Investigation of the Relational Strength Between Suspected Atrial Fibrillation Triggers and Detector-Based Arrhythmia Episode Occurrence

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Abstract: Atrial fibrillation (AF) treatment remains challenging, with current options often limited to anticoagulants and antiarrhythmic medications. Growing evidence suggests that acute exposures, referred to as AF triggers, can initiate AF in some patients. Therefore, identifying and managing personal triggers may serve as an effective strategy to complement conventional treatment. This study explores the utility of wearable-based biosignals to assess the relational strength between the suspected triggers and AF occurrence when episodes are detected using electrocardiogram (ECG) and photoplethysmogram (PPG). Biosignals from 33 patients with paroxysmal AF (mean age 61 $\pm$ 13 years), who wore an ECG patch and a wrist-worn PPG device during a 7.0 $\pm$ 0.7 day observation period, were used in the study. Suspected triggers due to physical exertion, psychophysiological stress, and lying on the left side were identified based on a detection parameter calculated over successive segments of the ECG and/or acceleration signals. The relational strength between a suspected trigger and AF episodes is quantified based on AF burden, defined as the ratio of time spent in AF to the total analysis time interval, assuming that the post-trigger AF burden is greater than the pre-trigger AF burden. The results indicate that the relational strength between suspected triggers and AF episode occurrence, as detected using ECG- and PPG-based AF detectors, differs from manual annotation by an average of 0.03$\pm$0.15 and -0.21$\pm$0.21, respectively. This study demonstrates the potential of wearable-based biosignals in providing personalized identification of suspected AF triggers. However, challenges such as non-wear periods and poor PPG signal quality remain to be addressed for practical applications.

1 INTRODUCTION

The management of atrial fibrillation (AF) remains a complex challenge (Lippi et al., 2021), with treatment options often limited to anticoagulants and antiarrhythmic medications, carrying serious side effects (Mani and Lindhoff-Last, 2014). Since acute exposures, referred to as AF triggers, may initiate AF in some patients (Hansson et al., 2004; Groh et al., 2019; Severino et al., 2019), an effective approach could involve addressing lifestyle and risk factors together with conventional treatment (Chung et al., 2020).

Identifying triggers on a patient-specific basis could become a key component of personalized AF management, allowing clinicians to address the root causes of AF episodes in individual cases. Meanwhile, patients could take an active role in managing their AF through targeted lifestyle adjustments.

Among suspected AF triggers (Hansson et al., 2004; Groh et al., 2019), alcohol has been the most extensively studied, with consistent evidence linking to the onset of AF episodes (Marcus et al., 2022). Other triggers associated with the occurrence of AF episodes include physical exertion (Abdulla and Nielsen, 2009; Guasch and Mont, 2017), lying on the left side (Gottlieb et al., 2021), and psychophysiological stress (Leo et al., 2023).

A major limitation of previous studies is their reliance on self-reported AF triggers, typically gathered through questionnaires (Hansson et al., 2004; Groh et al., 2019; Marcus et al., 2022), which are susceptible to bias. For instance, patients often identified multiple triggers (Groh et al., 2019), suggesting con-

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firmation bias, while others may have been reluctant to disclose certain triggers, such as those related to unhealthy behaviors.

With advancements in technology, wearable devices are now equipped with biosensors capable of acquiring various biosignals, potentially enabling the detection of AF triggers and self-terminating AF episodes using the same device. In our previous work, we introduced and examined an approach to quantifying the relation between suspected triggers detected in long-term biosignals and the occurrence of AF episodes (Pluščiauskaitė et al., 2024a; Pluščiauskaitė et al., 2024b). The previous study demonstrated the potential of the proposed approach using clinician-annotated AF episodes. However, applying this in a clinical practice is particularly challenging, as annotating long-term signals is a time-consuming process that requires enormous effort from cardiologists. Therefore, the present study focuses on the utility of wearable devices to assess the relational strength when AF episodes are automatically detected using electrocardiogram (ECG) and photoplethysmogram (PPG) biosignals.

