Ultra-high-frequency ECG Measurement

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Abstract

The aim of the present study is to introduce ultra-high-frequency and high-dynamic-range 12-lead ECG measurements using an electromagnetically shielded environment (Faraday cage) and a battery-powered ECG monitor with sampling of 25 kHz and 24-bit resolution. To demonstrate its diagnostic contribution we present the results of 14 subjects – 7 healthy volunteers and 7 ischemic patients during short 15-minute resting supine recordings. Both groups of subjects have the same width of the regular QRS complex with no ST-segment abnormalities. Wide-band power envelope analysis up to 1000 Hz was applied on each QRS complex region. Artifact-free QRS complexes from approximately 500 beats were averaged with the R-wave maximum from lead V2 as a trigger. The power envelopes consist of narrow and compact shapes in all leads in healthy young volunteers. In ischemic patients, there is a significant expansion and splitting of frequency components and differentiation in measured leads. In this study, we have shown the ability of ultra-high-frequency and high-dynamic-range ECG measurement to detect heart muscle pathology.

1. Introduction

Cardiac ischemia and various kinds of cardiomyopathies frequently result in structural damage to the heart muscle which can lead to heart rhythm disturbances or even risk of sudden cardiac death. Pathological changes often manifest themselves in the electrical conductivity of the heart and cannot be clearly identified from standard ECG records. Conventional 12-lead ECG creates most of the important basic measurements for heart revascularization differentiation. However, there are well known limitations and, for example, only 24 % to 60 % of patients with a final diagnosis of acute myocardial infarction may be diagnostic [5]. It seems that innovative technologies providing high-frequency high-dynamic-range electrocardiography measurements can offer better insight into diagnostics.

A lot of work has been devoted to high-frequency analysis of the depolarization phase during the QRS complex from ECG recordings (HF-QRS). The first papers appeared as early as the nineteen eighties. In 1981, Goldberg et al. in Circulation [1] presented the effect of myocardial infarction on high-frequency QRS potentials. He introduced methods based on the averaging of multiple QRS complexes to improve signal-to-noise ratio and FFT filtration. The QRS complex position is detected by correlation of a characteristic QRS complex template with each QRS. A correlation threshold (approximately 0.95) is used to eliminate artifacts in QRS, premature ventricular contractions (PVCs) and any QRS distorted morphology. Processing based on averaging requires the maintenance of shape clarity and removal of any artifacts. Since very weak high-frequency signals are analyzed, each single artifact significantly affects the results.

The Butterworth filter with a bandwidth of 150–250 Hz represents a typical and widely used filtration technique and range. This band can be considered the gold standard. A bandwidth with a different lower limit, for example 80–140 Hz [1, 4], occurs only rarely.

The Root-Mean-Square (RMS) value of the signal in the QRS region is then computed to set the QRS high-frequency potentials [1, 2, 3] level. The RMS reflects the averaged amplitude calculated by squaring each sample. RMS evaluation for determining the power of HF oscillation is typical of early works. A reduced RMS value is associated with pathological changes. In recent works, the Hilbert transform is used instead of RMS for time-domain signal power envelope computation [4].

The shape of the HF-QRS envelope is used as an additional parameter for the classification of pathological changes. Many studies [4, 6] have shown that HR-QRS morphology is modified by coronary occlusion or infarct induced ischemia in a pattern named "Reduced Amplitude Zones" (RAZ). The reduced amplitude or power of high-frequency oscillations in the middle of a QRS complex is associated with increased ischemia. Unambiguous quantification of RAZ in ECG leads serves as an important index of acute ischemia.

High-frequency RMS and RAZ parameters were compared to commonly used low-frequency parameters. These are mainly the width of the QRS complex, ST-segment abnormalities [3, 4], fragmented QRS [4] and upward and downward slopes of the QRS complex [4]. All papers report that heart ischemic pathology is detected with higher sensitivity using HF-QRS compared with conventional low-frequency methods.

