Evaluation of Limited and Alternative Lead Sets for the Reconstruction of the 12-Lead Electrocardiogram and Body Surface Potential Maps

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Abstract

In this study we evaluate limited lead sets for the reconstruction of 12-lead ECGs and Body Surface Potential Maps (BSPMs). For 12-lead ECG reconstruction, we focused on four available limited lead systems (V_2, V_1V_5, V_1V_6, V_2V_5) to derive the standard 12-lead ECG and the EASI lead system as an alternative to the existing 12-lead ECG. We used a data set of 44 continuous 16-lead balloon inflation ECG registrations during percutaneous coronary interventions. For reconstruction of BSPMs an optimal lead selection algorithm was applied to a set of 744 BSPMs, consisting of recordings from subjects with myocardial infarction, left ventricular hypertrophy, and no apparent disease.

Median Root Mean Square (RMS) error for 12-lead ECG reconstruction were in decreasing order: V_1V_6: 165 μV, V2 131 μV, V1V5: 124 μV, EASI: 96 μV, and V2V5: 87 μV. In the BSPM reconstruction experiments, it was shown that by repositioning the six precordial leads the RMS error decreased from 35.4 μV to 26.7 μV.

In summary, the results from this study have indicated that limited lead systems offer potential in all forms of cardiac monitoring and assessment, but certain lead sets show higher reconstruction errors.

1. Introduction

Electrocardiograms (ECGs) measured from numerous sites on the body can provide a comprehensive representation of the underlying cardiac activity. Well-known standard configurations are the 12-lead ECG used for routine cardiac diagnosis and body surface potential maps (BPSMs) used to measure the full electrical activity on the body surface. These 12-lead and BSPM configurations contain redundant information and in the past various strategies based on limited or alternative lead sets have been proposed [1, 2, 3, 4, 5, 6, 7]. The purpose of this study is to evaluate the use of limited leads for reconstruction of the 12-lead ECG and BSPMs.

2. Methods

2.1. 12-lead ECG reconstruction

For the evaluation of the 12-lead ECG reconstruction from a limited set of leads, we focused on five available limited lead systems [2, 3, 4, 5, 6] as presented in Table 1. For the reconstruction coefficients that were not publicly disclosed, coefficients were calculated from a learning set of 2372 10-second ECG recordings [3]. We used EASI coefficients corrected for the proximal placement of the limb electrodes [8].

Table 1. Overview of five limited lead systems.

Name	Investigator	Number of electrodes	Limited Lead Set
EASI	Dower (1988)	5	EASI
V_2	Nicklas (1991)	5	I, II, V_2
V_1V_5	Drew (2002)	6	I, II, V_1 , V_5
V_2V_5	Nelwan (2000)	6	I, II, V_2 , V_5
V_1V_6	Wei (2002)	6	I, II, V_1 , V_6

The five limited lead systems were evaluated on a separate data set of 44 continuous 16-lead ECG recordings obtained from patients undergoing a percutaneous coronary intervention at the Durham VA Medical Center (Durham, NC, USA). Informed consent was obtained from each patient. A total of 14 radiolucent electrodes were attached to each patient to allow simultaneous registration of the 12-lead and EASI ECG. Limb electrodes were placed on the Mason-Likar landmarks [8] and the six electrodes (V_1–V_6) were placed at the conventional precordial lead locations. The remaining four electrodes were placed at the EASI electrode locations.

For each recording, a 10-second, 16-lead ECG was marked at balloon inflation and extracted for further analysis. All ECGs were analyzed with the Modular ECG Analysis System (MEANS) [9]. MEANS computes average beats and provides measurements and diagnostic interpretation. ST-segment amplitudes were measured at 60 ms after the J point for all leads.

Reconstruction performance was assessed by calculating the RMS error between the original and reconstructed lead for each ECG. We also computed absolute ST_{60} differences between the reconstructed and original lead for each lead.

2.2. BSPM reconstruction

To find a reduced lead set for reconstructing BSPMs we applied a previously developed lead selection algorithm [7] to a set of 117 lead BSPMs. The layout of the 117 lead array is illustrated in Figure 1 and the procedure for recording this data has previously been described in [10]. The data set was made up of 744 recordings taken from 229 subjects who had no apparent disease, 278 subjects with myocardial infarction and 237 subjects with left ventricular hypertrophy.

