Inference of Epicardial Potentials from Multipolar Equivalent Sources Using Aimed Leads

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Inference of Epicardial Potentials

Abstract

Epicardial potentials are commonly inferred by calculating coefficients, which directly link epicardial and body surface potentials, via the boundary-element method (BEM). Epicardial potentials may also be found from multipolar cardiac-equivalent sources using the aimed-lead method (ALM). Because the inverse solution for the multipole sources in the ALM need not be dependent on heart geometry and may meet correlation constraints assumed for many regularization techniques better than the BEM, we hypothesized that the ALM may yield more accurate estimates of epicardial potentials than the BEM. To test the performance of each method, we compared ALM and BEM solutions in a 5-layer eccentric-spheres model with a dipole layer source. With optimal Tikhonov regularization, no noise, and no errors in geometry, the relative error for the ALM and BEM was 0.27 and 0.29, respectively. When 5% Gaussian noise (RMS noise value/RMS potential value) was added to body-surface potentials, the relative error for the ALM and BEM was 0.32 and 0.34, respectively. With optimal regularization, no noise, and an error of +/- 1 cm in the location of the heart, the average relative error for the ALM and BEM was 0.36 and 0.41, respectively. Both ALM and BEM were also applied to body-surface measurements of an adult male with a pacemaker. The pacing electrode was implanted at the ventricular apex. Torso geometry, the location of 190 electrodes, and the location and orientation of the transducer of an ultrasonic probe used to image the heart were measured to within 0.1 cm with an Immersion Personal Digitizer. Torso geometry was approximated by a tenth-degree spherical-harmonic model. The heart was modeled as a sphere with a radius of 2.79 cm. At 16 ms after pacing, the distance from the pacing electrode to the minimum of the epicardial maps for the ALM and BEM was 1.07 cm and 1.06 cm, respectively. These results suggest that inference of epicardial potentials with multipolar equivalent sources may yield improved estimates of epicardial potentials if appropriate regularization techniques can be devised for multipolar sources.

Aimed Lead Method (ALM) vs Direct Boundary Element Method (BEM)

1. The direct inference of epicardial potentials using the boundary element method (BEM) has been carefully studied; yet, even with optimal regularization, relative errors between inferred and actual epicardial potentials range from 0.43 to more than 1 when applied to humans.

2. In the aimed-lead method (ALM), epicardial potentials are inferred from weighted sums of multipolar cardiac-equivalent sources.

3. Determining epicardial potentials from multipolar sources may improve potential estimates because multipole terms:
   - Need not be dependent on heart geometry.
   - May be better regularized because they are more likely to be uncorrelated than epicardial potentials.

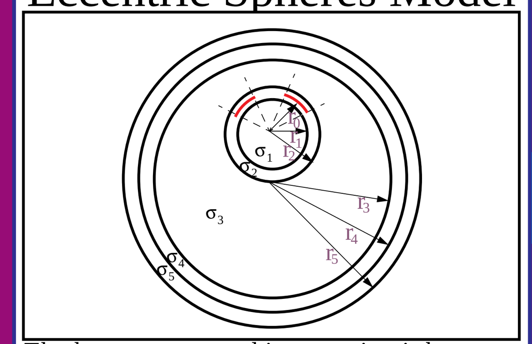
Objectives

1. Compare the ability of the ALM and BEM to infer epicardial potentials in an eccentric spheres model using optimal Tikhonov regularization in the presence of:
   - Errors in heart location
   - Noise in body surface potentials

2. Demonstrate and test the use of the ALM and BEM to infer epicardial potentials in humans

Eccentric Spheres Study

Eccentric Spheres Model



The heart, torso, and intervening inhomogeneities were represented as spheres, with the heart placed eccentrically within the torso. Cardiac sources were represented by a dipole layer (in red). Potentials were generated assuming conductivities σ_1 through σ_5 were 0.006, 0.002, 0.0005, 0.00125, and 0.0004 S/cm, respectively, and r_0 through r_5 were 4.7, 4.0, 5.1, 8.0, 9.0 and 10.0 cm, respectively.