It is typical of all papers dealing with HF-QRS that the presented methodologies have not been greatly changed or improved since the initial works. It can be said that the methodology of HF-QRS is accepted and stable which is not a typical finding in many other areas. However, the question arises as to why diagnosis based on HF-QRS has not yet been widely used in clinical practice.

Current ECG devices use low-pass filtering to eliminate noise. This is an understandable and often unavoidable step. ECG monitors bandwidth are lower than 100 Hz and often lower even than 45 Hz. HF ECG monitors have a higher sampling rate and bandwidth from 400 to 2000 Hz. The power of HF oscillations in the QRS complex region with higher frequencies rapidly decreases and simultaneously decreases signal-to-noise ratio. Beat-to-beat processing of HF-QRS is practically impossible and it is necessary to perform averaging over a large number of beats. The question is how this averaging, which is done in time domain filtered signal triggered on QRS pattern, affects the sensitivity of averaged QRS at high frequencies. This is perhaps the reason why the frequency of 250 Hz represents the upper limit which has not been surpassed. The currently used HF-QRS frequency range is strictly limited to 250 Hz, as ECG measured at higher frequencies is influenced by rapidly increasing noise and artifacts.

Here, we introduce ultra-high-frequency and high-dynamic-range 12-lead QRS (UHF-QRS 150–1000 Hz) measurement using an electromagnetically shielded environment (Faraday cage) and battery-powered ECG monitor with sampling of 25 kHz and 24-bit resolution.

2. Methods

We have used innovative technology located at the International Clinical Research Center in Brno to record ultra-high-frequency 12-lead ECG. An M&I data acquisition system was used to sample data at 25 kHz with a dynamic range of 24 bits. All measurements were performed in an electromagnetically shielded room (Faraday cabin, MR-Schutztechnik, Dieburg, Germany, 2013) located deep underground in a concrete basement. The M&I acquisition system is fully battery-powered without electromagnetic radiation. The digitized data is transmitted via an optic cable outside the shielded area. The technological solution presented completely eliminates the influence of external interference sources, including the 50 Hz network and telecommunications signals. The measured ECG therefore contains only the signal from the investigated subject.

Figure 1 shows an example of a single QRS complex with a bandwidth of 50, 100 and 1000 Hz – UHF-QRS. Low-frequency QRS up to 100 Hz completely eliminates high-frequency components in the QRS area.

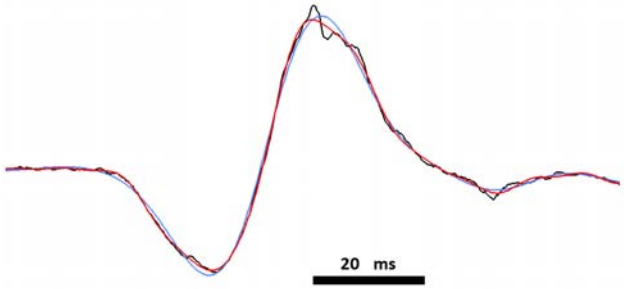

Figure 1. Single QRS complex, lead V2, healthy subject, BLACK – raw UHF-ECG, RED – pass band 0.3–100 Hz, BLUE – pass band 0.3–50 Hz.

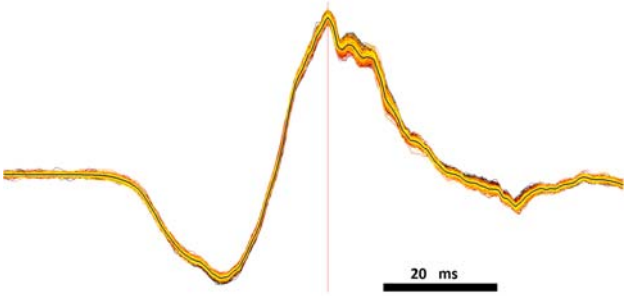

Figure 2. 500 consecutive QRS complexes, lead V2, UHF-ECG.

