Performance Challenges in ECG Pacemaker Pulse Detection Systems

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Abstract

The paced patient population has significantly increased recently making it a priority for modern patient monitoring systems to provide accurate results for paced patients. This task has become more complicated with modern pacemaker technology and changes in the paced patient population. Certain pace pulse morphologies and paced heart rhythms demand a significant increase in the complexity of pace pulse detection algorithms. A system wide approach that focuses on both improved pace pulse detection as well as improved artifact rejection is important. In this paper, we present an approach to address common performance challenges in pace pulse detection to improve the overall monitoring of paced patients in commercial patient monitoring systems. Intensive testing of this approach using proprietary ECG databases resulted in improvements in performance benchmarks.

1. Introduction

This paper outlines some performance challenges faced by commercial surface ECG patient monitoring systems when monitoring patients with modern pacemakers and implantable cardioverter defibrillators (ICDs) with pacing capability.

The ECG pace pulse detection system is a vital part of the patient monitoring system. It is tasked with accurately identifying the location of pace pulse artifacts in the ECG and removing them from the ECG signal of interest. If the pace pulses are not detected and removed they can be inappropriately detected as QRS complexes leading to inappropriately high measured heart rates and high heart rate alarms or the lack of an asystole or bradycardia alarm for true low heart rate conditions. In addition, if noise is falsely detected as a pace pulse there can be inaccurate pace pulse markers displayed on the monitor, this leads to difficulty viewing and interpreting the ECG. False pace pulse detections can also result in inappropriate QRS classification and thus inappropriate arrhythmia alarms.

Traditional ECG pacemaker pulse detection systems do not always perform well with modern pacemakers and implantable cardioverter defibrillators (ICDs). Modern devices provide multiple pacing vector options and automatic capture algorithms which both result in a smaller required pace pulse in both amplitude and width. The pacemaker/ICD patient population has also changed with more devices being used to treat heart failure with cardiac resynchronization therapy (CRT). This means there are more ventricular pace pulses per R-R interval with a shorter coupling interval compared to traditional devices that only had one ventricular pace pulse. In addition, because the frequency content of pacing pulses is above the bandwidth of standard ECG features, pace pulse detection usually occurs on an ECG signal sampled at a higher rate with less filtering that is not visible to the user. Thus inaccuracies in pace detection are very confusing to the user.

Surface ECG is also an important tool in the follow-up and assessment of paced patients [1, 2]. Both pacemakers and ICDs are being used with increased frequency, which makes accurately monitoring these patients a priority. In this paper, we discuss performance challenges faced in current pace pulse detection systems and improved signal processing techniques to address those challenges. We focus on issues of both false pace pulse detection and inability to detect true pace pulses. Both challenges make significant contribution to overall customer satisfaction of a patient monitoring system.

2. Missed pace pulse detections

Some common challenges experienced with commercial pace pulse detection systems include susceptibility to not detecting small pace pulses and abnormally shaped pace pulses. Figure 1 gives an example of a typical small amplitude pace pulse. AAMI standards [3] state that a patient monitor must detect pace pulses with amplitudes between 2mV and 700mV. However, with modern pacing devices the programmed pace pulse amplitude is smaller than with traditional devices and the pace pulses appearing on a surface ECG will often fall below the detection threshold. However, patient monitor users still expect the monitor to be able to correctly analyze a paced rhythm no matter what the pace pulse characteristics are, especially when no noise is visibly present on the ECG.

There are multiple ways a manufacturer of ECG monitors can address the demands of users to analyze insufficiently strong pace pulses.

One option is to drop the minimum pace pulse amplitude detection threshold. However, this introduces new challenges due to the fact that previously undetectable morphological elements and artifacts become detectable under the new relaxed threshold requirements. It is important to minimize the number of extra detections that occur. This can be done by assessing the signal quality of each lead and adjusting detection thresholds based on this, the system can then dynamically adjust the thresholds if the signal quality changes over time. Additional algorithm complexity can also be added to differentiate noise from true pace pulses as discussed in Section 3.

