Coefficients for the Derivation of an ST Sensitive Patch Based Lead System from the 12 Lead Electrocardiogram

Michael R Jennings[1], Ali S Rababah[1], Daniel Güldenring[2], James McLaughlin[1], Dewar D Finlay[1]

[1] Ulster University, Newtownabbey, United Kingdom
[2] Hochschule Kempten, Kempten (Allgäu), Germany

Abstract

Background: *There are limited datasets available to facilitate the evaluation of patch-based lead systems, so the leads must be derived from existing data, mainly the 12-lead ECG. We have previously introduced a short spaced lead (SSL) system consisting of two leads with the largest ST segment changes during ischaemic-type episodes. In this study, we aim to evaluate the derivation of this patch-based lead system from the 12-lead ECG.*
Method: *Thoracic body surface potential maps (BSPM) were recorded from n=734 patients. Using Laplacian interpolation, each recording was expanded to the 352-node Dalhousie torso. The eight independent channels of the 12-lead ECG were extracted (I, II, V1-V6) with the two leads of the SSL patch Coefficients were derived using linear regression from the 12-lead ECG to the SSL patch.*
Results: *The median Pearson correlation coefficients (CC) and root mean square error (RMSE) for each lead were calculated as follows (CC/RMSE): 0.986/74.3 µV (ST monitoring lead); 0.976/65.3 µV (spatially orthogonal lead).*
Conclusion: *We have developed coefficients that allow the derivation of a patch-based lead system from the 12-lead ECG. Given the high correlation, it is possible to generate short spaced lead systems from existing diagnostic lead systems, however, amplitude errors are introduced in the process.*

1.   Introduction

The 12-lead electrocardiogram (ECG) remains the most common tool in cardiac monitoring in a clinical setting [1]. However, the 12-lead ECG is inconvenient for ambulatory use, or when recording from body positions other than supine. Additionally, a 12-lead recording is usually between three to ten seconds in duration. This may not detect certain paroxysmal conditions such as atrial fibrillation or unstable angina [2]. A patch-based lead system is more convenient compared to the 12-lead ECG, with the capability for ambulatory monitoring. Furthermore, a patch-based lead system has been shown to be effective in the detection of cardiac arrhythmia [3, 4], including those that display intermittent ECG changes, such as ventricular tachycardia [5]. Existing patch-based lead systems such as the Zio XT and BradyDx CAM have shown comparable performance to the standard ambulatory Holter monitors [6], but with a longer recording period than 24 hours [7]. However, there are a lack of patch-based ECG systems sensitive to ST-segment changes [8], with many focusing on the reproduction of the 12-lead ECG for further analysis [9, 10]. This may be due to a lack of available datasets suitable for patch-based ECG development. We have previously reported on a patch-based lead system sensitive to ischaemic-type ST-segment changes associated with myocardial infarction [11]. This two-lead, four electrode, patch will form the basis of a short-spaced lead (SSL) system for our work. In this study, we aim to introduce and evaluate coefficients for the derivation an ST-sensitive SSL patch suitable for ambulatory monitoring. The SSL patch derivation coefficients have been included as derived in our work.

2.   Methods

2.1.   Data

The dataset used in this study has been described previously [12, 13]. The data were comprised of recordings (n=734) from patients experiencing myocardial infarction (n=271), left ventricular hypertrophy (n=237), and healthy controls (n=226). The data were recorded using a body surface potential map (BSPM) of 117 unipolar thoracic leads, recorded with respect to the Wilson central terminal (WCT). Distal limb leads were also recorded. Each recording was a single beat in length, sampled at 500 Hz. These were expanded to the 352-node Dalhousie torso [14, 15] using linear interpolation. The data were split at random to 80% training (n=587) and 20% test (n=147).

2.2. Coefficient Derivation

The eight independent channels of the 12-lead ECG were extracted from each recording (I–II, V1–V6). The two bipolar leads of the SSL patch were also extracted: an ST-sensitive lead (SSL_{ST}) and a spatially orthogonal lead (SSL_{orth}). The positions of these leads were decided based on previous work [11]. Specifically, the SSL_{ST} electrodes are at nodes 173 and 254 while SSL_{orth} is located between nodes 234 and 212 on the Dalhousie torso. The positions of these leads on the anterior torso are plotted in Figure 1.
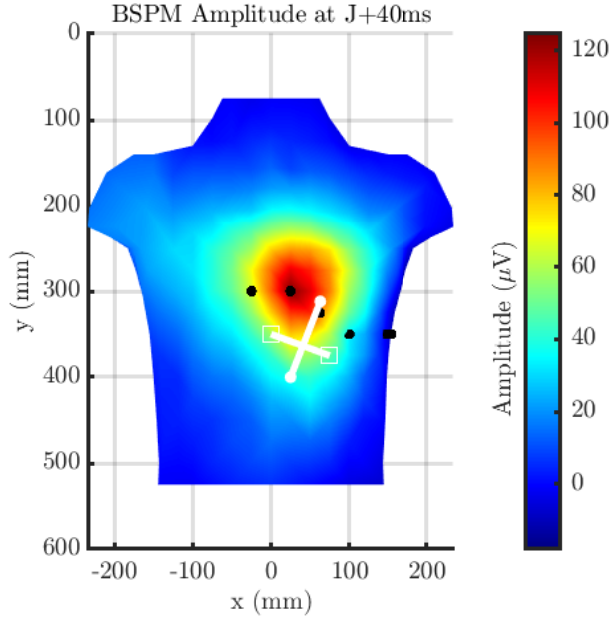

