Improved Spatial Sampling of ECG Potentials on the Body Surface by Repositioning Electrodes from the Standard 12-lead ECG

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Abstract

We propose a simple, practical approach to increase the diagnostic information content of the standard 12-lead ECG by repositioning selected chest leads. We used a set of 746 120-lead body surface potential maps (BSPMs). Coefficients to reconstruct all BSPM leads from the standard ECG were derived by linear regression. Similarly, BSPMs were reconstructed when two of leads V3-V6 were replaced by electrodes at other positions on the anterior part of the thorax. Repositioning lead V4 at two intercostal spaces below V2 and lead V6 at two intercostal spaces above V2 or at three intercostal spaces above V4 showed increased reconstruction performance as compared with the standard electrode positions in most parts of the anterior thorax, including regions that are known to contain important diagnostic information less well represented by the standard ECG. Also, this approach obviates the need to determine the precise location of V4, which may be difficult in women.

1. Introduction

Previous studies demonstrated that body surface potential maps (BSPMs) may furnish diagnostic information not easily retrieved from the standard 12-lead ECG [1-3]. Alternate lead sets that can recover the information in the BSPM have been proposed [4-9], but were found impractical in that they often required more than the 10 (9 + 1 reference) electrodes of the standard ECG and asked for unusual electrode positions. Consequently, none of these proposals has met with clinical acceptance.

In this study, we propose an alternative approach to increase the diagnostic information content of the standard ECG by repositioning selected chest electrodes, paying heed to the practicality of the approach. Sacrificing part of the usual precordial leads of the standard ECG without appreciable loss of information is possible because they contain a great deal of redundant information, which allows accurate reconstruction from the remaining leads [10].

Also, previous studies have shown that unrecovered diagnostic information is mostly confined to specific areas on the body surface, notably the upper mid- and left-sternal and the lower mid-precordial regions [5,6,9]. Therefore, it would seem sufficient to concentrate on the accurate recovery of heart activity in these areas only, rather than bother about accurate reconstruction of the information on the whole body surface, as was done in many previous studies.

The practicality of the approach was ensured by imposing the following constraints:

1. No electrodes in excess of the 9 electrodes of the standard 12-lead ECG should be necessary.
2. Given the ubiquitous use of the standard 12-lead ECG, any alternative lead arrangement should allow accurate reconstruction of all standard leads.
3. Repositioning should be considered for those electrodes of the standard ECG that are most easily misplaced in practical situations. In this respect, we considered electrodes V3-V6, and in particular V4 and V5, to be most vulnerable for misplacement, especially in women and the obese [11-13].
4. Alternative electrode positions should be on the anterior part of the thorax, electrodes at dorsal sites carrying too many practical problems.

2. Methods

2.1. Data set

We used a set of 746 120-lead BSPMs. About one third of the BSPMs were from healthy individuals, the remaining ones from patients with different abnormalities [14,15]. The lead array consisted of three extremity leads and 117 torso leads, with 81 electrodes located anteriorly and 36 posteriorly (Fig. 1). All leads were recorded relative to the Wilson central terminal. The data acquisition and processing procedure has been described previously [15]. For each BSPM, representative ECG complexes of all leads were obtained by coherent averaging, from which QRS complexes were taken for further analysis.

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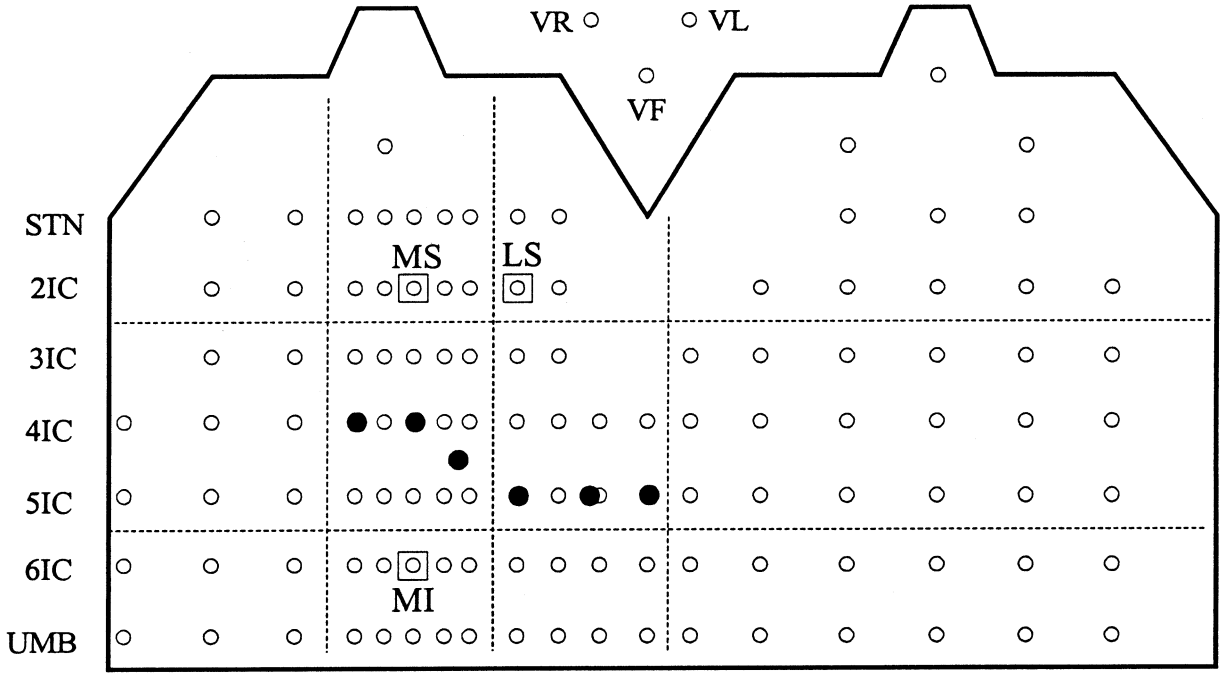

