Vector-based Pacemaker Pulse Detection Algorithm for the Surface ECG

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Abstract

The recent advancement of pacemaker technology: low power, biventricular (biV) pacing and adaptive pacing rate, has brought challenges for detection of pacemaker pulses (PPs) in the surface ECG. False positive PPs and undetected and unresolved PPs may consequently have a detrimental impact on a diagnostic ECG algorithm's rhythm or morphology interpretations. We have developed an algorithm to strengthen an existing PP detection algorithm using vector information to reject false positive PPs and detect the existence of a second biV PP closely spaced in time. We collected ECGs from both biV and non-biV pacemakers for algorithm development and performance validation. After training on the development dataset, our algorithm showed a biV paced rhythm detection sensitivity of 94.3% with a detection specificity of 99.3%.

1. Challenges

Pacemaker technologies have rapidly advanced over the last decades. A modern pacemaker consumes much less power to extend battery life using bipolar low-amplitude pulses just above the pacing threshold. Research has shown that rate-adaptive pacing is more compatible with the nature of human physiology and provides numerous benefits to patients [4]. An increasing number of heart failure patients are receiving cardiac resynchronization therapy (CRT), which uses a biventricular (biV) pacemaker that paces both left and right ventricles with closely spaced pulses to maximize cardiac output. All these improvements have brought challenges for detection of PPs in the surface ECG.

1.1. Low power and rate-adaptive

Since pacemakers consume less power with lower pulse amplitudes, PPs are now less distinguishable from environmental impulse noise. False-positive PPs cause inaccurate interpretation of pacemaker rhythm by automated algorithms. Detecting PPs at different frequency bands was proposed to improve detection accuracy [2]. The temporal distance has been used beat-to-beat across leads for identifying true PPs [1]. However, if the pacemaker is rate-adaptive, the varying temporal distance makes it difficult to find a reference for rejecting false positive PPs.

1.2. Biventricular pacing

Non-synchronous biV PPs are closely spaced in time, and provide challenges for detection of both ventricular chambers' PPs. Undetected and unresolved PPs may consequently have a detrimental effect on an automated diagnostic ECG algorithm's rhythm or morphology interpretations.

The projection of two biV PPs on a single ECG lead resembles only one ventricular PP. The electrodes implanted on the left and right ventricular walls do not produce pulses with the same orientation; typically there is about 100 degrees of angle difference between the vector projections. When you see one pulse clearly in an ECG lead, the other pulse's projection onto that lead is smaller, with an amplitude equal to the cosine of the angle difference multiplying its real amplitude in 3-D space; e.g., $\cos(100^{\circ})$ is -0.17. In addition, the interval between two biV PPs is usually as small as a few milliseconds, so recognizing whether it is one ventricular PP or two biV PPs is not an easy task, especially with the presence of a pacemaker recharge wave that further challenges pulse detection.

The discharge wave of the second biV PP may overlap with the recharge wave of the first PP. The overlapped vectors along with the discharge wave of the first PP will look like a single ventricular PP.

An ECG waveform is usually pre-processed by a low-pass filter, making the pulses wider and all of the previously mentioned challenges even more difficult.