2 METHODS

2.1 Database

One hundred eighty-two patients diagnosed with paroxysmal AF were recruited from the Cardiology Department at Vilnius University Hospital Santaros Klinikos. Only those who experienced at least one AF episode during the observation period (7.0 ± 0.7 days) were included, resulting in a subset of 33 patients (19 women) with a mean age of 61 ± 13 years. The study was approved by the Vilnius Regional Bioethics Committee (reference number 158200-18/7-1052-557). All patients provided written informed consent before participation in the study and were fully informed of the research objectives and procedures.

The database includes biosignals acquired during daily activities using a Bittium OmegaSnap™ one-channel ECG patch (Bittium, Finland) and a wrist-worn device developed at the Biomedical Engineering Institute of Kaunas University of Technology (Bacevičius et al., 2022). The ECG patch, positioned directly on the sternum, acquired continuous ECG at 500 Hz and tri-axial acceleration signals at 25 Hz, while the wrist-worn device acquired continuous PPG at 100 Hz. AF episodes were annotated by cardiology residents who reviewed the long-term ECGs and consulted an experienced cardiologist in uncertain cases. The biosignal database can be accessed on Zenodo (Bacevičius et al., 2024).

2.2 Detection of AF Episodes

Two detectors are used to detect AF episodes: one based on the analysis of the ECG (Petrėnas et al., 2015) and the other on the PPG (Sološenko et al., 2019). Both detectors rely on the irregularity of beat-to-beat intervals and elevated heart rate during AF. Additionally, the detectors include blocks for ectopic beat removal and suppression of bigeminy and sinus arrhythmia to reduce the number of false positives. The PPG-based AF detector also incorporates signal quality assessment to ensure that detection is not performed on low-quality pulses, whereas the ECG-based detector does not include signal quality assessment. Both detectors are configured to detect AF episodes as short as 60 beats.

2.3 Detection of Suspected Triggers

The detection of suspected triggers in biosignals is explained in detail in (Pluščiauskaitė et al., 2024b). Each type of suspected trigger, ie., physical exertion, psychophysiological stress, and lying on the left side, is detected based on a detection parameter calculated over successive segments of the ECG and/or acceleration signals, producing a time series that undergoes threshold-based detection.

Poor-quality ECG segments were excluded based on the *bsqi* index, which assesses the agreement of two QRS detectors (Behar et al., 2013), with an agreement threshold of 90%. Only segments free of premature atrial contractions, atrial flutter, and atrial tachycardia were considered for analysis.

Physical exertion is detected using the metabolic equivalent of task (MET), a measure of energy expenditure relative to the resting metabolic rate. The METs are estimated from acceleration and heart rate, accounting for patient-specific variability using a regression equation derived in (Moeyersons et al., 2019). A suspected trigger due to physical exertion is detected if the mean MET, computed over 1-minute intervals with non-AF rhythm, exceeds 5 METs.

Psychophysiological stress is detected when heart rate suddenly increases by more than 15 beats per minute within a 1-minute interval, excluding elevations due to physical activity or arrhythmia (Brouwer and Hogervorst, 2014). Physical activity is considered absent or negligible if the average mean absolute deviation of the tri-axial raw acceleration signal in the 5-minute segment before and during the analyzed 1-minute interval is below 22.5 mg (milligravity), indicating sedentary behavior such as sitting or standing still (Vähä-Ypyä et al., 2018).

Lying on the left side is detected when the mediolateral axis acceleration signal stays below −600 mg for at least 1 hour. Since position changes may occur frequently during the night, only the first detected trigger within the preceding 4 hours is considered.

2.4 Quantification of the Relational Strength

The primary assumption for identifying a trigger is that the actual trigger for a particular patient will increase the AF burden B, defined as the ratio of time the patient spends in AF relative to the total observation period.

