A Method For Removing Pacing Artifacts From Ultra-High-Frequency Electrocardiograms

Petr Andrla[1], Filip Plesinger[1], Josef Halamek[1], Pavel Leinveber[2], Ivo Viscor[1], Pavel Jurak[1]

[1]Institute of Scientific Instruments of the Czech Academy of Sciences, Brno, Czech Republic
[2]ICRC, St. Anne's University Hospital Brno, Czech Republic

Abstract

Cardiac resynchronization therapy (CRT) is an effective treatment for heart-failure patients with ventricular dyssynchrony. Analysis of ultra-high frequencies in ECG (UHFECG) has been shown to provide precise identification for the selection of CRT recipients, but the use of UHFECG for CRT optimization is limited due to the fact that UHFECG activity is buried under pacemaker stimuli. While removing the rising edge of a stimulus is quite straightforward, the localization and removal of the end of the post-stimulus recharge phase is more complicated due to its very low amplitude and interference with depolarization signals in QRS onset.

12-lead 5 kHz ECG during a 3–10 minute rest period was measured in 19 patients. We detected artifacts as 1.6-ms-long segments with high energy at frequencies of 1400–1900 Hz. We removed the area around the detected peaks in the time domain.

Detection of artifacts, the stimulating pulse and the end of the recharge phase was evaluated against manually annotated marks with sensitivity and specificity of 0.98 and 0.97.

1. Introduction

Cardiac resynchronization therapy (CRT) improves outcomes in heart-failure patients with severely impaired ejection fraction and conduction abnormalities, significantly reducing mortality and morbidity [1, 2]. Improved mechanical synchrony can be evaluated by reduced QRS complex duration in the ECG signal.

However, new findings reveal an additional source of information about cardiac electrical activity in ultra-high-frequency ECGs over 250 Hz (UHFECG). The main clinical potential of UHFECG lies in the identification of differences in electrical activation among CRT candidates and detection of improvements in electrical synchrony in patients with biventricular pacing [3]. The dyssynchrony descriptor is computed as a difference by subtracting the center of mass of V1 and V6 in smoothed averaged envelopes – Figure 1. The diagnostic contribution of UHFECG was introduced in [4] and verified in a further study [5].

UHFECG measures and evaluates very weak voltage potentials far below the level of millivolts, and is therefore highly dependent on signal quality. Stimulation peak detection and removal are the crucial parts of UHFECG signal pre-processing; it is necessary to remove all pacing artifacts from the ECG. While removing the rising edge of a stimulus is quite straightforward, the localization and removal of the end of the post-stimulus recharge phase is more complicated due to its very low amplitude and interference with depolarization signals in QRS onset.

Pacemaker technologies have advanced over recent decades. A modern pacemaker consumes much less power to extend battery life using bipolar low-amplitude pulses. Research has shown that rate-adaptive pacing is more compatible with the nature of human physiology and provides numerous benefits to patients [6]. These improvements have created other challenges for the detection of pacing artifacts (PA) in ECG.

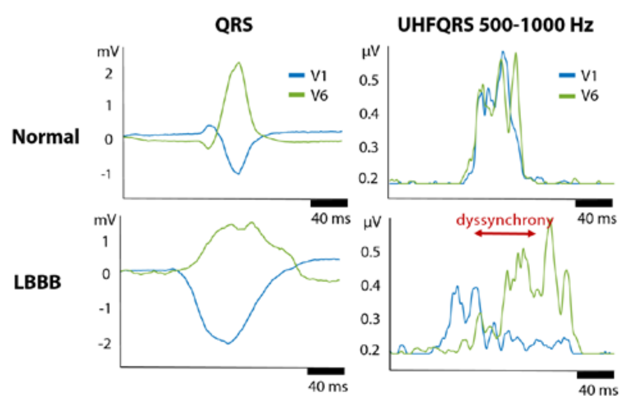

Figure 1. QRS and UHFQRS (averaged 500-1000 Hz V1 and V6 envelopes). Blue represents UHFQRS distribution in the septum and right ventricle and green represents UHFQRS distribution in the left ventricle. The mutual shift between the green and blue distribution shows dyssynchrony.

