Ectopic Beat Detection from Wrist Optical Signals for Sinus Rhythm and Atrial Fibrillation Subjects

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Abstract. Ectopic beats are abnormal cardiac beats originating from a location different than the sino-atrial node and therefore not being controlled by the autonomous nervous system. Thus, correct heart rate variability analysis inevitably requires accurate ectopic beat detection. Furthermore, an accurate ectopic beat detection is crucial to differentiate irregular cardiac rhythm due to different types of pathological arrhythmias from those caused by isolated ectopic beats. In this paper, we present an algorithm for ectopic beat detection based on wrist plethysmographic (PPG) signals. The proposed algorithm relies on analyzing the inter-beat patterns while considering the heart-rhythm condition; whether sinus rhythm (SR) or atrial fibrillation (AF). We monitor 29 patients recovering from surgery in the post-anesthesia care unit. During the recordings, 15 patients had SR and 14 patients had AF. The proposed ectopic beat detection algorithm achieves a sensitivity of $93.08 \pm 3.83\%$ and a specificity of $97.80 \pm 2.12\%$.

Keywords: photoplethysmography, ectopic beat detection, heart rate variability, atrial fibrillation

1 Introduction

Periodic impulses from the sino-atrial node cause the contraction and the relaxation of the heart muscle. When these impulses are incurred in unusual/abnormal locations, they result in disturbed and irregular beats, known as arrhythmias. The arrhythmias can consist in isolated irregular beats (generally known as ectopic beats), or pathological conditions such as atrial fibrillation (AF) or atrial flutter (AFl). While the ectopic beats are frequently encountered and do not present a significant health threat, AF or AFl can increase the risk of morbidity or mortality. One way to detect AF is based on inter-beat interval (IBI) variability [1, 2]. In such cases, ectopic beats can increase the IBI dispersion, possibly

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causing false alerts. Similarly, ectopic beats could affect other heart rate variability (HRV) analysis applications, such as stress or sleep monitoring. Thus, detecting ectopic beats is of vast importance for algorithms analyzing HRV or extracting various HRV parameters to study cardiac rhythm disturbances or arrhythmias.

Algorithms to detect and correct ectopic beats can be based on analyzing the variation of the instantaneous heart rate [3] or extracting morphological and rhythmical features of the ECG signal [4]. Different methods of ectopic beat detection, such as time and morphological methods, morphological transformation approach, wavelet transform, and their impact on HRV signal parameters are reviewed in [5].

In this paper, we tackle a slightly more challenging problem, which is to detect ectopic beats using photoplethysmography (PPG). PPG presents a simple and efficient alternative method to ECG to estimate heart rate (HR) and HRV [6]. It is a non-invasive technology that utilizes a light source and a photodetector to illuminate the skin and study the amplitude of the transmitted/reflected light to measure the volumetric variations of blood circulation, which, in turn, represents the pumping actions of the heart. This means that we can accurately estimate HR [7,8] and, in the absence of motion, IBI from PPG signals [9,10].

Ectopic beat detection from PPG signals has not been extensively studied, but there is an increasing interest in this domain especially in context of arrhythmia detection techniques. The proposed arrhythmia detection methods investigate the possibility of extracting IBI from PPG signals, usually finger or wrist-based, and taking the decision based on IBI series statistics [1,2].

This paper evaluates an ectopic beat detection algorithm. The algorithm is based on processing IBI extracted from wrist PPG signals. As PPG signals are highly sensitive to motion, varying ambient light, or other interferences, and IBI estimation is not reliable in such situations [11], a method to automatically screen out poor quality data is included as part of the method.

The paper is organized as follows. In Section 2, we describe the materials and the methodology used by the study. Section 3 presents the contribution of this work. It describes the proposed algorithm to detect ectopic beats in both sinus rhythm (SR) and atrial fibrillation subjects. The performance of the proposed ectopic beat detection scheme is evaluated in Section 4. Finally, Section 5 concludes the paper.

