

Electrocardiographic Signal Broadband Properties

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Abstract

Background: Low, high, and ultra-high-frequency ECGs measure ventricular activation differently. However, their principles and properties have not yet been studied systematically.

Method: 5 kHz ECG resting recordings were acquired in 134 subjects. We used an extended 12-lead ECG setup with 6 (V1-V6)+6 extended precordial leads. We measured the distance of all precordial leads to the ventricular geometrical center with the magnetic resonance images. We determined the amplitude of frequency components for each lead by computing the area of the averaged amplitude envelopes during the QRS complex. We used five frequency bands: LF (0.2-20 Hz), MF (20-80 Hz), HF (80-300 Hz), UHF1 (300-500 Hz), and UHF2 (800-1.000 Hz).

Results: The relative amplitude decreases with relative distance from the myocardial depolarization source and significantly differs in frequencies. The decay coefficient in the LF band is more than two times lower than the UHF2 band coefficient. All differences between frequencies are significant $p < 0.005$.

Conclusion: Lower frequencies are more sensitive to distant areas, and higher frequencies are more sensitive to near regions. Combining multiple frequency bands has the potential to localize activation sources more precisely.

1. Introduction

Electrocardiography (ECG) is an old technology that has been thoroughly researched [1,2]. The standard interpretation of ECG is based on the projection of electrical vectors onto individual electrodes on the body surface [3]. The propagation of a depolarizing wave creates these vectors [4]. The QRS complex in the ECG indicates the properties of electrical depolarization of the ventricles.

Figure 1 shows how the electrical vectors are projected onto a particular electrode in case of normal ventricular activation. Electrode V1 records activation in the right ventricle and septum and activation in the left ventricle's free wall, which is far from the electrode. Thus, in this low-frequency ECG, vectors are projected predominantly from the entire volume of the ventricles, and there is a low attenuation of the vector amplitude with electrode distance from the source.

In recent years, ultra-high-frequency ECG (UHF-ECG) methodology has been introduced [5] and used to describe activation patterns in cardiac pacing [6,7,8]. It was shown that the UHF-ECG activation maps [9,10] can accurately determine the temporal delays of right and left ventricular electrical activation. UHF-ECG's information is simple, straightforward, and fundamentally different from conventional QRS morphology. Many studies have shown the methodology's significant clinical benefit [11, 12].

In this study, we examined the properties of ECG signals at low, high, and ultra-high frequencies. We were interested in the spatial sensitivity associated with broadband ECG signal propagation.

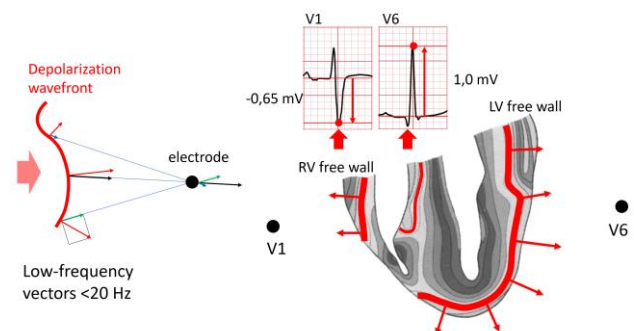


Figure 1. Projection of electrical low-frequency vectors onto electrodes V1 and V6. Body surface electrode V1 records depolarization even from the remote free-wall of

the left ventricle, and V6 from the right ventricle (negative notches), red arrows in QRS.

2. Methods

2.1. Data recordings

Ultra-high-frequency 5 kHz ECG supine resting recordings with a bandwidth of 1500 Hz were acquired in 134 subjects (64 normal, 70 with pathologies). We used an extended 12-lead ECG setup with 6+6 precordial leads – see Figure 2. The Ethics Committee of St. Anne's University Hospital Brno approved the study. All methods were performed according to relevant guidelines and regulations, and all patients gave their written informed consent.

We used magnetic resonance images to measure the distance of all precordial leads to the ventricular geometrical center.

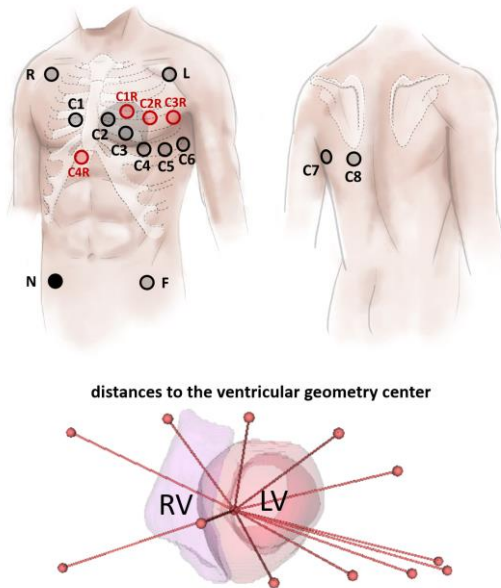


Figure 2. Top panel: electrode placement. Lower panel: determination of the electrodes' distance from the ventricles' geometric center by MR.

