Using Wearable Photoplethysmography for Detecting Atrial Fibrillation in Ambulatory Conditions

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Abstract

Atrial fibrillation is the most common sustained cardiac arrhythmia, and its occurrence will increase in the following decades due to aging of the population. As more resources will be needed to treat atrial fibrillation, more efficient detection methods than the current obtrusive 1–3-day Holter electrocardiogram are needed. A promising option is to use a photoplethysmography device worn on the wrist for an extended period to have an unobtrusive patient experience.

In this study, an optical method for atrial fibrillation detection is presented. Thirty patients suspected of having atrial fibrillation wore an optical device on their wrist for up to 48 hours. Proprietary algorithms were used to detect atrial fibrillation from the recorded photoplethysmography data. This method was then compared to the gold standard electrocardiogram recorded at the same time. Post-processing was done in 5-minute and 1-minute segments. A 97.9% accuracy, 94.1% sensitivity, and 98.1% specificity in detecting atrial fibrillation were obtained for the 5-minute segment length with 39.3% of the segments marked as undetermined and discarded from the analysis. The results show that the performance of wrist photoplethysmography is adequate for the screening of atrial fibrillation in ambulatory conditions.

1. Introduction

Atrial fibrillation (AF) is an arrhythmia during which the atria of the heart do not contract in organized manner causing irregular ventricular rhythm. It is the most common diagnosed sustained arrhythmia and if untreated, promotes atrial thrombosis, which may lead to embolic ischemic stroke. Common symptoms of AF include general fatigue, dizziness, shortness of breath, rapid heartbeats, and fluttering feeling in the chest, but AF may also be asymptomatic [1]. Especially, identifying the patients with subclinical silent AF is a challenge [2].

The prevalence of AF increases with age. As the population grows older, more and more resources will have to be reserved to AF detection and treatment. The European Society of Cardiology (ESC) estimates that 37% of individuals with European ancestry have a lifetime risk for AF [1]. Thus, it becomes imperative to have a detection system in place that is both economically feasible and easy to use for the patient and medical professionals alike. [3]

AF can be distinguished from a normal sinus rhythm (SR) by its irregularly irregular heartbeat rhythm [1]. Reliable heartbeat information can be compared using different techniques to label even short episodes as AF or SR. Many of these techniques operate on beat-to-beat information such as heart rate variability (HRV) or inter-beat intervals (IBI) [3,4].

Currently AF is diagnosed with an electrocardiogram (ECG) measurement [1]. However, conducting a relatively obtrusive ECG measurement for multiple days, typically with Holter monitoring, is cumbersome for the patient. Also, its analysis is time-consuming for the care provider.

Many patients suffering from AF do not experience it constantly. If the AF episodes only happen periodically and stop within 7 days without treatment, the AF is considered paroxysmal. As such, long-term monitoring solutions that can catch short AF episodes will be important in the long run. [5]

In the past decades, fitness devices and smart watches have renewed interest as an alternative method for monitoring the heart with the widespread use of reflective photoplethysmography (PPG) [3]. Instead of measuring the electrical activity originating from the heart, like in ECG, reflective PPG measures the changes in blood volume near the skin surface. [6]

While transmissive PPG is in use in medical care for the measurement of the heart rhythm and pulse oximetry, reflective PPG has been used much less in medical technology. With new advancements in miniaturization, battery technologies, signal processing and machine learning, reflective PPG becomes a valid option in gathering cardiovascular information in an unobtrusive, low effort manner. [3,8,9]

In PPG, a light is used to illuminate microvascular tissue and the absorption of light by the tissue is then measured

using a photodetector. This absorption changes along with the blood volume during the contraction and relaxation phases of the heart. Detecting the pulse wave maxima and minima enables the calculation of cardiovascular information such as the IBIs. [3–7]

While cheap and unintrusive, PPG has some inherent flaws. Measuring small changes in blood volume makes PPG very susceptible to artefacts caused by movement. Any movement of the tissue or the device will weaken signal quality and cause issues with further signal processing. [3]

Another flaw is that PPG measures different cardiovascular metrics than ECG [10]. Firstly, as PPG does not record the electric activity of the heart, no P-wave can be seen, and the analysis of the P-wave is often used to determine whether someone has AF [1,4,6,10]. Secondly, due to the imperfect filling of ventricles in AF, the pressure wave caused by the heart is weaker [3]. Both flaws can be overcome by good signal processing methods, such as algorithms for motion handling and for beat detection respectively [3].