2 Study Protocol and Materials

The study involves 29 subjects in the post-anesthesia care unit of Tampere University Hospital, immediately after surgery and prior to completely recovering from the anesthetics effects; 15 subjects (7 females, 67.5 ± 10.7 years old) belong to the SR group with normal continuous sinus rhythm and 14 subjects (8 females, 74.8 ± 8.3 years old) belong to the AF group with continuous AF rhythm. The subjects were lying in bed with their hands free to move during the whole duration of the recording. Each recording lasts approximately 1 hour and 30 minutes. In total, 23.52 hours of data is collected from the SR group and 21.96 hours of data from the AF group. The IBI values used by the proposed ectopic beat detection algorithm are extracted from the PPG recordings.

The wrist PPG signal and the 3D acceleration vector (Acc) data were recorded using the PulseOn Optical Heart Rate monitor (PulseOn Oy, www.pulseon.fi). The reference ECG signal is simultaneously recorded with GE Carescape™ B850 patient monitor (GE Healthcare Ltd., www.gehealthcare.com). Kubios HRV software (Kubios Ltd., www.kubios.com) is used to obtain the RR intervals (RRI) from the reference ECG signal. Finally, both the ECG signal and the corresponding RR intervals are visually inspected to construct the reference ectopic beats of the 29 recordings performed.

The study is registered at clinicaltrials.gov (NCT03081793). The study protocol, the devices used, and the documentation are all approved by the local ethical review board of Pirkanmaa Hospital District(ETL R17024), the Finnish National Supervisory Authority of Health and Welfare (Valvira), and the hospital technical department. The subjects provide a written consent to participate in this study and have the full right to withdraw from the study at any time. The experimental procedures comply with the principles of the Helsinki Declaration of 1975, as revised in 2000 and 2008.

3 Algorithm Description

In this section, we present the contribution of this paper and explain the proposed ectopic beat detection algorithm with arrhythmia feedback. To highlight the significance of the arrhythmia feedback, we first present ectopic beat detection without feedback (illustrated in Fig. 1). The algorithms used for the sub-blocks ***IBI Extraction***, ***IBI Evaluation***, and ***Arrhythmia Detection***, depicted in Fig. 1 and Fig. 3, are presented in [1, 2, 12].

3.1 Ectopic Beat Detection without Arrhythmia Feedback

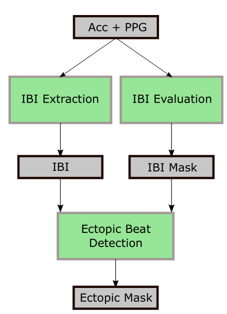

Fig. 1. Ectopic beat detection block diagram

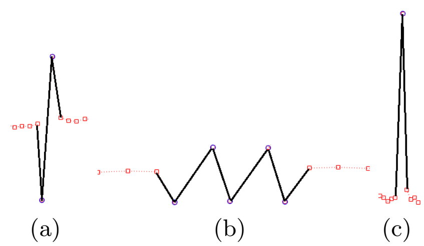

Fig. 2. Examples of ectopic beats (marked in blue circles)

The algorithm runs in real-time and its block scheme is presented in Fig. 1. The input signals are PPG and accelerometer data Acc. The main processing sub-blocks are:

– ***IBI Extraction***: estimates the IBI from the raw PPG signals.
– ***IBI Evaluation***: evaluates the reliability of the estimated IBI based on both PPG and Acc signals. It indicates whether the IBI is reliable (mask = 0) or not (mask = 1).
– ***Ectopic Beat Detection***: inspects the variation of the *extracted* IBI values that are marked as *reliable* and compares them with the characteristic patterns of ectopic beats (possible examples of IBI patterns corresponding to ectopic beats are shown in Fig. 2). Based on the similarity between the morphology of the received IBI sequences and the ectopic patterns, it labels the input beats as ectopic or not. In other words, if the IBI beat pattern satisfies certain *morphological conditions*, then the corresponding beats are marked as ectopic. These *conditions* are dynamically modified based on the input IBI values, however, they are independent of the IBI rhythm classification.

The drawback of the described algorithm reveals itself in the compromise it has to make between the *sensitivity* and the *specificity* (as defined in eq. (1)). In other words, to detect more ectopic beats (high sensitivity), the *morphological conditions* should be more relaxed, which results in increased number of falsely detected ectopic beats (low specificity) especially for AF patients. On the other hand, to reduce the number of falsely detected ectopic beats (high specificity), these *conditions* should be more conservative, which reduces the number of detected ectopic beats (low sensitivity) especially for SR patients. Here we choose to reduce the sensitivity to maintain high specificity for AF patients. Equivalently, we choose conservative *conditioning* to reduce the number of falsely detected ectopic beats.

