

# Detection of Pre- and Post-Trigger Atrial Fibrillation in Long-Term Photoplethysmogram Signals Acquired in Free-Living

Vilma Pluščiauskaitė<sup>1</sup>, Monika Butkuvienė<sup>1</sup>, Andrius Sološenko<sup>1</sup>, Karolina Jančiulevičiūtė<sup>1</sup>,  
Vaidotas Marozas<sup>1,2</sup>, Leif Sörnmo<sup>3</sup>, Andrius Petrėnas<sup>1,2</sup>

<sup>1</sup> Biomedical Engineering Institute, Kaunas University of Technology, Kaunas, Lithuania  
<sup>2</sup> Faculty of Electrical and Electronics Engineering, Kaunas University of Technology, Kaunas, Lithuania  
<sup>3</sup> Department of Biomedical Engineering, Lund University, Lund, Sweden

## Abstract

*Modifiable factors, such as alcohol or physical exertion, may trigger atrial fibrillation (AF) episodes. Identifying and eliminating these triggers can lead to effective strategies which reduce risk of AF recurrence. This study aims to evaluate pre- and post-trigger AF in long-term photoplethysmogram (PPG) signals obtained during daily living from patients with paroxysmal AF. Thirty-seven patients were instructed to wear a wrist-worn device for a week. They were also asked to log suspected triggers using a smartphone app. Of these patients, 15 experienced AF episodes, resulting in an average AF burden of 0.15.*

*The results indicate that longer post-trigger analysis time intervals resulted in better performance of PPG-based AF detection. The sensitivity was highest for the 16-h post-trigger interval (0.76) and lowest for the 4-h interval (0.43). In contrast, the specificity slightly decreased with an increasing longer post-trigger analysis time interval, being 0.98 and 0.95 for the 4-h and 16-h intervals, respectively. The PPG-based post-trigger AF burden was approximately half of that determined by the annotated ECG-based AF pattern. The study suggests that long-term PPG-based monitoring is a suitable alternative for detecting post-trigger AF instead of ECG-based. However, the accuracy of AF burden estimation using PPG-based technology still calls for improvement.*

## 1. Introduction

Growing evidence shows that specific acute exposures may trigger atrial fibrillation (AF) [1–6]. Few studies have compiled lists of suspected triggers by asking the study participants to complete a questionnaire [7–9]. Based on patient-reported lists, certain triggers, including, alcohol, physical exertion, and stress, can be modified, leading to behavioral interventions which in turn may be effective to reduce the risk of AF recurrence.

Presumably, approaches to identifying AF triggers should rely on the assumption that some parameter characterizing the post-trigger interval, such as AF burden or episode clustering, is altered compared to the pre-trigger interval. This reasoning is supported by findings showing that alcohol consumption increases the likelihood of an AF episode occurrence within the preceding 12 hours [4].

Currently, implantable devices and external electrocardiogram (ECG) recorders are the only tools for collecting AF patterns. However, implantable devices are costly and risky due to the implantation procedure [10], whereas even modern external ECG patches may be inconvenient for long-term monitoring due to adhesive electrodes [11]. Yet another alternative that still requires acceptance for use in clinical practice is photoplethysmography (PPG)-based monitoring. Despite that some smartwatch manufacturers, e.g., Apple, Huawei, and Samsung, offer AF detection, smartwatches do not search for AF continuously and therefore unsuitable for AF pattern analysis.

In a recent study, a PPG-based detector was developed to classify 5-min segments as AF, sinus rhythm, or undetermined in a free-living setting [12]. While one-third of the PPG segments were classified as undetermined, and thus omitted from further analysis, findings of study suggest that long-term PPG-based AF monitoring is a feasible alternative to conventional ECG-based monitoring. The present study builds upon the findings in [12] by exploring the possibility of evaluating pre- and post-trigger AF in long-term PPG signals acquired in daily life from patients with paroxysmal AF who were asked to enter suspected triggers using a smartphone app in daily living.