Figure 2 represents 500 consecutive heart beats re-drawn into a single UHF-QRS complex. The maximum of the QRS of lead V2 was used as a segmentation trigger. The differences between complexes are imperceptible. The long-term QRS morphology stability is extremely good.

Figure 3 demonstrates power envelopes in three frequency bands – 150–250 Hz, 250–500 Hz and 500–1000 Hz in a single non-averaged QRS complex. It is evident that even in the highest frequency band the UHF-QRS oscillations are easily detectable and the signal-to-noise ratio is extremely high. Figures 1, 2 and 3 demonstrate that UHF-QRS offers new and more detailed information about QRS morphology.

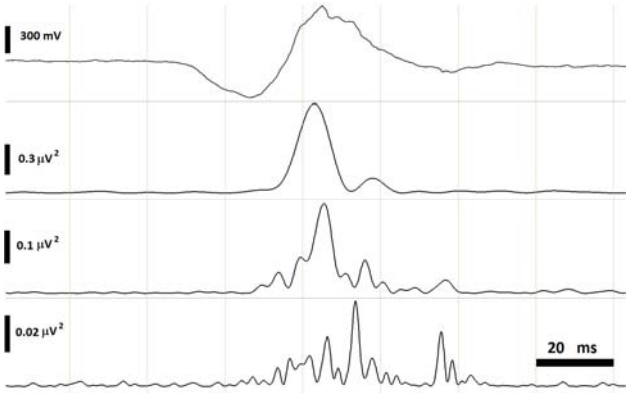

Figure 3. From the top: raw UHF signal – lead V2; power envelope in pass band 150–250 Hz; 250–500 Hz; 500–1000 Hz.

To find out whether UHF-QRS can diagnose heart ischemia not detectable in low-frequency QRS we compared 14 subjects – 7 healthy volunteers (mean age 36 ranging from 75 to 21 years, four males and three females) and 7 ischemic patients (mean age 54 ranging from 80 to 36 years, five males and two females). The ischemic patients were selected by the width of the QRS complex similar to healthy subjects.

We analyzed 15-minute resting supine position 12-lead ECG recordings. 25 kHz sampled data was filtered and down-sampled to 5 kHz with a pass band of 2 kHz. Using the Hilbert transform, the power envelopes in the two frequency bands 150–250 and 250–500 Hz were computed. Data was segmented with maximum of dominant lead (mostly V2). Artifact-free beats were averaged. Figure 4 shows the averaged power envelopes 150–250 Hz.

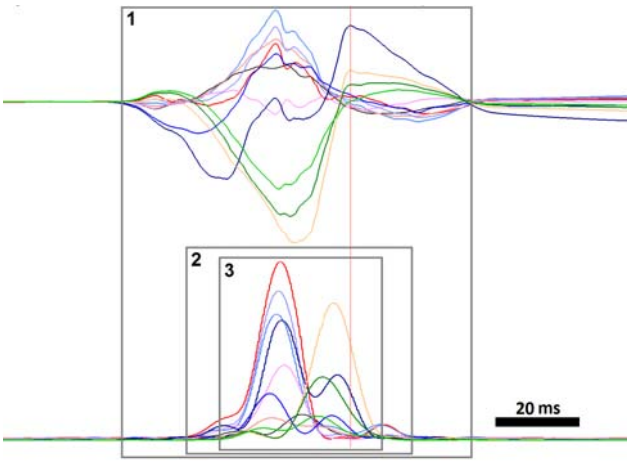

Figure 4. Upper panel: averaged UHF-QRS complexes from 500 artifact-free beats, 12-lead ECG; bottom panel: averaged power envelopes in pass band 150–250 Hz. The rectangles define the width of the QRS complex (1), width of the power envelope foot (2) and peak-to-peak distance (3).

For individual subjects, we determined the width of the QRS complex in 12-lead ECG – Fig 4, rectangle 1. Black rectangle 1 demonstrates the left and right boundaries of the raw QRS complex. Furthermore, we detected the width of the power envelope 150–250 Hz and 250–500 Hz foot (rectangle 2) and first-last peak-to-peak distance (rectangle 3). In all cases, the detection is performed on all leads. Table 1 shows the results of detection.

