# Heart-Surface Potentials Estimated from 12-Lead Electrocardiograms

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**Abstract**

We investigated whether the ischemic region due to coronary-artery occlusion can be visualized on the heart-surface display by using as input data just ST measurements from the 12-lead ECG. A boundary-element torso model was used to estimate heart-surface potentials from body-surface potential maps (BSPMs) obtained from 12-lead ECG via transformation developed from a design set (n = 892) of 120-lead ECGs by a least-square solution to the linear regression problem. The test set consisted of 120-lead ECGs acquired for 45 patients during ischemia induced by balloon-inflation angioplasty; subgroups of equal size consisted of patients whose LAD, LCx, and RCA were occluded, respectively. BSPMs at J point of each patient were predicted from the 12-lead ECG and similarity of original and predicted maps was assessed by a similarity coefficient SC (0–100%). By inverse solution, heart-surface potentials were then estimated from original and predicted BSPMs and visualized on a *bull's*-eye display. Reconstitution of known BSPMs from the 12-lead ECG achieved an overall SC 92.46 ± 6.95% (mean ± SD); for subgroups, SC was: 89.79 ± 9.95% for LAD, 93.89 ± 2.86% for LCx, and 93.70 ± 5.77% for RCA group. Estimated heart-surface potential distributions featured an area of positive potentials corresponding, in general, to the underperfused territory caused by the occlusion. Encouraging results can be attributed to the strongly dipolar character of BSPMs caused by injury current. This approach shows promise for ischemia detection and quantitation.

## 1. Introduction

Electrocardiographic monitoring in special care units allows non-invasive detection and documentation of cardiac ischemic and arrhythmic events and it has been widely used for detecting myocardial ischemia in patients with unstable coronary syndromes [1]; it is particularly useful in assessing thrombolytic treatment in patients with acute myocardial infarction, and in detecting sudden coronary artery closure in patients undergoing coronary intervention [2]. Most bedside monitors allow continuous monitoring by means of the 12-lead electrocardiogram (ECG).

The full potential of 12-lead ECG monitoring has not yet been utilized. The sensitivity and specificity with which bedside monitors detect myocardial ischemia can be improved by making better use of information provided by the 12-lead ECG. Lux at al. [3] hypothesised that BSPMs estimated from reduced lead sets (including the 12-lead ECG) can provide more information than the predictor leads alone, if the estimation method uses prior knowledge derived from large ECG datasets.

In the present study, we examined the spatial patterns of BSPMs recorded during balloon-inflation percutaneous transluminal coronary angioplasty (PTCA) in patients with single-vessel coronary artery disease and we investigated how well these patterns can be predicted from just 8 independent leads of the 12-lead ECG. We then went one step further: by using the inverse solution, we estimated heart-surface potential maps from both 120-lead BSPMs and from those derived from 12-lead ECG; by comparing results we assessed the ultimate capabilities of the 12-lead electrocardiography.

## 2. Methods

### 2.1. Patient population

The design set for developing transformation from the 12-lead ECG to BSPMs was the Dalhousie Superset consisting of 120-lead ECGs from 892 subjects, including 290 normal subjects, 318 with remote myocardial infarction and 284 with inducible ventricular tachycardia [4]. The test set consisted of 120-lead ECGs from the Dalhousie database for 45 patients with single-vessel coronary artery disease who underwent elective percutaneous transluminal coronary angioplasty (PTCA) [5]. Three subgroups of equal size consisted of patients whose left anterior descending (LAD), left circumflex (LCx), and right coronary artery (RCA) was occluded.

### 2.2. ECG acquisition and processing

The 120-lead recordings of the Dalhousie Superset were each made for 15 consecutive seconds, with subjects in supine position. ECGs were amplified, filtered (band pass from 0.025 to 125 Hz), multiplexed, and digitized at 500 Hz into 12-bit samples (with 2.5-μV resolution).

