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Precordial electrode placement for optimal ECG monitoring: Implications for ambulatory monitor devices and event recorders☆

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Abstract

Introduction: Detection of QRS complexes, P-waves and atrial fibrillation f-waves in electrocardiographic (ECG) signals is critical for the correct diagnosis of arrhythmias. We aimed to find the best bipolar lead (BL) with the highest signal amplitude and shortest inter-electrode spacing.
Methods: ECG signals (120 seconds) were recorded in 36 patients with 16 precordial electrodes placed in a standardized pattern. An average signal was analysed for each of 120 possible BLs obtained by calculating the difference between pairs of unipolar leads. Peak-to-peak amplitudes of QRS waves (50 ms around R-peak) and P waves (270–70 ms before R-peak) were calculated. For patients with atrial fibrillation, power of the fibrillatory (f) wave was used instead. Maximum values at each distance were considered and differentiation analysis was performed based on incremental changes (amplitude to distance).
Results: There was a significant correlation between distance and QRS-amplitude ($r = 0.78$, $p < 0.001$), P-wave amplitude ($r = 0.60$, $p < 0.01$) and f-wave power ($r = 0.79$, $p < 0.001$). The range of values was: QRS-amplitude 0.7–2.33 mV, P-wave amplitude 0.07–0.18 mV, and f-wave power 0.55–2.12 mV^2/s. The maximum value for the shortest distance was on a heart-aligned axis over the left ventricle for the QRS complex (1.9 mV at 8.7 cm) and over the atria for the P-wave (0.98 mV) and f-waves (1.45 mV^2/s at 8 cm, respectively).
Conclusion: There is a strong positive correlation between electrode distance and ECG signal-amplitude. Distance of 8 cm on a heart-aligned axis and over the relevant heart-chamber provides the highest signal amplitude for the shortest distance. These findings are essential for the design and use of ambulatory monitoring devices.

Keywords: Ambulatory; Patient monitoring; Electrocardiography (ECG); Atrial fibrillation

Introduction

Palpitations and arrhythmias are among the most common symptoms which prompt patients to consult healthcare services [1]. The diagnosis and treatment of these symptoms often proves to be strenuous, frustrating and elusive, despite numerous time-consuming and costly investigations. Cardiac arrhythmias and especially atrial fibrillation (AF) are the most common cause of palpitations [2]. Electrocardiographic (ECG) documentation during symptomatic episodes is necessary to establish causality, in order to guide the therapeutic strategy [3,4]. This is of paramount importance when it comes to detection of AF, which partially remains asymptomatic, especially after an ablation procedure [5–7].

Ambulatory monitoring with Holter-ECG, telemetry, implantable cardiac monitors, loop or event recorders have improved the detection and differentiation of arrhythmias. However, existing detection algorithms still fail to achieve high levels of sensitivity and specificity, due to motion artefacts and other ECG-noise caused by muscle myopotential activity [8–10].

While rhythm detection has traditionally focused on the QRS complex, P- and f-wave detection has been lately implemented in some diagnostic algorithms [11–15]. The amplitude of these waves highly depends on the positioning of the electrodes, which in term affects patient convenience

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[16]. In principle, a shorter distance between electrodes, possibly in a single device would yield a better patient compliance. Low-power electronics have allowed the development of numerous small devices that can be used for several days or weeks, especially for patients with AF [7,17,18]. However, hitherto little is known about the optimal size, electrode spacing and placement for such devices.

In this study we analysed the ECG signals from different precordial electrode positions of both AF patients and subjects without AF in order to estimate an optimal electrode location that provides the optimal signal quality with the smallest inter-electrode spacing possible.

