An innovative hybrid approach for detection of pacemaker pulses at low sampling frequency

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Abstract— **Accurate assessment of pacemaker function or malfunction is essential to make clinical interpretations on pacemaker therapy and patient symptoms. This article presents an innovative approach for detecting pacemaker pulses at sampling frequency as low as 125Hz. The proposed method is validated in wide range of simulated clinical ECG conditions such as arrhythmia (sinus rhythms, supraventricular rhythms, and AV blocks), pulse amplitudes (~100µV to ~3mV), pulse durations (~100µs to ~2ms), pacemaker modes and types (fixed–rate or on–demand single chamber, dual chamber, and bi–ventricular pacing), and physiological noise (tremor). The proposed algorithm demonstrates clinically acceptable detection accuracies with sensitivity and PPV of 98.1 ± 4.4 % and 100 %, respectively. In conclusion, the approach is well suited for integration in long–term wearable ECG sensor devices operating at a low sample frequency to monitor pacemaker function.**

Clinical Relevance— **The proposed system enables real–time long–term continuous assessment of the proper functioning of implanted pacemaker and progression of treatment for cardiac conditions using battery–powered wearable ECG monitors.**

I. INTRODUCTION

An artificial pacemaker is a small medical device implanted usually in the chest or abdomen with one or more electrodes placed in one or more heart chambers to improve heart function impeded by cardiac conditions including abnormal heart rhythms or arrhythmias such as bradycardia and heart failure. The sensing unit of a pacemaker comprising of electrodes senses the normal or abnormal electrical activity of heart and when the heart's natural impulse generator or pacemaker skips or fails, the pulse generator unit of the artificial pacemaker sends electrical impulses to the heart and regulate the heart's electrical conduction system, mechanical pumping and heart rate on a demand or fixed basis [1].

Detection of pacing pulses originating from implanted pacemaker using surface level ECG enables cardiologists to identify pacemaker driven rhythms and evaluate the functioning of the implanted pacemaker device in patients requiring such cardiac assist device leading to the determination regarding reprogramming of the pacemaker device for optimal treatment or pacemaker battery replacement [2].

Standard ECG or portable Holter ECG monitors are commonly used to place ECG electrodes on chest and/or limbs, attached to the monitor via wires, and record/display ECG waveforms and simultaneous pacemaker pulses noninvasively. As typical pacemaker pulse durations are in the order of µs to few ms, Nyquist frequency of at least 4kHz is required to reliably capture high frequency content of pacing pulses and display pacing pulses precisely using high bandwidth ECG monitors [3]. Such ECG monitors that are designed to capture surface ECG and pacemaker pulses are mostly used in a stationary bedside condition (tethered to hospital bed) for a very limited time duration.

On the other hand, Holter ECG recorders can be set to operate at high sampling frequency and allow collecting of surface multi–lead ECG and pacer pulse signals in ambulatory conditions at home for 24–48 hours. Holter monitors are typically used to record surface ECGs and analyzed offline using proprietary software tools to evaluate ECG morphological features and cardiac rhythms leading to clinical decision on the patient needing a pacemaker to restore regular cardiac rhythms. Holter recording in patients implanted with pacemaker can capture pacing pulses in addition to ECG signals when higher sampling frequency is available and used. However, Holter recorders present limitations including no real–time monitoring by physicians or cardiac technicians, added burden of returning of the Holter device for offline analysis, potentially extended waiting period to obtain the summary results, and often limited capabilities related to pacer detection and pacemaker diagnostic evaluation.

Such traditional bedside ECG monitors and Holter recorders are furthermore not suitable for continuous, long–term and real–time monitoring and management of pacemaker implanted patients in their free–living home conditions. Due to lack of unobtrusive convenient wearable ECG sensor device for long–term monitoring, the pacemaker implanted patients may not get periodic assessments on the functioning of the pacemaker or implanted cardiac assist device that may have delayed diagnosis of pacemaker's status and psychological implications including a perception to believe that the pacemaker device is functioning correctly. Thus, an unobtrusive wearable ECG monitor with real–time long–term continuous monitoring of pacemaker pulse recognition could be very valuable in assessing the functionality of implanted pacemaker and progression of treatment for cardiac conditions.

