Precise Pacing Artefact Detection

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Abstract

Introduction: An analysis of ultra-high-frequencies in ECG (UHF ECG, up to 2 kHz) reveals new information about the time spatial distribution of heart depolarization. Such an analysis may be important for diagnosing and treating patients with atrial and ventricular dyssynchrony. The UHF analysis in patients with a pacing device is complicated due to the pacing influence in the ECG. In that case, all pacing artefacts must be eliminated from the measured signal. The first step in removing those artefacts is to precisely detect their temporal position. Although pacing artefacts are usually clearly visible on a measured ECG, capturing the whole pacing artefact may be challenging.

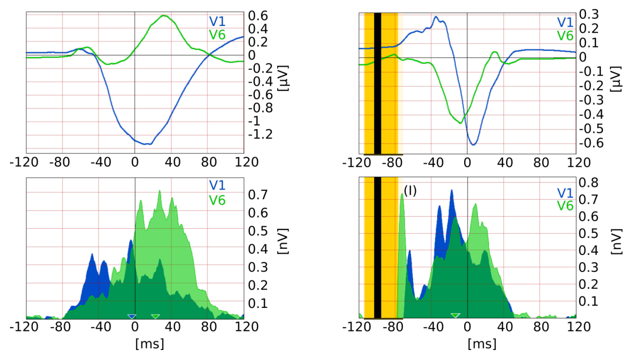
Methods: This paper compares different detection approaches and evaluates them on 19 records. Derivatives, a moving statistical window and complex envelope methods were tested followed by descriptive statistics approaches for making a peak detection. We evaluated the variability of the detection position by the distance variability from manual anotations. For each method, sensitivity and positive predictivity were evaluated.

Results: The method with the most precise temporal detection was the variance moving window with a standard deviation (SD) of ±0.11 ms mark placement. The best detection method was a SD moving window with sensitivity=100 and specificity=82.3 and was evaluated as the most appropriate.

1. Introduction

Patients suffering from heart failure and left bundle branch block are indicated for Cardiac Resynchronization Therapy (CRT). A biventricular pacemaker device (BiV) helps them to restore atrial and ventricular synchrony.

The CRT positive effect improves mechanical synchrony and increases the left ventricle ejection fraction. Mechanical synchrony can be evaluated by reducing the QRS complex duration in the ECG signal. However, new findings reveal an additional source of information about cardiac electrical activity and CRT synchrony improvement in high (HF, 150-250 Hz) and ultra high frequency (UHF, over 250 Hz) bands of ECG the signal [1]. [2] introduced a new DYS marker appropriate for detecting ventricular dyssynchrony and CRT patient selection based on an analysis in frequencies ranging between 500-1000 Hz. This analysis is complicated due to the interference of pacing artefacts (PA) in the analysed UHF range as shown in Fig. 1.



(a) (b)

Figure 1. Accumulated QRS complex. A - dyssynchrony of the subject without the ICD turned on. B - a corrupted analysis of the same subject with the ICD turned on. Yellow area a removed pacing artifact. PA interference is visible by the green peak (I).

Therefore, to analyse heart activity in UHF with CRT patients, we need to remove the pacing artefcts from the ECG.

A pacing artefact is composed of two parts (Fig. 2):

1. **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 [3].

2. **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 [3].

Pacing phase has very sharp rising edge - Fig. 2. In a

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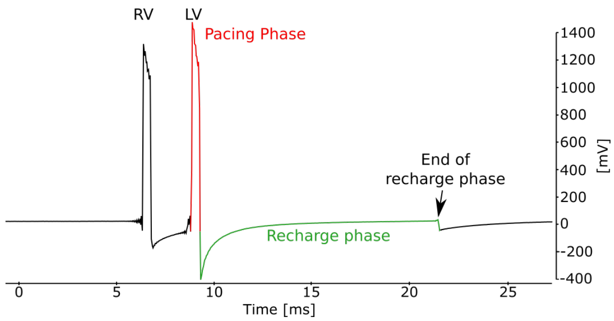
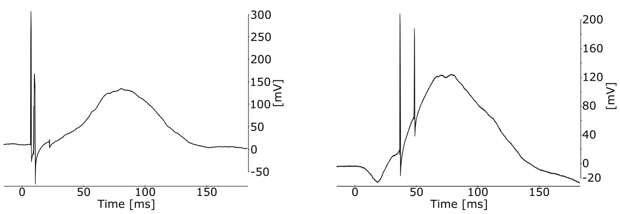