Methods

We included 36 patients (61 ± 16 years old) that presented in the outpatient clinic of our cardiology clinic for evaluation or follow-up of known heart disease, as a representative sample of typical real-world patients, occasionally requiring ambulatory monitoring. Patients were examined at rest in a supine position with 16 electrodes covering the precordial area, in order to minimize muscle myopotentials. Electrodes were placed between the 2nd and 5th inter-costal space (ICS) in a standardized pattern, aligned in columns over the sternum, the bilateral parasternal lines and the left mid-clavicular line. Left papilla mammaria was excluded due to patient compliance and the respective electrode was placed on the 5th ICS at the anterior auxiliary line. The distance between adjacent electrodes was fixed at 4 cm left to right, 3.5 cm superior to inferior and 5.5 cm diagonal. Fig. 1 illustrates the placement, numbering and distances between electrodes.

The 16 unipolar ECG signals were recorded against a right foot reference, over a period of 120 seconds and were digitalized with a sampling frequency of 4800 Hz. An averaged electrical signal was then calculated for all possible bipolar leads (BL) which were obtained by taking the difference between each pair of unipolar leads. From a total of 256 combinations generated, we excluded duplicates and zero values to finally examine 120 different BLs for each patient. Mean values were then obtained for each BL for all patients in the study. We then analysed BL amplitudes for the 19 different distances and selected the BL with the maximum value for each specific distance. BLs with a value more than 91% of the maximum value were defined as clinically equivalent (Tables 2–4). In order to specify the electrodes with the highest amplitude for the shortest distance, we performed differentiation analysis based on incremental change. Examples of signal analysis for the QRS, P and f-wave are presented in (Fig. 2).

In order to evaluate the validity of our findings we performed an additional differentiation analysis for every individual patient. We calculated the optimal BLs and their equivalents for every patient and then compared these with the optimal BLs as previously calculated (Table 5).

QRS amplitude

An averaged beat was obtained in order to remove noise, by applying a Butterworth filter with low-pass frequency of 100 Hz cut-off and notch Filter of 50 Hz. No high-pass filter was applied. The peak-to-peak QRS amplitude was defined as the difference between maximum and minimum amplitude (mV) in a window of 50 ms around the R-peak, which was sufficient to capture the largest QRS amplitude in all patients.

P-wave amplitude

For patients in sinus rhythm, the P-wave amplitude was calculated from an averaged ECG beat. The peak-to-peak

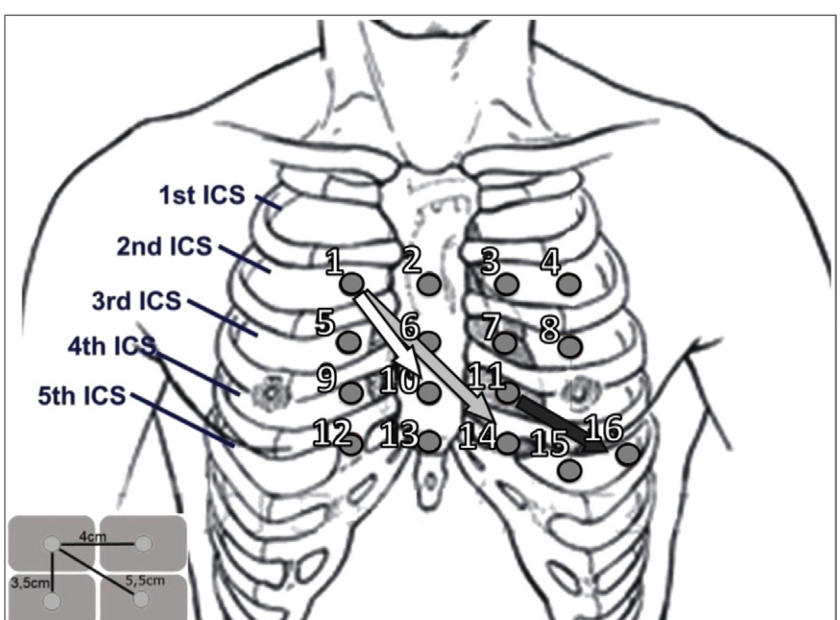

Fig. 1. Electrode position and distance between adjacent electrodes. Electrodes were covering the precordial area and named as depicted. The arrows illustrate bipolar electrode leads for optimal ECG monitoring based on the registration of ventricular (black), atrial (white) or both activities (grey). ICS = inter-costal space.