The long–term battery–powered wearable ECG sensor devices, to reduce processing and transmission power consumption, usually have a sampling frequency of less than 1000Hz, which is sufficient to capture predominant frequencies of interest corresponding to the ECG. But such

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low sample frequency in wearable ECG sensor device is insufficient to reliably acquire and display the pacemaker pulses in the order of μs to few ms as opposed to the high bandwidth ECG systems with a relatively higher sampling frequency of 75kHz [4], [5]. Thus, wearable low bandwidth ECG systems with low sampling frequency are inherently not designed to capture the pacemaker pulses and may sporadically capture one or more samples of the pacing pulses depending on the selection of operational settings of the implanted pacemaker.

In this article, a pacer detection method for low–bandwidth long term monitoring systems is proposed that utilizes surface Electrocardiogram (ECG) measured in implanted pacemaker patients to transform into a sensor output indicating presence or absence of pacer pulses at ECG sample level or cardiac cycle/beat level. This system overcomes the limitation of traditional ECG monitors for continuous unobtrusive ambulatory monitoring of pacemaker patients in their free–living conditions using a wearable ECG sensor device operating at a low sample frequency (for example, 125Hz).

II. MATERIALS AND METHODS

A. *Paced ECG database*

Automated detection of pacing pulses is necessary for the clinical assessment of proper functioning of the implanted pacemaker. The methods in the literature involve sophisticated analog detection circuitry for real–time pacing pulse detection or digital signal processing methods that rely on high sampling frequency [6]. Recently, to enable the development and testing of pacemaker pulse detection algorithms, open–access paced ECG database was provided [7]. The database contains 1404 paced ECG signals of 10–second duration recorded at high resolution of 128kHz to keep the pacing pulses intact. All ECG recordings are generated by arrhythmia simulator comprising a wide variety of sinus rhythms, supraventricular rhythms, and AV blocks. Furthermore 624 records in the database are corrupted by electromyographic (EMG) noise to mimic tremor movements, which is often the source of inaccurate pacing pulse detection. The pacing and recharge phases of the pacemaker pulses are generated to comprise a wide range of pulse amplitudes (~100μV to ~3mV), pulse durations (~100μs to ~2ms), and rising edge durations (10μs to 100μs). The pacing pulses are superimposed on the ECG recordings to simulate a wide variety of pacemaker modes and types such as fixed–rate or on–demand single chamber, dual chamber, and bi–ventricular pacing. This rich collection of paced ECG signals representing a wide range of clinical conditions is utilized in this paper to validate the proposed method.

B. *Pacemaker Pulse Recognition*

Unlike traditional ECG devices that utilize either special analog circuitry or high sampling frequency to detect pacemaker pulses in the continuous or digital domain [6], the proposed method utilizes simple analog processing followed by straightforward digital pacing pulse detection at low sampling frequency. In the proposed method, the analog surface ECG is processed to extract the energy of the pacing pulses using filters tuned to capture spectral content outside ECG frequencies of interest. Then the energy of pacing signal is scaled in time, sampled with the analog to digital converter (ADC) at a low sampling frequency (for example, 125Hz), and pacing pulses are detected from the digital signal. This process is explained in more detail as follows.

The analog ECG signal is first fed to the pacing filter to extract the energy of the pacing signals from the ECG. The pacing filter is an analog high or band pass filter, whose cut–off frequencies are outside the predominant spectral content of physiological ECG signal. The output of the pacing filter is compared against a threshold and fed to the monostable multivibrator, which generates a pulse of pre–defined duration when triggered based on the output of the comparator. Then, the output of the multivibrator is fed to an anti–aliasing filter and converted to digital streams using an ADC operating at low sampling frequency (for example, 125Hz). As a first step towards finding the location of pacemaker pulses, the digital streams are compared against threshold whose value is selected based on the sampling frequency. The output of the comparator is then fed to differentiator and compared to zero to obtain the location of pacing pulses. Thus, the presence or absence of pacemaker pulses and their corresponding locations is detected in the proposed method.

