M. Stenroos, H. Hänninen, M. Lindholm, I. Tierala, and T. Katila. 2005. Lead field formulation for epicardial potential in electrocardiographic localization of acute myocardial ischemia. IFMBE Proceedings, volume 11, pages 2265-1 - 2265-5.

LEAD FIELD FORMULATION FOR EPICARDIAL POTENTIAL IN ELECTROCARDIOGRAPHIC LOCALIZATION OF ACUTE MYOCARDIAL ISCHEMIA

M. Stenroos*, H. Hänninen**, M. Lindholm*, I. Tierala** and T. Katila*

* Helsinki University of Technology/Laboratory of Biomedical Engineering, Espoo, Finland
** Helsinki University Central Hospital/Division of Cardiology, Helsinki, Finland

matti.stenroos@hut.fi

Abstract: A method for estimating epicardial potential distribution from 120-lead Body Surface Potential Mapping (BSPM) data is applied. The method is developed further and used for characterization of myocardial ischemia.
BPSM was measured from 22 ischemic patients during PTCA operation. Epicardial potential problem is solved with boundary element method. Unit potential lead fields and template fields are constructed. Template fields are a modification of lead fields: the templates are built with a neighborhood potential function around a node. By varying extent and shape of the neighborhood function, a priori information on the epicardial potential can be brought into lead field matrix.
Template fields were used iteratively for localization of ischemic ST elevation. The results were compared to those obtained with direct and lead field based Tikhonov regularized solutions. Both template and lead field methods were able to localize the ischemia to anatomically logical location. Results from lead field based Tikhonov method are in better concordance with measured epicardial potentials (in literature) than the potentials obtained with direct inversion of the transfer matrix.

Introduction

Coronary artery disease leads often to occlusion of coronary arteries. The occlusion causes reduction of blood supply in myocardium. Reduced blood flow leads to lack of oxygen, which causes changes in myocyte electrophysiological conditions. For example, in ischemic cardiac cells the resting potential is smaller than in healthy cells. The differences between transmembrane potential of healthy and ischemic cells give rise to current field, which is connected to changes in endo– and epicardial potentials. These changes are easiest to detect during plateau phase of the ventricular activation, when healthy myocardium is in constant potential (ST segment in electrocardiogram). Transmural ischemia causes epicardial ST potential elevation close to ischemic area, and ST depression elsewhere in the epicardium [1]. The strength and shape of ST changes depend on extent of the ischemia and direction of cardiac muscle fibers [1–3]. Surface electrocardiogram (ECG) is uniquely defined by epicardial potential.

Acute ischemia is commonly detected with electrocardiography. Due to small number of electrodes, standard ECG techniques may fail to detect ischemia. Especially ischemia induced by culprit left circumflex (LCx) coronary artery is difficult to diagnose, if there are no dorsal electrodes. Quantification of size and severity of ischemia is also difficult with standard ECG techniques, as these methods are strongly based on a concept of a dipole as equivalent cardiac generator. Body Surface Potential Mapping (BSPM) provides a means for studying cardiac electric events in great detail. In this work we apply a method for estimating epicardial potential distribution from BSPM data [4,5]. The method is developed further and used for characterization of myocardial ischemia.

Material and Methods

120 channel Body Surface Potential Mapping was measured from 22 (19 M, 3 F) patients undergoing coronary balloon angioplasty (PTCA). The balloon was inflated either in left anterior descending (LAD, n = 8), LCx (n = 7), or right coronary artery (RCA, n = 7). Nine of the patients had suffered myocardial infarction. Measurements were done both before and during the inflation.

The data were pre-processed semi–automatically: 50 Hz adaptive filter was applied, baseline was removed with 3rd order spline fitting, and data were averaged (selective average of 11 beats). Bad channels were interpolated from good ones by minimizing the surface laplacian [6]. ST60 amplitude maps (J–point + 60 ms) were calculated. Amplitude maps were interpolated from electrodes to triangle midpoint with surface laplacian method. For further calculations delta maps were generated by subtracting

ISSN: 1727-1983

the map before balloon inflation from map measured during ischemic state. The delta maps serve as an idealized model of ischemia, as they represent the ECG changes caused by the balloon only.