2. Method

2.1. Data recording and subjects

A 12-lead ECG was collected at 5 kHz with a high dynamic range and a 2 kHz pass band (M&I Prague, CZ) – UHF-ECG. Measurements were taken at the International Clinical Research Center at St. Anne's

 ISSN: 2325-887X DOI: 10.22489/CinC.2018.106

University Hospital, Brno, Czech Republic. The UHF-ECG data were collected over 3–10 minutes in the resting supine position. 19 patients were analyzed in total – 16 patients with biventricular pacing and interventricular delay VVD 0 ms, -20 ms or -40 ms, and 3 patients without stimulation. There were 15 left bundle branch block (LBBB) and 4 right bundle branch block (RBBB) patients in the study.

2.2. Pacing artifact description

A pacing artifact is composed of three parts: the pacing phase, the recharge phase and the end of the recharge phase – Fig. 2.

The pacing phase (PP) is composed of a quick rising edge, followed by a slower droop and fast trailing edge. The duration of the pulse is defined by this phase [7]. The pacing phase has a very sharp rising edge. In a spectral analysis, its properties are similar to the Dirac impulse. It unfolds across a wide range of frequency spectra and interferes with the UHF spectral range.

The recharge phase (RP) pulse changes polarity in this phase and slowly rises. This is required so that the heart tissue is left with a net-zero charge [7].

The end of the recharge phase (ERP) often has an extremely low amplitude, but is still very pronounced in UHFECG and can degrade the entire analysis of high-frequency components.

In this paper, we present a method for precise temporal localization of the pacing phase and end of the recharge phase. The recharge phase was estimated using the statistical properties of the pacing phase and was removed together with detected artifacts.

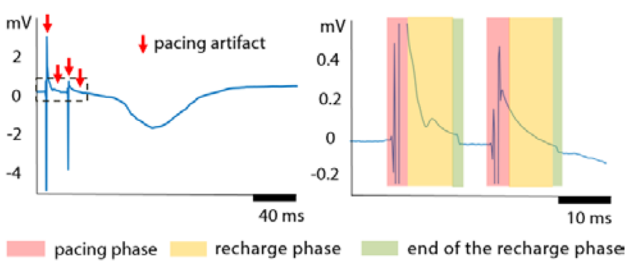

Figure 2: Manual annotations of pacing artifacts in raw ECG signal. Annotation of PP (red), RP (orange) and ERP (green) segments is shown on the zoomed image.

2.3. Annotations

To evaluate the success of detection of pacing peaks, it was necessary to create manual annotations of the records.

Artifacts were annotated in a raw ECG signal. Marks were placed in the middle of pacing artifacts (PP and ERP) as shown in Figure 2. Alignment of the mark was made on all leads (V1–V6); one mark was used for all leads. All further processing was performed for these six leads.

For analysis of ultra-high-frequency electrocardiograms, the most important area is around the QRS complex. Signal averaging of QRS complexes is used due to the low signal-to-noise ratio of amplitude envelopes. In order to evaluate the success of the algorithm in the target deployment, a second annotation of the stimulation artifacts was created directly on the course of the accumulated QRS complex.

QRS complexes were detected and sorted into categories using a robust multichannel approach. This technique was used to distinguish a regular rhythm from abnormal QRS shapes to focus the analysis primarily on the dominant rhythm. For every lead, median QRS was calculated as the median shape from all QRS complexes from the dominant rhythm. PP, RP and ERP segments were labeled on the median QRS – Figure 2.