C. *Performance Validation*

The algorithm is validated by comparing the location of the pacing pulses reported by the algorithm against the manually annotated reference pulse locations provided in the database. The performance of the proposed algorithm is assessed in terms of sensitivity $\left(Se = \frac{TP}{TP+FN}\right)$, positive predictive value $\left(PPV = \frac{TP}{TP+FP}\right)$, and detection error rate $\left(Error = \frac{FP+FN}{TP+FP+FN}\right)$, where TP, FP, and FN are true positive, false negative and false positive of detection, respectively. The timing delay in correct detection is evaluated by calculating the mean difference (t_{me}) and mean absolute difference (t_{mae}) between the reference and the algorithm pulse locations.

III. RESULTS

Fig. 1 and Fig. 2 show an example of biventricular and/or atrial pacing in the absence and presence of EMG noise respectively. In both cases, the pulse amplitude and pulse duration are 3mV and 2.18ms, respectively. The spectrogram shows the distribution of the pacer frequency components

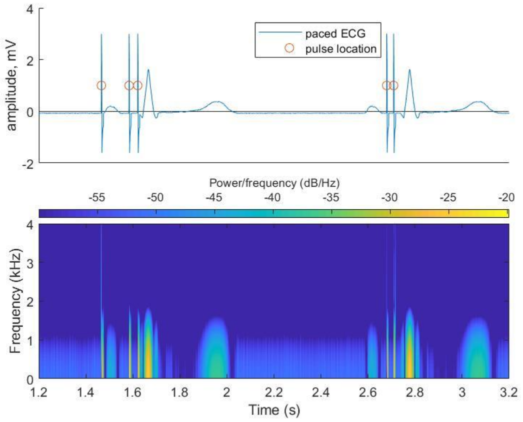

Figure 1. Example of pure paced ECG and spectral representation

TABLE I. PERFORMANCE OF PACEMAKER PULSE DETECTION IN PACED ECG DATABASE

Data	Sampling frequency (Hz)	Sensitivity	PPV	Error (%)	t_{me} (ms)	t_{mae} (ms)
Pure (N=780)	125	98.1 ± 4.4	100 ± 0	1.9 ± 4.4	-5.1 ± 1.9	5.4 ± 1.9
	250	98.9 ± 3.1	100 ± 0	1.1 ± 3.1	0.8 ± 2.0	1.8 ± 1.2
Tremor (N=624)	125	98.9 ± 3.7	97.5 ± 6.7	3.6 ± 7.2	-5.0 ± 1.9	5.2 ± 1.7
	250	99.5 ± 2.7	97.5 ± 6.7	3.0 ± 7.0	0.9 ± 1.9	1.9 ± 1.3

across different spectral bands that are utilized for pacemaker pulse detection.

While the spectral components of the pacemaker pulses are well delineated in the absence of motion as in Fig. 1, EMG noise overlaps significantly with the pacer frequencies in Fig. 2, thereby providing a diverse dataset for testing the accuracy of the proposed algorithm in real conditions.

Fig. 3 demonstrates the performance of the proposed pacing pulse detection algorithm for different pacemaker types, modes, and clinical conditions. The top panel of Fig. 3 shows atrial flutter rhythm where the pacing pulses precede QRS complexes whenever RR interval is prolonged. The pacing pulses simulate ventricular pacing on–demand with pulse amplitude and duration of 0.4mV and 0.977ms, respectively. The middle panel shows sinus rhythm with ventricular extrasystoles where ventricular pacing (pulse amplitude and duration of 3mV and 0.43ms, respectively) precedes normal beat after sensing atrial activity (VDD mode). The bottom panel of Fig. 3 shows sinus rhythm with bundle branch block and EMG noise. Fixed–rate pacing precedes each P wave and QRS complex with pacing amplitude and duration of 0.4mV and 2.18ms, respectively. The pacing pulses of different pulse amplitudes, durations, pacemaker type, and mode in Fig. 3 are accurately detected by the proposed algorithm even when pulses are not clearly visible during EMG noise.

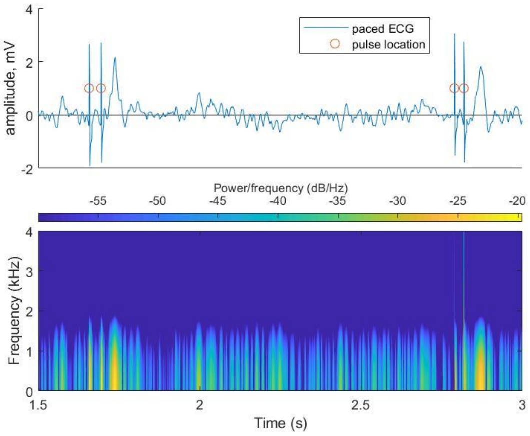

Figure 2. Example of paced ECG with tremor and spectral representation.