The test set consisting of 120-lead PTCA data was recorded from the same electrode array and by the same acquisition system as the Dalhousie Superset, except that the limb leads had electrodes at Mason-Likar [6] sites. Processing of both datasets involved averaging of ECG signals; for the PTCA set 15-second episodes at the "ischemic" state (after 60 seconds of inflation) were used and the ST measurements were made from the averaged complexes at the J point [5].

## 2.3. Estimation of heart-surface potentials

Following the approach of Lux et al. [7], potentials at body-surface nodes of the boundary-element torso model were estimated from 120-lead or 12-lead input data via transformation developed from the design set by a least-squares solution to the linear regression problem, using SAS procedure PROC REG [8]. The torso model was used to estimate 202 potentials $\Phi_H$ on the heart surface from 352 potentials $\Phi_B$ on the body surface. Integral equations relating $\Phi_B$ and $\Phi_H$ were derived by application of the Green's theorem and discretized into the system of linear algebraic equations [9]

$$\Phi_B = A\,\Phi_H\,, \qquad (1)$$

with the matrix A depending only on the torso geometry. The system (1) has to be solved for $\Phi_H$; due to ill-conditioned nature of A, Tikhonov regularization has to be used [10], which replaces the inverse problem implied in (1) with a least-squares problem of minimizing the objective function

$$\min\{\| A\Phi_H - \Phi_B \|^2 + t \| B\Phi_H \|^2\}, \qquad (2)$$

where ||.|| denotes the Euclidean norm, t is the regularization parameter, and B is (in this application) a second-order regularizing operator. The solution $\Phi_H(t)$ of the least-squares problem (2) satisfies the equations

$$(A^T A + tB^T B)\Phi_H(t) = A^T \Phi_B. \qquad (3)$$

To choose an optimal t; we used the L-curve method [11]. The heart-surface maps were displayed on a bull's-eye projection of the heart surface [12] and the ischemic zone was provisionally defined as the region with $\Phi_H \geq 250\mu V$.

## 2.4. Comparison of potential distributions

Potential distributions were compared by means of a similarity coefficient (SC), in percent. For the actual and estimated potentials at a given time instant for a node i denoted as $V_i$ and $V_i'$, respectively, the similarity coefficient between two distributions comprising n nodes is a ratio

$$SC = \frac{\sum_{i=1}^{n} V_i V_i'}{\sqrt{\sum_{i=1}^{n} \left(V_i\right)^2}\sqrt{\sum_{i=1}^{n} \left(V_i'\right)^2}}$$

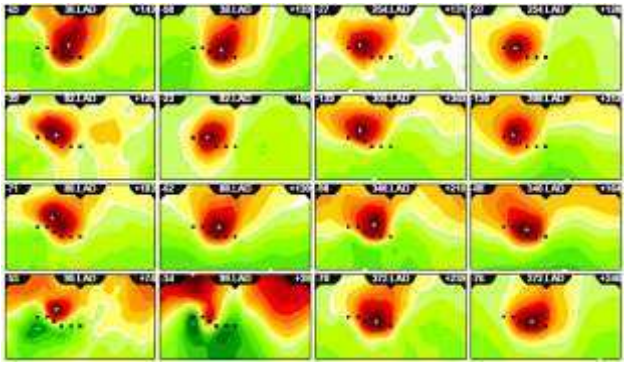

Figure 1. Actual and estimated BSPMs at J-point during ischemia due to occlusion of the LAD coronary artery. For each of the 8 patients of LAD subgroup (n = 15) a pair of side-by-side maps is shown; in columns 1 & 3 are maps obtained from 120 leads, and in columns 2 & 4 those estimated from the 12-lead ECG. Each map is an unrolled cylindrical projection of the chest; sites of 6 precordial leads are marked as black squares.