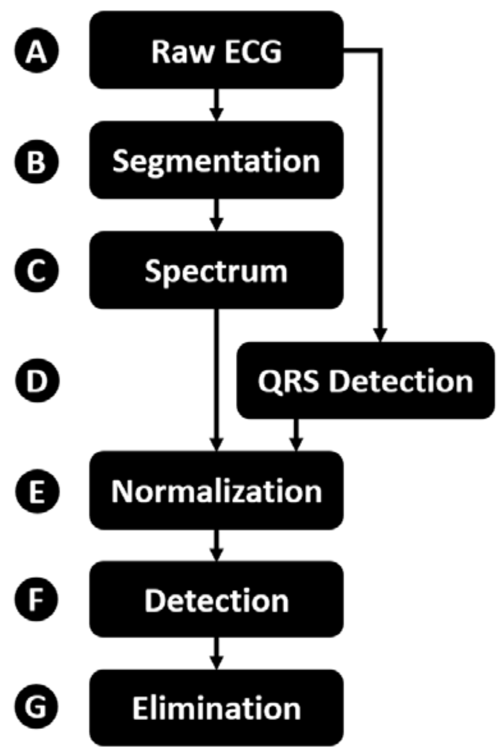

Figure 3: Processing of stimulation artifact elimination. ECG record (A) was divided into a 1.6-ms-long segment with a 0.8 ms overlap (B). The amplitude spectrum was computed for every segment using a fast Fourier transform (C). QRS complexes were detected (D). Normalization was performed (E) and the stimulation peaks were detected (F). The area around the detected peaks was removed (G).

2.4. PA detection and elimination

Pacing peaks were detected including the entire area that was degraded by stimulation. The area around the detected peaks was then removed. The processing consists