Another way to improve detection of low amplitude pace pulses is to use multiple ECG leads. When multiple pacemaker leads are placed in various positions in the heart and pacing can occur from various vectors, there is no single lead and in many cases no two leads that will effectively detect all pace pulses for a given patient. Therefore using more than two leads and cross checking the results between leads can be an effective way to improve pace pulse detection.

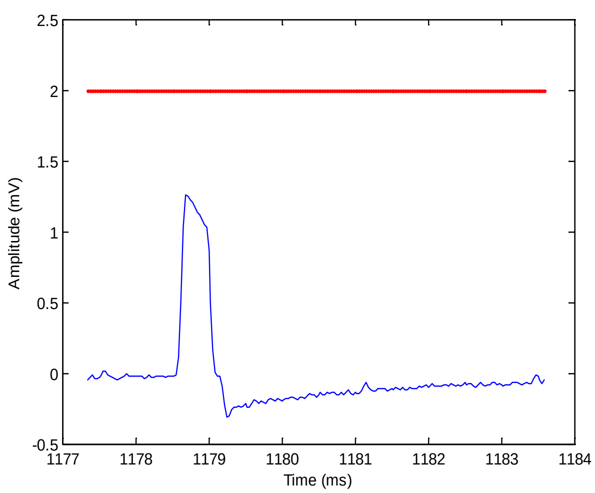

Figure 1. Typical implanted pacemaker pulse on ECG lead II (blue), AAMI amplitude requirement for pace pulse detection (red).

Figure 2 gives an example of an abnormally shaped pace pulse that may not be detected by current pace pulse detection systems. Current slope based pace pulse detection systems expect a pace pulse to be square shaped and detect pace pulses by identifying a sharp onset slope followed by a flat or slowly decreasing plateau followed by a sharp falling edge. The pace pulse in Figure 2 does not match these requirements and is more reminiscent of noise spikes commonly seen on the relatively unfiltered ECG signal channels used for pace pulse detection. Even though this is not the standard pace pulse morphology, this pace pulse will consistently have the same morphology on this lead over time. It also has other common pace pulse characteristics such as a timing pattern consistent with its programmed pacing mode and a corresponding pace pulse on other ECG leads. These characteristics can be used to identify abnormally shaped pace pulses.

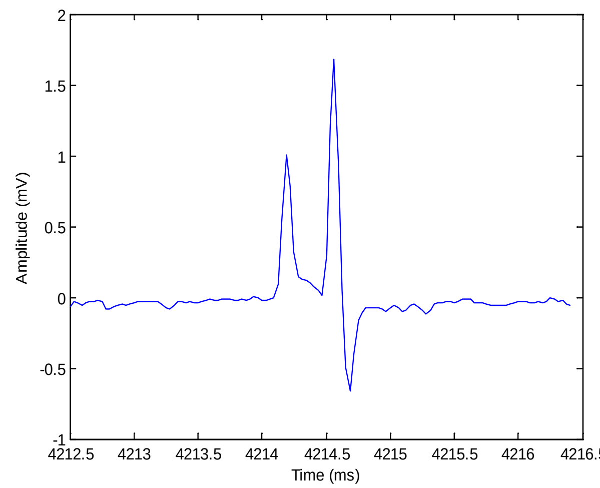

Figure 2. Abnormally shaped pace pulse which is difficult to detect with traditional slope based pace pulse detection methods.

3. False pace pulse detections

An ECG patient monitoring system is required to be robust to noisy inputs. The main contributors of noise are electrical interference, motion of a subject, muscle noise and electrode preparation. Electrical interference is usually of a high-frequency nature which can be suppressed from the heart signal content using conventional filtering techniques. However, this high frequency noise often overlaps with the pace pulse signal of interest which makes it difficult to remove with filtering techniques without distorting the pace pulse information. In addition, lowering the pace pulse detection threshold as described in Section 2 will make the system more susceptible to falsely detecting noise as pace pulses. Figure 3 shows a noise pulse with morphology similar to a typical pace pulse morphology that would be incorrectly detected as a pace pulse by some current pace pulse detection systems.