3.2 Ectopic Beat Detection with Arrhythmia Feedback

To resolve the drawback of the algorithm presented in Section 3.1, we propose a feedback loop scheme between the ***Ectopic Beat Detection*** sub-block and the ***Arrhythmia Detection*** sub-block (see Fig. 3):

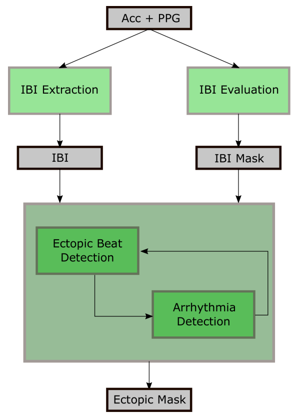

Fig. 3. Feedback loop scheme between ectopic beat detection block and arrhythmia detection block

– ***Arrhythmia Detection***: processes the input IBI values and their corresponding reliability masks to label them as SR or AF using the Markov model approach, similar to the work of Moody and Mark [13].
– ***Ectopic Beat Detection***: operates in a similar fashion as the one without arrhythmia feedback, however, it utilizes the SR/AF labels from the ***Arrhythmia Detection*** sub-block to tune the strictness of the *morphological conditioning* used to label the input beats.

To highlight the significance of the proposed method, consider the scenarios depicted in Fig. 4 and Fig. 5. Both figures show IBI signals of similar morphology, however, one IBI signal contains ectopic beats (SR case), while the other contains non-ectopic AF beats (AF case). The proposed algorithm successfully discriminates between the two by strictly analyzing PPG and Acc signals. We show the ECG reference plot corresponding to each signal; the disturbance in the cardiac rhythm shown in Fig. 4 is due to the presence of ventricular ectopic beats, while that shown in Fig. 5 is due to atrial fibrillation.

Other than the improved ectopic beat detection due to the arrhythmia feedback, the proposed scheme also presents an additional advantage in the feedback going from the ***Ectopic Beat Detection*** sub-block to the ***Arrhythmia Detection*** sub-block. Note that the performance of the feedback loop scheme depends on both ***Ectopic Beat Detection*** and on ***Arrhythmia Detection*** sub-blocks: *the ectopic beat detection algorithm is accurate if and only if the arrhythmia detection algorithm is accurate.*

4 Performance

We evaluate the performance of the proposed ectopic beat detection algorithm with arrhythmia feedback using the metrics given in Section 4.1. The results are presented and discussed in Section 4.2.

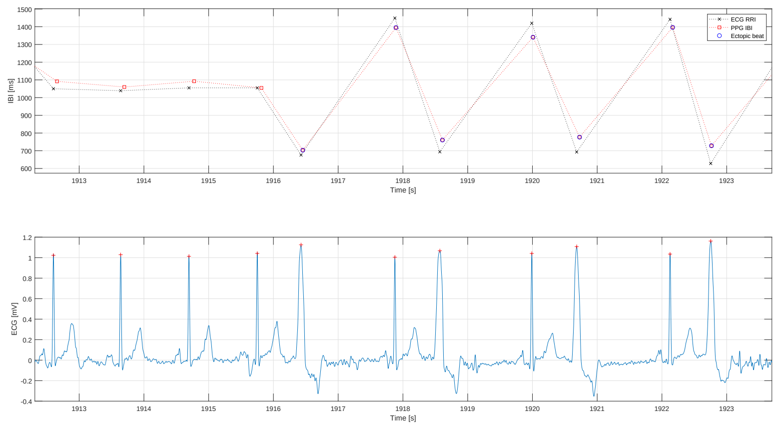

Fig. 4. Example of ectopic beats during sinus rhythm correctly detected by the algorithm with arrhythmia feedback.

