A Real-Time Digital Pacemaker Pulse Detection Algorithm

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Abstract

In this paper, we analysed the features of pacing pulses and challenging noises from clinical datasets collected at high sampling rate. A two-stage algorithm is proposed to detect pacing pulses for real-time application purpose. In the first stage, pulse candidates were picked up preliminarily after enhancing the rising and falling edges of the pulses and attenuating high frequency noises. More detailed morphology features were checked in the second stage to validate and confirm the candidates. The sensitivity and positive predictivity of the algorithm on the training and testing datasets both exceed 99%. The evaluation results illustrate the pretty good performance of the proposed algorithm.

1. Introduction

After the invention in the 1950s, pacemakers have been widely applied as a treatment to heart diseases like sick sinus syndrome, heart block (especially 3° atrio-ventricular block) etc. More and more patients benefit from the installation of pacemakers with the more and more mature clinical techniques.

Electrocardiogram (ECG) monitoring is commonly needed for in-hospital patients with pacemaker implanted to keep the clinicians aware of the patient's heart status. To keep watching the ECG signal of the patient with a pacemaker, it's essential for a patient monitor to appropriately detect the pacing pulses generated by the pacemaker so that the paced rhythm can be differentiated from other arrhythmia rhythms. In some cases, the patient monitor may also need detecting and locating the pacing pulses to eliminate the large pulse spikes in the ECG signals so that those spikes will not be falsely recognized as QRS complexes. Several medical device standards also have explicit requirements on the pacing detection capability. For example, the IEC60601-2-27 standard [1] requires the display capability for pacing pulses with amplitudes of ± 2 mV to ± 700 mV and durations of 0.5 ms to 2.0 ms. The relevant statement in the IEC60601-2-25 standard [2] is slightly different which requires detection of pacing pulses with the amplitudes of ± 2 mV to ± 250 mV and durations of 0.1 ms to 2.0 ms.

Pacing pulse detection can be implemented by hardware, software or a combination of both. The hardware detection usually detects the rapid rising edge of the pacing pulses with a fixed threshold. It's simple and fast, but not flexible to the variable features of pacing pulses and ECG noises. The software detection requires digital processing and analysing on high sampling-rate ECG signals which is more complicated, but capable of handling more challenging situations.

Nowadays bipolar pacing technology is widely used which generates pacing pulses with much lower amplitude than old unipolar pacing. Some pacemakers even have the function to automatically measure the capture threshold and adjust output energy according to the threshold changes. The pacing pulse's amplitude in the surface ECG signal may easily decrease to less than 2 mV which is the lowest amplitude required by the standards. On the other hand, pacing pulse detection needs to consider the influences of high frequency noises like electrostatic noise, electromyographic (EMG) noise etc. Pacemakers may also generate lead-integrity pulses, minute-ventilation (MV) pulses, and telemetry communication signals that can be incorrectly identified as pacing pulses. In order to deal with the more and more challenges for pacing pulse detection, the software detection scheme becomes a more popular solution.

This paper introduces the design of a software pacing pulse detection algorithm, which is supposed to effectively detect pacing pulses in real-time and can be applied in ECG devices, e.g. patient monitors etc.

2. Materials and methods

2.1. Datasets

High sampling-rate data used for algorithm developing and testing was obtained from patients with pacemaker installed from three hospitals using Mindray T Series / N Series monitors with special MPM Platinum modules. The whole dataset was divided in two parts: data entries collected from 168 patients between March 2015 to January 2016 were used as the developing dataset, and data entries from 162 patients between March 2019 to November 2019 were used as the testing dataset.

The original sampling-rate of the data entries was 128

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ksps. Data entries recorded 4 leads of ECG signals (I, II, III and V in Mason-Likar monitoring lead placement) with varied lengths from 15 min to 60 min. Most of the patients in the datasets were implanted with permanent pacemakers, and only a few (17/330) were installed with external temporary pacemakers. Major pacemaker manufacturers were covered by the datasets, including Medtronic, St. Jude, Boston Scientific, Biotronik etc. Pacing mode details of the datasets are illustrated in Table 1. Pacing pulse positions were firstly marked by a dedicated program which analysed data records retrospectively and detected pacing pulses using record-specific strategies. Then all annotations were manually checked and adjusted.

