Electrocardiographic Imaging (ECGI) of Cardiac Electrophysiology In Humans

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Abstract: Electrocardiographic Imaging (ECGI) is a cardiac functional imaging modality, noninvasively reconstructing epicardial potentials, electrograms and activation sequences (iscochrones) from multi-channel body surface potential recordings obtained with 250 electrodes on the torso. Electrode positions and epicardial geometry are obtained simultaneously from ECG-gated thoracic computed tomography (CT) scans. This novel noninvasive imaging modality depicts the true underlying cardiac electrophysiology and brings about a promise for better diagnosis and study of mechanism of arrhythmias. The procedure involves solving Laplace’s equation in the source free volume conductor between heart and torso. We discretize the torso and epicardial surfaces by Boundary Element Method (BEM), using an isoparametric linear interpolation scheme over triangular surface elements to obtain a relationship \( \Phi_L = \Phi_T \), where \( \Phi_L \) and \( \Phi_T \) denote epicardial and torso potentials respectively. We use ECGI to noninvasively image epicardial potentials, electrograms and isochronal images in normal human subjects. We also use image repolarization by constructing activation recovery interval maps on the epicardium. We show the ability of ECGI to image abnormal cardiac activity in humans with single examples of right bundle branch block (RBBB), right (RV) and left ventricular (LV) pacing, and atrial flutter (AF). Further, we formulate a quadratic interpolation (QI) scheme for potentials over six-noded triangles for our ECGI problem. We show using examples of paced beats in humans, that the new QI scheme can improve accuracy of localization in both right and left ventricles.

1. Normal Activation and Repolarization
   a) Epicardial Potentials
      A. Before Breakthrough
         Right, activation front approaching the right ventricular epicardium (10 ms) generates positive (+) potentials. Left, corresponding measured potentials in chimpanzee heart. (Spach et al.²)
      B. Right Ventricular Breakthrough
         Upon breakthrough (21 ms), a local intense potential minimum (blue) appears at the breakthrough site (measured chimp potentials², left).
   b) Electromgrams
      Measured Chimpm Electromgrams (Spach et. al.)
      ECGI reconstructed noninvasive electrogram in one of our normal human subjects.

2. Abnormal Activation
   a) Right Bundle Branch Block (RBBB)
      Noninvasive epicardial potential map in a human subject R with RBBB, showing a delayed right ventricular breakthrough (49 ms) at location 1.
   b) Electrograms
      Measured Chimpm Electromgrams (Spach et. al.)
      ECGI reconstructed noninvasive electrogram in one of our normal human subjects.
   c) Isochrones (Activation Sequences)
      Noninvasive epicardial isochronal maps from three of our normal human subjects.

3. Abnormal Activation
   A. Anterior and diaphragmatic views of epicardial potential maps during T wave. Maps during T-wave onset (top row), peak (middle row) and end (bottom row) are shown (see lead II for timing). B. Epicardial recovery-time isochores. C. Epicardial Activation Recovery Interval (ARI) map. D. Epicardial QRS-integral map.

4. Ventricular Repolarization
   a) Right Bundle Branch Block (RBBB)
      Noninvasive epicardial isochronal map in RBBB subject.
      The earliest activation sites were along the left paraseptal region, corresponding to the anatomical location of left bundle branch, and the latest activation was on the basal right ventricle.
   b) Ventricular Pacing
      i) RV Pacing
         i) Anterior view of reconstructed epicardial potential map showing potential minimum (dark blue) in the apical RV region. The pacing site is reconstructed to within 7 mm (LI) and 2 mm (QI) of the pacing lead location as determined from CT.
      ii) Epicardial potential maps during activation (42 ms after pacing) during LV pacing in the same subject. Errors of localization of pacing site are 15 mm (LI) and 7 mm (QI).
   c) Atrial Flutter
      Atrial activation. a) Normal atrial isochrones shown for reference. Left, superior posterior view. Right, lead V2 of ECG, with P-wave shaded in light blue. b) Isochrones during atrial flutter in subject AFI. Four views are shown. ECG lead V2 is shown, with imaged flutter cycle shaded blue. Black arrows in anterior view indicate the reentrant circuit, beginning from isthmus, entering the septum, reentering Bachman bundle and propagating down right atrial free wall (RAFW) to reenter isthmus again (a segment of the circuit is also indicated in right lateral view by black arrow). Solid arrows indicate epicardial activation. The asterisk (*) indicates breakthrough at Bachman bundle. White arrows indicate waveform propagation around SVC (inferior IVC) and up to end of RA-EVF. Activation of LA is shown by gray arrows in anterior and posterior views.

Conclusions
- Results demonstrate the ability of ECGI to image human cardiac electrophysiology noninvasively.
- ECGI located pacing sites simulating ectopic arrhythmogenic foci, to within 2 mm (RV) and 7 mm (LV). The quadratic interpolation (QI) scheme provides a higher accuracy of localization compared to linear interpolation (LI).
- ECGI imaged the reentry circuit responsible for atrial flutter, showing that the circuit was located entirely in the right atrium (RA), with the isthmus between IVC and tricuspid annulus being a critical component of the reentry circuit (consistent with it being a target for ablation therapy).

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References