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Best Electrode Locations for a Small Bipolar ECG Device: Signal Strength Analysis of Clinical Data

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Abstract—New miniaturized portable electrocardiogram (ECG) measuring devices may require small interelectrode distance. However, finding a suitable location for a tiny measurement device may prove tedious, as reducing interelectrode distance reduces signal strength. The objective of the study was to define the optimal location for a very closely located (5 cm) bipolar electrode pair. A total of 120 bipolar leads were analyzed from a body surface potential map (BSPM) data with 236 subjects with a normal ECG. The average and standard deviation (SD) of the QRS-complex and the P-wave amplitudes in each electrode location and for each subject were determined. The results showed that deviation in signal amplitude between different subjects is significant. However, judging from average values, the best orientation for a closely located bipolar electrode pair is diagonally on the chest. The best locations for QRS-complex and P-wave detection are around the chest electrodes of the standard precordial leads V2, V3, and V4, and above the chest electrodes of leads V1 and V2, respectively.

Keywords—Body surface potentials, Signal amplitude, Bipolar lead, Electrode orientation.

INTRODUCTION

Developments in measurement technologies have led to the emergence of new portable and wireless electrocardiogram (ECG) monitoring devices.[1] Sensor technology for implantable applications has also been developed to enable measurement of biosignals inside the human body.[10] The new portable and wireless devices would seem to point the way forward in biomedical measurement technology. As electronic equipment is becoming smaller, the size of monitoring devices can also be reduced. Hence, such devices could benefit from a small interelectrode distance. However, since reduction in interelectrode distance inevitably reduces signal strength, it is crucial to identify the optimal locations for the measuring electrodes when designing such small measurement systems. In addition, the signal strength obtained varies between different electrode positions, and individual variations may cause deviation in results. Body surface potential maps (BSPM) that include recording of an ECG signal at several locations on the chest provide an invaluable tool for assessing different lead configurations. BSPMs have been widely analyzed in order to locate the sites that offer the most electrocardiographic information.[2] BSPMs have also been used for studying new bipolar leads, which enhance P-wave magnitudes.[8] The main objective here was to study how a very closely lying bipolar electrode pair should be located on the chest in order to obtain a reliable and strong ECG signal for diagnostic purposes.

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MATERIAL AND METHODS

Body surface potential mapping is a technique used to capture high-resolution recordings of the heart's activities by measuring biopotentials from several electrodes on the subject's chest. The material used in this study was Kornreich's clinical body surface potential map (BSPM) data on 120-lead ECG acquired from 236 normal subjects.[7] In this set, 120 unipolar lead ECG signals were recorded using the Wilson's central terminal as the reference. For the present study, the bipolar lead ECG signals were formed by calculating the difference between two unipolar lead signals.

Two analyses were conducted in order to optimize the bipolar electrode pair location to ensure a strong and reliable ECG signal: analysis of QRS-complex and P-wave amplitudes, and analysis of the deviation in these amplitudes between individuals. These methods were used to study the signal strength in bipolar electrode pairs located on the left side of the chest. The electrode pairs were chosen among and close to the chest electrodes of the standard precordial leads V1–V6, as their location is commonly known, and as