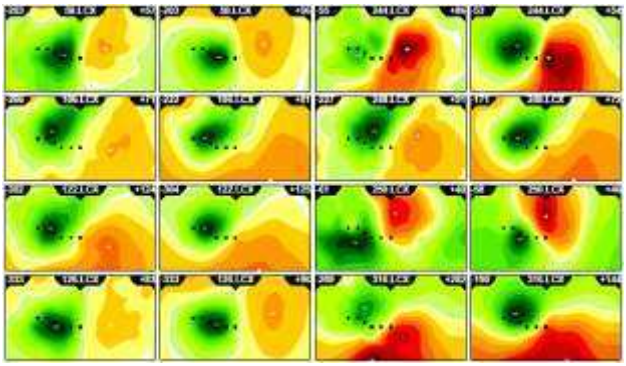

Figure 2. Actual and estimated BSPMs at J-point during ischemia due to occlusion of the LCx coronary artery for 8 patients of the LCx subgroup (n = 15). The same layout as in Fig. 1.

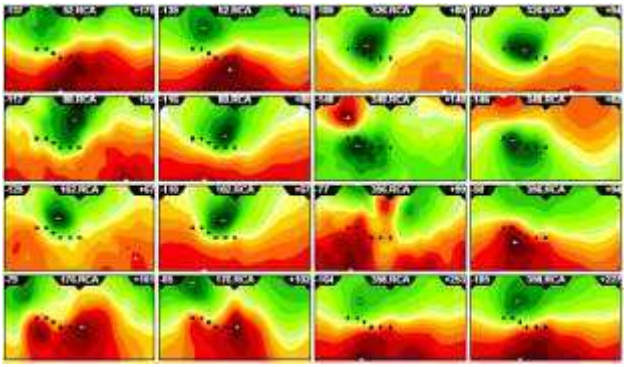

Figure 3. Actual and estimated BSPMs at J-point during ischemia due to occlusion of the RCA for 8 patients of the RCA subgroup (n = 15). The same layout as in Fig. 1.

## 3. Results

Figures 1–3 show (each for 8 randomly selected patients of one subgroup) how BSPMs constructed from all 120 recorded leads and those estimated from 8 independent leads of the 12-lead ECG compare. In quantitative terms, reconstitution of 352-node BSPMs from the 12-lead ECG achieved for all 45 subjects of the test set a SC of 92.46 ± 6.95% (mean ± SD); SC for LAD subgroup (Fig. 1) was 89.79 ± 9.95%, for LCx subgroup (Fig. 2) 93.89 ± 2.86%, and for RCA subgroup (Fig. 3) 93.70 ± 5.77%.

Figures 4–6 show how the differences in full-fledged BSPMs and those estimated from the 12-lead ECG translate into heart-surface maps obtained by the inverse solution. Since the actual measurements from the heart surface are not available, we can only judge these heart-surface images qualitatively by determining whether the area of positive potentials is in the given coronary artery's territory, as defined in terms of left-ventricular segments [12]. For LAD occlusion (Fig. 4) principal areas of positive heart-surface potentials appear in the anterior/anteroseptal region (9:00 to 1:00 on the "clock face" of bull's eye display); for LCx occlusion (Fig. 5) in the lateral region (1:00 to 5:00 on the clock); and for RCA occlusion (Fig. 6) in the inferior/inferoseptal region (5:00 to 9:00 on the clock), as expected. Of particular interest while inspecting Figs. 4–6 is whether the heart-surface maps estimated from 120 ECG leads and those estimated from just 8 independent leads of the 12-lead ECG point to the same ischemic region; this is the case in most maps, at least when principal positive areas are compared. SC comparing the two sets of estimated heart-surface maps was for all 45 patients of the test set 74.08 ± 16.31%; for LAD subgroup (Fig. 4) it was 67.02 ± 17.50%, for LCx subgroup (Fig. 5) 80.45 ± 12.89%, and for RCA subgroup (Fig. 6) 74.77 ± 16.32%.

## 4. Discussion

The purpose of this study was to investigate whether the established approach to solving the inverse problem of electrocardiography can be used to extract, from just the 12-lead ECG, heart-surface potential distributions during acute ischemia that would reveal the culprit coronary artery. Since ST-segment changes are known to be the best indicators of ischemia, we confined our investigation to BSPMs at J-point. Our results show that, despite the patient-to-patient variability of the electrophysiological changes observed during inflation of the PTCA balloon (Figs. 1–3), there are distinct common features in the BSPMs at J point that can be identified when each of the three main coronary arteries is occluded. These features are reproducible and they reveal the origin of ischemia.

