Ultra-high-frequency electrocardiography

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Abstract

Background: We introduce a new technology that uses the ultra-high-frequency components (150-1000 Hz) of the electrocardiogram (UHF-ECG).

Method: The UHF-ECG components represent weak signals generated by depolarization of myocardial cells. The amplitude of UHF oscillations decreases with distance from the source. This property and the different timing of depolarization in the ventricles' volume enable mapping of the ventricular activation from the chest ECG leads. Because of a low signal-to-noise ratio of UHF oscillations, averaging must be performed. Single recording thus lasts 30 seconds and more.

Results: UHF-ECG defines the time-spatial distribution of myocardial electrical activity. Corresponding numerical parameters are electrical dyssynchrony (e-DYS) and the duration of local depolarization (Vd). UHF ventricular depolarization maps present details of electrical activation.

Conclusion: The UHF-ECG uses a new source of information originating in ventricular volumes that is different from the standard ECG. It provides information about the volumetric electrical activation associated with mechanical contraction. Its primary clinical utilization is in cardiac resynchronization, pacing optimization, and conduction system pacing.

1. Introduction

Electrocardiography (ECG) is old and deep-explored technology with huge clinical significance. The parameters obtained from the ECG are derived from various morphologies of individual waves in the ECGs.

Recently, the use of multifactorial analysis and deep learning techniques has significantly expanded. It can identify pathologies and their combinations in noisy low sampling frequency records, including home monitoring and telemedicine. This direction is very progressive, and it enables the processing of low-quality ECG recordings. At the same time, technologies that focus on gaining more information are based primarily on expanding the number of electrodes. Significant progress has been made over the last 20 years in the electrocardiographic imaging (ECGI) method and its clinical applications [1,2].

The ECG analysis is mainly based on low-frequency (up to 100 Hz) properties of the projection of the main electrical vector into individual leads. A promising technique based on different principle is high-frequency electrocardiography (HF-ECG). The first introduction of HF-ECG (150-300Hz) and its interpretation was published in the 1980s [3]. Currently, HF-ECG is used for the determination of acute coronary artery occlusion [4], measurement of late ventricular potentials [5], and especially the determination of local ischemia [6,7]. Clinically, these techniques are used to only a limited extent.

The study that introduced an ultra-high frequency ECG (frequencies up to 1000 Hz, UHF) and at the same time focused on the description of the timing of electrical activation in the ventricles was first published in 2017 [8]. This work showed the occurrence of UHF-ECG oscillations in the QRS region at frequencies up to 1300 Hz. At the same time, it discussed the possibilities of their origin in individual parts of the heart ventricles – volumetric measure.

The first step to validate the volumetric measure was performed in the [9] on ex-vivo experiments. We showed that the UHF-ECG activation time corresponds

approximately to the depolarization of the area in the middle of the ventricle wall.

Our primary goal was to develop simple and easy-to-use UHF-ECG technology intended for clinical medicine.

2. Methods

2.1. Data recording

The optimal frequency range of the UHF-ECG is up to 1kHz (sampling >4kHz). Nevertheless, with some limitations, it is possible to analyse 1kHz Holter data [10,11].

The clinically most common electrode configuration is a 12-lead ECG, the primary target of UHF-ECG. Nevertheless, the number of electrodes can easily be expanded up to a configuration comparable to ECGI. UHF uses the direct inverse projection of the UHF components from the body-surface electrode to the ventricular volumes [8]. Thus, the calculation of single electrode parameters does not depend on the signals of the other electrodes. It allows choosing any electrode configuration, for example, an extension for right precordial leads.

The distance of the electrodes from the heart and the human thorax geometry is a crucial parameter for UHF-ECG. We assume that the amplitude of the UHF oscillations decreases with the square of the distance from the source. This property enables to distinguish sources at the electrodes that are close and far from the source. The remote (limb) electrodes lose the localization capability, and the signal-to-noise ratio is low.

Figure 1A shows an example of an activation map using 5kHz 96 electrodes UHF body-surface potential mapping (BSPM). Figure 1B shows an unfolded normalized UHF amplitude map. Normalization is performed at each point to the maximum value of UHF amplitude during the whole QRS complex. Figure 1C shows a map of UHF amplitudes without normalization. From this figure, a significant difference of amplitudes associated with the distance of the heart from the individual electrodes is evident. In essence, this difference gives UHF-ECG the ability to distinguish near and far sources and locate activation (see Figure 2).