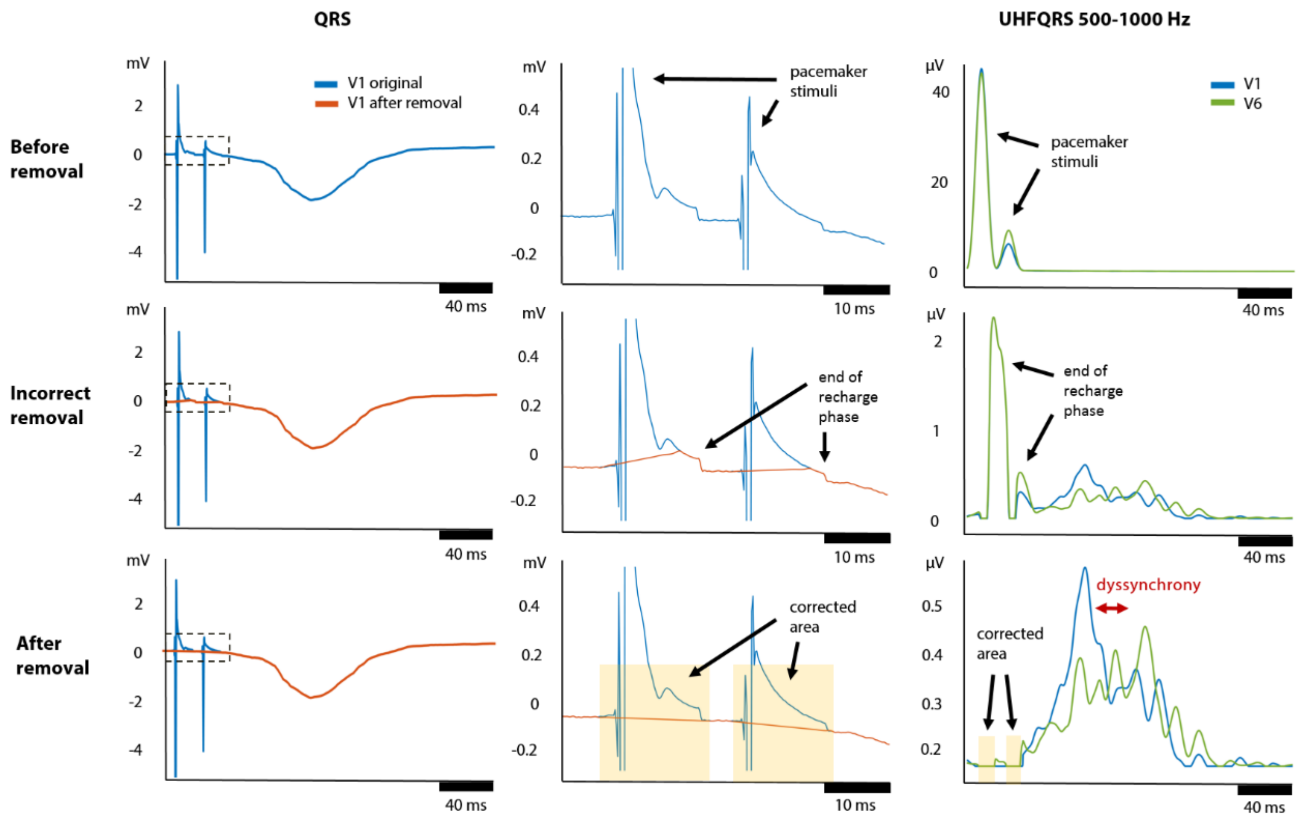

Figure 4: QRS and UHFQRS before stimulation artifact elimination (top), after stimulation artifact elimination (bottom) and example with poorly executed removal of the stimulus peaks (middle). Lead V1 (green) and V6 (blue) are shown for UHFQRS. For QRS, lead V6 is shown before (blue) and after (red) stimulation artifact elimination.

of the following steps which are also shown in Figure 3.

In the first step, the ECG record is divided into a 1.6-ms-long segment with a 0.8 ms overlap.

An amplitude spectrum was computed for every segment using a fast Fourier transform. From the amplitude spectrum, only frequency components in a 1400–1900 Hz range are used for detection. The high energy in this frequency band indicates the presence of the pacing pulse in the segment.

However, high-frequency components are also included in the QRS complex. Therefore, normalization was performed before stimulation peak detection. QRS complexes in the record were detected and all 1.6 ms segments belonging to any QRS complex were selected. The median of all of these was then calculated (NK).

Every 1.6 ms segment was compared with NK, and all segments three times larger than NK were marked as a stimulation.

The area around detected peaks was removed in the time domain by applying a linear function supplemented by a spline function on the edges.

After artifact elimination, the amplitude envelopes of the QRS complex were computed in a frequency band of 500–1000 Hz and averaged (UHFQRS) [3, 5].

3. Results

The sensitivity (SE) and specificity (SP) were evaluated in the raw ECG signal. All removed sections were compared with the manual annotation. Each removed section with a located annotation stimulation peak was counted as a true positive. If the stimulus pulse was annotated but not recognized, it was counted as a false negative. Deleted sections without any annotation were counted as a false positive. Detection of the pacing phase was performed on all 19 subjects with sensitivity and specificity of 0.98 and 0.97. All occurrences of the PP were found and removed. All the artifacts that failed to detect belonged to EPS.

This method has been developed primarily for use in the processing of UHFECG. Therefore, the accuracy of removal of stimulation pulses was tested on UHFQRS data. Although the proposed method can successfully eliminate pacemaker stimuli, a relatively large amount of the signal is lost (35 ± 13 ms on average). Removal of the pacing was compared to annotation prepared on the median shape of the QRS. 98 % of annotated stimulations were detected, and the removed area was only 14 % larger than the annotated area.

In three records without stimulation, the pacing was detected in only a few cases, and only where the signal was noisy.

4. Discussion

We present an algorithm that enables the detection of pacing artifacts from modern pacemakers used for cardiac resynchronization therapy. The algorithm has a high level of pacemaker stimuli classification performance with very good specificity and sensitivity. Our method is able to detect stimulation pulses and also to precisely determine which portion of their surroundings needs to be removed.

