Towards Long-term Monitoring of Atrial Fibrillation using Photoplethysmography

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Abstract: This study investigates the feasibility of long-term monitoring of atrial fibrillation (AF) using wrist-worn device, capable of acquiring photoplethysmogram (PPG) and motion data. Moreover, the performance of AF detectors, initially developed to detect AF in electrocardiogram (ECG) signals, is evaluated on PPG. The study population consisted of 12 patients undergoing cardiac rehabilitation. Based on accelerometer data, 65% of recording time was considered as motion-free, which resulted in 86.8 hours of data with AF and 85.4 hours without. The performance of AF detectors was found to be comparable when both ECG and PPG are used for constructing heart rhythm series. Considering that 2/3 of monitoring time PPG was of satisfactory quality, the wrist-worn device has potential to be applied for long-term mass screening of target population.

1 INTRODUCTION

Atrial fibrillation (AF) is a widespread cardiovascular disease, affecting nearly 3% of adults aged >20 years (Haim et al., 2015). Although AF is not life-threatening itself, patients suffering from this condition are more often hospitalized, have an increased risk of stroke and heart failure (Kirchhof et al., 2016). AF is a progressive disease, with primary AF episodes being usually brief, thus timely detection is crucial in order to start the treatment, i.e., oral anticoagulation.

The majority of AF cases are still identified using a standard 12-lead electrocardiogram (ECG), which normally records ECG just for several seconds, thus only prolonged AF can be detected. Twenty-four hour Holter monitoring can be prescribed to detect self-terminating paroxysmal AF, however the adhesive electrodes and the device connecting wires are uncomfortable for many patients (Turakhia et al., 2013).

Emerging technologies for data acquisition provide a possibility to record physiological signals in a less obtrusive way. For example, it has been shown that photoplethysmogram (PPG) can be successfully applied for AF detection, employing the inbuilt camera of a smartphone (Lee et al., 2013). Several studies have been conducted to evaluate the suitability of this technique for mass AF screening (McManus et al., 2016; Chan et al., 2016). However, by using this approach, PPG is recorded for short period of time ($\sim$1 min). Hence, self-terminating AF events, occurring outside the monitoring period, i.e., during night, cannot be detected.

The aim of the present study is two-fold: (1) to investigate the feasibility of long-term monitoring using wrist-worn device, capable of acquiring PPG, and (2) to evaluate the performance of the algorithms, initially developed to detect AF in ECG, but transferred to PPG. To the best of our knowledge, this paper is among the first which addresses the question whether PPG-based detection performance is comparable to that obtained using ECG.

2 MATERIALS AND METHODS

2.1 Wrist-worn Device and Signals

The developed wrist-worn device is capable of synchronously acquiring PPG, motion data (3-axis acceleration), and ECG; the later unit is used to obtain reference signals (Fig. 1). ECG, PPG, and motion data are sampled at 500 Hz, 100 Hz, and 100 Hz, respectively. An example of synchronously recorded ECG

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and PPG signals during normal sinus rhythm and AF are shown in Fig. 2.

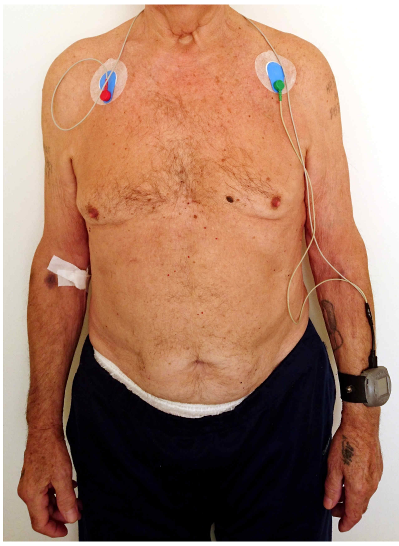

Figure 1: Wrist-worn device for acquiring PPG and motion data. The ECG leads serve for the purpose to obtain reference signals.