In Table I, the performance of the proposed pacemaker pulse detection method is summarized. At a sampling frequency of 125 Hz, the proposed algorithm has high detection sensitivity and PPV of 98.1 ± 4.4% and 100% respectively. Both t_{me} and t_{mae} are within 1–sample resolution of 8ms. Analysis of the failures show that false negatives occur predominantly in the records with simulated biventricular pacing when the separation between two pulses is as low as 14.7ms. To detect these pulses, the sampling frequency needs to be increased beyond 125Hz. For instance, when the sampling frequency is increased to 250Hz, the percentage of mean error reduces from 1.9 to 1.1%. Finally, in the presence of EMG noise (tremor), the proposed method has a high PPV without compromising sensitivity of detection.

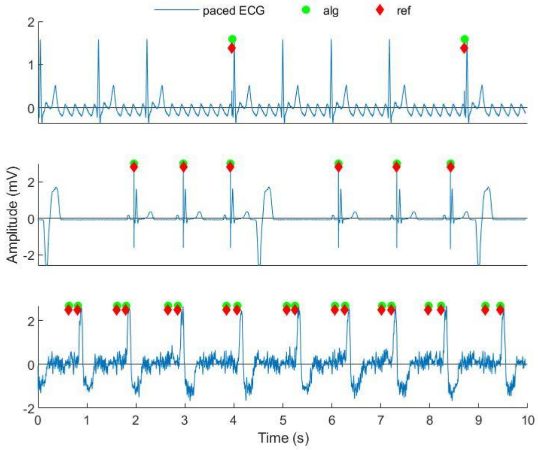

Figure 3. Illustration of algorithm (alg) detection performance compared to reference (ref). Top panel: On–demand ventricular pacing during atrial flutter. Middle panel: Sinus rhythm with ventricular extrasystoles and ventricular pacing before each normal beat in VDD mode. Bottom panel: Sinus rhythm with bundle branch block and fixed–rate dual chamber pacing during EMG noise.

IV. DISCUSSION

Accurate assessment of pacemaker function or malfunction is essential to make clinical interpretations on pacemaker therapy and patient symptoms. In this paper, the feasibility of accurate pacer detection that overcomes the limitations of the traditional ECG monitors is demonstrated. Accurate pacer detection enables clinicians to monitor pacemaker patients in ambulatory and free–living conditions, and to determine the functional characterization of the pacemaker including pacer mode, pacer rate, pacer timing, pacing incidence, effective and ineffective pacing or pacer malfunction. Such system is well suited for the evaluation of the functioning of pacemaker device in long–term continuous monitoring settings.

In traditional ECG monitors with high sample frequency in the order of several kHz, the entire pacemaker pulses along with ECG can be captured by ADC and the digital output signal can comprise of ECG signal and the concurrent incidences of pacemaker pulses intact. Continuous transmission of this high bandwidth data is not practically feasible due to extremely high power consumption [8]. On the other hand, low bandwidth wearable ECG sensor devices are not capable of capturing entire pacemaker pulses, but using the proposed method, such sensors can identify the location of pacing pulses and provide pacer detection output markers. It is to be noted that the proposed system is not intended to replace existing standard–of–care patient monitoring practices in hospitals which may require intact display of pacemaker pulses, but act as a secondary, adjunct remote patient monitor for continuous long–term assessment of pacemaker function especially in free–living conditions.

Traditional management of patients with implanted pacemakers involve clinical follow–up every 3 to 12 months to assess device functioning [9]. Remote monitoring of pacemaker function using a long–term battery–powered wearable system provides continual surveillance post–discharge, enables early diagnosis of device failure, and reduces the burden on pacing centers [10].

In summary, the present study proposes a novel algorithm for detection of pacemaker pulses at low sampling rates. The performance of the proposed algorithm demonstrates acceptable accuracy with sensitivity and PPV of 98.1 ± 4.4% and 100% respectively in the paced ECG database. Thus, the proposed algorithm can be a useful diagnostic aid for assessment of the functioning of implanted pacemaker and enhance care in the cardiac population group.

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