The relational strength between suspected triggers and AF episode occurrence in individual patients is assessed based on a cumulative principle (Plusčiauskaitė et al., 2024a), summing the events where the post-trigger AF burden $B_{1,n}$ is greater than the pre-trigger AF burden $B_{0,n}$. The reason for invoking the cumulative principle is based on the fact that it is unlikely a trigger will consistently influence B, even if a patient is prone to that particular trigger. Instead, triggers are more likely to contribute to the sporadic initiation of AF due to their interaction with the arrhythmogenic substrate and modulating factors (Vincenti et al., 2006; Nattel and Dobrev, 2016; Severino et al., 2019). The relational strength γ is quantified as follows (Plusčiauskaitė et al., 2024a):

$$\gamma = \sum_{n=1}^{N_t} \frac{B_{1,n}}{1+B_{0,n}} H(B_{1,n} - B_{0,n}), \quad (1)$$

where N_t represents the number of suspected triggers during the observation period, n is the number of detected suspected triggers, and $H(\cdot)$ is the Heaviside step function. The analysis time interval T, used to compute $B_{1,n}$ and $B_{0,n}$, is set to 4 hours (Marcus et al., 2021). The relational strength computed for annotated and detector-based AF episode occurrences is denoted as γ_a and γ_d, respectively.

3 RESULTS

Fig. 1 illustrates the annotated occurrence of episodes in a patient with paroxysmal AF, along with episodes detected using ECG- and PPG-based AF detectors, and their effect on the relational strength. For this particular example, lying on the left side is only shown, which was detected four times over a 7-day observation period. For an annotated AF episode occurrence, the relational strength γ is 2.21, suggesting a strong relation between the suspected trigger and increased post-trigger B. Short-duration false positives from the ECG-based AF detector increase the pre-trigger AF burden B_0, causing a slight decrease in the relational strength (γ = 2.17). Conversely, poor PPG signal quality and non-wear time of a wrist-worn device affect both the pre-trigger B_0 and post-trigger B_1 burdens, leading to a substantial reduction in the relational strength (γ = 1.08).

To provide further insight into the impact of AF episode detection errors on the relational strength, Fig. 2 shows how changes in B affect γ. The results indicate that an increase in B, caused by falsely detected AF episodes from the ECG-based detector, tends to increase γ. This tendency is observed across all types of suspected triggers. Conversely, due to non-wear time, PPG-based detection almost always results in a lower B, which leads to a decrease in γ.

Figure 3 illustrates the error in the relational strength computed for detector-based and annotated AF episodes. The results show that PPG-based AF detection results in a markedly underestimated γ (mean = -0.21), while the error for ECG-based AF detection is low (mean = -0.03).

4 DISCUSSION

Considering the practical applicability of the proposed approach for detecting AF triggers in biosignals, it is unrealistic to rely on manually annotated occurrences of AF episodes for every patient; thus, automated AF detection becomes essential. To address this, we examined both a chest ECG patch and a wrist-worn device capable of acquiring PPG signals. Since reliable detection of AF episodes requires long-term monitoring and robust AF detectors (Butkuvienė et al., 2024), understanding how detection errors affect episode occurrence – and, in turn, relational strength – is a crucial area of investigation.

The main finding of the study is that misdetections and non-wear periods considerably reduce the relational strength between suspected triggers and AF episode occurrence. However, the limitations of AF detectors do not render the proposed method impractical, due to the cumulative principle used in calculating relational strength. This principle ensures that the relational strength increases as the number of suspected triggers grows, indicating that a longer observation period is needed to achieve the same effect on γ. While clinical studies are still needed to determine how γ should be interpreted, we suggest using γ values greater than 1.5 as a starting point for considering