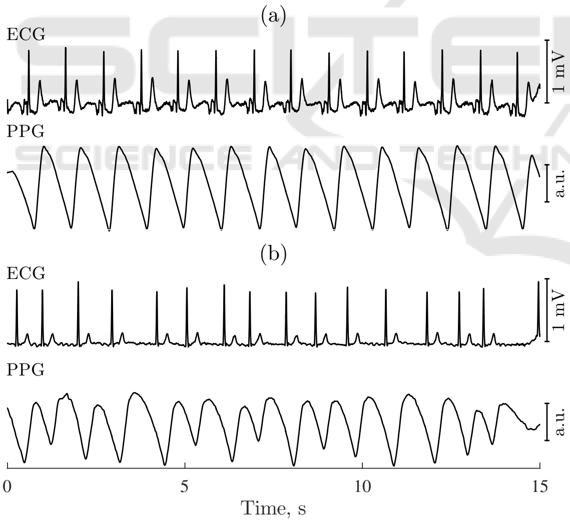

Figure 2: Example of synchronously recorded ECG and PPG signals during (a) sinus rhythm and (b) AF.

PPG quality is commonly unsatisfactory during arm motion, thus to properly compare AF detection performance using different signal sources, motion-free episodes should only be analysed. According to (Bouten et al., 1994; Karantonis et al., 2006), amplitude-integrated motion is defined by,

$$A = \frac{1}{T}\left(\int_T |a_x(t)|dt + \int_T |a_y(t)|dt + \int_T |a_z(t)|dt\right), \quad (1)$$

where T determines the integration interval, and a_x, a_y and a_z represent high-pass filtered accelerometer output from x, y and z directions, respectively. Motion corrupted episodes are excluded whenever A exceeds the fixed threshold η. The parameters T and η were determined empirically and set to 5 s and 0.12 g units, respectively. The time intervals between adjacent heart beats, required for AF detection, were extracted from motion-free ECG and PPG by finding peaks of the corresponding waves. The Shannon energy envelope was obtained from the normalized ECG (Liang et al., 1997; Manikandan and Soman, 2012), and the slope sum function was used to enhance the upslopes of the PPG pulses (Zong et al., 2016). Then, peaks were detected by applying the adaptive amplitude-dependent threshold. Since ECG represents electrical activity of the heart, whereas PPG reflects blood volume pulsation, rhythm information, extracted from these signals, may differ in some cases. To make this distinction, time series, obtained from ECG and PPG, are further referred to as *RR* and *PP*, respectively.

2.2 AF Detectors under Comparison

During AF, the ventricles are activated at irregular time instances, thus solely hearth rhythm information can be applied to detect AF. Four approaches to AF detection are chosen for comparison: Poincaré plot (Sarkar et al., 2008), the root mean square of successive differences (Dash et al., 2009), the coefficient of sample entropy (Lake and Moorman, 2011) and the simplified sample entropy (Petrėnas et al., 2015; Stankevičius et al., 2016). The former three algorithms have already been employed for PPG-based AF detection (Lee et al., 2013; McManus et al., 2016; Chan et al., 2016), whereas the later one is among the best performing.

- *Poincaré plot* based AF detector (the resulting output of this detector is denoted by $\mathcal{O}_P$) was developed for primary use in implantable devices (Hindricks et al., 2010). By using this approach, a sequence of RR intervals is collected and then represented in the Poincaré plot. Since each rhythm type takes a specific pattern, a set of rules is applied to determine which pattern is observed.

- *Root mean square of successive differences* ($\mathcal{O}_R$) is a straight-forward statistical approach used to evaluate variability of RR intervals. Rhythm variability is usually much higher in AF than that during regular rhythms, thus the parameter is expected to take higher values when arrhythmia occurs.