Forward Problem

Forward problem coefficients were calculated assuming:
- The heart was homogeneous with conductivity $\sigma_1 = 0.006$ S/cm and radius $r_2 = 5.0$ cm.
- The torso was homogeneous with conductivity $\sigma_5 = 0.002$ S/cm and radius $r_5 = 10.0$ cm.
- The eccentricity of the heart was 1.3 cm.

and using:
- 512 nodes on the heart and body surfaces.
- Radon 7-point numerical integration.

Methods

1. Potentials generated on the heart and torso surfaces by a distributed cardiac source were calculated analytically, using a 5-layer eccentric spheres model.

2. Forward problem coefficients were calculated for the ALM and BEM using only the conductivities for the heart and torso.

3. Epicardial potentials were inferred using the ALM and BEM with optimal Tikhonov regularization, when torso potentials were:
   - Calculated with a different eccentricity of the heart than was assumed for the forward problem coefficients
   - Corrupted with Gaussian noise.

Inverse Problem

- For the ALM, the multipole source was found as:

$$M = (T_{BO}^{*}T_{BO} + tH)^{-1}T_{BO}^{*}\Phi_B$$

where M are coefficients, (a_{nm}, b_{nm}), describing the multipole sources, T_{BO} are coefficients relating the multipole at an origin to torso potentials, Φ_B. The potential measured by an aimed lead, V_{aimed}, at location (θ_o, ϕ_o) on a sphere of radius R is given by

$$V_{\mathrm{aimed}} = \sum_{n=1}^{\infty}\sum_{m=0}^{n}\frac{2n+1}{2nR^{n-1}}P_n^{\ m}(\cos\theta_o) \bullet (a_{nm}\cos(m\phi_o) + b_{nm}\sin(m\phi_o))$$

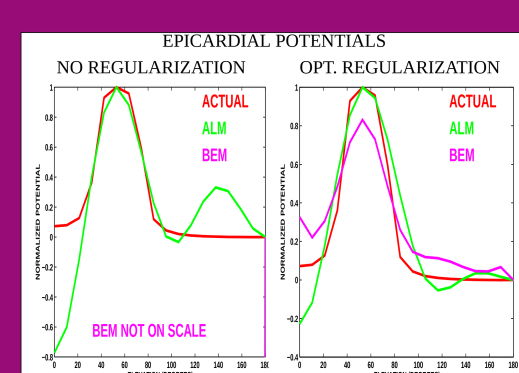
- For the BEM, epicardial potentials were found directly as:

$$\Phi_H = (Z_{BH}^{*}Z_{BH} + tH)^{-1}Z_{BH}^{*}\Phi_B$$

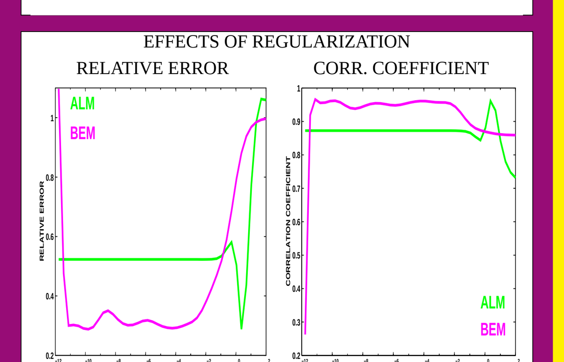
where Z_{BH} are coefficients relating epicardial and torso potentials.

Regularization

- For the ALM, the regularization matrix was constructed assuming signal and noise are spatially uncorrelated and uniformly distributed and that each term in the multipole expansion contributes equally to signal power on the heart surface. The result is a diagonal matrix whose terms are dependent on the radius of the heart and the multipole term.
- For the BEM, the regularization matrix was set equal to the identity matrix.
- Optimal regularization was assumed for the value of t which minimized relative error in the inferred epicardial potentials.



Inverse calculated epicardial potentials without regularization and with optimal Tikhonov regularization when no noise or errors were added to the system.