Figure 1. Unfolded thorax, showing the BSPM electrode positions by open circles. The left-hand side of the image represents the front, the right-hand side the back of the thorax. The top electrode row is at the level of the sternal notch (STN), the bottom row is near the umbilicus (UMB), with intermediate rows at different intercostal (IC) spaces. The black dots indicate the standard V1-V6 electrode positions. The squared dots are proposed as alternative electrode positions (see text for further description).

2.2. Lead reconstruction

Data were randomly split in a learning set and a test set of equal size. First, using the learning set, we determined to which extent leads V3-V6 could be reconstructed from the remaining standard leads, and thus which electrodes were most eligible for repositioning. Second, one or two of leads V3-V6 were removed from the standard lead set and replaced by leads from different sites on the torso to reconstruct all other BSPM leads. All reconstruction coefficients were derived by linear regression.

2.3. Performance evaluation

Reconstruction performance was assessed on the test set by correlation coefficients between the original and the reconstructed leads and by similarity coefficients [5,16]. The similarity coefficient (SC) is defined as SC = 1 – RMS(original–reconstructed lead) / RMS(original lead).

To assess reconstruction performance in areas of differing diagnostic importance, we divided the body surface in 12 regions, 9 in the front and 3 in the back, as shown in Fig. 1. For each region, median performance measures were computed over all leads in the region.

3. Results

Table 1 shows how well, on the test set, one or two of leads V3-V6 could be reconstructed from the remaining standard ECG leads. For a single precordial lead, V5 was reconstructed best and V3 worst. When two precordial leads were to be reconstructed, combinations of two non-adjacent leads performed best, as was to be expected.

Table 1. Accuracy of selected precordial leads reconstructed from the remaining standard ECG leads.

Leads	Correlation Coef	Similarity Coef
V3	99.5 (98.2-99.8)*	84.9 (76.0-90.0)*
V4	99.7 (99.1-99.9)	86.1 (77.0-91.9)
V5	99.8 (99.4-99.9)	90.0 (80.7-93.8)
V6	99.6 (98.7-99.9)	86.0 (73.1-91.6)
V3, V4	99.2 (97.6-99.7)	80.8 (67.5-87.9)
V3, V5	99.6 (98.7-99.9)	87.7 (77.8-92.6)
V3, V6	99.6 (98.5-99.8)	85.7 (74.9-90.8)
V4, V5	99.2 (97.7-99.7)	80.5 (67.1-87.7)
V4, V6	99.5 (98.8-99.8)	83.6 (73.8-90.1)
V5, V6	99.1 (96.8-99.6)	77.1 (63.2-86.0)

* Values denote median (interquartile range), in %.

Table 2. Median values of the similarity coefficients (SCs) between original and reconstructed leads in 12 areas on the body surface. Leads are reconstructed from the standard 12-lead ECG and after replacement of V4 and V6 by selected leads on the anterior thorax. SC improvements of >5% are in bold.

	Right frontal			Mid frontal			Left frontal			Dorsal		
Leads	S*	C	I	S	C	I	S	C	I	S	C	I
Standard	86.0	76.1	69.1	73.4	87.4	70.2	69.4	89.3	80.3	72.4	63.0	68.6
V4, V6 → MI, MS	87.8	78.0	72.1	**88.8**	91.7	**86.4**	**78.8**	85.2	81.7	71.7	62.0	67.6
V4, V6 → MI, LS	86.7	77.5	71.7	**81.0**	91.6	**86.3**	**87.9**	85.3	81.1	72.0	62.1	68.0

* S=superior, C=central, I=inferior.

† MI, MS, and LS refer to electrode positions on the chest (see Fig. 1).

