VDI Vision - Analysis of Ventricular Electrical Dyssynchrony in Real-time

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Abstract

Background: *Ventricular electrical dyssynchrony can be examined using ultra-high-frequency (UHF-ECG) analysis. Furthermore, UHF-ECG analysis would allow direct optimization of pacing therapy. Here we introduce VDI Vision (Ventricular Dyssynchrony Imaging), a desktop application for the real-time processing of UHF-ECG recordings.*

Method: *Incoming ECG data (5kHz, 26 bits, 24 channels) are processed as follows: QRS detection, pacemaker stimuli elimination, QRS clustering, amplitude envelopes in nine frequency bands, and final combination into the Ventricular Depolarization (VD) map. The VD map is updated whenever a new QRS is detected.*

Results: *We developed the VDI vision using the .NET platform. Until the end of March 2021, the VDI-monitor was used to analyze 773 and 4,849 recordings at ICRC-FNUSA hospital (Brno, Czechia) and FNKV hospital (Prague, Czechia), respectively. The median length for ICRC-FNUSA recordings was 124 (IQR 121-139) seconds. The median length for recordings at FNKV hospital was 157 seconds (IQR 127-200).*

Conclusion: *The VDI vision delivers information about electrical ventricular dyssynchrony in real-time. The instant analysis allows using the software during implant procedures for optimizing electrode placement and pacing. The presented real-time solution also significantly minimized measurement duration.*

1. Introduction

During a normal (synchronous) heart cycle, the left and right ventricles contract simultaneously. However, these contractions might become dyssynchronous under certain circumstances, typical for the Left or the Right Bundle Branch Block (LBBB, RBBB). Also, significant ventricular dyssynchrony can be observed in premature ventricular contractions and paced beats, typically in patients with unphysiological right ventricular pacing and sub-optimally set bi-ventricular pacemakers.

An Ultra-high-frequency (UHF) ECG method has been developed to analyze this electrical dyssynchrony [1], [2]. Following studies have shown the potential of UHF-ECG analysis in cardiac resynchronization therapy [3], [4]. Furthermore, the UHF-ECG method has been used in His-bundle pacing [5], RV pacing and left septal pacing to analyze the synchrony of heart ventricles for specific electrode positions [6]. Mentioned studies prove that the UHF-ECG method is valuable, especially with pacing and its proper setup or implant location.

This paper introduces VDI Vision (ver. 0.9.9) – a desktop application to acquire, process, and analyze UHF-ECG signals in real-time (Fig.1).

2. Method

The software is designed to work fully automatically without adjusting any features. Therefore, a user is expected to execute measurement (Fig.1A) and wait until a count of acquired QRS complexes is sufficient for acceptable Ventricular Depolarization (VD) map (Fig.1B). Then the user stops recording, and the VDI Vision saves an image of the VD map, raw signals, post-processed signals, and detected QRS complexes.

2.1. Software input

Software input is an ECG signal acquired from a patient in a supine resting position (Fig.2A). The minimal channel setup is a common 12-lead ECG with added V7 and V8 leads, further expandable to 24 leads. Analog signals are digitalized (5kHz, 26 bits) in the acquisition hardware by M&I, Prague, Czechia (Fig.2B) and sent as a User Datagram Protocol (UDP) packets to the processing PC (Fig.2C). Then, the UDP packets are encoded (Fig.2D) to the digitalized raw ECG signals.

Fig. 1 – The VDI Vision software graphical unit interface when the measurement is finished. When a new measurement is started (A), the Ventricular Depolarization map (B) is instantly updated whenever a new QRS complex is detected in incoming ECG signal (C). Inner processes may be further checked using other display modes (D).

2.2. Signal processing

Processing starts with computing (i.e., mounting) V1-V8 leads from C1-C8 leads using the Wilson lead (Fig.2E). Then comes preliminary QRS detection, pacemaker elimination, QRS position refinement using cleaned data, classification of QRS into morphological groups, and building amplitude envelopes in nine frequency bands. Finally, these amplitude envelopes (separately for each lead) are accumulated to increase the signal-to-noise ratio and rendered to the VD map. However, this processing chain runs on continuously incoming data, and, therefore, its computational blocks are executed asynchronously.