Figure 4. Heart-surface potentials estimated from BSPMs recorded during LAD occlusions (Fig. 1). Bull's eye projection of ventricular segments after Cerqueira et al. [12]. Areas of positive potentials >250 μV are depicted in red.

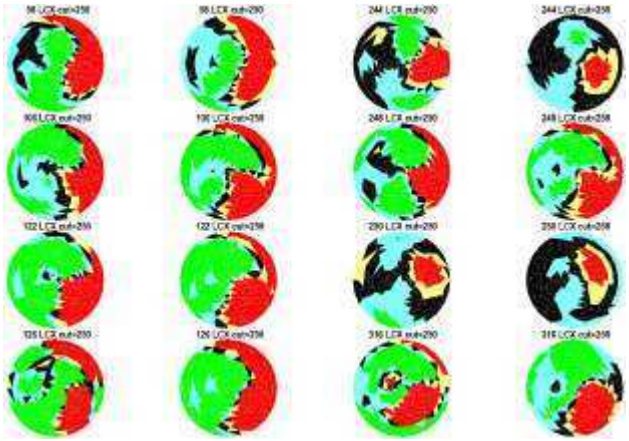

Figure 5. Heart-surface potentials estimated from BSPMs recorded during LCx occlusions (Fig. 2).

Figure 6. Heart-surface potentials estimated from BSPMs recorded during RCA occlusions (Fig. 3).

Inflations in the LAD artery produce a very distinctive pattern of J-point BSPMs, whereas those resulting from inflations in the RCA and LCx arteries are similar in some cases. However, since there is a posterior region of the ventricular myocardium that can be supplied by either the RCA or LCx artery, depending on the patient-specific coronary tree, one would expect both the BSPMs and heart-surface maps from such cases to have similar features. Our previous study [13] validated the electrocardiographic inverse solution by comparison with SPECT imaging and showed excellent agreement between these techniques, as did a more recent study [14] comparing ECG estimates of location of myocardium at risk with those obtained by MRI and SPECT.

The criteria for acute ischemia require the presence of ST elevation > 100 μV in two or more contiguous leads of the 12-lead ECG [1]. However, in some patients with acute coronary syndromes (particularly those whose LCx coronary artery is occluded) these criteria are not met [15]. In contrast, the approach tested by the present study reveals the acute ischemia due to LCx occlusion (Fig. 5) clearly in all cases: in 5 cases (58LCX, 106LCX, 122LCX, 126LCX, 248LCX) as crescent-like area and in 2 cases (244LCX, 250LCX) as a round area of positive potentials in the lateral region; in one case (316LCX) a round region of positive potentials infringes on the inferolateral segment that is supposed to be a part of the RCA territory. Heart-surface potentials corresponding to LAD occlusion (Fig. 4) show beside areas of positive potentials in anterior/anteroseptal segments also "spurious" red areas, most often in inferolateral segments; this pattern seems to be consistent in all bull's eye maps derived from 120-lead ECG, but the spurious peaks disappear in 5 out of 8 maps (38LAD, 82LAD, 88LAD, 99LAD, 308LAD) derived from 12-lead ECG.

## 5. Conclusion

The results of this study show that, for patients with acute myocardial ischemia, both the body-surface and heart-surface potential maps estimated from the 12-lead ECG correlate well with those constructed from 120 ECG leads. In addition, estimated heart-surface potential maps during ST segment feature an area of positive potentials, which corresponds, in general, to the underperfused territory caused by the occlusion of coronary artery. Thus this approach promises to be useful in ischemia detection and quantitation.

## Acknowledgements

Support for studies at Dalhousie University was provided by the Heart & Stroke Foundation of Nova Scotia and by the Canadian Institutes of Health Research.

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