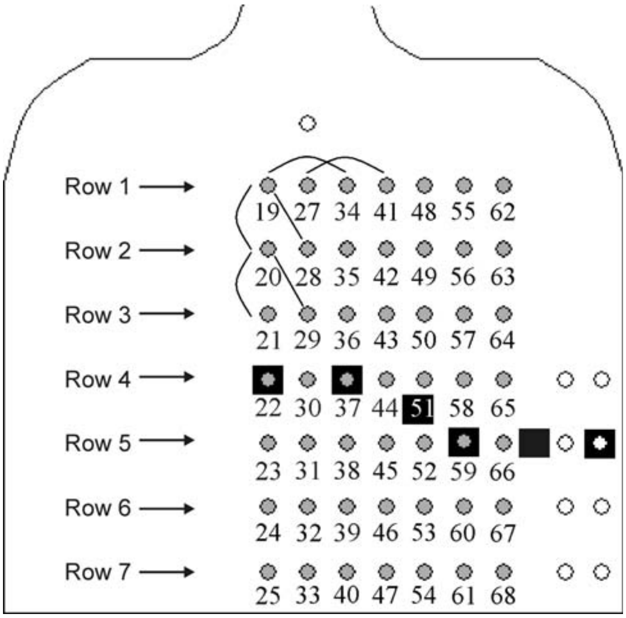

FIGURE 1. Front view of body surface potential map electrode locations. Electrodes analyzed in terms of signal strength are numbered and colored in grey. Black squares denote the location of the chest electrodes of the standard 12-lead system precordial leads V1–V6. Bipolar electrode pairs were constructed diagonally (e.g. 19–28), vertically (e.g. 19–20) and horizontally (e.g. 19–34).

the ECG signal arises from that area. Forty-nine electrodes out of the original 120 were selected, and 120 bipolar electrode pairs were constructed from these (Fig. 1). The pairs were combined diagonally, vertically and horizontally, as illustrated in Fig. 1, in order to assess the effect of orientation on signal amplitude. The electrode distances of the bipolar leads constructed were approximately 6.0 cm diagonally, 5.2 cm vertically and 6.0 cm horizontally, depending on the person's size.

QRS-Complex and P-Wave Amplitudes

For comparison of the different electrode locations, we wrote a Matlab script calculating the QRS-complex and P-wave amplitudes from the 120 bipolar lead signals. We used the peak-to-peak value of the QRS-complex to give the full amplitude during the ventricular activation. Similarly, we used the P-wave amplitude, with the baseline adjusted to the TP-segment, to give the amplitude during the atrial activation. These amplitudes were defined in 120 bipolar electrode pairs and for each subject and the average amplitudes within different subjects were determined. The P-wave was targeted, as it is usually one of the smallest of the diagnosed parameters in the ECG, and thus is the first to disappear under noise.

For reference, we compared the signal amplitudes obtained to noise levels of 15 and 60 μV, these values representing a fairly low and a rather high noise level in normal ECG measurements.[4–6] Noise values were taken from the literature, as noise could not be analyzed from readily parameterized and preprocessed clinical data. Also results with lower noise levels in biopotential recordings have been published,[11] but we sought to take into account cases representing less optimal circumstances.

Signal Strength Deviation Between Subjects

In addition to the fact that signal strength varies between different electrode positions also individual variations may cause deviation in results. To define which electrode location reliably provides a strong signal independent of the subject, the standard deviation (SD) of average QRS-complex and P-wave amplitudes between cases were calculated for the same 120 bipolar electrode pairs. The SD shows the extent to which the data samples differ from the average value[3]; thus it describes how stable the recording site is between individuals. To compare different leads, we further calculated the ratio between the SD and the average signal strength to normalize the results, as the SD increases concomitant with signal strength.

RESULTS

QRS-Complex and P-Wave Amplitudes

Figure 2 illustrates the average QRS-complex (left side) and P-wave (right side) amplitudes obtained from 120 bipolar electrode pairs. The uppermost, middle and undermost figures represent signal strengths obtained from electrode pairs directed diagonally, vertically and horizontally, respectively. Each graph includes electrode pairs from different rows on the chest (see Fig. 1 for row numbering) denoted as, e.g. R 1 or R 1–2.

The diagonal electrode pairs provided the highest QRS-complex and P-wave amplitudes, especially among rows 3–6 (Fig. 2). Among rows 1–2 and 6–7, there was little difference between the amplitudes obtained with different orientations. It should be noted that the diagonal electrode pairs lie in the direction of the heart's electrical axis, and thus detect the strongest activation in the heart area.