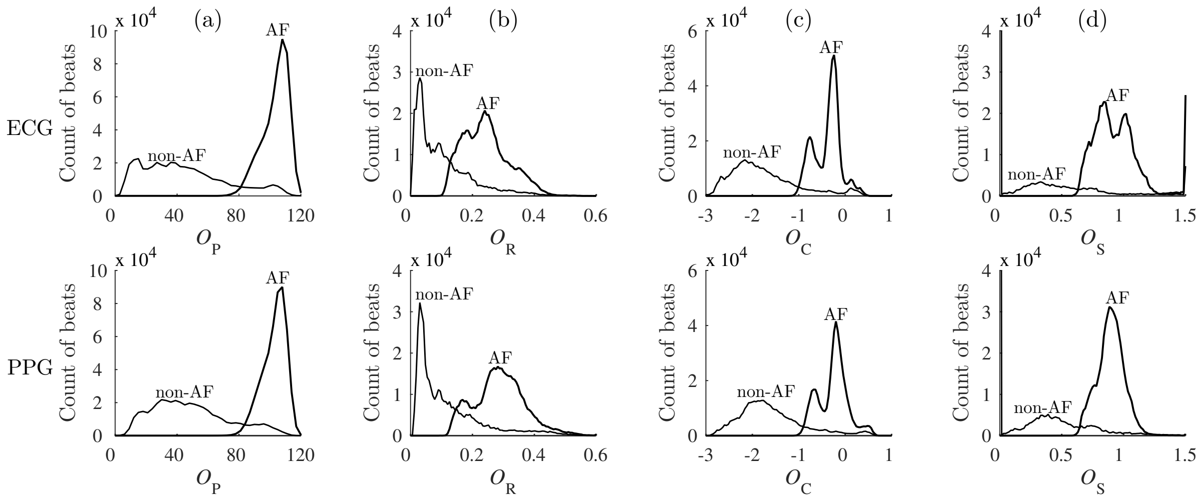

Figure 3: Distribution of output values of AF detectors during rhythms of non-AF and AF: (a) the Poincaré plot, (b) the root mean square of successive differences, (c) the coefficient of sample entropy, and (d) the simplified sample entropy.

- *Coefficient of sample entropy* ($\mathcal{O}_C$) was proposed in accordance to the growing interest in detection of AF in short physiological time series. The coefficient of sample entropy represents repeatability of RR pattern throughout the RR sequence, thus entropy increases when repeatability of RR series is low.
- *Simplified sample entropy* ($\mathcal{O}_S$) based AF detector is similar to the coefficient of sample entropy, however, such important aspects as suppression of ectopic beats and bigeminy are accounted. Hence, false alarm rate due to other irregular rhythms is reduced.

2.3 Study Population

Two groups of participants were involved at Kulautuva Rehabilitation Hospital of Kaunas Clinics, Lithuania. The first group consisted of 6 patients with AF, 71.8 $\pm$ 9.2 years old, with body-mass index 29.2 $\pm$ 3.6 kg/m^2, total monitoring time 127.5 hours (21.3 $\pm$ 2.6 hours per patient). The second group consisted of 6 patients without AF, 64.3 $\pm$ 9.4 years old, with body-mass index 30.5 $\pm$ 6.7 kg/m^2, total monitoring time 136.1 hours (22.7 $\pm$ 2.8 hours per patient). This study was approved by Kaunas Region Biomedical Research Ethics Committee (No. BE-2-20).

2.4 Performance Measures

The performance was investigated in terms of sensitivity (*Se*), specificity (*Sp*) and positive predictive value (*PPV*). Sensitivity is defined by the number of correctly detected AF beats divided by the total number of AF beats. Specificity is defined as the number of correctly detected non-AF beats divided by the total number of non-AF beats. Positive predictive value is the number of correctly detected AF beats divided by the total number of beats detected as AF.

3 RESULTS

3.1 Evaluation of AF Detectors

Motion-free data covered 65.4%$\pm$5.7% of recording time on average. This resulted in 86.8 hours of data with AF and 85.4 hours without AF.