Stimulation peak detection and removal are the crucial parts of UHFECG signal pre-processing. It is necessary to remove all the pacing artifacts from the ECG. At the same time, it is necessary to preserve as much signal as possible. Knowing the exact area of pacing artifact occurrence allows for the reconstruction of only the part of the signal that is affected by artifacts. This is more important in cases when artifacts are close to the QRS region or even inside the QRS.

When using biventricular stimulation, ECG records contain many artifacts. Although the proposed method can successfully eliminate pacemaker stimuli, a relatively large amount of the signal is lost. Suppressing the effect of the stimulator while maintaining a useful signal is a task for the future. The recharge phase could contain a useful signal. There is a need in the area of the recharge phase to appropriately suppress the effect of stimulation to maintain useful high-frequency components. There is still potential for improvement.

Our algorithm was designed to remove the stimulation from ultra-high-frequency electrocardiograms. Using it on a signal with a lower sampling rate would result in a significant decrease in accuracy.

5. Conclusion

UHFECG represents a method with the potential to display electrical ventricular depolarization in patients before and during biventricular pacing. As part of the preprocessing, it is, of course, necessary to remove any stimulus artifacts. We introduced a method that detects stimulus artifacts with great success, as well as a method for removing the detected artifacts.

Acknowledgements

The research was supported by the Czech Science Foundation, project GA17-13830S, by the Ministry of Education, Youth and Sports of the Czech Republic (project LO1212 and LQ1605) and by the Czech Academy of Sciences (project RVO:68081731).

References

[1] Prinzen FW, Vernooy K, Auricchio A. Cardiac Resynchronization Therapy: State-of-the-Art of Current Applications, Guidelines, Ongoing Trials, and Areas of Controversy. Circulation 2013;128:2407-2418.

[2] Linde C, Ellenbogen K, McAlister F. Cardiac Resynchronization Therapy (CRT): Clinical Trials, Guidelines, and Target Populations. Heart Rhythm 2012;9:S3-S13.

[3] Jurak Pavel, Josef Halamek, Jaroslav Meluzin, Filip Plesinger, Tereza Postranecka, Jolana Lipoldova, Miroslav Novak, et al. 2017. Ventricular Dyssynchrony Assessment Using Ultra-High Frequency ECG Technique. Journal of Interventional Cardiac Electrophysiology: An International Journal of Arrhythmias and Pacing 49 (3): 245–54.

[4] Plesinger Filip, Pavel Jurak, Josef Halamek, Petr Nejedly, Pavel Leinveber, Ivo Viscor, Vlastimil Vondra, et al. 2018. Ventricular Electrical Delay Measured From Body Surface ECGs Is Associated With Cardiac Resynchronization Therapy Response in Left Bundle Branch Block Patients From the MADIT-CRT Trial (Multicenter Automatic Defibrillator Implantation-Cardiac Resynchronization Therapy). Circulation. Arrhythmia and Electrophysiology 11 (5): e005719.

[5] Plesinger Filip, Pavel Jurak, Josef Halamek, Pavel Leinveber, Scott McNitt, Arthur J. Moss, Wojciech Zareba, and Jean-Philippe Couderc. 2017. The VED Meter - a New Tool to Measure the Ventricular Conduction Abnormalities in Heart Failure Patients. In 2017 Computing in Cardiology Conference (CinC).

[6] Tse HF, Siu CW, Lee KL, Fan K, Chan HW, Tang MO, et al. The Incremental Benefit of Rate-Adaptive Pacing on Exercise Performance during Cardiac Resynchronization Therapy. J Am Coll Cardiol 2005;46.12: 2292-2297.

[7] Kruse J, Redmond C. Detecting and Distinguishing Cardiac Pacing Artifacts 2012;1–6.

Address for correspondence:
Petr Andrla
Institute of Scientific Instruments of the CAS, v.v.i.
Kralovopolska 147,
Brno 612 64, Czech Republic

E-mail address:
andrla@isibrno.cz