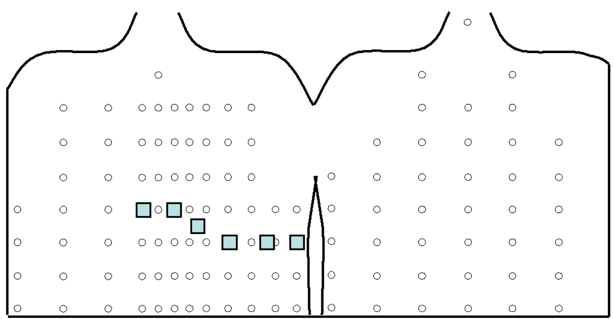

Figure 1. Layout of 117 lead BSPM electrode array. Black squares are representative of the placement of the six precordial leads V_1-V_6.

All isopotential map frames from the PQRST of each recording were pooled. This pool of PQRST isopotential map frames was then partitioned into two subsets (75% and 25%) to facilitate lead selection and subsequent independent validation. The lead selection algorithm was applied to the selection portion of the dataset. A final measure of performance was established by determining how well isopotential map frames in the remaining validation portion of the dataset could be reconstructed using the selected leads.

The lead selection algorithm builds a limited lead set by iteratively finding the sites which most accurately estimate entire surface potential distributions i.e. BSPMs. In this study the algorithm was run over 25 iterations resulting in the suggestion of the best 25 recording sites. This number of recording sites has been deemed adequate for accurate reconstruction of BSPMs [1].

Two measures of performance, RMS error and correlation coefficient between measured and estimated BSPM frames, were considered. If P_1 and P_2 are the vectors of the measured and estimated potentials respectively, and n is the number of sites at which potentials have been estimated, the spatial RMS error e can be determined by the equation:

$$e = \frac{P_1 - P_2}{\sqrt{n}} \tag{1}$$

Correlation coefficient between measured and reconstructed map frames was found using equation:

$$\rho = \frac{PP'}{|P||P'|} \tag{2}$$

3. Results

3.1. 12-lead ECG reconstruction

Figure 2 shows the median (interquartile range) RMS errors at balloon inflation of the five limited lead systems. Of the 5-electrode systems, EASI had a lower RMS error than the lead subset strategy V_2. For the 6-electrode systems, the combination of I, II, V_2 and V_5 had the lowest RMS error. Of the 6-electrode systems, the precordial leads consisted of leads V_1 or V_2 and a left-lateral lead.

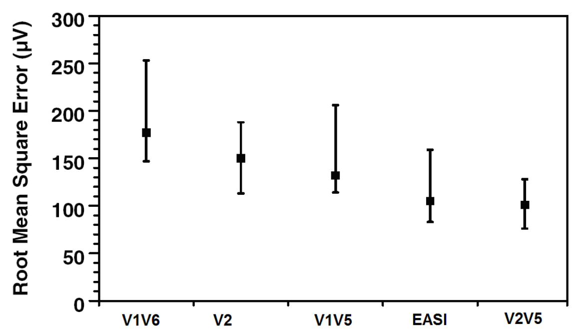

Figure 2. Median (interquartile range) RMS errors of five limited lead systems.

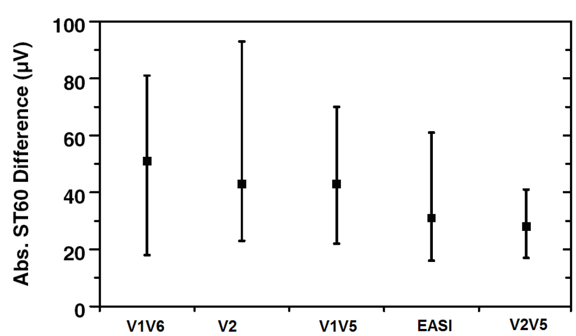

Figure 3. Median (interquartile range) absolute ST_{60} differences of five limited lead systems.

Absolute ST_{60} differences between the original and reconstructed leads at balloon inflation are presented in Figure 3. The order of the worst to best limited lead sets was equal to Figure 2. In contrast to Figure 2, limited lead set V_2 had a lower median difference than lead set combination V_1V_6, but showed the largest interquartile range.

3.2. BSPM reconstruction

Figure 4 illustrates the positions of the top 25 recording sites, in the 117 lead array, as chosen using the lead selection algorithm. The positions of the six precordial leads have been included for comparison.