Figure 2. BiVentricular (BiV) pacing artefact with right (the first) and left (the second) ventricle stimulation pulses. The end of the recharge period is shown approximately at the 22^{nd} millisecond. (ECG Frank lead H, F_s=25 kHz)



(a) (b)

Figure 3. PA near of the QRS. (a) PA at the beginning of QRS with a clear recharge period. (b) PA inside of the QRS and a recharge period buried in the QRS complex.

spectral analysis, its properties are similar to the Dirac impulse. It unfolds across the wide range of frequency spectra and interferes with the UHF spectral range. The first step in removing PA is its precise temporal detecition - the beginning of the pacing phase and the end of the recharge phase. Knowing the exact area of PA occurence allows for the reconstruction of only part of the signal that is affected by PA. This is more important in cases when PA is close to the QRS region (Fig. 3a) or even inside of the QRS (Fig. 3b).

In the PA detection process, the easiest part is localizing the beginning of the rising edge of the stimulating pulse. On the other hand, localizing the end of the recharge phase is more complicated due its low amplitude (Fig 2). However, it can be estimated using the statistical properties of the pacing phase [4].

In this paper, we present a method for comparing the most precise temporal localization at the begining of the pacing phase.

2. Methods

2.1. Data acquisition

Measured data were collected by battery-powered acquisition system (M&I Prague) with a sampling rate of 25 kHz, 24 bits resolution (10 nV) and a 22-lead electrode setup. Data were recorded at the International Clinical Research Center at St. Anne's University Hospital, Brno, Czech Republic.

2.2. Protocol and subjects

We analysed 19 subjects with an implanted BiV ICD. The cohort was composed of patients with various BiV devices. Patients were in a resting supine position and each recording was 5 minutes long.

As mentioned in [5], the high sampling rate allows us to much more accurately detect PA than data acquired at a lower sampling rate. UHF ECG analysis uses frequencies up to 2 kHz. For this reason, analysed data is at a 5 kHz sampling rate (downsampled from 25 kHz). To find out which data are more suitable for making a precise PP detection, we have compared the detection on both of them.

2.3. Annotations

All annotations were made manually using SignalPlant software [6] at 25 kHz data. Marks were always placed at the beginning of the PP before the sharp rising edge as shown in the Figure 4.

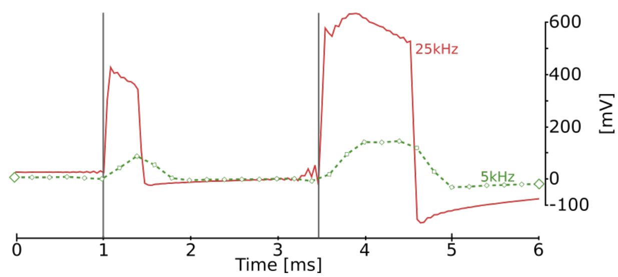


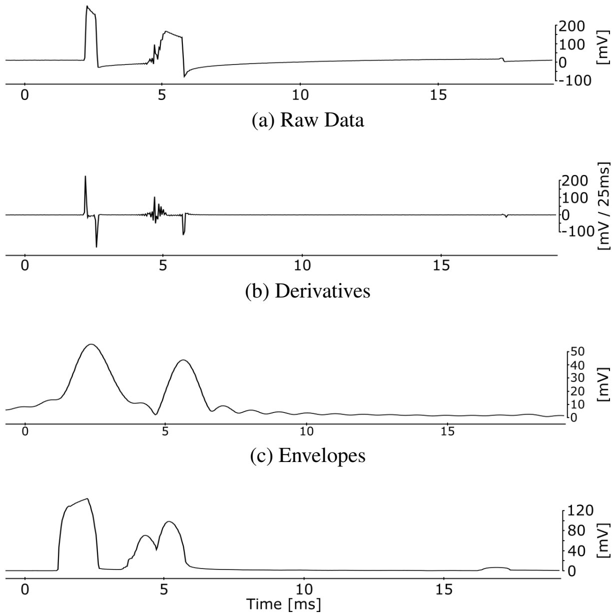
Figure 4. Manual annotation of the data. The mark is always placed at the beginning of the rising edge. The picture shows ECG Frank Lead M.

