Optimisation of Electrode Placement for New Ambulatory ECG Monitoring Devices

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Abstract

In this study we aim to determine, from body surface potential map (BSPM) data, the optimal bipolar chest electrode placement for maximum R-wave amplitude. The study data consisted of 117-lead 352-node BSPM data recorded from 229 healthy subjects. The dataset was split into a training set of 172 subjects and a testing set of the remaining 57 subjects. Optimal electrode placement was determined using a lead selection method based on the difference in R-wave amplitude across all 352 nodes for each patient. R-wave values were then extracted and used to create a median BSPM of the training data. From this median BSPM the optimal electrode placement was defined as the location of the minimum and maximum R-wave values. On the testing dataset this new optimal bipolar chest lead (R-lead) was then compared to all of the leads of the Mason-Likar 12-lead ECG and previously described bipolar chest leads, CM_5, CS_5, CC_5 and CB_5. The R-lead showed significant improvement in median R-wave amplitude over the next best lead, CM_5 (2562μV vs. 2420μV, Wilcoxon sign ranked test, $p<0.001$). Given the improvement in signal strength, an improvement in automated R-wave detection and R-R interval analysis from single lead ECG monitors may be achieved.

1. Introduction

Cardiac arrhythmias are common and can be associated with severe clinical events. An example of this is Atrial Fibrillation which has been shown to affect approximately 2% of the population and is associated with a significantly increase in the risk of stroke events [1]. Currently, if a patient is suspected of suffering from an arrhythmia they are given a 12-lead electrocardiogram (ECG). If the arrhythmia is not diagnosed on the 12-lead ECG, which can be the case with patients experiencing short intermittent arrhythmic episodes, continuous ambulatory ECG monitoring is usually performed. Ambulatory monitoring can be used for a number of different reasons, the most common being for the investigation of cardiac rhythm [2]. Over the past decade a number of new and novel devices for continuous ambulatory ECG monitoring have emerged. These devices are mainly aimed for the detection of arrhythmias [3]. However, it is only now that new ambulatory ECG devices are being integrated into patient care and management. These devices usually record a single-lead ECG and incorporate automated algorithms to detect arrhythmias. A challenge faced by such ECG devices is the relatively low signal-to-noise ratio of the ECG in monitoring applications. The low signal-to-noise ratio can lead to false positive alarms [4]. The most common lead system used for recording of the ECG during exercise is the Mason-Likar 12-lead ECG [5]. However the electrode locations associated with the ML 12-lead ECG interfere with echocardiography and defibrillation in a clinical setting [6]. Also, the increased number of electrodes compared to single and three lead ECG systems and wires can reduce patient comfort.

Before multichannel ECG systems were readily available single-lead ambulatory ECG monitoring was commonly performed using bipolar chest lead (BCL) CS_5. This BCL is still commonly recorded today in certain clinical situations such as for example operating rooms [7]. In this study we aim to determine the optimal placement of bipolar ECG electrodes in order to obtain an ECG lead with maximized R-wave amplitude. In addition, we compared the performance of this new lead (R-lead) to all leads of the Mason-Likar (ML) 12-lead ECG and to a number of other previously described BCLs.

2. Ambulatory ECG lead systems

2.1. The Mason-Likar 12-lead ECG

In 1966, Mason and Likar discovered that when the limb electrodes were repositioned to more proximal locations on the torso the signal quality of the 12-lead ECG during exercise was greatly improved. The authors compared ECG recordings from the conventional 12-lead ECG to ECG recordings made with the limb electrodes being

moved progressively to more proximal positions up the arms and then over the upper anterior chest. They concluded the optimal electrode positioning for the limb electrodes was the right arm electrode placed on the infraclavicular fossa medial to the border of the deltoid muscle and 2cm below the lower border of the clavicle. The left arm electrode placed on the corresponding position and the left leg electrode placed on the anterior axillary line halfway between the costal margin and the iliac crest [2], [5]. The ML limb electrode positions are shown in Figure 1.

2.2. Bipolar chest leads

Before the ML 12-lead ECG was established as the gold standard for exercise ECG testing, BCLs were frequently utilized for the recording of exercise ECG data. These BCL leads are not commonly used in current day clinical practice. This is due to the suboptimal performance in detecting ST depression compared to multiple lead systems [8]. Previous work on BCLs has primarily focused on the analysis of the ST-T segment [9]–[11]. In addition, a bipolar precordial lead recorded between V2 and V5 has previously been shown to increase the sensitivity for the detection of type 1 Brugada pattern during ajmaline tests. The authors described this lead as lead $V_{2\text{-}5}$ [12].