2.2. UHF-ECG processing

The processing is based predominately on increasing the signal-to-noise ratio of weak UHF oscillations [12]. For this, averaging the UHF components over the detected QRS complexes is used – Figure 3A.

Because different frequency bands provide different morphologies of UHF components (frequency variability), averaging is also performed across the frequency bands. Therefore, the longer the measurement and the higher the frequency content, the more reliable results.

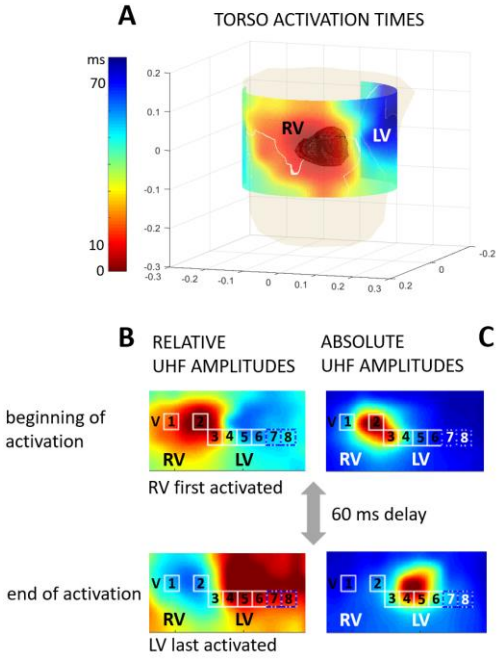

Figure 1. **Body-surface UHF-ECG.** LBBB subject, 60 ms delayed LV free wall activation. A – activation times, B – relative UHF-ECG amplitudes, C – absolute UHF-ECG amplitudes - the intensity of UHF components on the body surface. The distance of the heart from the surface of the body is smallest in locations of the maximal UHF amplitudes. In the case of a 14-lead ECG, the amplitude of the UHF component is most substantial in leads V2-V4, while the amplitude is lowest in leads V1, V7, and V8.

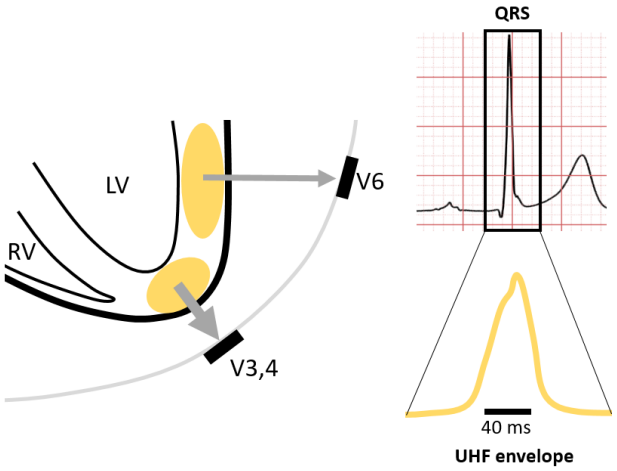

Figure 2. **UHF-ECG interpretation**. The UHF envelope represents the time distribution of simultaneously depolarized myocardial cells in the ventricular segment (volume) close to the electrode.

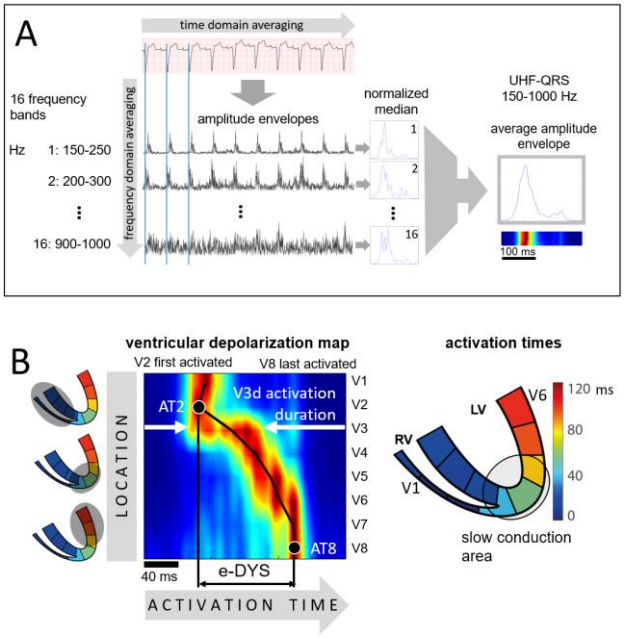

Figure 3. **UHF-ECG processing.** A - Averaging in the time domain (QRS complexes) and frequency domain (16 frequency bands). B – Ventricular depolarization map from 14-lead ECG, electrical dyssynchrony (e-DYS), and local activation duration (Vxd).