Public datasets and previous studies on arrhythmia detection with PPG in an ambulatory environment are few. In their study 2018, Bonomi et al. concluded that a PPG device can accurately discern between AF and SR [11]. The present study aims to verify the conclusion of Bonomi et al. using the same general data processing flow but a different dataset, PPG device and analysis algorithms.

Bonomi et al. used 1-minute-long segments for the comparison of the PPG and ECG data [11]. However, other segment lengths have also been used in literature. For example, Saarinen et al. [5] and Chang et al. [12] used a 5-minute-long segment. A secondary aim for this study is to compare the performance metrics between these two segment lengths.

2. Methods

2.1. Data collection

Thirty-one patients were recruited for the purpose of collecting PPG and ECG data under normal daily conditions outside of the hospital. The patients were recruited from those referred for therapeutic evaluation of AF at the Tampere Heart Hospital, Wellbeing Services County of Pirkanmaa, Tampere, Finland.

The patients were asked to participate based on the criteria of having a history of paroxysmal AF and being over the age of 18.

The patients were instructed to wear a non-invasive PPG device (Aino1 prototype device, PulseOn Oy) on their wrist and a 5-lead ECG device (Faros 360 ECG, Bittium Biosignals) on their torso. The patients were measured with both devices for approximately 48 hours after which they returned the devices to the hospital personally or by mail.

2.2. Data analysis

The PulseOn wrist device has IBI calculations and AF detection built in. In this study it was necessary to process the collected raw PPG and acceleration data again as the proprietary algorithms have been further developed since the data collection period. For offline data analysis and signal processing, Matlab 2022b and Python 3.10 were used.

IBI information is calculated from the PPG signal. Each recognized heartbeat interval is labeled as either reliable or unreliable utilizing also the data of an on-board accelerometer and the morphology of the PPG signal. If the acceleration norm deviates significantly from 1 g or the morphology of the PPG wave does not match the expected shape, the beat is considered unreliable as to avoid erroneous IBIs. Each beat is additionally marked as having AF or SR based on the PulseOn online algorithm.

In the analysis done for the current paper, the PPG-based IBI series was then split into 5-minute-long segments. Each segment was analyzed for enough reliable beats marked as AF. If found, the segment was marked as containing AF. If not, the same evaluation was done for SR. In case neither was true, the segment was labeled as undetermined due to too many unreliable beats.

A reference IBI series was created from the ECG signal using the Kubios software (Kubios Oy). The raw ECG signal was inspected and marked unreliable if artifacts affected the beat detection algorithm.

The ECG data was analyzed for arrhythmias by a telehealth company (MDT-Medical Data Transfer) with emphasis on labeling AF periods. The AF periods were then marked in the ECG IBI series.

The ECG IBI series was synchronized with the 5-minute segments of the PPG-based IBI series. This was done by starting with the timestamps of the IBI series and then sliding the windows within tolerance until the error between the two IBI series was minimized.

The PPG-based segments were then compared to the ECG-based reference segments and used for statistical calculations. The process was repeated for 1-minute segments.

2.3. Ethical considerations

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Tampere University Hospital (R17175).

Each patient was asked to give an informed consent to participate to the study and for the usage of their PPG, ECG, and movement data for the purpose of this study.

3. Results

Out of the 31 recruited patients, 30 completed the measurement session. One patient had to drop out due to technical issues with the study devices.

Out of the 30 patients who completed the study period, 15 were male. The patients' ages ranged between 21 and 83 years with an average age of 59.

The annotating doctor diagnosed 10 patients as having paroxysmal AF, 10 as having a normal SR, and 10 as having other arrhythmias such as first-degree atrioventricular block, irregular sinus node activity or frequent supraventricular ectopy.

In total 1193 hours of PPG data with an ECG reference was collected averaging approximately 40 hours per patient.

3.1. 5-minute segments

Dividing the PPG data in 5-minute segments resulted in a total of 13972 segments. Out of these, 8481 (60.7%) could be labeled as either AF or SR with the rest being labeled as undetermined.

Ignoring the undetermined data, the labeled PPG-based segments were then compared to the ECG-based segments resulting in 97.9% accuracy, 94.1% sensitivity, and 98.1% specificity as summarized in Table 1.