Thoracic volume conductor was modeled with Dalhousie thorax model containing heart and body surfaces. The number of triangles in the heart and body surfaces was 400 and 700. Conductivity inside thorax was assumed homogeneous.

Potential problem was solved with integral equation approach. Green's theorem was first applied to surfaces of the heart and body [4]. The resulting boundary integral equations were discretized with constant basis functions and point collocation weighing. The collocation points were placed in centroids of the triangles. The discretized equations are

$$\frac{1}{2}\Phi^H = \Omega^{HB}\Phi^B - \Omega^{HH}\Phi^H - G^{HH}\Gamma^H \quad (1)$$

$$\frac{1}{2}\Phi^B = \Omega^{BB}\Phi^B - \Omega^{BH}\Phi^H - G^{BH}\Gamma^H, \quad (2)$$

where H and B label heart and body surfaces, and Ω^{kl} are solid angle matrices containing solid angles spanned by triangles of surface l at triangle centroids on surface k:

$$\Omega_{ij}^{kl} = -\int_{T_j^l} \frac{(\vec{c}_i^k - \vec{r}_j^l)}{|\vec{c}_i^k - \vec{r}_j^l|^3} \cdot \vec{dS}'. \quad (3)$$

Matrix G^{kl} and vector Γ^H contain

$$G_{ij}^{kl} = \int_{T_j^l} \frac{1}{|\vec{c}_i^k - \vec{r}_j^l|}\, dS \quad (4)$$

$$\Gamma_i^k = \nabla\Phi_i^k \cdot \vec{n}_i^k, \quad (5)$$

where $\vec{c}$ is centroid of a triangle, subscripts refer to triangles, and superscripts to surfaces. Integration is performed over triangles. Processing Eqs. 1 and 2, we arrive at

$$[T^{BB} + G^{BH}(G^{HH})^{-1}\Omega^{HB}]\Phi^B = [\Omega^{BH} - G^{BH}(G^{HH})^{-1}T^{HH}]\Phi^H, \quad (6)$$

where

$$T^{HH} = \left(\frac{1}{2}I + \Omega^{HH}\right), \quad T^{BB} = \left(\frac{1}{2}I - \Omega^{BB}\right). \quad (7)$$

With equation 6 the potential on one surface can be computed, when potential on the other surface is known.

The solid angles were calculated analytically [7], and integrals G_{ij}^{kl} were computed with gaussian quadrature. Singularities in the diagonal entries of the G^{HH} matrix were removed by performing integration in polar coordinates. Tikhonov 2 regularization was used in inverse potential problem.

Lead field matrix for epicardial potential is constructed by forming unit potentials for each node in epicardium, interpolating the potentials to triangle midpoints, and calculating resulting body surface potentials with Eq. 6. Because the lead fields are node based, number of basis functions is reduced to about half of the basis functions needed with the traditional method (Eq. 6). In addition, lead field approach gives a possibility to choose the nodes used for fitting the potential. For example, transfer matrix from epicardial nodes to body surface electrodes can be generated by interpolating lead fields from triangle midpoints to electrode positions.

Template fields are a simple modification of standard lead fields: instead of focal unit potentials, the lead fields are built with some neighborhood potential function around a node. By varying extent and shape of the neighborhood function, a priori information on the epicardial potential can easily be brought into lead field matrix. The template fields can be used like standard lead fields: epicardial potential can be written as linear combination of template fields, coefficients defined by inverting template field matrix. Another way to use the template fields is to find iteratively the template field that best fits the measured data. In this work the template fields shown in Fig. 1 were used for characterizing the ischemic epicardial potentials.

Results

Measured delta potential maps for representative patients are visualized in Fig. 2. The maps resemble closely those published in [8]. Some epicardial potential estimates and map reconstructions for these patients are shown in Figures 3 - 5. For each case, solution a) is calculated from Eq. 6, b) with unit potential lead fields, and c) with best fitting template from neighborhoods in Fig. 1.