2.2. UHF-ECG outputs

Figure 3B shows the ventricular electrical activation map and the most important parameters: the electrical dyssynchrony e-DYS, the local electrical activation time ATx (x means V1, V2, …, V8 leads), and the activation duration in the given segment Vxd. The AIx (activation index) parameter is a normalized amplitude integral corresponding to the volume of simultaneously depolarized myocardial cells under the lead. The Vxd and AIx parameters are sensitive to the content of UHF components in the ECG signal and require broadband recordings with frequency averaging.

3. Results

The UHF-ECG output for 12 or 14 lead ECGs includes a ventricular depolarization map, amplitude envelopes, and numerical parameters. The results are supplemented by commonly used outcomes required by cardiologists - Figure 4.

The crucial property of the SW solution (VDI Vision SW) is beat-to-beat real-time processing. It allows the use of UHF-ECG during the pacemaker implantation and settings.

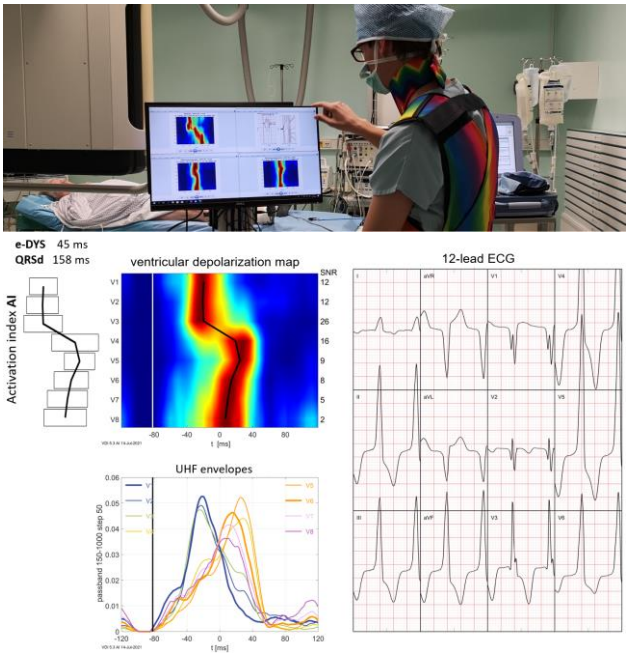

Figure 4. **12(14)-lead UHF-ECG results** (VDI monitor, VDI-Vision SW).

4. Discussion

Ventricular electrical dyssynchrony is most often measured by QRS morphology, QRS area, QRS duration, or the distance of maxima of QRS complexes in selected precordial leads. In all cases, this is an indirect measure without spatial specificity. Currently, new techniques of physiological pacing are intensively developed. These techniques require accurate measurement of local activation, including identification of pacing-induced LV intraventricular and RV-LV interventricular dyssynchrony. It is the area where UHF-ECG is beneficial technology. Some studies have already been published using UHF-ECG to describe the ventricular activation pattern with various types of pacing [13-15]. These studies have shown that knowing the volumetric activation of the ventricles is key information to determining activation patterns during cardiac pacing.

Limitations: UHF-ECG is still not yet widespread technique. The reason may be the unavailability of new acquisition technologies and stereotypes that are difficult to overcome. Nevertheless, the higher quality of the acquisition system does not currently represent a technical limitation and does not affect the difficulty of diagnostics in any way.

5. Conclusion

UHF-ECG is a new methodology for determining

ventricular electrical activation patterns. It is not just another way to process an ECG, but it is a source of new information. In principle, it measures volumetric electrical activation, so it is more associated with mechanical contraction. These features are the key to optimal cardiac pacing therapy.

Acknowledgments

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