2.2. Frequency-related amplitude decay computation

We determined the amplitude of frequency components for each lead and subject by computing the area of the averaged amplitude envelopes during the QRS complex.

We used five frequency bands: Low-frequency LF (0.2-20 Hz), middle-frequency MF (20-80 Hz), high-frequency HF (80-300 Hz), ultra-high-frequency UHF1 (300-500

Hz), and UHF2 (800-1000 Hz).

For each subject, we determined the decay coefficient N of the power function $1/X^N$ and calculated the dependence of the signal amplitude decrease with distance from the ventricular geometrical center for different frequencies – Figure 3.

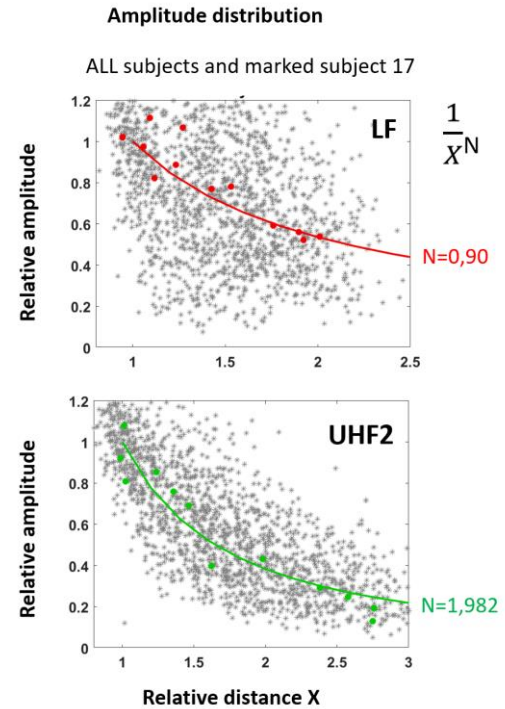


Figure 3. Graph of the relationship between electrode relative (shortest distance equal to one) distance X from the geometry center and ECG signal amplitude. The top panel is the LF band, and the lower panel is the UHF2 band. The color-coded red and green waveform shows single-subject decay. Gray marks represent complete measured amplitudes and distances over all subjects.

3. Results

The complete results are shown in Figure 4. We have determined the decay coefficients for each frequency band and in each subject and computed median values of decay coefficients over all subjects. The lowest value of the decay coefficient is in the case of LF ($N=0.76$), the crucial frequency band for determining the morphology of the QRS complex. The highest decay coefficient is for the maximal analyzed frequency, UHF2 800-1000 Hz ($N=1.79$). Figure 4, lower panel, shows box plots of N coefficients over all frequencies.

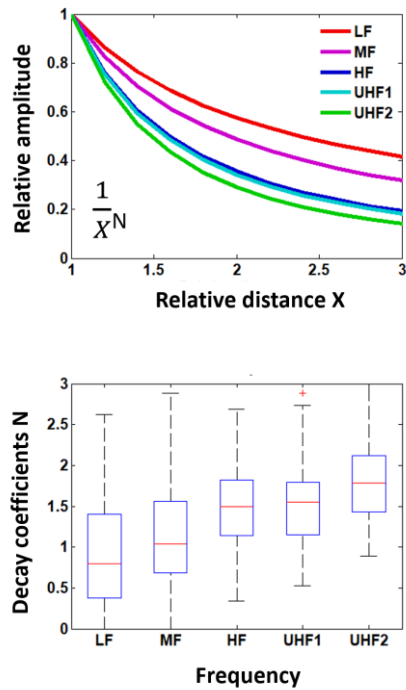


Figure 4. Decay coefficients for individual frequency bands. Top panel $1/X^N$ functions for different frequencies. Lower panel box plots – the red line indicates the median value (P50), the blue box the percentiles P25 and P75, and the black dashed line the percentiles P05 and P95.