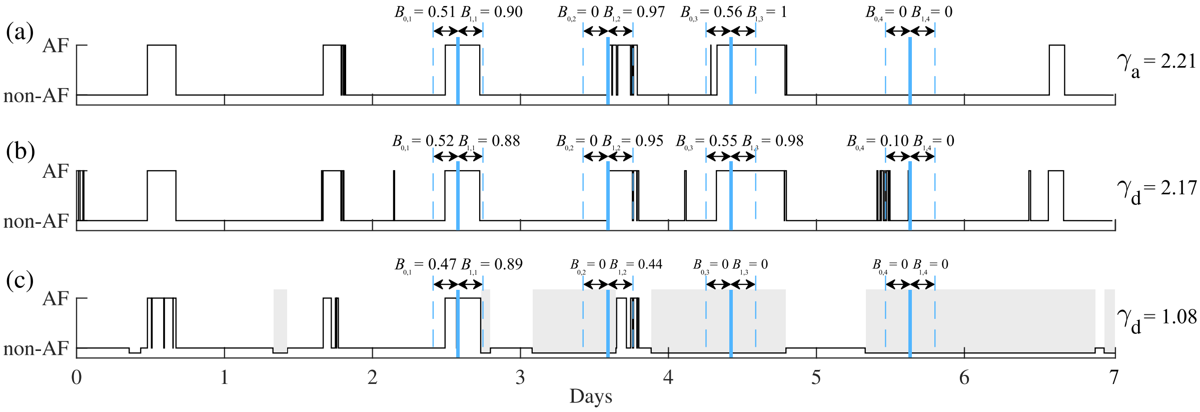

Figure 1: Illustration of the relational strength γ for AF episodes identified by (a) annotation, (b) ECG-based detection, and (c) PPG-based detection. The onsets of a suspected trigger, attributed to lying on the left side, are shown in blue. Grey rectangles indicate periods of non-wear or poor PPG quality. Note that the ECG-based AF detector prioritizes sensitivity, resulting in more false positives, while the PPG-based detector emphasizes specificity, leading to missed or truncated episodes.