In many cases, noise does not have a morphology that is as consistent as pace pulse morphology. Therefore evaluating potential pace pulse morphology over time can help differentiate more random noise from true pace pulses.

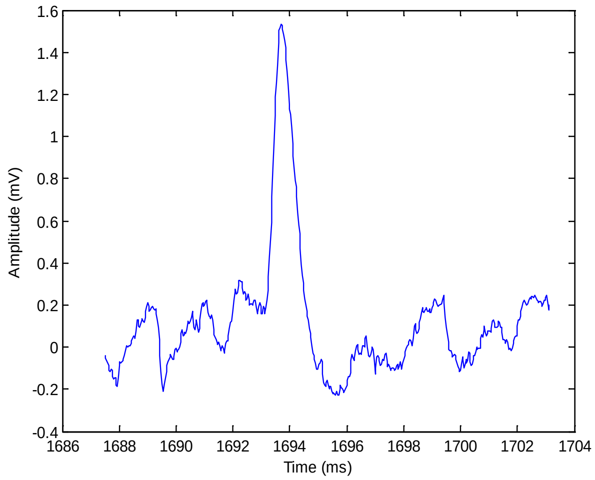

Figure 3. Noise/artifact similar in morphology to a pace pulse.

In other cases these noise pulses will occur more frequently than possible with typical pacemaker timing cycles (Figure 4). Therefore, analyzing the intervals between potential pace pulses over a larger time interval can be used to discriminate noise from true pace pulses.

When there is noise and pace pulses occurring simultaneously (Figure 4), preventing false pace detections while detecting true pace pulses becomes more complicated. One possible solution is to use the timing interval between pace pulses in combination with morphology, to identify pulses with similar morphology that are occurring at non-pacemaker timing intervals that can be discarded and not reported as pace pulses. To capture subtle morphology differences between true pace pulses and noise it is important to have a high-end analog front end with high sampling rate, dynamic range, amplitude resolution and low noise floor.

In noisy environments, the morphology of a pace pulse can be distorted, while pacemaker timing cycles often adapt based on the patient's heart rhythm. Therefore it may require additional delays to analyze the surrounding context of an event as well as additional storage space to save historical timing and morphology patterns for a specific patient.

4. CRT challenges

Cardiac resynchronization therapy is being increasingly used to treat heart failure [4]. It requires multiple pace pulses to be delivered to the ventricles with short coupling intervals, sometimes less than a few milliseconds. Figure 5 shows typical bi-ventricular pace pulses with a short coupling interval that can complicate discriminating noise from pace pulses as described in Section 3. To address this complication, we did not just look at the coupling interval between a series of two or three potential pace pulses but took a more global look at the history of many timing intervals in combination with the corresponding potential pace pulse morphology to differentiate a pace pulse from a noise pulse and identify CRT pacing.

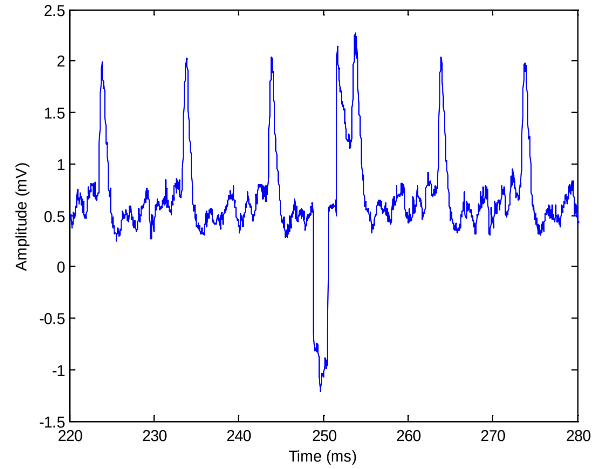

Figure 4. Noise occurring too frequently to be a pace pulse timing cycle. This noise distorts the morphology of the pace pulse tail.