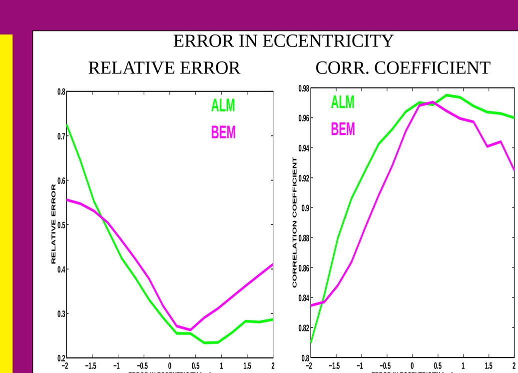


Relative errors and correlation coefficients as a function of regularization parameter, t, when no noise or errors were added to the system.

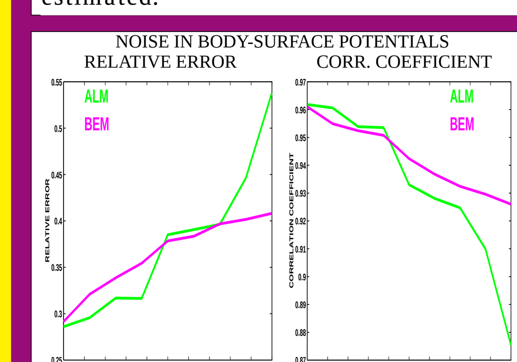
Results

Optimal Regular.	Relative Error		Corr. Coeff.	
	ALM	BEM	ALM	BEM
No Noise Exact Geom	0.27	0.29	0.97	0.96
5% Noise Exact Geom	0.32	0.34	0.95	0.95
No Noise Geom +1cm	0.25	0.33	0.97	0.96
No Noise Geom -1cm	0.47	0.49	0.91	0.87

- When forward problems were calculated with an error in eccentricity of less than ±1 cm, results were better for the ALM than BEM.
- The ALM performed better than the BEM when less than 10% noise was added to body-surface potentials.



Relative errors and correlation coefficients as a function of error in eccentricity. Both methods performed better when eccentricity was overestimated rather than underestimated.



Relative errors and correlation coefficients as a function of noise added to body-surface potentials. Percent noise is the RMS value of the noise divided by the RMS value of the actual torso potential.

Application to Humans

Methods

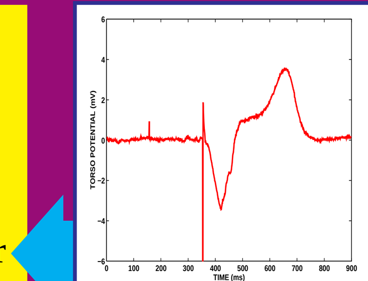
1. Measurements were made on an adult male with a pacemaker. The pacing electrode was implanted at the ventricular apex.
   - Potentials were measured during pacing, over the entire torso.
   - Heart position and size were determined from ultrasound scans of the patient.
   - Torso geometry and electrode location, as well as location and orientation of the ultrasound probe, were measured with an Immersion Personal Digitizer to within 0.1 cm.

2. Heart and torso models were made from the geometry measurements.
   - Torso geometry was represented with a spherical-harmonic approximation.
   - The heart was approximated as a sphere.
   - The heart and torso were assumed to have conductivities 0.002 and 0.006 S/cm.

3. Forward problem coefficients were calculated using the ALM and BEM.

4. Epicardial potentials were inferred 10-20 ms after pacing, using the ALM and BEM with Tikhonov regularization.

Body-Surface Electrocardiogram

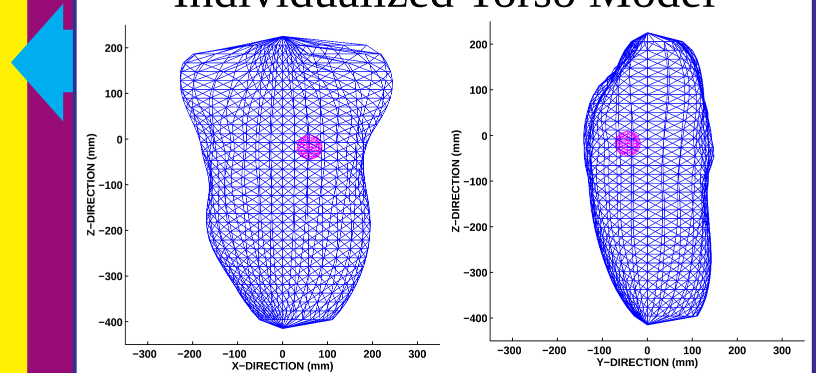


Electrocardiogram measured on the precordium, referenced to the right arm lead. Body surface potentials were measured at 190 sites on the torso and averaged over 3 beats.