Figures 2a–2c show that for all electrode pair orientations, the best area for detecting QRS-complex was between rows 4 and 5. The electrode pairs providing the highest amplitudes are indicated with filled squares. More precisely, the diagonal electrode pairs

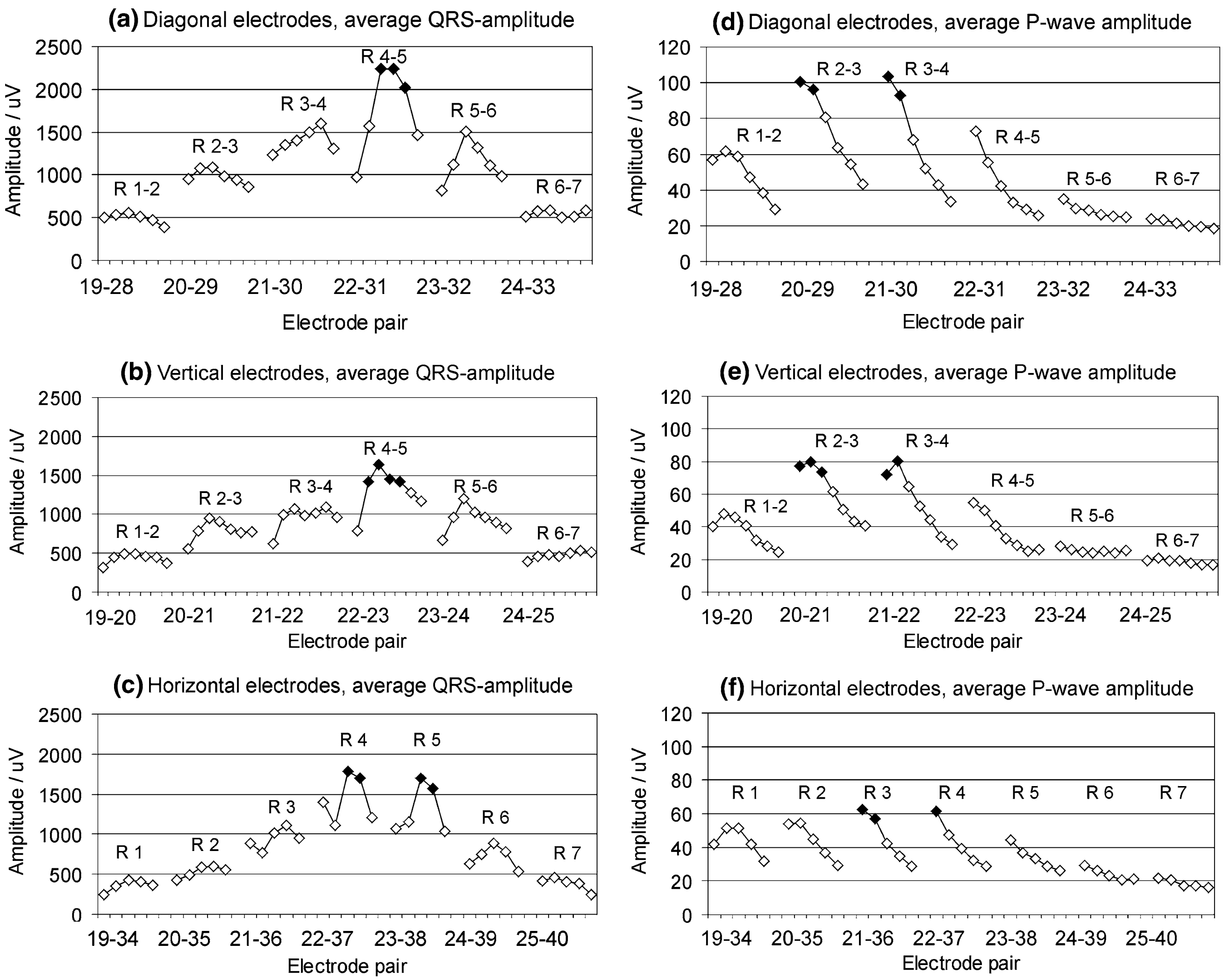

FIGURE 2. QRS-complex (*left*) and P-wave (*right*) amplitudes obtained from 120 electrode pairs on the BSPM. The uppermost, middle and undermost curves indicate amplitudes for electrode pairs oriented diagonally, vertically and horizontally, respectively. The rows in which electrodes are located are denoted as R 1–2, R 2–3, etc. In each row, there are 6 squares for diagonal, 7 squares for vertical and 5 squares for horizontal pairings. In each row, moving to the right on the graphical illustration, the electrode pair is moving toward the left side of the subject's chest. In the *x*-axis only the first electrode pairs are denoted for each row. The filled squares denote the electrode pairs providing the highest signal amplitudes. See Fig. 1 for rows and electrode numbering.