Figure 1. Location of short spaced leads SSL_{ST} (white circles) and SSL_{orth} (white squares). Torso-wide median amplitude 40 ms after the J-point in patients with myocardial infarction (n=271). Precordial chest leads (V1–V6) plotted as black circles.

Both recorded leads (12-lead) and leads to be derived (SSL patch) were used in generating the coefficients. All training set recordings (n=587) were concatenated prior to computation. Linear regression was used to calculate transform coefficients as shown in Equation 1:

$$\beta = \left[\left(RL_{train}^T \cdot RL_{train}\right)^{-1} RL_{train}^T \right] \cdot DL_{train} \quad (1)$$

Where β represented an 8x2 matrix of transform coefficients. RL_{train} and DL_{train} were matrices of m_{train}x8 and m_{train}x2 respectively. They represented recorded leads (I–II, V1–V6) and leads to be derived from the training dataset (n=587). m_{train} was the total number of samples in the training dataset (n=171,708).

2.3. Lead Derivation

Using the coefficients derived in section 2.2, the leads to be derived can be calculated from the test dataset (n=147). These were calculated using Equation 2:

$$\hat{DL}_{test} = RL_{test} \cdot \beta \quad (2)$$

Where $\hat{DL}_{test}$ was an m_{test}x2 matrix containing an estimate of the derived leads: SSL_{ST}, and SSL_{orth}. RL_{test} was an m_{test}x8 matrix of recorded leads (I–II, V1–V6) taken from the test dataset (n=147). β was the 8x2 matrix of derivation coefficients as defined in Equation (1). m_{test} indicates the total number of ECG samples in the test set (n=42,990)

2.4. Performance Measurement

Recorded leads from the test dataset were used to benchmark how accurately the leads were derived. Pearson correlation coefficients (CC) and root-mean square errors (RMSE) were calculated by comparing the recorded leads (x), previously extracted from the BSPM data, with our derived equivalents (y). CC was calculated as shown in Equation 3:

$$\rho_{(x,y)} = \frac{1}{M-1} \sum_{m=1}^{M} \left(\frac{\overline{y_m - \mu_y}}{\sigma_y} \right) \left(\frac{x_m - \mu_x}{\sigma_x} \right) \quad (3)$$

Where $\rho_{(x,y)}$ is the CC. x and y represent the recorded leads (RL_{test}) and derived leads ($\hat{DL}_{test}$) respectively. M indicates the number of samples, μ is the mean, σ is the standard deviation and m is the sample number. Similarly, the RMSE between recorded and derived leads was calculated using Equation (4):

$$RMSE_{(x,y)} = \sqrt{\frac{1}{M} \sum_{m=1}^{M} (x_m - y_m)^2} \quad (4)$$

3. Results

The coefficients calculated in section 2.2 (β) are shown in Table 1. They are arranged in an 8x2 matrix where the rows represent the recorded leads (I–II, V1–V6), and the columns represent the leads to be derived of the SSL patch (SSL_{ST}, SSL_{orth}). CC and RMSE for each lead are included at the bottom: For the ST-sensitive SSL, SSL_{ST}, the CC was highest with 0.986. However, it also had the highest RMSE with 74.3 μV. The spatially orthogonal lead, SSL_{orth}, had a marginally lower CC of 0.976, with a lower RMSE of 65.3 μV

Figure 2 shows the leads to be derived (DL_{test}) and the derived leads ($\hat{DL}_{test}$) for one recording, as performed in

Table 1. Derived lead coefficients (β) and their calculated performance as CC and RMSE

| | | Derived Leads | |
		SSL_{ST}	SSL_{orth}
Recorded Leads	I	0.4337	-0.1571
	II	-0.7155	-0.0244
	$V1$	-0.5004	-0.8134
	$V2$	0.4325	-0.0577
	$V3$	0.2980	0.0401
	$V4$	-0.0682	0.6915
	$V5$	0.1282	-0.1009
	$V6$	0.0367	-0.0523
	CC	0.986	0.976
	$RMSE$	$74.3\mu V$	$65.3\mu V$

section 2.3. The recording was taken from a patient undergoing myocardial infarction. The leads to be derived are shown with a dashed line, and derived leads are shown as a solid line.