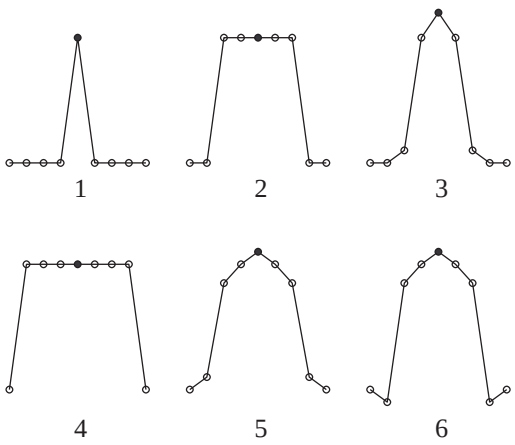

Figure 1: Some template fields for epicardial potential. Template 1 describes neighborhood function of a standard lead field for potential.

ISSN: 1727-1983

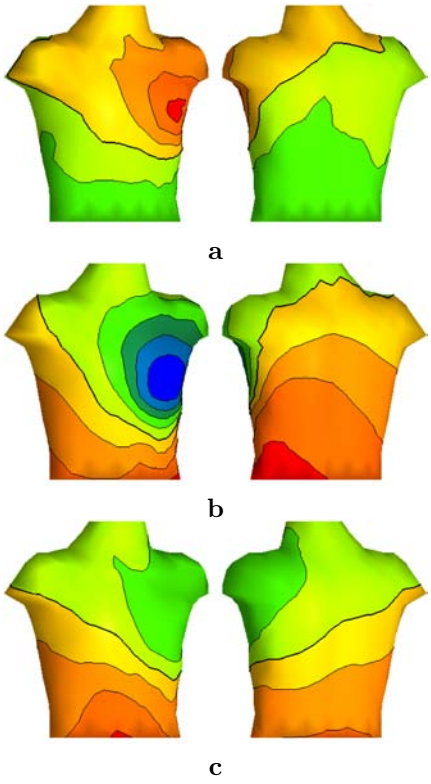

Figure 2: ST60 delta potential maps measured from a a) LAD patient, b)LCx patient and c) RCA patient. Contour step is 50μV.

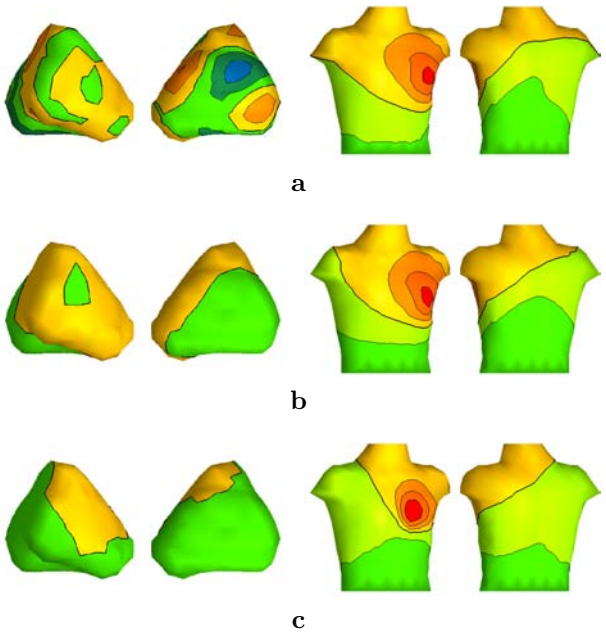

Figure 3: Calculated epicardial potentials and corresponding map reconstructions for a LAD patient computed with a) traditional Tikhonov 2 regularization, b) Tikhonov 2 regularized lead fields, and c) best template field (template no. 4). Contour step is 1 mV for body surface and 50μV for epicardial potential.