## 2. Methods and materials

### 2.1. PPG-based AF detection

Atrial fibrillation is detected using a wrist-worn device with the embedded algorithm that analyses peak-to-peak

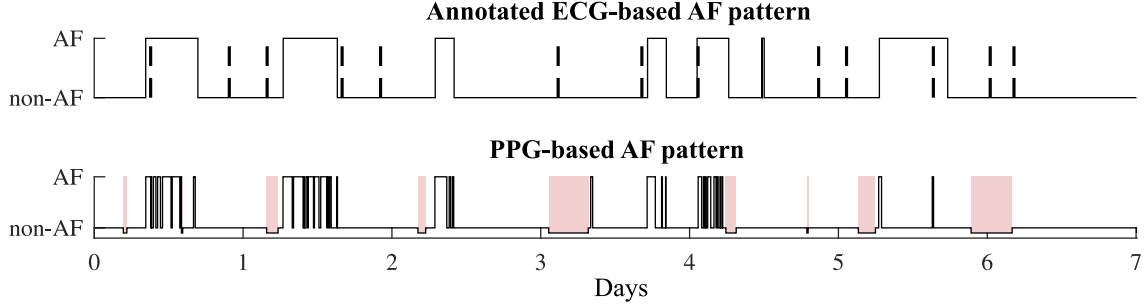


Figure 1. Example of an annotated ECG-based and a PPG-based AF patterns. Black dashed lines show suspected triggers logged by the patients. A red area indicates an interval of non-wear time when the wrist-worn device was not used. In the given example, low signal quality (is not displayed) and non-wear time account for 63% and 12.7% of the total observation period, respectively.

intervals in the PPG signal [13, 14]. To increase robustness against false alarms, the detector involves blocks of signal quality assessments, suppression of ectopic beats, bigeminy, and respiratory sinus arrhythmia. Irregularity of peak-to-peak intervals  $q_k$  is characterized by

$$T_k = \frac{2}{N(N-1)} \sum_{i=0}^{N-2} \sum_{j=i+1}^{N-1} H(|q_{k-i} - q_{k-j}| - \gamma), \quad (1)$$

where  $N$  is the number of peak-to-peak intervals,  $H(\cdot)$  is the Heaviside step function, and  $\gamma$  is the difference of peak-to-peak intervals in seconds.

The parameter  $T_k$  is then adjusted by heart rate:

$$I_k = \frac{\bar{T}_k}{\bar{q}_k}, \quad (2)$$

where  $\bar{T}_k$  and  $\bar{q}_k$  are smoothed versions of  $T_k$  and  $q_k$ , processed using second-order exponential averaging. The degree of smoothing is determined by the smoothing factor which is set to 0.02 as done in [13, 15].

The PPG quality is evaluated by comparing it to a template pulse at different time shifts. The first template pulse is a predefined pulse with a diastolic notch. The subsequent template pulse is derived from the previous pulse, but only if its quality is deemed acceptable. If the quality is unacceptable, the template pulse is reinitialized to the initial pulse. The correlation coefficient between the PPG pulse and the template pulse is computed, and, whenever the correlation coefficient exceeds 0.7, the PPG pulse quality is considered acceptable.

## 2.2. Database

Patients who had been diagnosed with paroxysmal AF and had received treatment at the Cardiology Department of Vilnius University Hospital Santaros Klinikos (Vilnius,

Lithuania) were asked to participate in a study. The patients were instructed to wear a wrist-worn device capable of acquiring continuous PPG signals and an eMotion Faros 180 (Bittium Corporation, Oulu, Finland) recorder used to acquire reference ECG for one week. Additionally, the patients were asked log suspected triggers using a smartphone app. The timestamps and types of suspected triggers were saved and synchronized with PPG and ECG signals. Cardiology residents manually annotated the ECGs for AF and consulted with a cardiologist in uncertain cases. The resulting database consists of 37 recordings with an average duration of 6.9 days, ranging from 0.8 to 8.2 days. Fifteen of the patients had paroxysmal AF episodes. Figure 1 displays the annotated ECG-based and PPG-based AF patterns along with the timestamps of the manually entered suspected triggers.

Before participating in the study, all eligible patients were required to sign a written informed consent in accordance with the principles outlined in the Declaration of Helsinki. The study was approved by the regional bioethics committee (No. 158200-18/7-1052-557).

## 2.3. Performance evaluation

Assuming that the post-trigger effect on AF occurrence varies depending on a trigger type and amount, analysis time intervals of 4, 8, 12, and 16 hours were chosen for investigation. The entire analysis time interval was considered to contain AF if it had at least one AF episode of  $\geq 30$  s. PPG-based detection performance is investigated in terms of sensitivity ( $Se$ ), specificity ( $Sp$ ), and Matthews correlation coefficient ( $Mcc$ ). Sensitivity involves the total number of AF cases correctly detected in the post-trigger interval, whereas specificity involves the total number of correctly identified non-AF cases. Matthews correlation coefficient, normalized to the interval  $[0, 1]$ , is chosen to provide overall performance given the substantial imbal-

ance of AF and non-AF cases [16].