Given the described improvement in lead-vector magnitude from BCLs [2], this may make them an appropriate choice for single-lead ambulatory ECG monitors focused on assessing cardiac rhythm.

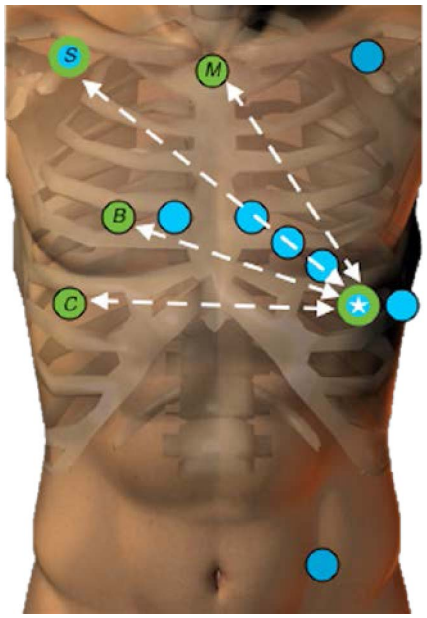

Figure 1. Electrode locations of the Mason-Likar 12-lead ECG (blue) and bipolar chest leads (green) for exercise testing. All bipolar chest leads are measured in respect to precordial lead V5 with the negative electrode placed in a range of different positions.

3. Method

3.1. Study data

The study population consisted of 117-lead BSPMs from 229 healthy subjects. The BSPM data have previously been described in [13]. The BSPM-leads at the 117 recording sites were sampled with respect to Wilson's central terminal. In order to provide greater spatial resolution, the 117-lead BSPMs were transformed, using a Laplacian 3D interpolation procedure, into 352-nodes which correspond to the nodes on the Dalhousie torso [14].

Some of the required electrocardiographic leads were not available as a direct subset of the interpolated BSPMs. Body surface potentials that were required but not available as a direct subset of the interpolated BSPMs were obtained using linear interpolation. Random sampling was used to divide the study population into a training data set consisting of 172 patients and a testing data set consisting of the remaining 57 subjects.

3.2. Lead selection method

To determine a point in time were the maximum R-wave deflection occurred for each subject we calculated the difference in R-wave amplitude (R_{diff}) across all 352-nodes of the BSPMs, as outlined below.

$$R_{diff}(n) = R_{max}(n) - R_{min}(n). \quad (1)$$

Were $R_{diff}(n)$ is the maximal R-wave amplitude for a defined point in time n, R_{max} is the maximum R-wave value across all 352 BSPM nodes at n, R_{min} is the minimum R-wave value across all 352 BSPM nodes at n.

The point in time containing the maximum R-wave amplitude for each subject was defined as location whereby the greatest difference in R-wave amplitude occured. R-wave values at this instance in time were then extracted across all 352-nodes. To alleviate any bias attributable to dominant R-wave values from individual subjects each subjects R-wave values were normalised between 0 and 1, as outlined below.

$$R_{norm} = \frac{R_{amp} - \min(R_{amp})}{\max(R_{amp}) - \min(R_{amp})}. \quad (2)$$

Where R_{norm} is the normalised R-waves value and R_{amp} is the non-normalised R-wave value.

This method was repeated for all 172 subjects of the training set producing one BSPM, of R-wave amplitudes, for each subject. A population based R-wave BSPM was then produced by taking the median of the R-wave potentials on each node of the BSPM across all 172 subjects of the training dataset, resulting in a single BSPM

of R-wave amplitudes across the population.

The median BSPM of the training dataset was used to determine the optimal BCL. This optimal BCL was defined as the lead measured between the maximum and minimum R-wave amplitude locations.

3.3. Statistical analysis

The primary analysis compared the best lead for R-wave amplitude to the second best performing lead. A comparison of the median R-wave amplitude values between the different leads was performed using the Wilcoxon signed-rank test.

4. Results

The optimal placement of bipolar electrodes for recording of maximum R-wave amplitude is the fourth left intercostal space adjacent to the sternum and the 5th left intercostal space on the mid clavicular line. These positions also correspond to precordial leads V2 and V5 of the 12-lead ECG. The R-lead showed significant improvement in median R-wave amplitude compared to the next best ECG lead, CM_5 (2562μV vs. 2420µV, Wilcoxon sign ranked test, p<0.001).