37–45, 44–52, and 51–59 detected the highest QRS-complex amplitudes (Fig. 2a). Among the vertical electrode pairs, the highest amplitudes were obtained from pairs 30–31, 37–38, 44–45, and 51–52 (Fig. 2b). Among the horizontal pairs again, the best were 37–51, 44–58, 38–52, and 45–59 (Fig. 2c). All of these electrode pairs are located around the chest electrodes of the standard precordial leads V2, V3, and V4. Their locations are illustrated in black in Fig. 3.

Figures 2d–2f show that the best area for detecting the P-wave was on rows 2–3 and 3–4. The electrode pairs providing the highest amplitudes are indicated with filled squares. More precisely, the diagonal pairs 20–29, 28–36, 21–30, and 29–37 detected the highest QRS-complex amplitudes (Fig. 2d). Among the vertical electrode pairs (Fig. 2e), the highest amplitudes were obtained from pairs 20–21, 28–29, 35–36, 21–22, and 29–30. Among the horizontal electrode pairs (Fig. 2f), the best ones were 21–36, 29–43, and 22–37 (corresponds to the chest electrodes of the precordial leads V1–V2). All of these pairs are located among or right above the chest electrodes of the standard precordial leads V1 and V2. Their locations are further indicated in grey in Fig. 3.

When we compared the results to a reference noise level of 15 μV, which corresponds to a low noise situation, all electrode pairs studied provided a detectable P-wave. If the reference noise level was 60 μV, the P-wave disappeared under noise in all horizontal and in most diagonal and vertical electrode pairs; only some

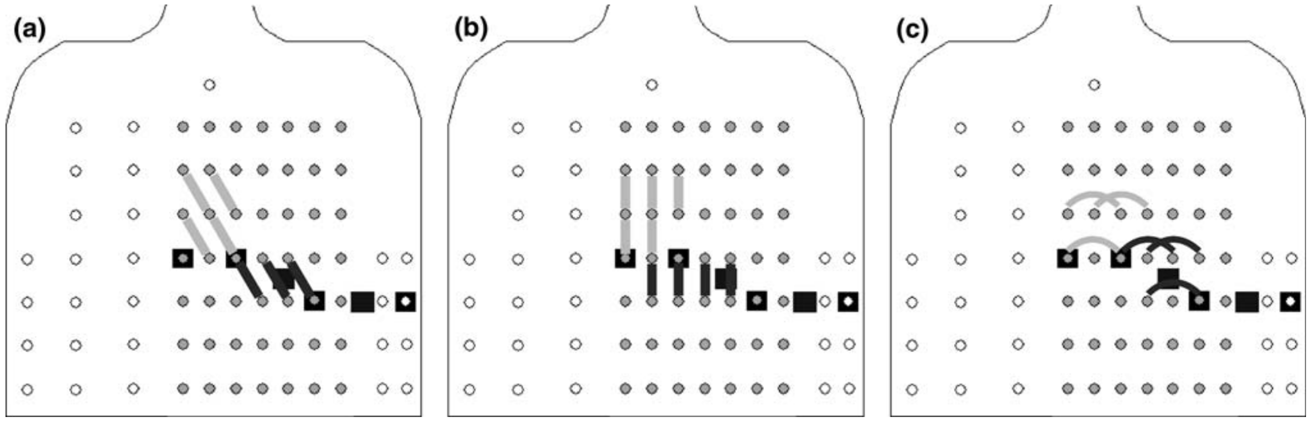

FIGURE 3. The diagonal (a), vertical (b) and horizontal (c) bipolar electrode pairs providing the highest QRS-complex (*black*) and P-wave (*grey*) amplitudes. Black squares denote the location of the chest electrodes of the standard 12-lead system precordial leads V1–V6.

