NONINVASIVE ECG IMAGING [ECGI] OF CARDIAC ARRHYTHMIAS

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Cardiac arrhythmias are a major cause of death and disability
(prevalence: 3.9 million/yr; mortality: about 325,000/yr in U.S.; mortality is estimated at 7 million/yr worldwide)

**Current Method for NonInvasive Diagnosis**

- **ECG** (or its extension to many torso surface electrodes) –
  Obtains and analyses data on the body surface, far away from the heart, and cannot resolve or locate electrical events in the heart

- **Lacks sensitivity**
  Cannot detect arrhythmogenic substrate in many cases, or sufficiently early for preventive intervention

- **Lacks specificity**
  Cannot provide specific diagnosis of mechanism for specific therapy
How are Torso ECG Potentials Generated from Epicardial Potentials?

\[ V_{ECG} = \frac{1}{4\pi} \int V_{EPI} \nabla \left( \frac{1}{r} \right) ds + [\text{Other Terms}] \]

Over Entire Heart Surface

Epicardial Potentials     Torso Potentials

Ramsey et. al., Circ Res, 1977
Electrocardiographic Imaging (ECGI)

- Noninvasive imaging is a corner stone of the practice of modern medicine (CT, MRI, Ultrasound). It is used for risk stratification, diagnosis, guidance of therapy, and follow-up.

- Noninvasive imaging is also used extensively for research of disease processes in humans.

- Despite the need, a noninvasive imaging modality for cardiac arrhythmias does not exist yet.

ECGI is a new imaging approach that reconstructs potentials, electrograms, isochrones and repolarization patterns on the heart surface from body-surface electrocardiographic measurements, noninvasively.
The ECGI Procedure

CT Scan → CT Images → Heart-Torso Geometry

Electrodes Strips → 250 Electrocardiograms

Body Surface Potentials → Epicardial Surface

PNAS 2006;103:6309-6314
http://rudylab.wustl.edu
Volume between the heart and the body surface is source free - governed by Laplace’s Equation:

\[ \nabla^2 \Phi = 0 \]

Green’s 2\textsuperscript{nd} theorem: integrals of \( \Phi \) over the heart and torso surfaces

Forward Problem

\[
\begin{bmatrix}
\Phi_T
\end{bmatrix} = \begin{bmatrix}
A
\end{bmatrix} \begin{bmatrix}
\Phi_E
\end{bmatrix}
\]

Torso potential

Heart (epicardial) potential

Boundary Element Method
The reconstruction of $\Phi_E$ from $\Phi_T$ is an ill-posed inverse problem.

Cannot simply invert

\[
\begin{bmatrix}
\Phi \\
\Phi_T
\end{bmatrix}
= \begin{bmatrix}
A
\end{bmatrix}
\begin{bmatrix}
\Phi \\
\Phi_E
\end{bmatrix}
\]

because $A$ is ill-conditioned and $A^{-1}$ is close to singular.
Cardiac Inverse Problem - Methods

I. Tikhonov regularization

\[ \min_{\Phi_E} \left[ \left\| A\Phi_E - \Phi_T \right\|^2 + t \left\| L\Phi_E \right\|^2 \right] \]

- \( t \) = regularization parameter
- \( L \) = Unity, Gradient or Laplacian operator

Laplace's equation

constraint
II. Generalized Minimal Residual Method (GMRes) – an iterative approach

- $A^{-1}$ is approximated by polynomial $p(A)$

\[
\Phi_E = p(A) \Phi_T
\]

- $p(A) \Phi_T$ defines a Krylov subspace, $K$

- For $n$ iterations, $K_n = \text{span}\{\Phi_T, A \Phi_T, A^2 \Phi_T, \ldots, A^{n-1} \Phi_T\}$

- The order of $p(A) \Phi_T$ increases with each iteration

- Residual $||A \Phi_E - \Phi_T||$ decreases with each iteration

- Iteration stops when: residual $< \text{specified tolerance}$ or number of iterations exceeds a specified maximum

- Best iterate is chosen as the solution

Ann Biomed Eng 2003;31:981-994
The approach was validated extensively in torso-tank and animal experiments in normal and infarcted hearts.