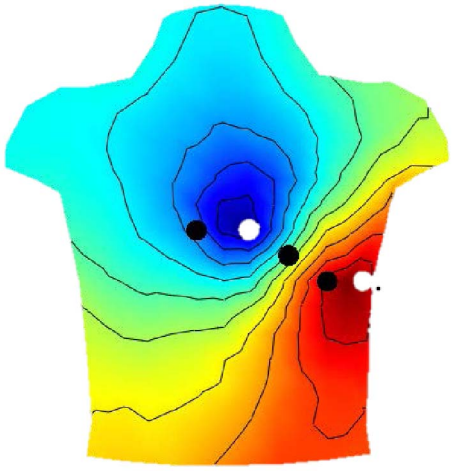

Figure 2. Median BSPM created from the training dataset (172 patients). A bipolar chest lead recorded between V2 and V5 can provide a significant improvement in R-wave amplitude across the testing dataset. The optimal electrode placement highlighting in white with the remaining four precordial leads mark in black.

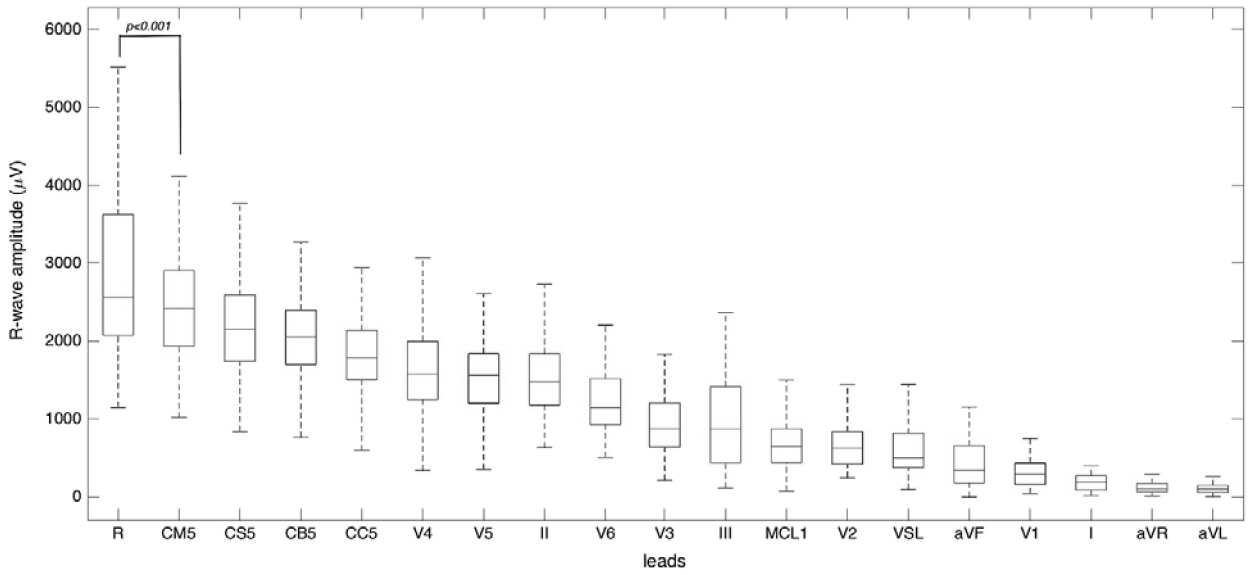

Figure 3. R-wave amplitude from all investigated ECG leads. The R-lead outperformed all other leads in terms of median R-wave amplitude (2562μV vs. 2420µV, Wilcoxon sign ranked test, p<0.001).

5. Discussion

Accurate automated detection of R-waves during high signal noise still remains a challenge. As such, many false positive alarms in a clinical setting can be made attributable to low R-wave amplitude and in turn low signal to noise ratio [15]. In this study we have focused on determining the optimal placement of ECG electrodes for the recording of maximum R-wave amplitude. The lead selection method implemented in this study analyses all available ECG information during ventricular depolarization to determine the point in time where the greatest R-wave amplitude occurred for each subject. The R-lead found in this study outperforms all other

investigated leads in terms of R-wave amplitude. The R-lead could be used for applications such as long term ambulatory cardiac rhythm monitoring. Given the improvement in signal magnitude it is expected that an improvement in automated R-wave detection and improved R-R interval analysis may be possible. As the R-lead is recorded between precordial lead V2 and V5 it can also be referred to as a bipolar precordial lead. What remains to be tested is the performance of the R-lead during events of myocardial ischemia. This will be of interest as BCLs CS_5 and CM_5 have been previously been described to detect up to 90% of all ST segment depression identified by multi-lead ECG systems [2][16].

6 Conclusion

In situations where only a single lead ECG is available The R-lead can provide an improvement in the signal amplitude of the R-wave when compared to the ML 12-lead ECG and previously described BCLs. This new electrode position may lead to more accurate identification of R-peaks during times of high signal noise such as, for example, intense exercise.

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