4. Discussion

SSL_{ST} shows ST-elevation symptomatic of myocardial infarction, whereas SSL_{orth} provides increased spatial resolution by showing cardiac activity orthogonally from SSL_{ST}. A high CC value was reported for both SSL_{ST} and SSL_{orth}. This may be due to the proximity of these leads to the precordial chest leads used during derivation. SSL_{ST} had a higher CC, but also a higher RMSE. This is potentially due to the median energy present in SSL_{ST} recordings being higher than that of SSL_{orth}. In the detection of ST-elevation myocardial infarction (STEMI), the ST criteria for the precordial leads of the 12-lead ECG requires between 150-250 μV depending on age and sex. The 74.3 μV of SSL_{ST} is below that range. However, a patient presenting with a marginal STEMI using a 12-lead ECG may not be detected using a patch-lead system. Furthermore, the error may result in more false positives in women, whose ST-elevation criteria are lower than men. No specific criteria exist for cardiac abnormality detection using patch-based devices, especially regarding behaviour of the ST-segment. To fully evaluate such a lead system in the detection of disease, a clinical consensus must be reached. Placement errors are an issue for all lead systems, including the 12-lead ECG [16]. A placement error for a patch-based lead system may have a more amplified effect than those of the 12-lead ECG due to the decreased spatial resolution of a patch across the torso. The non-standard locations of this lead system may result in a larger number of placement errors than existing ambulatory systems such as the Holter monitor or Zio XT. In the data collection de-
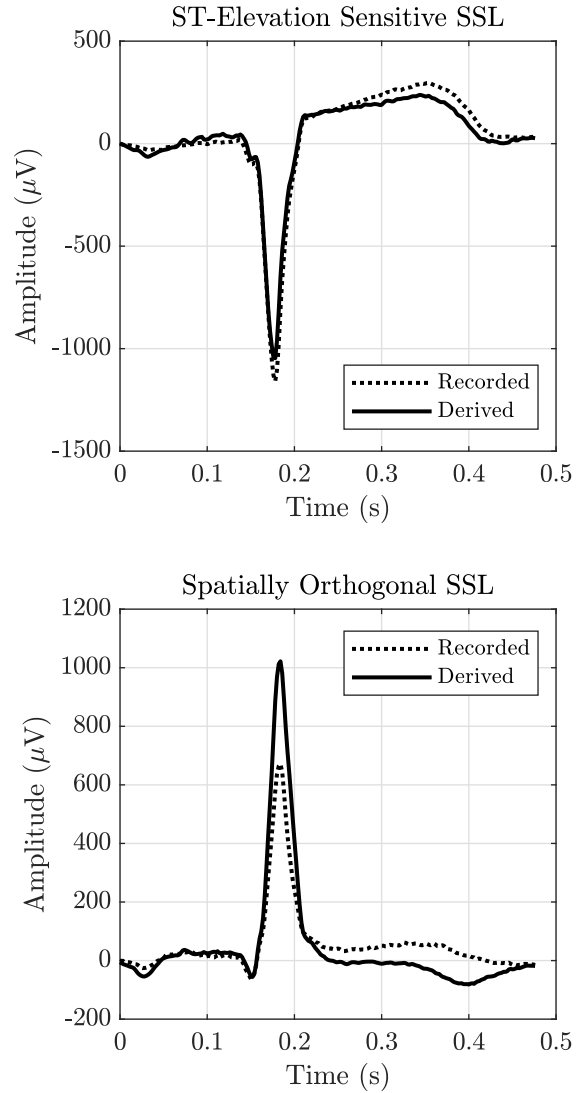

ST-Elevation Sensitive SSL

Spatially Orthogonal SSL

Figure 2. Leads to be derived (DL_{test}) and derived leads ($\hat{DL}_{test}$) for both the ST-elevation sensitive SSL (SSL_{ST}) and the spatially orthogonal SSL (SSL_{orth}) from a patient with myocardial infarction

scribed previously, a homogeneous torso was used to interpolate the 117-node recordings to the 352-node Dalhousie torso. This may not be representative of all patients, further exacerbating derivation errors. There are limited datasets available to evaluate patch-based lead systems. This emphasises the need to derive them from other, more prominent, datasets such as the 12-lead ECG. The efficacy of such a lead system in the detection of cardiac abnormalities cannot be fully determined since limited data specific

to this lead configuration exist. More data is required to evaluate patch-based leads further.

5. Conclusion

We have provided coefficients towards the derivation of a patch-based short-spaced lead system from the 12-lead electrocardiogram using linear regression. The Pearson's correlation coefficient and root mean square error were above 0.97 and below 75 μV for both leads respectively.