The position of the beginning of the sharp rising edge of the PP may vary across leads because of the different shapes in different leads. For that reason, the alignment of the mark was made on one lead (C2). All our tests were performed on this lead as well.

Downsampling of the dataset from 25 kHz to 5 kHz involves antialiasing low pass filter, meaning that PPs become wider. That fact complicates localising the PP rising edge. For example, for a PP with a length of 1 ms at 25 kHz, it becomes 1.6 ms at the 5 kHz sampling rate. Figure 4 compares the same PP at the 25 kHz (a) and 5 kHz (b) sampling rates.

2.4. Compared methods

PA detection methods could be split into two parts:



(a) Raw Data

(b) Derivatives

(c) Envelopes

(d) Moving Statistical Window

Figure 5. Data transformation applied to 25 kHz data.

1. **Data transformation**. The ECG was transformed into three formats for peak detection:

- **Derivatives**. The first derivative of the signal was performed.
- **Envelopes**. Power envelopes in the spectral range of 500 2200 Hz. This range was common for both 5 and 25 kHz data.
- **Moving Statistical Window**. We used two different statistics with two different window sizes. Variance and Standard deviation were combined with the 0.5 ms and 1 ms window sizes. Transformation examples are shown in the Fig. 5.

2. **Peak Selection Method**. For peak selection, we chose methods that were based on the statistical properties of the transformed signal. To distinguish between them, we used the following criteria:

- **The mean plus standard deviation** (StdMean)

$$Std(data) + Mean(data) \quad (1)$$

- **The maximum divided by the constant value** (cMax):

$$\frac{Max(data)}{20} \quad (2)$$

- **The mean plus the maximal value divided by the constant** (MeanMax):

$$\frac{Mean(data) + Max(data)}{20} \quad (3)$$

3. Evaluation and results

Detection of the pacing phase was performed on all 19 subjects and sensitivity (SE) and specificity (SP) were evaluated. The maximum distance when the mark was evaluated as being correct was set to 2 ms from manually anottated marks. Detection with the same settings was performed on both 25 and 5 kHz data for comparision.

Table 1. A comparision of sensitivity and specificity for 25 kHz and 5 kHz data.

Transform method	Peak selection	25 kHz Se	25 kHz Sp	5 kHz Se	5 kHz Sp
Derivative	StdMean	100	75.52	91.88	86.24
	cMax	95.83	93.76	85.98	87.66
	MeanMax	95.83	93.76	85.98	87.66
Envelopes	StdMean	99.91	30.33	93.16	86.6
	cMax	94.7	46.54	91.81	88.48
	MeanMax	94.68	46.63	91.78	88.73
Statistics (std;0.5 ms)	StdMean	100	82.3	81.9	73.17
	cMax	95.83	92.48	78.31	78.32
	MeanMax	95.83	92.5	78.28	78.33
Statistics (std;1 ms)	StdMean	96.79	88.47	87.51	83.78
	cMax	95.07	93.14	85.05	86.82
	MeanMax	95.06	93.25	85.05	86.84
Statistics (var;0.5 ms)	StdMean	80.26	99.97	65.38	73.5
	cMax	70.79	99.98	58.18	73.46
	MeanMax	70.75	99.98	58.18	73.46
Statistics (var;1 ms)	StdMean	79.93	99.97	72.07	85.81
	cMax	68.94	99.98	66.51	85.82
	MeanMax	68.93	99.98	66.51	85.82

For the preciseness of detection, we evaluated the average distance and its standard deviation. This was performed just for marks in the range of 2 ms of manual anottations.