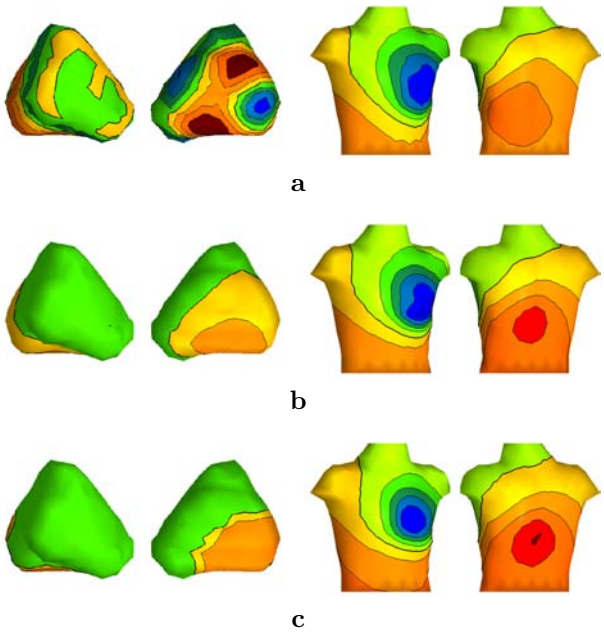

Figure 4: Calculated epicardial potentials and corresponding map reconstructions for a LCx patient computed with a) traditional Tikhonov 2 regularization, b) Tikhonov 2 regularized lead fields, and c) best template field (template no. 4). Contour step is 1 mV for body surface and 50μV for epicardial potential.

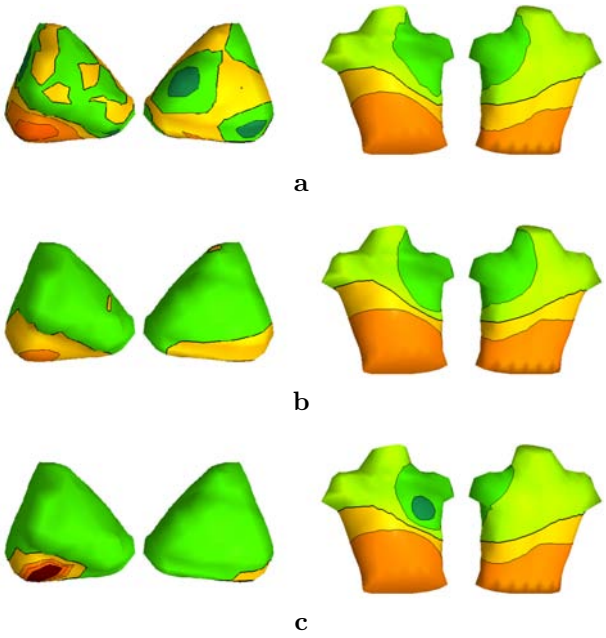

Figure 5: Calculated epicardial potentials and corresponding map reconstructions for a RCA patient computed with a) traditional Tikhonov 2 regularization, b) Tikhonov 2 regularized lead fields, and c) best template field (template nr. 3). Contour step is 1 mV for body surface and 50μV for epicardial potential. The models are tilted in order to show the bottom part of the epicardium.

ISSN: 1727-1983

Regularization parameters in Tikhonov methods were chosen so that both methods reconstructed the measured data with nearly same goodness of fit G:

$$G = \frac{\sum_i (\phi_{\text{meas,i}} - \phi_{\text{calc,i}})^2}{\sum_i \phi_{\text{meas,i}}^2}. \qquad (8)$$

Both Tikhonov methods reproduce the measured fields well – $G \approx 0.95 - 0.98$ – while producing reasonable epicardial potentials. The epicardial potentials produced by lead field methods (b) are however remarkably smoother than those produced by direct inversion (a). Without invasively mapped reference data it is impossible to compare the performance of the methods quantitatively, but the results obtained with lead field are morphologically in better concordance with measured results published e.g. in [1].

The best fitting templates can not reproduce the measured BSPM as well as the Tikhonov methods. This was expected, because the templates are rather rough. The locations suggested by the templates are however closely correlated with regions of maximal potential given by lead field based Tikhonov method. The positive regions match also well with typical coronary artery anatomy.

Template field localizations for all the patients are shown in Fig. 6. LAD maps are generally localized close to apex or to superior part of the epicardium close to anatomical long axis, slightly on the right side. LCx maps are best explained by templates located at left side, in the lower part of the free wall. RCA localizations lie on the inferior surface of the epicardium.