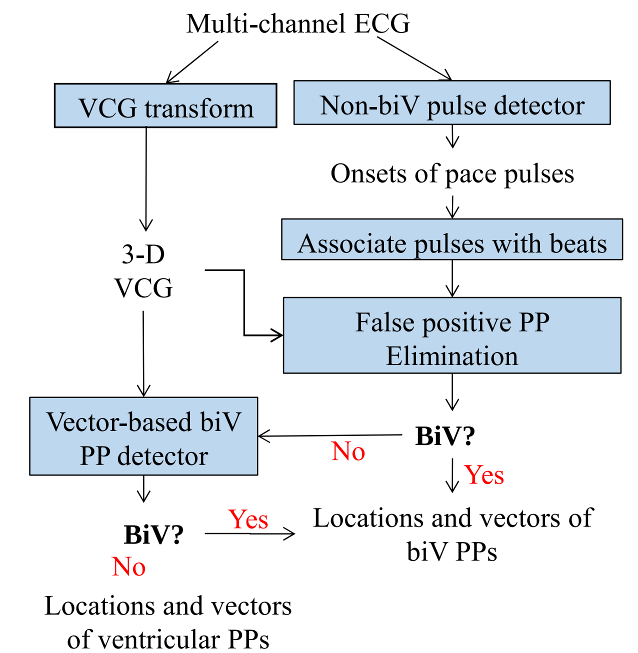

Figure 1. Block diagram of the detection algorithm.

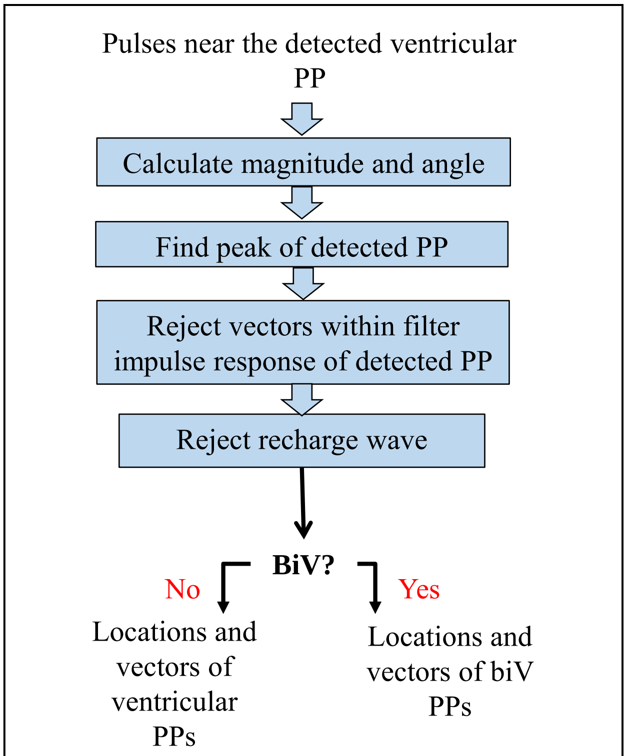

Figure 2. Block diagram of the vector-based biventricular pacemaker pulse detector.

Petrutiu et al proposed the use of 75 kHz sampling rate sensing devices to detect the biV PPs [3]. A high sampling rate provides higher temporal resolution to distinguish PPs, but it needs not only specialized hardware but also specialized software for signal processing. However, with a sampling rate 150 times that of a regular 500 sps device, the problem of PP detection becomes one of how to distinguish the discharge wave from the recharge wave and how to recognize and reject high-frequency noise.

2. Pacemaker pulse detection algorithm

The spatial angle of a PP only depends on the location the electrode is implanted on the ventricular wall. Different pacemaker settings have no effect on the pulse spatial angle. Therefore, we propose an algorithm to strengthen an existing PP detection algorithm using spatial angle to reject false positive PPs and detect the existence of a second biV PP closely spaced in time. Despite a pacemaker being rate-adaptive, or the occurrence of impulse noise near QRS onset, the spatial angle of a PP is still consistent. Utilizing the spatial angle feature, we can detect the possibly unrecognized second PP in a biV paced ECG, when two biV PPs are closely spaced in time or overlapped, seemingly appearing as only one ventricular PP in an individual lead.

The block diagram of the detection algorithm is shown in Figure 1. The multi-channel ECG is first converted to vectorcardiogram (VCG) as 3-dimensional vectors [6]. The algorithm then performs two major functions: 1) false-positive PP elimination; and 2) vector-based biV PP detection.