Geometry Measurement

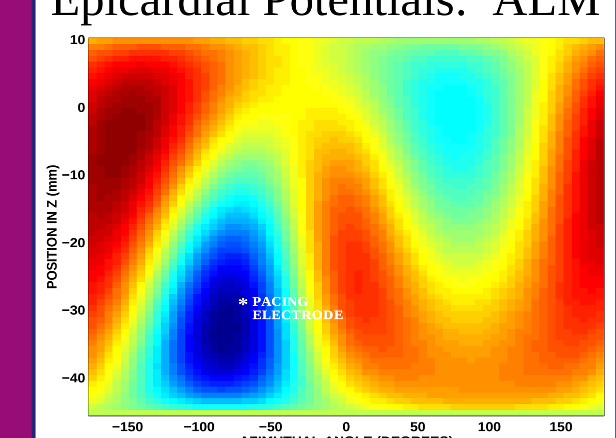
- Electrode locations were measured by placing the tip at the center of each electrode.
- Torso geometry was measured by dragging the tip along the torso and sampling tip positions.
- Anterior locations were taken with the patient lying supine on a mattress filled with clay.
- Posterior locations were measured from the impression made in the clay and aligned with anterior measurements using fixed reference points.

Individualized Torso Model



A triangular-element model of the torso was generated from uniform samples of a 10th degree spherical-harmonic approximation. This approximation fit measured torso locations with an RMS error of 0.4 cm. The heart was approximated as a sphere of radius 2.79 cm, located at the center of and surrounding the left ventricle.

Epicardial Potentials: ALM

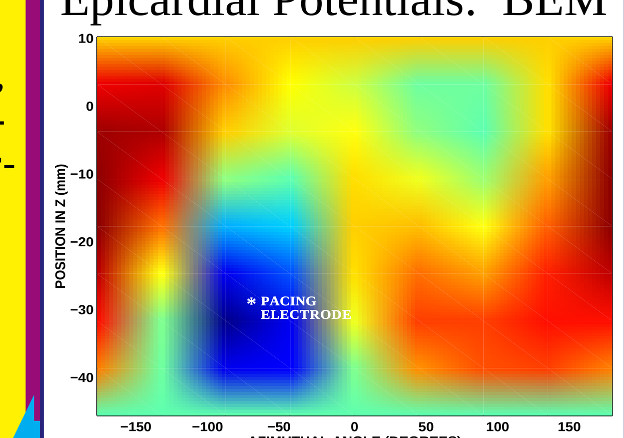


Epicardial potential map 16 ms after pacing. The distance between the pacing lead and the minimum of the reconstruction was 10.7 mm. The ALM allows continuous reconstruction of potentials, so no interpolation was needed.

Results

- Without regularization, the location of the pacing lead was not apparent in the inferred epicardial potentials for either the ALM or BEM.
- With regularization, both methods showed an activation front near the pacing site.

Epicardial Potentials: BEM



Epicardial potential map 16 ms after pacing. The distance between the pacing lead and the minimum of the reconstruction was 10.6 mm. Potentials between nodes are approximated using bilinear interpolation.

Conclusions

The aimed-lead method (ALM), which combines multipole-equivalent sources to infer epicardial potentials, performed better than the boundary-element method in low noise tests and for eccentricities less than 1 cm in an eccentric-spheres model, and was comparable to the BEM in determining placement of the pacing electrode in a human. These results suggest that inference of epicardial potentials with multipole-equivalent sources and appropriate regularization may yield improved estimates of epicardial potentials.

References

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2. R. C. Barr, M. Ramsey and M. S. Spach, Relating epicardial to body surface potential distributions by means of transfer coefficients based on geometry measurements, *IEEE Trans. on Biomed Engr*, **BME-24**, pp. 1-11 (1977).
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