Discussion and Conclusions

Epicardial potential with lead field formulation can be used for characterization of acute myocardial ischemia. Compared to direct inversion of matrices in Eq. 6, the methods presented here provide smoother solutions with better defined ST elevation region. With same goodness of fit, lead field approach produces more simple epicardial fields than the direct method. This behavior outcomes likely from smoothing feature of partially overlapping basis functions.

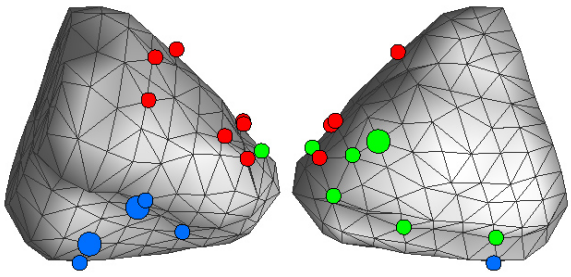

Figure 6: Locations of potential maxima in optimal templates for all the patients. LAD, LCx and RCA are marked with red, green and blue. A large dot represents location for two patients.

Iterated fitting of template fields is a simple, but powerful method for rough localization of ischemic region. The simple template fields are not able to reproduce measured potential as well as Tikhonov methods – erroneous reconstruction occurs especially near maxima and minima. Main morphological features of the surface maps are however correct. The template method localized the epicardial ST elevation to anatomically typical region in all the patients. In localizations of LAD and LCx maps there was slight overlap. The template method can be improved by introducing a larger variety of neighborhood functions. The results obtained with this method can also be used as a priori estimates in more advanced localization and regularization methods. It is also possible to iterate solutions allowing more than one source region.

All the calculations were performed with a standard torso model. Use of patient specific torso models would likely improve the results. Construction of accurate torso models requires however anatomical data, which can be obtained with magnetic resonance imaging (MRI) or X-ray computed tomography (CT). But, if MRI is available, anatomical scans can often be accompanied by perfusion imaging, which can already localize the ischemic region. Hence, if aiming at clinically feasible BSPM methods for ischemia localization, it is important to develop source characterization techniques that are robust enough to work without a patient specific volume conductor model.

Acknowledgements

The torso model used here is courtesy of Prof. B.M. Horáček, Dalhousie University, Halifax, Canada. Gaussian quadrature routines for standard triangle were programmed by Prof. J. Sarvas, Laboratory of Electromagnetics, Helsinki University of Technology.

References

[1] D. Li, C.Y. Li, A.C. Yong, P.R. Johnston, and D. Kilpatrick. Epicardial ST depression in acute myocardial infarction. *Circulation Research*, 85:959–964, 1999.

[2] D. Li, C.Y. Li, A.C. Yong, and D. Kilpatrick. Source of electrocardiographic ST changes in subendocardial ischemia. *Circulation Research*, 82:925–970, 1997.

[3] M.C. MacLachlan, J. Sundnes, and G.T. Lines. Simulation of ST segment changes during subendocardial ischemia using a realistic 3-D cardiac geometry. *IEEE Transactions on Biomedical Engineering*, 52:799–807, 2005.

[4] 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 Biomed Eng*, BME-24:156–166, 1977.

[5] B.M. Horáček and J.C. Clements. The inverse problem of electrocardiography: A solution in terms of single– and double–layer sources on the epicardial surface. *Mathematical Biosciences*, 144:119–154, 1997.

[6] T.F. Oostendorp, A. van Oosterom, and G. Huiskamp. Interpolation on a triangulated 3D surface. *J Comp Physics*, 80:331–343, 1989.

[7] A. van Oosterom and J. Strackee. The solid angle of a plane triangle. *IEEE Transactions on Biomedical Engineering*, pages 125–126, 1983.

[8] B. M. Horáček, J. W. Warren, C. J. Penney, R. S. MacLeod, L. M. Title, M. J. Gardner, and C. L. Feldman. Optimal electrocardiographic lead for detecting acute myocardial ischemia. *Journal of Electrocardiology*, 34, 2001.

ISSN: 1727-1983