Figure 3 displays the distribution of the output values of the detectors under investigation for AF and non-AF rhythms using *RR* and *PP* series as an input. The results suggest that incorrectly detected peaks in PPG increase irregularity in non-AF *PP* sequence, thus leading to slightly higher output values.

Table 1: Sensitivity, specificity and positive predictive value for different AF detectors, evaluated on ECG and PPG signal database. The results are obtained for the fixed detection window of 128 beats. The detection thresholds are set to the same values as used in the original studies.

Methods	**ECG**			**PPG**		
	***Se*, %**	***Sp*, %**	***PPV*, %**	***Se*, %**	***Sp*, %**	***PPV*, %**
$\mathcal{O}_P$	99.9	81.3	88.2	99.9	78.9	86.3
$\mathcal{O}_R$	100	64.3	79.6	100	66.2	79.6
$\mathcal{O}_C$	100	82.2	88.7	100	80.4	87.1
$\mathcal{O}_S$	99.4	89.9	93.2	99.9	91.5	94.0

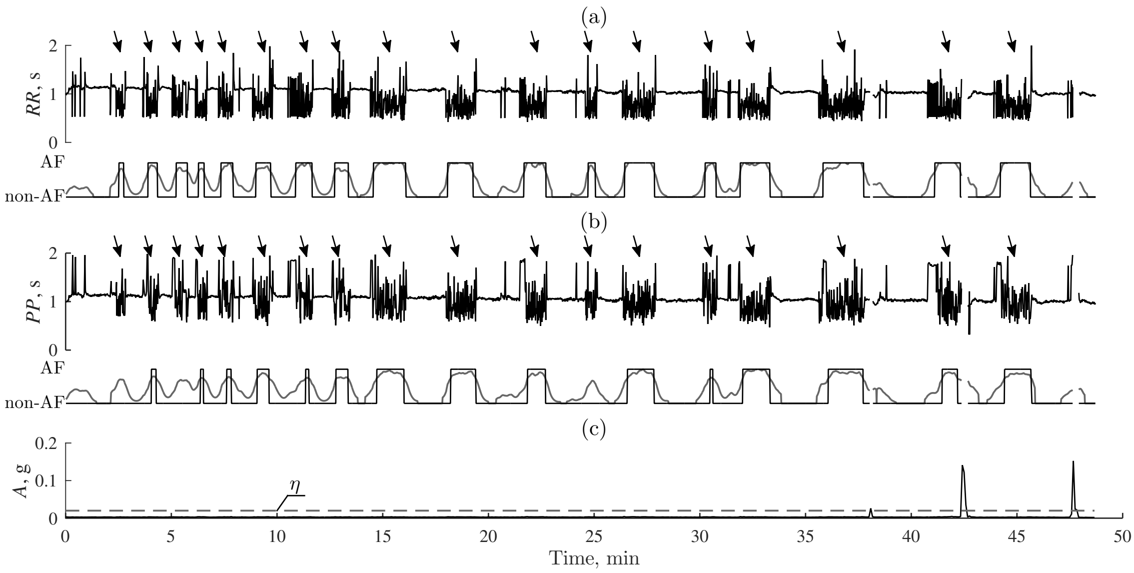

Figure 4: Example of self-terminating paroxysmal AF detection using (a) ECG and (b) PPG. AF episodes are marked with arrows. A grey line represents the output $\mathcal{O}_S$ of the simplified sample entropy. A black solid line stands for threshold based AF detection. The window length for this example was set to 8 beats. Motion corrupted data are rejected when amplitude-integrated motion A exceeds the threshold η (c).