Considering that the electrode position for lead V4 is one of the most inconvenient to locate accurately, especially in women [13], we chose to reposition either V4 or V4 and V6 at different sites of the anterior thorax. From the many electrode sites that were explored, those at two intercostal spaces below and above V2 (see Fig. 1) and at three intercostal spaces above V4 showed improved reconstruction, as compared with the standard electrode positions, of the lead signals in most parts of the anterior thorax. Table 2 gives the performance results in terms of median similarity coefficients (only similarity coefficients are shown because of the highly nonlinear nature of the correlation coefficient and the fact that it resembles similarity in shape rather than amplitude). Particularly the superior mid- and left-sternal areas and the inferior mid precordium, regions that are known to contain relevant diagnostic information less well represented by the standard ECG, show increased reconstruction performance. The use of precordial lead combinations other than V4-V6 for repositioning gave only slight differences with the values in Table 2 (absolute differences <2%).

To determine the effect of small changes in the new electrode positions, we determined by interpolation the signals at about 2 cm to the right, left, above, and beneath the new positions and repeated our experiments. Results were relatively insensitive to these changes (differences <2.5% with the values in Table 2).

4. Discussion

We propose a simple, practical method to improve the sampling of diagnostic information from the body surface by repositioning two electrodes out of V3-V6. The question which two electrodes are best selected, is dependent on the accuracy by which the replaced precordial leads can be reconstructed (non-adjacent leads are reconstructed best) and by practical considerations (leads V4 and V5 may be difficult to locate precisely in women and are therefore best sacrificed). One of combinations V3-V5, V4-V6, or V4-V5 would therefore seem most appropriate, the first two allowing the most accurate reconstruction of leads, the last combination being most attractive from a practical point of view. Our results indicate that, whichever combination of two precordial electrodes is taken, overall results in the 12 regions of the body surface are hardly affected.

To determine the best alternative positions of the two precordial electrodes, we mainly looked at reconstruction performance in the superior mid- and left-sternal areas and the inferior mid-precordium. This choice of regions was based on previous studies that showed diagnostic information in these areas is not well covered by the standard 12-lead ECG. Gratifyingly, most other regions on the anterior thorax showed improvement as well, the only exception being the left-precordial central area with a decrease in SC of about 4%. This does not come as a surprise, considering that two of the precordial leads were moved out of this area. The resultant SCs of approximately 85% are acceptable and comparable with those from the other diagnostically important regions.

Previous studies also indicated diagnostic information to be present in the left dorsal region, mainly around electrode V8 [9,17]. We felt that putting an electrode in this region would compromise the practicality of our approach too much. Also, in these studies the leads involving such a back electrode were bipolar, with the other electrode positioned in the opposite, upper frontal area. However, it is debatable whether bipolar leads derived from opposite sites yield additional diagnostic information as compared to the so-called unipolar leads that were used in this study.

We found two sites on the upper part of the thorax, above V2 and above V4, which, in combination with the site below V2, gave more or less comparable reconstruction performance. The site above V2 will probably be easier to locate in routine practice, and may therefore be preferred. On the other hand, our findings indicate that none of the sites is very sensitive to small misplacements.

We emphasize the practicality of our approach, which only requires two electrodes to be replaced, does not need additional electrodes, and allows accurate reconstruction of the standard 12-lead ECG. Also, our proposal obviates some problems with accurately positioning the standard precordial electrodes, particularly in women. One may wonder whether other lead systems could not equally well be adjusted to do a similar or even better job. For example, the EASI lead system was specifically designed for convenient electrode placing, needs only 5 electrodes, and was shown to be able to reconstruct the standard 12-

lead ECG in good approximation. Following our approach, the EASI system could easily be extended by another few electrodes, and is then likely to perform equally well as our proposed arrangement, with fewer electrodes. However, we see the wide propagation of the standard 12-lead ECG, the familiarity of technicians with standard electrode sites, and the availability of four of the original precordial leads, as the major advantages of our approach.

The main limitation of this study is that we did not actually show the improvement in diagnostic yield that supposedly is associated with a more accurate sampling of the body surface potentials. In this we fared on the amply available evidence from earlier studies that showed the diagnostic limitations of the standard 12-lead ECG as compared to BSPMs. But although we do not doubt that improvement is to be gained from our method, we presently can only speculate on its amount. Before clinical acceptance on any scale can be contemplated, further studies will have to show substantial diagnostic improvements. Another important goal of such studies would be the establishment of simple diagnostic criteria for different ECG abnormaties that involve the newly proposed leads.

Another limitation is that we only used the QRS complexes in our analyses. The ST-T wave also carries important diagnostic information, and reconstruction coefficients derived from the whole QRS-T complex, or from segments within the complex, may possibly further improve diagnostic interpretation.

In conclusion, we demonstrated that improved sampling of ECG potentials on the body surface is possible by repositioning electrodes from the standard 12-lead ECG, and suggest that this approach is a viable way to improve the diagnostic yield of the ECG.

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