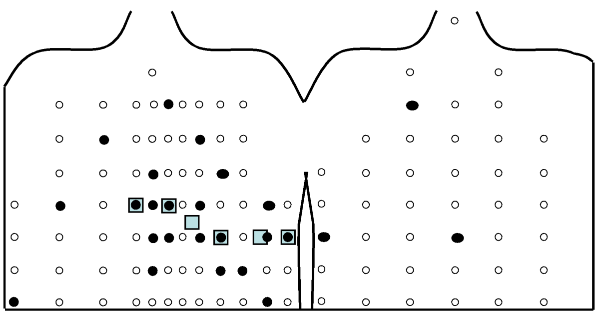

Figure 4. Positions of the top 25 recording sites as indicated by black circles. (Grey squares are representative of the placement of the six precordial leads V_1–V_6)

It can be seen that the top 25 recording sites, as illustrated in Figure 4, are largely concentrated around the precordial region. It can also be seen that sites are chosen in the same positions of the four precordial leads which are part of the 117 lead array. The selection algorithm has also included sites from regions which are not interrogated using the conventional 12-lead ECG. In particular, three sites on the right anterior and three sites on the posterior. This would indicate that for the studied population there is useful information located in these regions.

Because of the iterative nature of the selection process all subsets of the 25 recording sites are valid. This allows us to observe what the outcome would be if we optimally repositioned the six precordial leads of the 12-lead ECG. The positions of the six optimal leads as generated by the selection process are shown in Figure 5.

On comparing the positions of the six optimal sites with that of the precordial leads it can be seen that just one of the sites chosen by the lead selection algorithm occupies the same location as one of the precordial leads (V_6). One further site is chosen in close proximity to V_3 and the remaining sites are between one and three intercostal spaces above and beneath leads V_1 to V_4.

The performance of the top 25 sites in reconstructing the BSPMs in the test set are listed in Table 2. Included

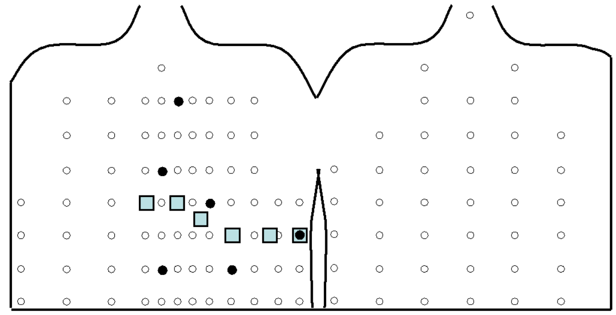

Figure 5. Positions of top 6 recording sites as generated by the selection process.

Table 2. Performance of various recording sites in reconstructing BSPMs.

	RMS Error	Correlation Coefficient
Top 25	14.8 (11.8–19.3)	0.988 (0.980–0.993)
Top six	26.7 (21.8–34.3)	0.952 (0.929–0.970)
Six precordial	35.4 (28.1–49.0)	0.913 (0.860–0.948)

in this table are the performances of the six optimal leads along with the six precordial leads in reconstructing the same BSPMs. It should be noted that six leads, precordial or optimal, are unlikely to allow reconstruction of BSPMs with the precision required for accurate clinical diagnosis. The reconstruction accuracy that these leads yield (i.e. how accurately the entire surface potential distribution is estimated) does, however, provide an indication of the amount of information captured.

On considering the reconstruction performance it can be seen that the top 25 recording sites exhibit almost half of the RMS error exhibited by the top six recording sites. The performance advantage of the additional leads is also reflected in the values for correlation coefficient. In turn the top six recording sites outperform the six precordial leads both in terms of RMS error and Correlation Coefficient. When tested using the Wilcoxins signed rank test this difference was found to be significant ($p < 0.001$).

4. Discussion and conclusions

This study has investigated limited lead systems designed with two particular purposes in mind. Firstly, various lead systems for reconstructing the 12-lead ECG have been assessed. Secondly, a limited lead system for reconstructing BSPMs has been proposed and evaluated. The latter has also allowed for assessment and comparison of the standard six precordial leads with optimally positioned leads.

The study has shown that leads V_2 along with V_5 in addition to the limb leads I and II are the best candidates for accurate reconstruction of the 12-lead ECG. For the accurate reconstruction of BSPMs it has been shown that sites from both within and outside of the precordial region are required. It has also been shown that recording sites chosen using the selection algorithm capture more of the total ECG information projected onto the body surface than the conventional precordial leads. This observation strengthens the argument for reconsidering the current locations of the recording sites used to record the 12-lead ECG. Although the recording sites chosen in this study have been shown to capture more of the total body surface potential distribution diagnostic criteria for any new leads is yet to be established.

Generalized transformation coefficients were used for the reconstruction of the information in the 12-lead ECG and the BSPM. Further performance improvements may be obtained by using patient-specific coefficients [2, 3]. However, patient-specific reconstruction requires a previously recorded reference 12-lead ECG or a BSPM.

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