Table 1 shows that AF detection performance is comparable when both ECG and PPG are used to construct rhythm series. Nevertheless, misdetected pulse peaks during non-AF resulted in approximately 2% lower specificity for $\mathcal{O}_P$ and $\mathcal{O}_C$. On the other hand, somehow surprisingly, specificity slightly increased for $\mathcal{O}_R$ and $\mathcal{O}_S$. This can be explained by the fact that ECG quality for one patient with non-AF was lower compared to synchronously recorded PPG. The best performance on PPG database is achieved by the simplified sample entropy based AF detector $\mathcal{O}_S$ with *Se*, *Sp*, and *PPV* of 99.9%, 91.5%, and 94.0%, respectively.

3.2 Paroxysmal AF Detection

Figure 4 displays the performance of the simplified sample entropy based detector on synchronously recorded ECG and PPG signals with recurrent self-terminating AF episodes. Even though *RR* and *PP* series are slightly different, it has only minor influence on AF detection. All AF episodes are detected when *RR* series is used as an input to the algorithm, whereas 15 out of 18 episodes are detected when *PP* series is applied instead. The shortest detected AF episode is of 38 beats (25 seconds).

4 DISCUSSION

To this day, no guidelines exist on arrhythmia interpretation on PPG, thus the presence of AF must be confirmed by analysing ECG (Kirchhof et al., 2016). However, unobtrusive PPG-based monitors can be valuable for mass screening of patients older than 65 years. Then, the diagnosis could be verified by using the established technique, such as 24-hour Holter monitoring.

This pilot study is a step towards evaluating AF diagnostic accuracy of PPG technology implemented into wearable device (Carpenter and Frontera, 2016). Our preliminary results show that AF detectors, developed for ECG analysis, can be successfully applied to motion-free PPG signals. Although, the pulse wave of PPG is much smoother than the QRS complex of ECG, an inaccurate detection of fiducial point has only slight effect on the overall performance of AF detectors.

Motion artefacts have large impact on distorting PPG shape, and often lead to incorrect beat detection. On the other hand, substantial changes in PPG morphology can be encountered during other types of arrhythmia, i.e., bigeminy (see Fig. 5). These morphological changes result in different heart rhythm compared to that obtained from the ECG. This limitation of the PPG-based technology could also be viewed as an opportunity to develop the PPG-specified AF detector.

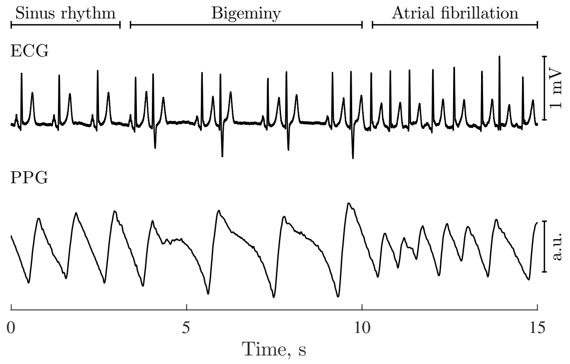

Figure 5: ECG and PPG during sinus rhythm, bigeminy and AF. Note, that only every second beat is reflected in the PPG during bigeminy.

The present study was performed on a population undergoing cardiac rehabilitation. Considering that older patients with cardiovascular condition are less physically active, this allowed us to obtain 2/3 of the total recording time suitable for analysis. Our findings are similar to those reported in another study, where about 36% of the monitoring time was rejected from analysis (Bonomi et al., 2016). Nevertheless, larger amounts of corrupted data could be expected when more active individuals are enrolled. Therefore, only proper dealing with motion artefacts could move this technology to home-based screening applications (Steinhubl et al., 2016).

Limitations of the present study are small number of patients and the homogeneity of the recordings. During monitoring, patients experienced either normal rhythm or AF, thus the performance of AF detectors was not investigated on recordings with paroxysmal AF.

5 CONCLUSIONS

This pilot study suggests that AF detectors, initially developed for analysis of ECG signals, can successfully be applied for the use of PPG signals. Considering that 2/3 of monitoring time PPG was of satisfactory quality, the wrist-worn device has potential to be applied for long-term mass screening of target population.

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