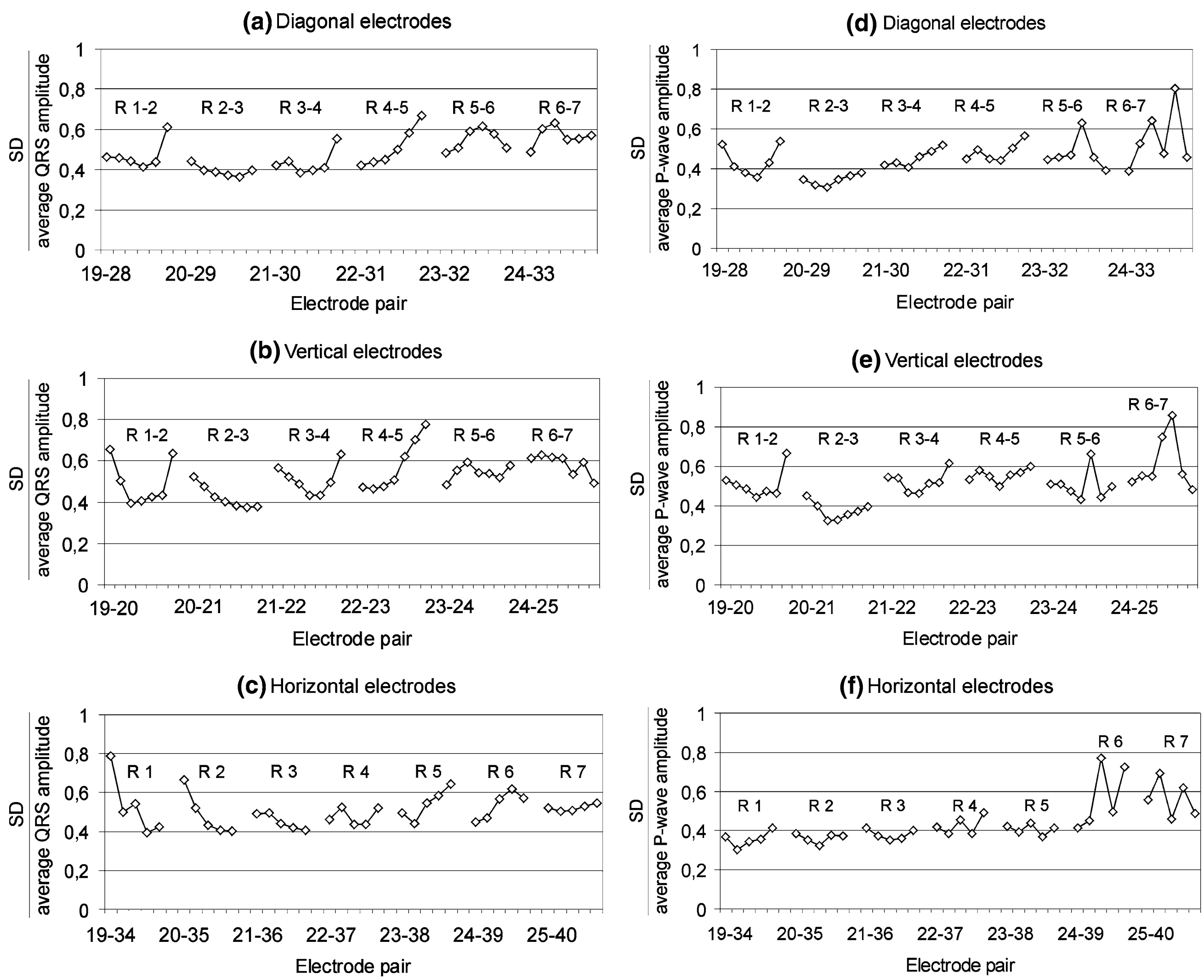

FIGURE 4. The ratio between standard deviation (SD) and average of QRS-complex (*left*) or P-wave (*right*) amplitudes obtained from 120 bipolar electrode pairs on the BSPM. See details for electrode pairs in Fig. 2.

pairs between rows 2–3 and rows 3–4 provided amplitudes higher than 60 μV. In contrast, the QRS-complex amplitude was higher than the reference noise levels in all electrode pairs studied.