Table 1. Confusion matrix when using 5-minute segments displaying accuracy, sensitivity, and specificity.

	AF	SR	
True	523	7778	Accuracy: 97.9%
False	147	33	
	Sensitivity: 94.1%	Specificity: 98.1%	

Of the 147 false AF labels, 91 (61.9%) were in measurements of patients with paroxysmal AF. 34 (23.2%) false labels were in measurements of patients with other arrhythmias. 22 (15.0%) false labels were in measurements of patients that had SR throughout the duration of the measurement.

All 33 segments labeled falsely as SR were in measurements of patients with paroxysmal AF who also had segments with true AF labels.

3.2. 1-minute segments

Using a segment length of one minute, 69931 segments were obtained. Out of these segments, 33632 (48.1%) could be labeled as AF or SR with the rest being labeled as undetermined.

However, the performance metrics of the labeled segments improved to 98.8% accuracy, 95.5% sensitivity, and 99.0% specificity as summarized in Table 2.

Table 2. Confusion matrix when using 1-minute segments displaying accuracy, sensitivity, and specificity.

	AF	SR	
True	2141	31073	Accuracy: 98.8%
False	317	101	
	Sensitivity: 95.5%	Specificity: 99.0%	

Of the 317 false AF labels, 208 (65.6%) were in measurements of patients with paroxysmal AF, 70 (22.1%) false labels in measurements of patients with other arrhythmias and 39 (12.3%) false labels were in measurements of patients that had SR only.

Like with 5-minute segments, all 101 segments labeled falsely as SR were in measurements of patients with paroxysmal AF who also had segments with true AF labels.

Table 3 summarizes key performance metrics and their differences between the 5-minute and 1-minute segment lengths.

Table 3. Comparison of the two different segment times and their performance metrics.

Segment length	5 minutes	1 minute
Accuracy	97.9%	98.8%
Sensitivity	94.1%	95.5%
Specificity	98.1%	99.0%
Segments of sufficient quality	60.7%	48.1%
False AF labels in patients without AF	38.2%	34.4%

4. Discussion

Thirty patients wore a PPG device on their wrist and a 5-lead ECG on their chest for up to 48 hours. The data resulted in 8481 5-minute-long segments or 33632 1-minute-long segments of suitable quality for rhythm analysis. The segments were analyzed for AF resulting in a sensitivity of 94.1% and specificity of 98.1% for 5-minute segments or 95.5% sensitivity and 99.0% specificity for 1-minute segments.

The study demonstrates that AF can be reliably detected using wrist-mounted PPG. However, the presence of other arrhythmias, such as irregular sinus node activity in this study, can result in false positives. False positives can lead to false diagnoses, additional work for the medical professionals and, if the patient is informed of the results, added stress. Currently, diagnosis of AF requires having ECG of at least 30 seconds with irregular rhythm and lack of P-waves. Further studies and development should be conducted to better distinguish AF from other types of arrhythmias.

Additionally, almost 40% and over 60% (for 5-minute and 1-minute segment lengths, respectively) of all collected data was labeled undetermined due to unreliable PPG signal and IBIs. Algorithms that robustly handle artifacts would result in a better signal yield. In this study motion artifact handling especially was very strict and could be improved. Further studies on different measurement device setups, beat detection algorithms and arrhythmia labeling algorithms would be needed to enhance the data quality ratio. This in turn could lead to even faster and more reliable AF detection.

A shorter segment length during the post-measurement data analysis resulted in clear enhancements in performance metrics, but also caused more data to be discarded as undetermined. Further studies would be needed to determine whether the data loss is worth the increase in performance.

For AF detection and diagnosis, it is imperative that no patient with even short periods of AF is labeled solely as SR because this can lead to a false diagnosis and wrong treatment. In this study every false SR flag was in the measurement of a patient that had also true AF labels. As such, every patient with AF in the reference ECG was correctly identified during the 48 hours. These results suggest that with a longer monitoring time even infrequent paroxysmal AF can be detected using a wrist-worn PPG device.

5. Conclusion

A wrist-worn PPG device made by PulseOn was used to monitor patients with history of AF in an ambulatory setting. It was found that the PPG device was adequate to reliably screen for paroxysmal AF during a measurement time of 48 hours in an ambulatory environment.

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Conflicts of interest

SYM and KN declare no conflict of interest. TH and AV are employees of PulseOn Ltd.

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