A clinical feasibility study of atrial and ventricular electromechanical wave imaging

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BACKGROUND Cardiac resynchronization therapy (CRT) and atrial ablation procedures currently lack a noninvasive imaging modality for reliable treatment planning and monitoring. Electromechanical wave imaging (EWI) is an ultrasound-based method that has previously been shown to be capable of noninvasively and transmurally mapping the activation sequence of the heart in animal studies by estimating and imaging the electromechanical wave, that is, the transient strains occurring in response to the electrical activation, at both high temporal and spatial resolutions.

OBJECTIVE To demonstrate the feasibility of transthoracic EWI for mapping the activation sequence during different cardiac rhythms in humans.

METHODS EWI was perfor`med in patients undergoing CRT and a left bundle branch block (LBBB) during sinus rhythm, left ventricular pacing, and right ventricular pacing, as well as in patients with atrial flutter (AFL) before intervention, EWI findings from patients with AFL were subsequently correlated with results from invasive intracardiac electrical mapping studies during intervention. In addition, the feasibility of single-heartbeat EWI at 2000 frames/s is demonstrated in humans for the first time in a patient with both AFL and right bundle branch block (RBBB).

RESULTS The electromechanical activation maps demonstrated the capability of EWI to localize the pacing sites and characterize the bundle branch block activation sequence transmurally in patients with CRT. In patients with AFL, the EWI propagation patterns obtained with EWI were in excellent agreement with those obtained from invasive intracardiac mapping studies.

CONCLUSIONS Our findings demonstrate the potential capability of EWI to aid in the assessment and follow-up of patients undergoing CRT pacing therapy and atrial ablation, with preliminary validation in vivo.

KEYWORDS Ablation; Arrhythmias; Noninvasive imaging; Pacing

ABBREVIATIONS **AFL** = atrial flutter; **CRT** = cardiac resynchronization therapy; **ECG** = electrocardiogram; **EW** = electromechanical wave; **EWI** = electromechanical wave imaging; **LA** = left atrium/atrial; **LBBB** = left bundle branch block; **LV** = left ventricle/ventricular; **NYHA** = New York Heart Association; **RA** = right atrium/atrial; **RBBB** = right bundle branch block; **RF** = radiofrequency; **RV** = right ventricle/ventricular

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Introduction

Left bundle branch block (LBBB) and atrial tachyarrhythmias are associated with heart failure, morbidity, and mortality and can be treated with biventricular pacing therapy and radiofrequency (RF) ablation, respectively. These treatment strategies would benefit significantly from the availability of a noninvasive imaging modality capable of accurately mapping of the electrical activation in the heart. The only noninvasive tool widely available to the physician is the 12-lead electrocardiogram (ECG). The 12-lead ECG does, however, have limitations in reliably determining the site of origin or specific underlying mechanism of atrial tachyarrhythmias, such as macroreentrant atrial flutter (AFL) vs focal atrial tachycardia. A detailed mapping of cardiac electrical activity during arrhythmias can be achieved with intracardiac electroanatomical mapping. This approach is, however, costly, time-consuming, and, as with any invasive procedure, carries some degree of risk. Both 12-lead ECG and invasive methods are also limited in their utility for monitoring response to cardiac resynchronization therapy (CRT) over an extended period of time. The mechanisms by which CRT can reverse heart failure are not fully understood, and the lack of tools to longitudinally study the electromechanical effects of CRT has limited the development of effective techniques for the optimization of pacing parameters.[1,2]

Electromechanical wave imaging[3–6] (EWI) is an ultrasound-based imaging method that can noninvasively map the cardiac electromechanical activity in all 4 heart chambers[5] by tracking, at high temporal and spatial

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resolutions, the electromechanical wave (EW), that is, the transient deformations occurring in response to the local electrical activation. Previous in vivo and in silico animal studies indicated that EWI can map the activation sequence in normal and abnormal hearts in which electrical and electromechanical activations remain correlated, such as sinus rhythm, electrical pacing, LBBB, atrioventricular block, and even fibrillation in vivo.[5,7–9,18] When this correlation disappears in conditions such as ischemia, the ischemic region could be mapped with high accuracy.[4] Other studies have also reported a correlation between the onset of mechanical activity and the electrical activation sequence.[10–12] In addition, the EWI isochrones obtained in normal human subjects reflected accurately the expected activation sequence of normal sinus rhythm.[5] In this study, we investigate the clinical feasibility of EWI for treatment monitoring of CRT in patients with LBBB and treatment planning of AFL ablation.