Signal Strength Deviation Between Patients

Figure 4 illustrates the ratio between SD and average QRS-complex amplitude (left side), and SD and average P-wave amplitude (right side) for 120 bipolar electrode pairs. The figure reveals the deviation in signal strength between patients to be remarkable. This means that the location of electrodes providing stable values for signal strength applicable to the whole population is difficult to define. Figures 4a–4c show that the ratio between SD and average QRS-complex amplitude was similar in diagonal, vertical and horizontal electrode pairs. When considering rows 4 and 5, which provided the highest QRS-complex amplitudes, the ratio increased toward the left side of the chest. This might arise from the fact that the QRS axis varies between individuals and causes deviation in signal strength in measuring from the heart area. Figures 4d–4f show that the ratio between SD and average P-wave amplitude was slightly lower in horizontal electrode pairs. On rows 2–3, where the P-wave amplitudes were among the highest, the ratio was quite low compared to other locations.

DISCUSSION

For the purpose of analyzing and defining suitable electrode locations for lightweight wireless ECG measurement with small interelectrode distance, the clinical data were analyzed in terms of average signal strength and SD within subjects. A preliminary study with a smaller number of electrodes was presented in BEM NFSI 2005 conference in Minnesota.[9] According to the present study, the best orientation for a bipolar electrode pair was diagonally on the chest. The highest QRS-complex and P-wave amplitudes were obtained from the diagonal electrode pairs 37–45, and 21–30, respectively. The diagonal electrode pairs are the most sensitive for ECG changes, due to their parallel direction with heart's electric axis.

Generally, for all electrode pair orientations, the highest QRS-complex amplitudes were obtained around the chest electrodes of the standard precordial ECG leads V2, V3, and V4. Correspondingly, the best area for P-wave detection was among or right above the chest electrodes of leads V1 and V2. This was to be expected, since the QRS-complex arises from ventricular and P-wave from atrial activation.

The results were also compared to reference noise levels of 60 and 15 μV in order to see whether the QRS-complex or P-wave would disappear under the noise. With a reference noise level of 60 μV, the P-wave disappeared under noise in all horizontal and in most diagonal and vertical electrode pairs. The diagonal and vertical electrode pairs illustrated in Fig. 4 provided P-wave amplitudes higher than 60 μV. As to the QRS-complex amplitude, it was clearly higher than the noise in all electrode pairs studied. This means that for applications requiring only the heart beat, all electrode pairs studied would be adequate. When comparing to a reference noise level of 15 μV, which corresponds to a low noise situation, all electrode pairs studied provided also a detectable P-wave.

In terms of interindividual variation, the results showed the SD in signal strength between subjects to be significant in all electrode pairs studied. This means that an adequate signal level for an individual person is difficult to predict. This was expected, since the variation within individuals' anatomy and physiology affect the signal level obtained. This might be especially marked in the case of bipolar chest leads compared to the unipolar leads normally used in ECG measurements. When considering rows 4 and 5, which provided the highest QRS-complex amplitudes in this study, the relative SD increased moving to the left on the chest (Figs. 4a–4c). This might be attributed to the fact that the QRS axis varies between individuals and causes deviation in signal strength in measurements over the heart area.

It should be noted that the results were calculated as an average of 236 subjects, and amplitude values vary among individuals. However, the findings give an indication of the optimal location for a closely located bipolar electrode pair for different purposes. If the purpose is to detect the heart rate variability then the optimum location is likely to be that providing the highest QRS amplitude. In the case of detecting and classifying cardiac arrhythmias the location providing the highest P-wave amplitude is better. This information is useful, e.g. when designing electrode locations for small wireless or wearable one-lead ECG measurement devices. Such small electrode systems could be used for general ECG diagnostics or simply for detecting heart rate. In addition, it may give information as to possible locations for subcutaneous ECG recorders.

CONCLUSION

Clinical BSPM data from 256 subjects were analyzed in order to find the best locations for bipolar ECG electrodes set at small interelectrode distances.

The results showed that the best locations for QRS-complex and P-wave detection are around the chest electrodes of the standard precordial ECG leads V2, V3, and V4, and above the chest electrodes of leads V1 and V2, respectively. The optimal orientation for an electrode pair is diagonally. This information is useful when using and designing new wireless and portable one-lead ECG measurement systems.

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