Acknowledgments

References

[1] Thygesen K, Alpert JS, Jaffe AS, Chaitman BR, Bax JJ, Morrow DA, White HD. Fourth universal definition of myocardial infarction (2018). European Heart Journal aug 2019;24(3):107–138. ISSN 26187620.

[2] Fesmire FM, Percy RF, Bardoner JB, Wharton DR, Calhoun FB. Usefulness of automated serial 12-lead ECG monitoring during the initial emergency department evaluation of patients with chest pain. Annals of Emergency Medicine jan 1998;31(1):3–11. ISSN 01960644.

[3] Wimmer NJ, Scirica BM, Stone PH. The clinical significance of continuous ECG (ambulatory ecg or holter) monitoring of the ST-segment to evaluate ischemia: A review. Progress in Cardiovascular Diseases 2013;56(2):195–202. ISSN 00330620.

[4] Simpson TF, Goldschlager N. Sudden cardiac death preceded by ST segment elevations during ECG patch monitoring. Journal of Electrocardiology 2018;51(2):330–331. ISSN 15328430.

[5] Cai Z, Li J, Zhang X, Shen Q, Murray A, Liu C. How Accurate are ECG Parameters from Wearable Single-lead ECG System for 24-hours Monitoring. In Computing in Cardiology, volume 46. IEEE Computer Society. ISBN 9781728169361. ISSN 2325887X, Sep 2019; 1–4.

[6] Rho R, Vossler M, Blancher S, Poole JE. Comparison of 2 ambulatory patch ECG monitors: The benefit of the P-wave and signal clarity. American Heart Journal sep 2018; 203:109–117. ISSN 10976744.

[7] Karunadas CP, Mathew C. Comparison of arrhythmia detection by conventional Holter and a novel ambulatory ECG system using patch and Android App, over 24 h period. Indian Pacing and Electrophysiology Journal 2020;20(2):49–53. ISSN 09726292.

[8] Duncker D, Ding WY, Etheridge S, Noseworthy PA, Veltmann C, Yao X, Bunch TJ, Gupta D. Smart Wearables for Cardiac Monitoring—Real-World Use beyond Atrial Fibrillation. Sensors 2021 Vol 21 Page 2539 apr 2021; 21(7):2539. ISSN 14248220.

[9] Guldenring D, Finlay DD, Bond RR, Kennedy A, McLaughlin J. Limitations of the smartphone based single ECG-lead evaluation of STEMI. Journal of Electrocardiology jan 2018;51(1):e3. ISSN 00220736.

[10] Muhlestein JB, Le V, Albert D, Moreno FL, Anderson JL, Yanowitz F, Vranian RB, Barsness GW, Bethea CF, Severance HW, Ramo B, Pierce J, Barbagelata A, Muhlestein JB. Smartphone ECG for evaluation of STEMI: Results of the ST LEUIS Pilot Study. Journal of Electrocardiology mar 2015;48(2):249–259. ISSN 0022-0736.

[11] Jennings M, Guldenring D, Bond R, Rababah A, McLaughlin J, Finlay DD. ST Changes Observed in Short Spaced Bipolar Leads Suitable for Patch Based Monitoring. In Computing in Cardiology, volume 46. IEEE Computer Society. ISBN 9781728169361. ISSN 2325887X, Sep 2019; 1–4.

[12] Kornreich F, Montague TJ, Rautaharju PM. Body surface potential mapping of ST segment changes in acute myocardial infarction: Implications for ECG enrollment criteria for thrombolytic therapy. Circulation 1993;87(3):773–782. ISSN 00097322.

[13] Schijvenaars BJ, Kors JA, van Herpen G, Kornreich F, van Bemmel JH. Interpolation of body surface potential maps. Journal of Electrocardiology jan 1995;28:104–109. ISSN 00220736.

[14] Horacek BM. Numerical model of an inhomogeneous human torso. Advanced Cardiology 1974;10(51).

[15] Horacek B, Warren JW, Penney CJ, MacLeod RS, Title LM, Gardner MJ, Feldman CL, Horacek BM, Warren JW, Penney CJ, MacLeod RS, Title LM, Gardner MJ, Feldman CL. Optimal electrocardiographic leads for detecting acute myocardial ischemia. Journal of Electrocardiology oct 2001; 34(4):97–111. ISSN 00220736.

[16] Bond RR, Finlay DD, Nugent CD, Breen C, Guldenring D, Daly MJ. The effects of electrode misplacement on clinicians' interpretation of the standard 12-lead electrocardiogram. European Journal of Internal Medicine oct 2012; 23(7):610–615. ISSN 09536205.

Address for correspondence:

Michael R Jennings
NIBEC, Ulster University, NEWTOWNABBEY, UK
Jennings-m5@ulster.ac.uk