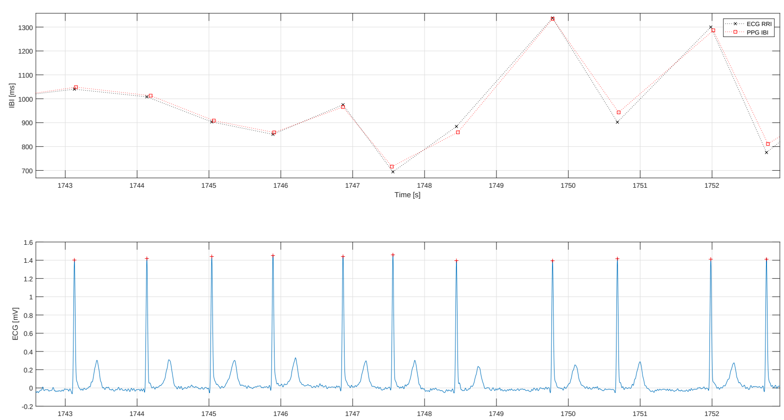

Fig. 5. Example of AF beats correctly not marked as ectopic by the algorithm with arrhythmia feedback.

4.1 Evaluation Metrics

The RR intervals from the ECG signal are labeled as ectopic or not based on close visual inspection of the ECG signal. These labels constitute the reference ectopic beats used to evaluate the performance of the ectopic beat detection algorithms applied to the PPG signal.

The two metrics used to evaluate the performance of these algorithms are the sensitivity and the specificity, defined as,

$$\begin{aligned} \mathbf{Se} &= 100 \times \frac{\mathbf{TP}}{\mathbf{TP}+\mathbf{FN}} \\ \mathbf{Sp} &= 100 \times \frac{\mathbf{TN}}{\mathbf{TN}+\mathbf{FP}}, \end{aligned} \tag{1}$$

where **TP**, **FN**, **TN**, and **FP** denote 'True Positive,' 'False Negative,' 'True Negative,' and 'False Positive,' respectively.

4.2 Results and Discussion

In this section, we discuss the performance of the algorithm with arrhythmia feedback and compare it with that of the algorithm without arrhythmia feedback. For comparison, we also implement the ectopic beat detection algorithm presented by Matteo et al. in [3]. In their work, they propose a method to detect anomalous beat positions based on the variation of the instantaneous heart rate.

	Method from [3]	**Proposed method**	
		Without feedback	**With feedback**
Sensitivity (%)	99.86 ± 0.12	78.83 ± 13.10	93.08 ± 3.83
Specificity (%)	82.08 ± 12.38	99.18 ± 0.70	97.80 ± 2.12

Table 1. Ectopic beat detection results

From the results shown in Table 1, one could see that the method proposed in [3] detects ectopic beats with 99.86% sensitivity. However, the shortcoming of this method is that it has low specificity (82.08%), because it only targets SR data and cannot differentiate AF beats from ectopic beats. Consequently, its specificity is low for AF data sets (64.48%) and high for SR data sets (98.20%). Thus, this method accurately detects ectopic beats for SR data sets only. On the other hand, the ectopic beat detection algorithm without arrhythmia feedback detects ectopic beats with 99.18% specificity, because of the conservative *conditioning* discussed in Section 3.1. However, it suffers from low sensitivity (78.83%). Indeed, to maintain a high specificity, this algorithm fails to detect ectopic beats efficiently for SR data sets. Finally, our proposed method of ectopic beat detection with arrhythmia feedback guarantees fairly high sensitivity 93.08% and high specificity 97.80%. In other words, it improves the specificity for AF data sets (compared to the method from [3]) without significantly decreasing the sensitivity.

5 Conclusion

This study evaluates the accuracy of an ectopic detection algorithm with arrhythmia feedback for sinus rhythm and atrial fibrillation subjects using wrist PPG and acceleration signals. The sensitivity of the proposed method is $93.08 \pm 3.83\%$ and the specificity $97.80 \pm 2.12\%$.

This work shows that the IBI patterns for both SR and AF subjects can very much look similar, however the causes of this variation/disturbance can be different. To efficiently differentiate between variations caused by ectopic beats and those caused by AF, it is crucial to implement a feedback loop scheme where the ectopic beat detection sub-block and the arrhythmia detection sub-block exchange information.

Finally, given that the proposed algorithm does not require ECG signals and solely relies on wrist optical and acceleration signals, it could be used as a comfortable and unobtrusive method to detect ectopic beats and utilized in HRV or AF detection applications.

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