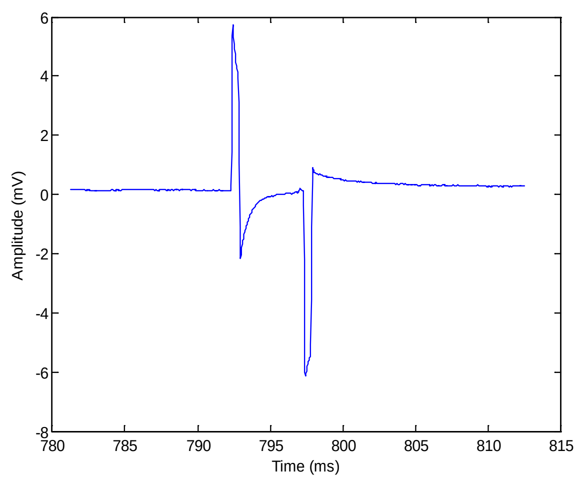

Figure 5. Typical bi-ventricular pacing with a short coupling interval

5. Results

This study involved a patient monitor with high-end analog front end to allow acquisition of four channels of high speed ECG data at a sampling rate of 32 kHz. The data set included several minutes of data from 43 adult patients. Each patient had either, an external pacemaker, an implanted pacemaker or an ICD with pacing capability; all devices were at their regularly programmed pacing settings and were currently in a paced heart rhythm. All patients required and were currently undergoing routine ECG monitoring in the electrophysiology lab, ICU or telemetry ward. The devices were from various device manufacturers, many with bi-ventricular pacing capability.

The performance of a slope based detection system was compared to that of an advanced pace pulse detection system. The slope based detection system used two leads of ECG data down-sampled to 16 kHz. The advanced detection system was designed to address the challenges described in the previous sections of this paper. It used four leads of 32 kHz ECG data and more sophisticated signal processing techniques to: a) detect low amplitude pace pulses, b) detect abnormally shaped pace pulses, c) detect CRT pacing pulses, and d) reject noise and artifacts.

Performance statistics, sensitivity, positive predictive value and accuracy were calculated for the data set and the two methods compared. The advanced pace detection algorithm had a sensitivity of greater than 96%, a positive predictive value of greater than 98% and an accuracy of greater than 95%. This performance is significantly better than the traditional method in all three performance statistics. This confirms that dropping the pace pulse detection threshold and loosening the pace pulse shape requirements will aid in detecting low amplitude and abnormally shaped pace pulses as illustrated by the increase in sensitivity and that introducing additional algorithm components will aid in rejecting false pace detections as illustrated by the increase in the positive predictive value. The overall system accuracy increase emphasizes that the advanced pace pulse detection system provides improvement in terms of both detecting all pace pulses appropriately with fewer over detections especially in the presence of noise and muscle artifact.

6. Conclusions

This paper highlights challenges that arise in the development of a pace pulse detection system for surface ECG patient monitors. Demand for a system that is able to detect all types of pace pulses in a clinical environment conflicts with the goal of reducing susceptibility to false pace pulse detections. These contradictory user requirements can be addressed with advances in patient monitor analog front end technology in combination with advanced signal processing and algorithm techniques.

The advanced system described in this paper includes a higher sampling rate, more ECG leads, historical patient specific pace pulse morphology analysis and historical patient specific pace pulse timing analysis and dynamic detection thresholds to significantly improve the pace pulse detection system in a patient monitoring system. These improvements lead to improved cardiac monitoring of patients with pacemakers and ICDs in terms of pace detection, rejection of noise as well as accurate heart rate, arrhythmia monitoring and alarm generation. More tests are still needed to verify the effectiveness of this approach, especially in an embedded real-time monitoring environment.

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