### 3. Results

The average AF burden of the 15 patients with paroxysmal AF determined from annotated ECG-based AF patterns was 0.15, with a range of less than 0.001 to 0.68. Additionally, the average duration of AF episodes was 54.7 min, ranging from 30.2 sec to 115.3 hours. A total of 288 triggers were recorded by 37 patients, with 237 of them being logged while wearing a wrist-worn device, see Table 1.

Table 1. The number of suspected triggers logged.

Suspected trigger	Total number
Coffee	126
Lack of sleep	43
Physical exertion	38
Emotional stress	36
Alcohol	33
Cold food/drink	6
Overeating	6

Table 2 displays the performance measures for different post-trigger analysis time intervals. Overall, AF detection performance, as reflected by  $Mcc$ , tends to improve as the analysis time interval becomes increasingly longer.  $Se$  of AF detection ranged from 0.43 for the 4-h interval to 0.76 for the 16-h interval, whereas  $Sp$  remained consistently high for all intervals under analysis, ranging from 0.95 to 0.98.

Table 2. Performance measures for different post-trigger analysis time intervals.

	Post-trigger analysis time interval			
	4-h	8-h	12-h	16-h
$Se$	0.429	0.609	0.678	0.758
$Sp$	0.981	0.962	0.961	0.949
$Mcc$	0.748	0.780	0.813	0.833

Figure 2 illustrates the AF burden computed for pre- and post-trigger analysis time intervals in both annotated ECG-based and PPG-based AF patterns. The results show a tendency towards a larger average post-trigger AF burden for both annotated ECG-based and PPG-based patterns. Nonetheless, the average AF burden for the PPG-based AF pattern is half of that of the annotated ECG-based pattern. This can be explained by the property of a PPG-based detector to favor specificity over sensitivity.

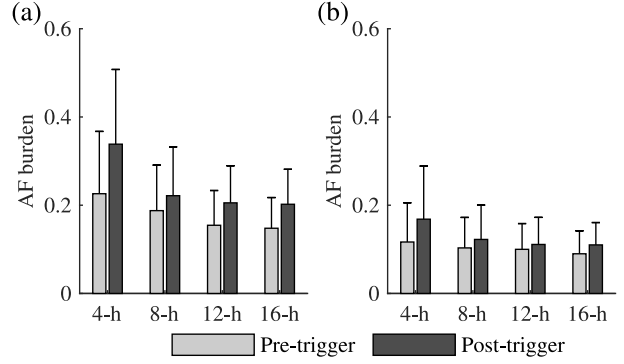


Figure 2. Pre- and post-trigger AF burden for different analysis time intervals when computed from (a) annotated ECG-based and (b) PPG-based AF pattern. The results are given as mean  $\pm$  confidence interval (95%).

### 4. Discussion

Wrist-worn PPG devices offer a convenient means to monitor AF in daily living. However, current technology still faces challenges such as motion artifacts, noise, and non-wear time that need to be addressed. Most AF detectors have been tested on artifact-free signals, which may result in the loss of essential information, i.e., applicability in daily living. In our study, we found that PPG-based estimation of AF burden had an approximate error of 50%, which is substantial considering that a trigger-induced increase in AF burden may only be a few percentage points [6]. These findings highlight the need to improve PPG technology to ensure accurate and reliable monitoring of AF in daily living.

In this study, almost half of the total PPG signal duration (48.2%) was excluded due to poor quality and non-wear time. This exclusion percentage turns out to be similar to that found in a related study in [12], which achieved a coverage of 52%, despite that these patients were encouraged to wear a watch overnight. However, in our study, we did not specifically ask the patients to prioritize wearing the watch overnight. Instead, the patients were instructed to wear the device as frequently as possible.

### 5. Conclusion

This paper explores the potential of long-term PPG monitoring as an alternative to conventional ECG-based monitoring for identifying triggers of AF episodes in patients with paroxysmal AF. The results suggest that long-term PPG-based monitoring can be suitable for detecting post-trigger AF. However, accurate estimation of AF burden still needs improvement in PPG-based technology and AF detectors.

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Address for correspondence:

Vilma Pluščiauskaitė  
Biomedical Engineering Institute  
Kaunas University of Technology  
K. Baršausko st. 59, LT-51423 Kaunas, Lithuania.  
vilma.plusciauskaite@ktu.lt