical activation, one can obtain isochrones strongly correlated to electrical isochrones. B. During atrial flutter, the strains are periodic. C. During atrial fibrillation, the strains are chaotic and no period of zero strains are observed as in A. D. During focal tachycardia, distinct events, as in the case of sinus rhythm, can be observed. See corresponding Supplementary video 1.

cardiac arrhythmia, i.e., premature ventricular complex, focal tachycardia, atrial flutter and atrial fibrillation. We first show that while the previously developed approach of Electromechanical Wave Imaging (EWI) is apt at characterizing premature ventricular complex and focal tachycardia, which are focal rhythms, it might not be optimal in fully describing reentrant rhythms such as atrial flutter and fibrillation. To palliate this issue, we developed a novel technique for the description of electromechanical strains during reentrant rhythms based on the Fourier analysis. We introduced a single acquisition sequence that can be used for either standard EWI or for the Fourier analysis of electromechanical strains which constitutes this novel diagnostic tool namely 'electromechanical activation mapping', which can describe the electromechanical strains propagation patterns during both focal and reentrant arrhythmias. To our knowledge, no other previously reported study can characterize atrial strains during arrhythmia. We demonstrate that the local deformations of the atria are often closely correlated with their electrical activation and could be used to better assess the role of cardiac mechanics in arrhythmia and, potentially, to better plan ablation treatments and monitor their efficacy non-invasively and in real-time, longitudinally.

2. Methods

The study protocol was approved by the Institutional Review Board (IRB, protocol AAAA9333) of Columbia University, and written informed consent was obtained from all human subjects prior to scanning. All human subjects underwent a diagnostic ultrasound scan a few minutes to a few hours prior to an electroanatomic mapping and ablation procedures. The cardiac arrhythmias of the patients were confirmed during that procedure: premature ventricular complex ($n=1$), atrial flutter ($n=5$), focal atrial tachycardia ($n=1$), and atrial fibrillation ($n=1$). Patients for which ectopic foci were located outside the echocardiographic apical 4-chamber view were excluded. The total number of subjects was equal to 9, i.e., 8 patients and 1 control.

Strain maps were first generated using methods akin to the ones developed for single-heartbeat electromechanical wave imaging (EWI) [13]. More specifically, a Verasonics system with a 2.5-MHz probe was calibrated and customized to adhere to FDA standards both in terms of mechanical index and of spatial-peak-temporal-average intensity and was deemed a non-significant risk and approved for human use by the IRB of Columbia University. The ultrasound scan was composed of two sequences. First, a motion-estimation sequence, in which a spherical ultrasonic wave was emitted with a virtual focus 10.2 mm behind the probe at 2000 fps during 2 s. Immediately following this sequence, a standard B-mode acquisition was performed during 1.5 s to accurately depict the heart anatomy. This additional sequence is necessary because the B-mode images obtained from the motion-estimation sequence provide low contrast due to the use of diverging waves and is thus of limited clinical use. Frames from the motion-estimation sequence were reconstructed by generating 128 beams in post-processing via a delay-and-sum algorithm with a reconstructed sampling frequency of 20 MHz. The motion-estimation rate and the motion-sampling rate were 1000 and 2000 fps, respectively. The window used for motion-estimation was of 9.2 mm with an overlap of 95.8% (window shift of 0.3 mm) and the kernel used for strain estimation was 4.9 mm. Beamforming, motion-estimation, strain estimation, spatial moving-average of the strains (12 mm by 10 lines), and the automated contour tracking technique were performed off-line using a Tesla GPU (Nvidia, Santa Clara, CA) and the Matlab parallel processing toolbox (The Mathworks, Nattick, MA) at a computing speed of 2.4 frames/s.

As high frame-rate mechanical data was acquired in patients with different types of rhythms, it became apparent that focal and reentrant arrhythmias had to be analyzed differently. Fig. 1 and Supplementary video 1 show the strains mapped in subjects who have sinus rhythm (Fig. 1a), atrial flutter (Fig. 1b), atrial fibrillation (Fig. 1c), and atrial focal tachycardia (Fig. 2d). In subjects in sinus rhythm, the strains in one location, e.g., one pixel in the LA, presented two main events over time that corresponded

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