2.2.1 QRS detection and elimination of pacing stimuli

QRS complexes are detected using leads V1, V3 and V6. A copy of data is filtered (the 2nd order IIR, resonance 18 Hz, sharpness 0.98), and signal behavior (standard deviation and amplitudes) is inspected to find QRS complexes (Fig.2F). Next, power grid noise is suppressed (2nd order IIR), and pacemaker artifacts are found and eliminated [7] in a close neighborhood of each QRS in all V-leads (Fig.2G).

2.2.2 Refining position of QRS annotations

Since QRS complexes were detected approximately, we provide iterative refinement of QRS annotation marks using signals V1, V3, and V6 with removed pacemaker artifacts. For each of these three channels, the surroundings of a QRS from -0.1 to +0.1 second is differentiated. Next, absolute values are used to compute a center of gravity. Then, an average center of gravity from cleaned V1, V3, and V6 channels defines the new position of the QRS annotation mark. Refinement using the center of gravity is done five times (found experimentally). This process moves the QRS annotation mark to a virtual center of a QRS activity, which is later important to reduce computational time for morphological clustering. It is also convenient for visual observation. After this refinement, QRS annotation marks are visually centered in QRS complexes regardless of the type of conduction disease, level of QRS fragmentation, or noise (Fig.2H).

2.2.3 QRS morphology clustering

Only QRS complexes from the major (i.e., the most common) morphological group should be used for VD maps. For example, ventricular premature beats (or fusion beats or ectopic beats) would blur the resulting map.

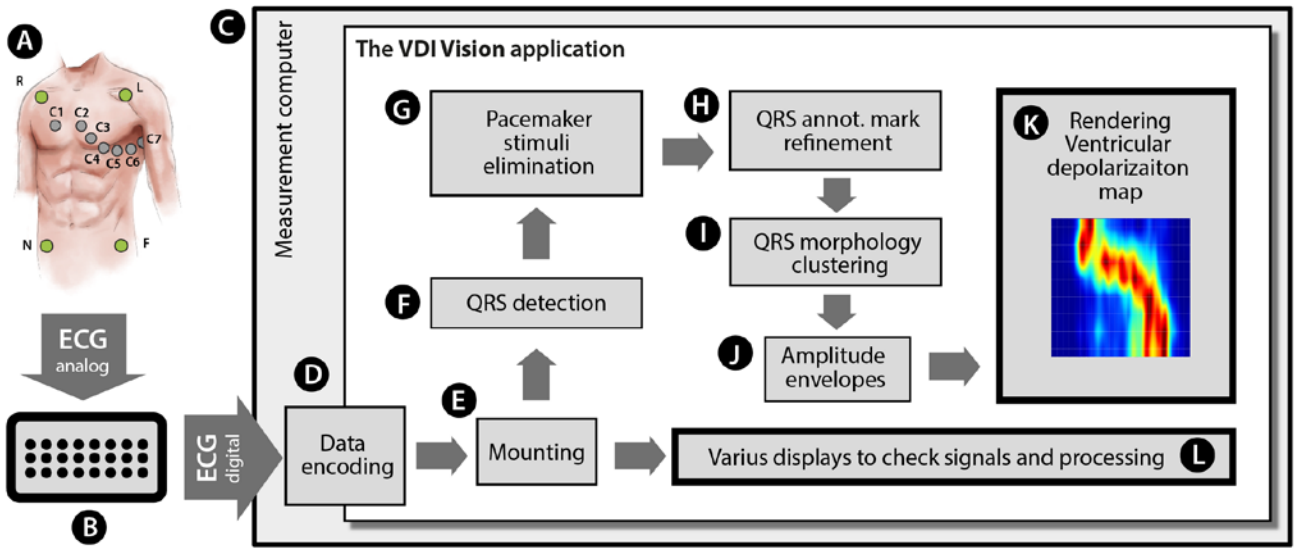

Fig. 2 – Data flow into and inside the VDI Vision application. ECG signals are acquired from a patient (A), amplified, converted to digital signals (B), and transferred to the measurement computer (C). Data are then decoded to raw ECG signals (D), mounted using Wilson lead (E), displayed (L), and used by processing chain leading to the ventricular depolarization map. QRS complexes are detected (F), pacemaker stimuli are eliminated (G), QRS annotation marks are centered to QRS complexes (H), and clustered into morphological groups (I). Amplitude envelopes are generated from the area surrounding each QRS and accumulated (J), and, finally, rendered to ventricular depolarization map (K). Mentioned blocks work asynchronously, meaning that, for example, while new QRS is detected, envelopes are computed for some previous QRS complexes, and at the same time, a block of new incoming data is mounted.