Methods

Patient selection

The study protocol was approved by the Institutional Review Board of Columbia University, and informed consent was obtained from all human subjects prior to scanning. Normal subjects (aged 21–23 years; n = 3) were imaged by a trained cardiologist. Three subjects treated with CRT (n = 3) were scanned during scheduled routine device checks. The device was first configured to pace only from the left ventricle (LV), after which EWI was performed in the 4-chamber view. EWI was then performed when the device was set to pace only from the right ventricle (RV) and when the device was not pacing. The pacing rate was adjusted to sufficiently high values to minimize beats triggered by sinus rhythm. In patients with AFL (n = 3), EWI was performed a few minutes to a few hours prior to the scheduled mapping and ablation procedures.

EWI

EWI is performed by mapping the transient deformations (strains) occurring during the electrical activation of the heart using RF speckle cross-correlation. Achieving sufficient imaging frame rate is the main challenge in mapping the EW for 2 reasons: First, the EW must be tracked without aliasing, which we estimated could be avoided above approximately 120 fps.[8] Second, the mapped displacements and strains have to be estimated with high accuracy. This accuracy is mostly dependent on the frame rate: it is acceptable above 300 fps but optimal when reaching approximately 1000 fps. Such frame rates are not typically achieved with commercial imaging sequences in a full field of view for cardiac applications.

Two imaging methods were used to perform EWI in this study. The automated composite technique[13] (Figures 1–4) is based on conventional image formation using standard ultrasound systems: images are formed by using focused ultrasound emissions, that is, 1 per line. To achieve sufficiently high frame rates (320–400 fps in this study), the full view of the heart was divided into overlapping sectors and reconstructed by using motion matching,[4] a method similar to ECG gating. Images in single-heartbeat EWI (Figure 5) are formed by using diverging emissions that probe the entire field of view in a single emission.[7] This technique allows frame rates that are typically 100 times larger (up to 2000 fps in this study) than with conventional image formation. While the automated composite technique is easier to implement on existing ultrasound scanners, it requires long acquisition times (~20 seconds) and is limited to repeatable rhythms. Single-heartbeat EWI requires a modern ultrasound scanner that allows the sampling of individual piezoelectric elements but can be performed in real time. A detailed description of the EWI methods is provided in Supplementary Material 1.

Results

Biplane EWI ciné loops and isochrones were obtained in apical views (Figure 1), in which the electromechanical activation corresponds to a transition from lengthening (positive strains) to shortening (negative strains). Our previously described methodology[5] was used for all the patients in this study, with the exception of the patient with AFL and right bundle branch block (RBBB) presented in Figure 5, for which single-heartbeat EWI was used.[7]

Normal subjects

In all 3 normal subjects scanned for this study (Figures 2A–C; Supplemental Material 2), the EW was found to originate in the right atrium (RA), propagating toward the left atrium (LA). During the QRS complex, the EW propagated in the ventricles from multiple origins and propagated transmurally from the endocardium to the epicardium. Figures 2D and 2E depict, respectively, the atrial and ventricular activation of the first normal subject (Figure 2A) in greater detail. The EW originated in the superior wall of the RA, near the lateral wall, and propagated toward the LA (Figure 2D). The site of the earliest activation is compatible with the expected location of the sinus node. In the 2-chamber view (Figure 2D), which depicts the LA and the LV, the EW originated in the superior wall of the LA and propagated toward the posterior and anterior walls. The last region to undergo electromechanical activation was located in the LA anterior wall, near the mitral valve (Figure 2D). After a delay similar to the PR segment, the ventricles were activated from three main origins, that is, near the apex in the posterior wall, at the mid-level of the septum, and near the base in the anterior wall, as depicted in the electromechanical activation isochrones (Figure 2E). From these three origins, the EW propagation occurred transmurally from the endocardium toward the epicardium (Figure 2E; Supplemental Material 2).

Cardiac resynchronization therapy

EWI was performed in subjects with CRT with an underlying LBBB during either sinus rhythm, LV epicardial pacing only, or RV pacing only in three subjects (n = 3) with New