As shown in Table 1, the best method for data transformation was the moving window with a standard deviation and window size of 0.5 ms. In combination with the StdMean peak selection method, it reached the best sensitivity and acceptable specificity. When compared to the 5 kHz dataset, there was a drop of sensitivity and specificity in most of the cases. The sensitivity drop for 5 kHz data is below the acceptable level for UHF ECG analysis.

From the temporal preciseness point of view, the best technique for peak detection was again a moving window statistic with a window size of 1 ms. The standard deviation for 25 kHz data was $\pm$0.11 ms meaning just $\pm$2-3 samples. Again, for the 5 kHz dataset, there was as increase in the derivative method as a drop in the preciseness of detection for other methods(Table 2.

To evaluate the best method, we need to look at all three parameters. The highest sensitivity and specificity has to be combined with the lowest value of standard deviation. From the selected methods, the best was a moving window with a standard deviation statistic and a window size of 0.5 ms.

Table 2. Temporal preciseness of detecting the PP [ms].

Transform method	Peak selection	25 kHz Mean	25 kHz Std	5 kHz Mean	5 kHz Std
Derivative	StdMean	0.31	0.25	1.41	0.18
	cMax	0.31	0.24	1.39	0.17
	MeanMax	0.31	0.24	1.39	0.17
Envelopes	StdMean	0.36	0.17	1.44	0.30
	cMax	0.32	0.14	1.44	0.30
	MeanMax	0.32	0.14	1.44	0.30
Statistics (std;0.5 ms)	StdMean	0.34	0.2	1.45	0.31
	cMax	0.35	0.2	1.45	0.30
	MeanMax	0.35	0.2	1.45	0.30
Statistics (std;1 ms)	StdMean	0.3	0.21	1.47	0.28
	cMax	0.3	0.21	1.48	0.26
	MeanMax	0.3	0.21	1.48	0.26
Statistics (var;0.5 ms)	StdMean	0.38	0.14	1.31	0.22
	cMax	0.39	0.14	1.29	0.22
	MeanMax	0.39	0.14	1.29	0.22
Statistics (var;1 ms)	StdMean	0.31	0.12	1.46	0.20
	cMax	0.31	0.11	1.44	0.21
	MeanMax	0.31	0.11	1.44	0.21

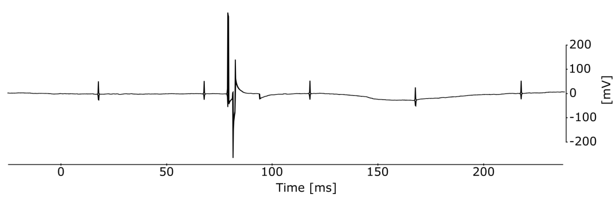


Figure 6. Strong respiration pulses influencing the analysis. Channel C2 from the most problematic subject is shown.

4. Discussion

The best method for pacing phase detection was evaluated as a moving window with a standard deviation statistic and a window length of 0.5 ms. There was achieved a 100% sensitivity of detection across all subjects. Specificity was lower for some subjects caused by a strong presence of respiration pulses as you can see in Figure 6. The purpose of this paper was to compare methods for marking pacing phase presence. If a pacing device has turnsed on a respiration sensor during analysis, those artefacts also have to be removed from the ECG for making a UHF analysis. This is the subject of the next research project on how to detect all pacing device artefacts for proper UHF ECG analysis.

5. Conclusion

Three methods for precisely detecting PP were evaluated and compared. Temporal preciseness was evaluated by a standard deviation of automatic and manual annotations. We compared the sensitivity and specificity of selected PP detection methods. A comparison was made between the 25 kHz sampling rate and the 5 kHz rate. Based on our results, a moving window with a standard deviation statistic and a window size of 0.5 ms was evaluated as being the most appropriate for precisely detecting the pacing phase in UHF ECG recordings.

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