Table 1. Pacing mode distribution in the datasets

Pacing Mode	Developing Dataset	Testing Dataset
DDD	56	69
DDDR	50	16
VVI	35	38
VVIR	9	4
AAI	0	5
AAIR	5	11
Biventricular	8	6
Unknown	5	13
Total	168	162

2.2. Features

Features of pacing pulses and noises in the collected database were visually checked and summarized:

1) Pulse width – More than 90% pacing pulses in the collected datasets were with the width setting of 0.4 ms. Permanent pacemakers are usually programmable for pulse widths, while the typical pulse width used in clinical application is 0.4 ms which is also the default setting of most permanent pacemakers. Pacing pulses produced by external temporary pacemakers are often wider (typically more than 1 ms) and fixed. Figure 1 shows the examples of permanent pacing pulses from a permanent pacemaker and a temporary one. The pulses were slightly widened after digitally acquiring from the body surface. The pulse width can be considered as a constant during pacing pulse detection processing.

2) Pulse amplitude – Unipolar pacing pulses were outstanding to be recognized in the surface ECG signals with the amplitudes from dozens to hundreds of millivolts. Amplitudes of bipolar pacing pulses were much smaller varying from 0.1 to tens millivolts. The pulse amplitudes were far below the upper limit 700 mV required by the IEC60601-2-27 standard, but pulse amplitudes of all recorded ECG leads were below the lower limit 2 mV in more than 15% of the data entries. The pulse amplitudes often varied a lot by leads. Figure 2 shows an example that the pulse amplitudes were very small in lead III and V, but much higher in lead I. Combination analysis for multiple leads information shall be helpful to detect pacing pulses with lower amplitudes.

3) Pulse morphology – The pacing pulse typically consists of steep rising and falling edges and a plateau in between. An overshoot with opposite polarity usually follows the pulse. The overshoot amplitude is normally less than the pacing pulse, but sometimes comparable. For example, as shown in Figure 1, the typical permanent pacing pulse has a small overshoot while the external pacing pulse has a large one. In the datasets, some pacing pulses were noticed in which have sharp and high spikes at the rising and falling edges with a very low plateau. This kind of morphology as shown in Figure 3 is not rare in the collected data entries, and shall be taken care in the pulse detection. Although the pacing pulse may present different kinds of morphologies, its morphology is supposed to be consistent when the pacing site, pacemaker configurations and surface electrode placement are not changed.

4) Noises – Low frequency noises like baseline wandering, powerline interference etc. may not have impact on the pacing pulse detection [3]. High frequency noises like electrode contact interference, electrostatic discharge, EMG noise may intermittently affect the detection, while the spike noises produced by pacemakers intentionally can have more critical influences. Some modern pacemakers may generate extra spikes along with pacing pulses to test the lead integrity or measure the minute ventilation. When interrogating with a telemetry programmer, some types of pacemakers may also produce dense spikes in the surface ECG signals. Figure 4 illustrates some examples of those spike noises. The amplitudes of those spikes may be even higher than the pacing pulses, but the widths were narrower (typically less than 0.1 ms). The spike noises usually had similar morphology in a same case, and were significantly different from pacing pulses.

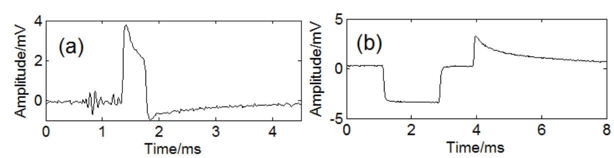

Figure 1. Examples of (a) A typical permanent pacing pulse, (b) a temporary pacing pulse with large overshoot.

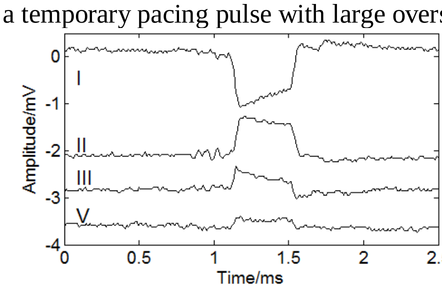

Figure 2. Pacing pulse amplitudes varied a lot by leads.