3. Results

Table 1: QRS and power envelope width in ms (mean value and standard deviation from seven healthy and seven ischemic subjects) measured in averaged signal from 500 beats within each subject.

	Healthy mean, SD ms	P ANOVA	Ischemic mean, SD ms
QRS	87.1±4.3	0.6	88.3±3.3
150–250 Hz, foot	79.9±8.5	**0.02**	113.1±31.8
150–250 Hz, peak	52.9±8.6	**0.007**	73.1±14.4
250–500 Hz, foot	66.2±7.7	**0.03**	82.9±16.0
250–500 Hz, peak	51.6±9.5	0.2	63.6±19.1

Numerical results of QRS and power envelope width are shown in Table 1. As mentioned above, ischemic patients with width of QRS complex comparable to healthy subjects and no ST-morphology changes have been selected. The difference of QRS width between groups is therefore minimal and not significant. Low-frequency conventional ECG is not able to distinguish ischemic pathology in these groups.

The situation is different in high-frequency ECG. In healthy young volunteers, the width of power envelopes is distinctly lower than the width of ischemic subjects.

Even in ischemic subjects the width of the 150–250 Hz power envelope foot is wider than the width of the QRS complex. Unfortunately, there is the highest standard deviation. This may indicate possible errors and ambiguity in foot detection.

Table 1 clearly shows significant (column P) differences between healthy and ischemic subjects in high and ultra-high-frequency power envelope measurement. The significance was computed as a standard ANOVA test. The lower significance in the 250–500 Hz power peak-to-peak parameter is caused by the small number of subjects and one outlying value.

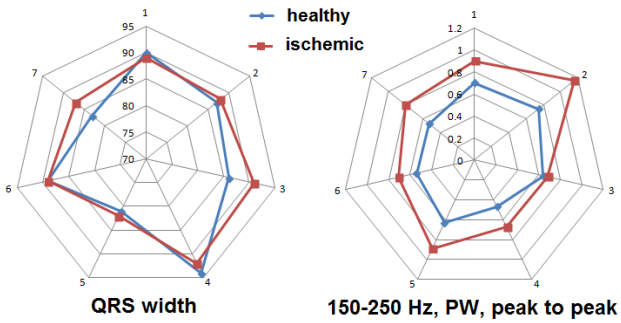

Figure 5. Circular graph of all 7 healthy (blue) and ischemic (red) subjects. Left: QRS width in ms. Right – normalized 150–250 Hz peak-to-peak values. Normalization was performed on the width of the QRS complex.

4. Discussion

This study introduces ultra-high-frequency and high-dynamic-range 12-lead ECG measurements in an electromagnetically shielded room and pilot results. To demonstrate the contribution made by high-resolution UHF-QRS measurement, a parameter not commonly used in HF-QRS analysis (the width of UHF-QRS power envelopes using all 12 leads) was selected. The reason why this parameter has not been used so far is its high sensitivity to artifacts and noise.

Although the results are shown on a small number of subjects, the differences are significant. Figure 5 shows QRS width and 150–250 Hz power envelope width measured peak-to-peak for all healthy and ischemic subjects. In the left part of the figure, the blue (healthy) circle intersects with the red (ischemic) circle. In the right part of the figure, the blue circle lies inside the red one. This means that all the ischemic patients have wider power envelopes than the healthy patients.

5. Conclusion

The UHF-QRS measurement presented here can accurately identify the inhomogeneity of heart ventricle activation. The preliminary results show the ability of the method to diagnose severe cardiac disease. The diagnostic procedure is fast and noninvasive and does not differ from routine ECG recordings. The added value of this method resides in the use of first-class technologies.

Moreover, the UHF ECG technology allows the use of various methods of QRS complex signal analysis. For example, phase and coherent analysis, beat-to-beat dynamic changes of UHF-QRS parameters and spatial distribution of potentials and localization of pathology.

Acknowledgements

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