Therefore, QRS annotation marks are clustered by morphology into groups [8]. The major group might change during the measurement (imagine a change of pacing settings during an optimization procedure). Also, here we try to slightly shift QRS annotation marks to find the biggest correlation between compared QRS complexes. Finally, resultant QRS complexes perfectly fit one on each other (Fig.2I), which is essential for the next step – generating of amplitude envelopes.

2.2.4 Generating amplitude envelopes

Amplitude envelopes of all V-leads (cleaned from pacemaker activity) are generated in nine frequency bands (width 100 Hz, step 100 Hz). Therefore, the first band covers frequencies between 150Hz-250Hz; the last one covers frequencies between 950-1050 Hz. We use Fourier and Hilbert transforms to compute amplitude envelopes centered to each new QRS complex; the window length is one second. The resulting envelopes are accumulated with previously computed amplitude envelopes from the same morphological group (Fig.2J).

2.2.5 Preparing a dyssynchrony map

We remove baseline from accumulated envelopes (Fig.2K) for each lead and frequency band, starting 0.2s after the QRS annotation mark (i.e., a center of each envelope) and lasting 0.1s. Then, each baseline-corrected envelope is smoothed using a rectangular window, length 80 samples, and normalized. Next, we sum these envelopes over frequency bands and normalize them. Therefore, now we have only one signal per V-lead. It is cropped since the display area in the VD map is only between -0.12 and +0.12 from the QRS annotation mark, forming a fully processed envelope (FPE). Each FPE is copied as a row to a dyssynchrony matrix (DM, 1200x1200). Since DM y-resolution is much higher than the number of V-leads, rows between leads are interpolated. Finally, the DM data are rendered to the resulting VD image map (size 400x400 pixels). The DM values are mapped to colors using a color range from blue (minimal values) to red color (maximal values).

2.3. Software output

The main software output is the VD map (Fig.1B) for a major morphological QRS group (*.png files). The map is accompanied by both recorded and post-processed signals (*.bin files and *.log files) with QRS annotation marks (*.sel files); these outputs can be directly loaded into SignalPlant [9] software. Also, the software outputs a 12-lead ECG image (25 mm/sec, 0.1 mm per mV). Mentioned output items are saved to a disk after a measurement.

2.4. Additional functionality

Although the main output of the software is a VD map, another functionality allows users to check signals or inner processes.

For each lead, we display envelope quality check values based on abahevior of accumulated envelopes (Fig.1B - numbers just next to the right border of the map)

For convenience, the standard ECG is displayed beside the VD map(Fig.1C). However, the other display modes are available (Fig.1D) as displaying running leads, raw unmounted incoming signals, partially or fully processed signals together with QRS positions. Also, displays showing the current state of morphological clustering or accumulated envelopes are available.

3. Results

We developed the VDI vision using the C# language and .NET framework (ver. 4.6) under MS Windows 10. It was deployed on a mini-PC NUC with quad-core CPU Intel i7-8650U at 1.9GHz GHz with 16 GB of RAM.

Until the end of March 2021, the VDI Vision was used to analyze 773 and 4,849 recordings at ICRC-FNUSA hospital (Brno, Czechia) and FNKV hospital (Prague, Czechia), respectively. The median length for ICRC-FNUSA recordings was 124 (IQR 121-139) seconds. The median length for recordings at FNKV hospital was 157 seconds (IQR 127-200), less than half of measurement time from former off-line processing (median 323, IQR 312-366 seconds). Recordings were acquired from healthy subjects and patients before, during (FNKV only), and after pacemaker implantation.

Significant reduction of time of one clinical evaluation contribute to better optimization during pacemarker implantation and to compare different type of pacing [5].

4. Conclusion

The VDI Vision delivers information about electrical ventricular dyssynchrony in real-time. The main software output is a ventricular depolarization map, updated continuously during a measurement. This instant analysis enables using the VDI Vision during implant procedures for optimizing electrode placement and pacing. The presented real-time solution decreases (approximately two-times) measurement duration in comparison to our previous, only post-processing solution.

In the future, we plan to update the QRS detection method and pacemaker stimuli elimination technique with deep-learning models, which should further improve the VDI vision's performance.

Acknowledgments

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