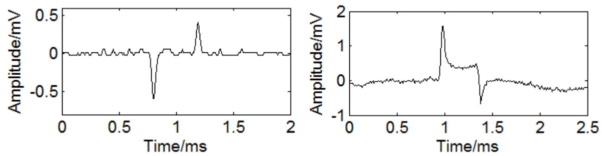

Figure 3. Pacing pulses with a very low plateau and high spikes at the rising and falling edges.

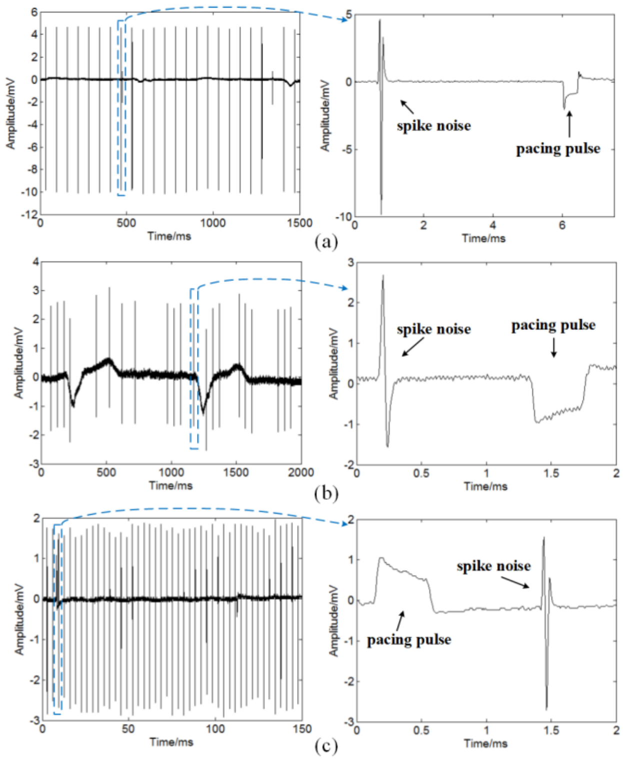

Figure 4. Examples of spike noises generated along with pacing pulses, (a) minute ventilation, (b) lead integrity, (c) telemetry interrogating.

2.3. Algorithm design

An algorithm was designed based on the feature analysis accordingly, and iteratively tuned using the developing dataset. The block diagram of the algorithm design is shown in Figure 5.

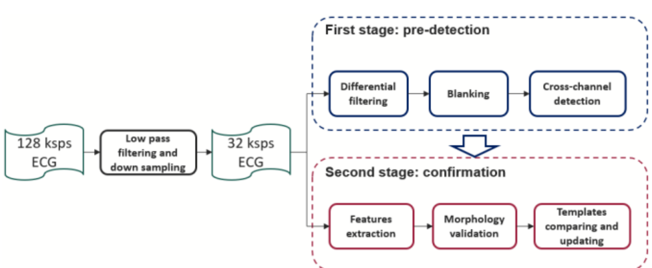

Figure 5. Algorithm block diagram

The original 128 ksps data is firstly processed by a low pass filter with the cut-off frequency of 8 kHz, and then down-sampled to 32 ksps. The sampling rate of 32 ksps is chosen as a balance between the detection accuracy and the computation workload [4]. Multi-channels of the 32 ksps data are fed into the algorithm. The number of channels can be adjusted according to the computation power of the target platform where the algorithm is supposed to run.

The algorithm operates in two stages: the pre-detection stage and the confirmation stage. The pre-detection stage runs fast identify potential pacing pulse candidates with less calculation demanding. The confirmation stage is to validate the candidates in more details with more time-consuming calculation.

In the first stage, a simple differential filter [5] is used to enhance the rising and falling edges of the pacing pulses and remove low frequency components. A window-blanking method is then applied to process the differentiated data by channels which is to attenuate narrow spikes noises. The maximum positive and negative peaks in each 2-millisecond segment of the differentiated data are searched. The distribution of the amplitudes and widths of the maximum peaks in the recent 250 2-millisecond segments (i.e. recent 500 milliseconds) is continuously updated, and the positive and negative amplitude thresholds and window width for the blanking process are then determined based on the distribution statistics and detected pacing pulse features. In the blanking process, only those sample values continuously exceeding the amplitude thresholds for more than the window width are retained, and other values are set to zero. Figure 6 shows an example of the effects of the differential filtering and blanking process. Most spike noises are removed, while real pacing pulses are preserved. Data of multi-channels after the blanking processing are crossly checked, and paired positive and negative peaks are picked out as pacing pulse candidates.