Circulation; Circ Res; JACC; and http://rudylab.wustl.edu
Validation by Invasive Surgical Mapping

CT

BSPM

ECGI

Compare

Recording Strips

Epicardial Patches

Venous Cannula

Temporary epicardial pacing leads (RV)
Noninvasive Electrograms (Sinus Rhythm)

Anterior RV

Invasive Noninvasive

CC=0.98 (6ms)
0.97 (8ms)
0.94 (8ms)
0.96 (7ms)
0.94 (13ms)
0.96 (0ms)
0.97 (14ms)
0.97 (8ms)
0.92 (2ms)
0.93 (6ms)

Heart Rhythm
2005;2:339-354
Atrial Arrhythmias

Atrial Flutter

Atrial Fibrillation
TYPICAL ATRIAL FLUTTER

Normal Isochrones

Flutter Isochrones

LAA: Left atrial appendage
IVC: Inferior vena cava
SVC: Superior Vena cava
TA: Tricuspid Annulus
MA: Mitral Annulus
PV: Pulmonary vein
RAFW: Right atrial free-wall
SEP: Septum
CrT: Crista terminalis.

Cycle length: 200 ms

Example: PAROXYSMAL ATRIAL FIBRILLATION

Both focal triggers and spiral waves are observed.

LIPV

Red: Activation Front
Abnormal Ventricular Repolarization

Early Repolarization Syndrome
Normal Ventricular Repolarization

A. Epicardial Potential Map
   Onset of T-wave
   - Lead II
   - Anterior
   - Diaphragmatic

   Peak of T-wave

B. Electrograms
   - RV
   - LV
   - 1: 30 ms, 255 ms
   - 2: ARI: 225 ms, ARI: 265 ms, DARI=40 ms

C. Recovery Time Isochrones
   - Anterior
   - Posterior
   - Color scale: 260 ms to 360 ms

D. Activation Recovery Intervals (ARI)
   - Anterior
   - Posterior
   - Color scale: 290 ms to 260 ms

7 SUBJECTS
Mean ARI=235 ms
Mean LV apex-to-base ARI dispersion=37 ms

PNAS 2006;103:6309-6314
Repolarization abnormalities create substrate for reentry and arrhythmia

Can this substrate be detected noninvasively?
Early Repolarization Syndrome associated with Sudden Death: ECG of Identical Twins

Heart Rhythm 2010;7(4):534-537
Early Repolarization associated with Sudden Death: Activation and Repolarization Maps of Surviving Twin [Sinus Rhythm]

- Islands of very short ARI=140ms (normal is 235ms)
- Extremely large local repolarization gradients: DARI=107ms/cm (normal is 11ms/cm)

Heart Rhythm 2010;7(4):534-537
Electrocardiographic Imaging (ECGI) of Cardiac Resynchronization Therapy in Heart-Failure Patients: Observation of Variable Electrophysiological Responses

Heart Rhythm 2006;3:296-310
Heart failure \(\rightarrow\) LV conduction delay
(LBBB pattern)

Electrical Dyssynchrony

↓

Mechanical Dyssynchrony

↓

↓ Pump Function
HEART - FAILURE SUBSTRATE

Native Rhythm (NR)

- Heterogeneous LBBB activation patterns
- Relatively normal RV activation
- LV activation is delayed 90ms relative to RV (normal is less than 40ms)
- Anterior lines of block/slow conduction, U-shaped activation around block
- Latest activation region varies; lateral LV base is most common

*Heart Rhythm* 2006;3:296-310

Esyn = lateral (RV – LV) activation
Native Rhythm and BiV Pacing  ( 2 responders )

- Large inter-patients variability in activation patterns and synchrony

- Patient 5: Lateral LVP; BiV improved Esyn from -113 to 20ms

- Patient 3: Anterior LVP; BiV improved Esyn from -93 to -45ms

*Heart Rhythm* 2006;3:296-310
Native Rhythm and BiV Pacing (2 non-responders)

- Patient 8: Lateral LVP; BiV improved Esyn from -56 to -26ms (QRS did not shorten); Latest activation in anterior LV (132ms)

- Patient 4: Anterior LVP; lateral LV activation was greatly slowed relative to NR

*Heart Rhythm 2006;3:296-310*
Fusion Beats during LV Pacing

- 3 of 4 patients with intact AV conduction showed fusion with intrinsic excitation during LV pacing with optimal AV delay.

- Degree of fusion increased with increase of AV delay (delay from atrial pacing to LV pacing), because intrinsic RV activation occurred progressively earlier relative to LV pacing.

- Esyn improved as fusion increased.

*Heart Rhythm* 2006;3:296-310
Yong Wang                         Bruce Lindsay
Subham Ghosh                     Ed Rhee
Li Li                            Mitch Faddis
Ramya Vijayakumar                Russell Canham
Junjie Zhang                     Pamela Woodard
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Alan Desouza                     Dan Cooper
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Raja Ghanem          Robert Gilkeson
Paul Ryu              Bruce Stambler
Anselma Intini       Niraj Varma
Albert Waldo          William Stevenson
Alan Markowitz       Pedro Brugada
Michel Haissaguerre

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