2.1. False positive pacemaker pulse elimination

The detected PPs from an existing non-biV PP detector (in our case, the detector in [1] is used) are associated with beats for classifying atrial- or ventricular-paced beats, and these PPs are further checked for their spatial angle to eliminate false-positive pulse detections. The PPs from a specific electrode should have approximately the same vector angle, so those pulses with very different angles than most of the atrial or ventricular pulses are considered noise and eliminated from the set of possible PPs. After eliminating the false positive PPs, the algorithm can decide the type of paced rhythm. If there are two ventricular PPs detected in a majority of the beats, the rhythm can confidently be classified as biV paced rhythm. However, if there is only one ventricular PP detected, the algorithm needs to further search to see if there is an undetected ventricular PP close to the detected ventricular PP.

	Sensitivity	Specificity	PPV	NPV	Number of cases
Training	95.3%	100%	100%	94.6%	466
Testing	94.3%	99.28%	98.7%	96.8%	1099

Table 1. The performance of biventricular paced rhythm detection on training and testing sets.

2.2. Vector-based biventricular pacemaker pulse detection

The vector-based biV PP detector examines the vectors of the pulses in the vicinity of previously detected ventricular PPs for the existence of an undetected ventricular PP, as shown in the block diagram of Figure 2. The vector characteristics of the surrounding pulses are examined and rejected if they are considered: 1) the low-pass filter impulse response of the detected PP; or 2) the recharge wave of the detected PP.

The magnitude and angle of the vectors near the detected ventricular PP are calculated. The vector with maximal magnitude is identified as the peak of the detected ventricular PP. For each surrounding pulse, its angle to the peak is calculated. When a vector is within the range of the filter impulse response and it has an angle with the detected ventricular PP close to 0, it is considered the impulse response of the detected ventricular pulse and won't be considered a candidate for an undetected biV PP. When a vector following the peak has an angle close to π, it is considered the recharge wave and also won't be considered a candidate for an undetected biV PP. If there is a pulse that is not considered as the filter impulse response nor as the recharge wave, it is considered a biV PP. If a biV PP is found in a majority of beats, the algorithm classifies the ECG tracing as biV paced rhythm.

3. Validation

The biV pacemaker pulse detection algorithm has been implemented in the Philips DXL 12/16 lead diagnostic ECG algorithm. The validation ECG dataset was collected at Chang-Gung Memorial Hospital in Taoyuan, Taiwan, using a Philips TC70 cardiograph. We collected 500sps continuous 12-lead ECGs from 8 patients with biV pacemakers of various manufacturers, while gradually changing the RV-to-LV pacing intervals from 70msec to -70msec. The minimum pulse amplitude that allowed cardiac capture was used. The continuous 12-lead signals were segmented into 658 total cases of 10sec biV paced ECGs. The biV ECGs were mixed with 907 cases of non-biV paced ECGs from a different population of patients and then split to make both training (n=466) and testing (n=1099) sets. The biV pacing dataset was designed to cover a variety of biV pacemaker hardware settings, whereas the non-biV pacing dataset was designed to represent paced ECGs generally from a wide variety of patients.

3.1. Results

After training on the development dataset, the algorithm showed a BiV paced rhythm detection sensitivity of 94.3% with a detection specificity of 99.3%. The complete results are shown in Table 1. The performance was designed not to overcall biV pacing, so almost perfect specificity and positive predictive value (PPV) was preferred and reached.

4. Conclusion

We present a novel algorithm that enables an existing non-biV PP detection algorithm to detect PPs from modern biV pacemakers used extensively for cardiac resynchronization therapy. The algorithm has a high level of biV pacemaker rhythm classification performance (94%) with near-perfect specificity. We showed that vector information is able to help remove false-positive PP detections and identify biV paced rhythms. Future use of the PP vector angle could include recognition and diagnostic of a malfunctioning pacemaker, such as "run-away" non-sensing pacing, because the vector angle is only related to the electrodes' implanted location in the ventricular wall. Our biV paced rhythm detection algorithm has been implemented in the Philips DXL 12/16 lead diagnostic ECG algorithm, allowing a reduction in ECG over-reading physicians' workload with an automated diagnosis of biV paced rhythm.

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