In the second stage, the delineation of the pacing pulse is searched on the pre-processed 32 ksps signal around the candidate's position detected in the first stage. Detailed morphology features of the pulse like amplitude, width, polarity, existence of plateau, width of plateau, similarity to triangle morphology etc. are calculated. These features are then checked with typical pacing pulse criteria established from the developing datasets. If the features not passing the typical pulse check, they will be compared with the existing templates to determine if the candidate is a pacing pulse. In the end, the candidate will be marked as questionable if not being accepted yet. A template can be built and updated when candidates with consistent morphologies and regular occurrence timing are accumulated to some extent. Pacing pulses with non-typical morphologies may be missed for several instances at the beginning, but can be eventually detected when the template established after their regular occurrences. This "learning" phase should be acceptable for long-term patient monitoring.

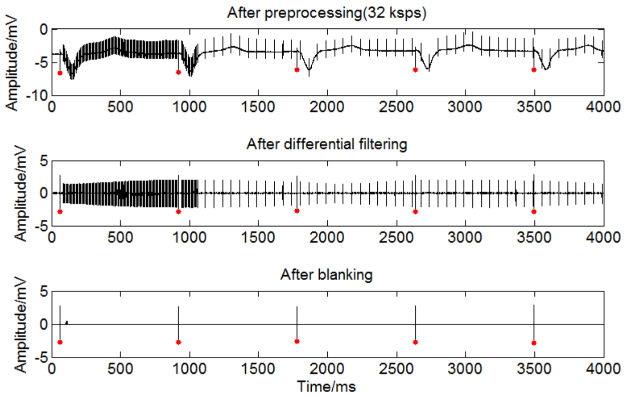

Figure 6. An example of the effects of the differential filtering and blanking process in a situation with dense spike noises; pacing pulses marked with red dots.

3. Results and discussion

The performance of the proposed algorithm is evaluated on the collected datasets. A detection of a pacing pulse within ±2 ms range of an annotated pulse location is taken as a correctly matched detection. In the evaluation, the refractory period for pulse detection was set to 6 ms, and the first two recorded leads (I and II) were used for analyzing. The performance results were actually close when other channel compositions were used. Sensitivity (Se) and positive predictivity (+P) are used as the benchmarks defined as Se = TP / (TP + FN), and +P = TP / (TP + FP), where the true positive (TP) is the number of correct detections, the false negative (FN) is the number of missed detections, and the false positive is the number of false detections. The evaluation results are shown as in Table 2, which illustrates the pretty high performance of the proposed algorithm.

Table 2. Evaluation results of the algorithm

Dataset	Annotated Pulses	Se (%)	+P (%)
Developing	271554	99.79	99.90
Testing	310519	99.70	99.83

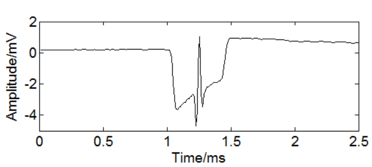

Figure 7. Missed detection of a pacing pulse overlapped with a spike noise.

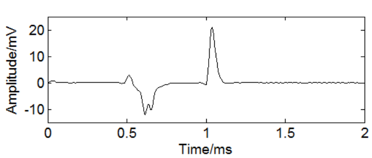

Figure 8. False detection of coupled narrow spike noises.

As an example, shown in Figure 7, some spike noises may happen to overlap a pacing pulse so that the pacing pulse can be missed in the morphology validation. Some narrow spike noises occur very close and their combinations may be falsely detected as pulses as an example shown in Figure 8. These are typical known issues in the evaluation results, and could be future improvements for the algorithm.

4. Conclusion

Features that need to be taken care of in pacing pulse detection are analyzed. An algorithm suitable for real-time pacing pulse detection is proposed based on the known features. The evaluation results on clinical datasets shows the good performance of the algorithm.

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