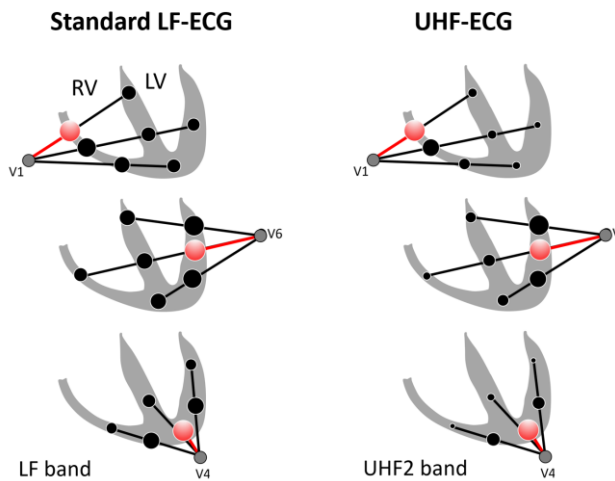


Figure 5. The signal intensities from RV, LV, and septal ventricular segments in electrodes V1, V4, and V6 on the body surface. The area of the circles corresponds to the signal amplitude recorded in a particular electrode. The circle marked in red has an area of 1 and is at the smallest distance from the electrode. The left panel includes the LF band, and the right panel consists of the UHF2 band of 800-1000 Hz.

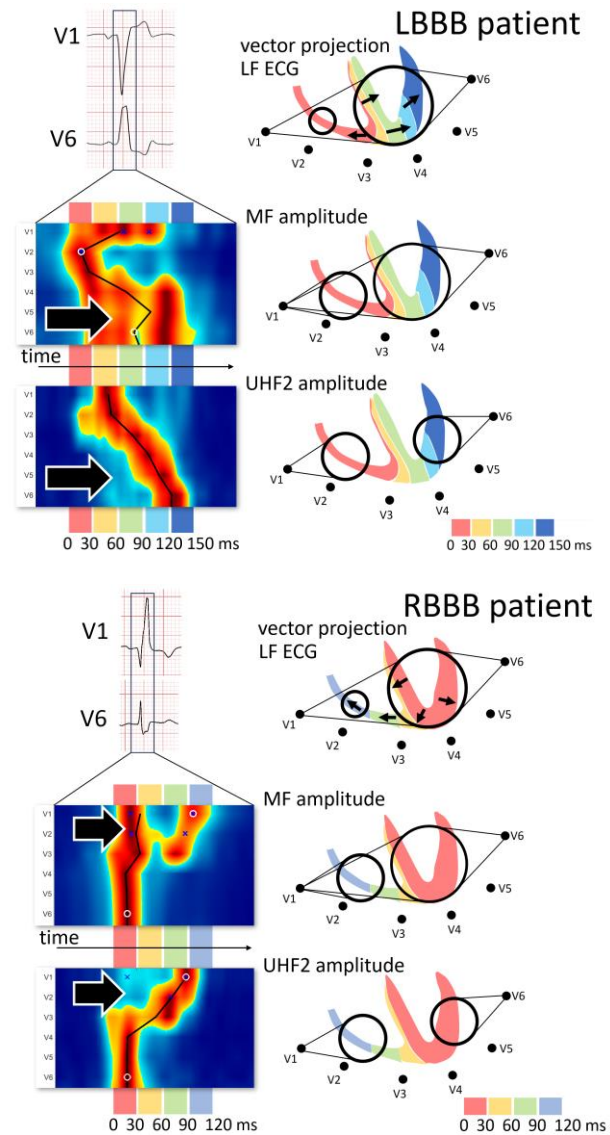


Figure 6. Comparison of ECG and activation maps for LBBB and RBBB patients. Increasing frequency leads to focusing on closer areas. By comparing frequencies, we can distinguish between near and far activations. The arrows point to these differences, mainly related to septal activation.

4. Discussion

In the present study, we observed lower frequencies are more sensitive to distant areas, while higher frequencies are more sensitive to near regions. Figure 5 shows the detectability of the low and UHF oscillations in the individual electrodes on the chest surface. The low frequencies detect the signal nearly from the entire volume. UHF frequencies show a significant difference in intensity between the near and far segments. UHF frequencies are sensitive to activation predominantly from the near left and

right ventricular free walls and, with less intensity, the remote septal region.

The described properties can be used for more accurate localization of electrical activation by comparing activation maps for different frequency bands and determining the differences. Thus, the timing of septal activation can be localized more accurately. This is shown in examples in Figure 6 for two different activation disturbances, the left bundle branch block (LBBB) and the right bundle branch block (RBBB). While the QRS complexes show typical morphologies for a given activation disorder, activation maps at lower and higher frequencies can distinguish activated segments. The arrows show differences in the maps associated with different septal activations during LBBB and RBBB. The time and location of activation can be measured precisely.

5. Conclusion

The study introduced the attenuation properties of the ECG signal at different frequencies. Low frequencies have a much lower signal amplitude drop; therefore, the surface electrodes record activity from almost the entire volume of the ventricles. The ultra-high-frequency components of the ECG have significantly higher decay, and thus, the surface electrodes record near activation much more strongly.

The described frequency characteristics of ECGs indicate the potential to localize ventricular activation sources with high accuracy.

Acknowledgments

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