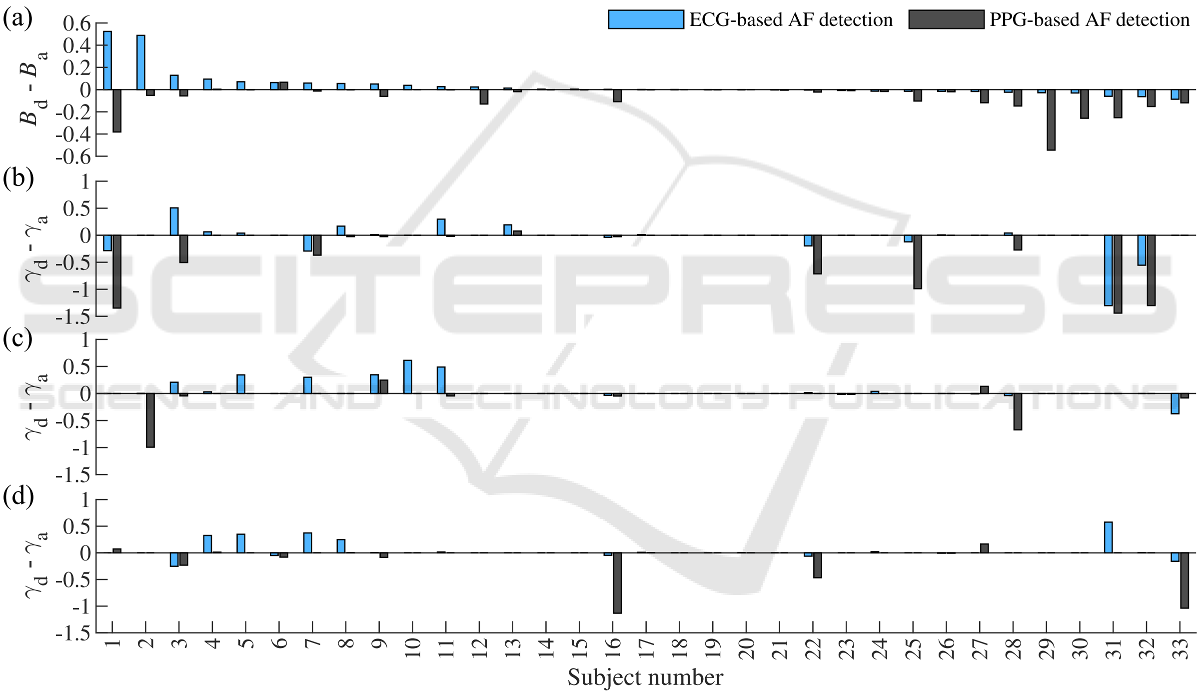

Figure 2: (a) The difference in AF burden B between annotated episodes and those detected using ECG- and PPG-based AF detection, along with its impact on the difference in relational strength γ for suspected triggers of (b) physical exertion, (c) psychophysiological stress, and (d) lying on the left side. Subjects are arranged in descending order based on the difference in B observed with ECG-based detection.

a suspected trigger as an actual trigger (Pluščiauskaitė et al., 2024a). A γ value above 1.5 can be indicative of a strong relation, as achieving such a value requires at least two suspected triggers for which $B_{1,n}$ is much greater than $B_{0,n}$.

Understanding how triggers affect AF episodes in individual patients remains an unresolved question. In this study, we focused on three suspected triggers based on their relations with AF occurrence and their feasibility for detection in biosignals. High-intensity exercise is a known trigger for AF episodes, both in athletes and the general population (Shamloo et al., 2018). Psychophysiological stress releases stress hormones, elevating heart rate and cardiac contractions, which may also trigger AF (Leo et al., 2023). Meanwhile, the left lying position is commonly self-reported as an AF trigger (Groh et al., 2019), likely due to increased pressure on the atrial

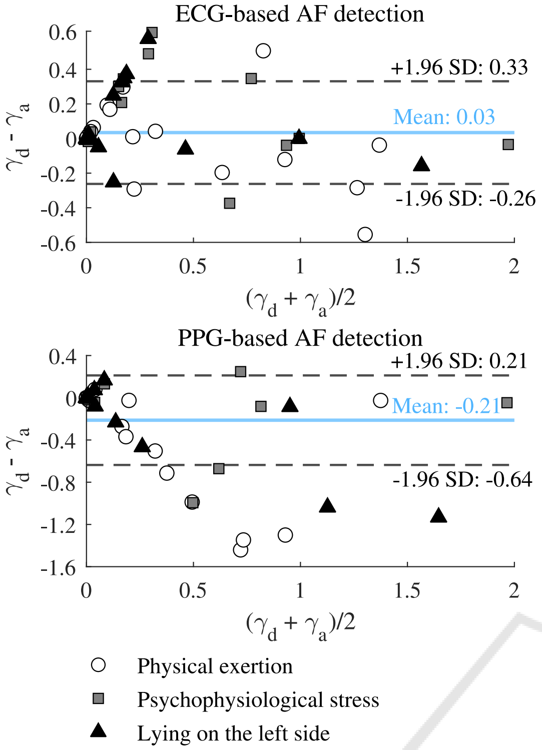

Figure 3: The error in relational strength computed for detector-based and annotated AF episodes across different types of suspected triggers.

walls and pulmonary veins (Gottlieb et al., 2021; Gottlieb et al., 2023). In our previous work, we also investigated sleep disturbances as a suspected trigger, quantified by the standard deviation of beat-to-beat intervals, which serves as an indicator of the dominant sympathetic and vagal activity components (Malik and Camm, 2004). However, we did not include sleep disorders in this study due to the lack of difference when compared to the control γ.

The study has several limitations. Within the initial cohort of patients diagnosed with paroxysmal AF, only 18% experienced at least one AF episode during the one-week observation period. Consequently, the findings, based on this relatively small dataset, should be interpreted with caution. Another limitation lies in the lack of a reference for triggers, leaving it unclear whether the detected suspected triggers were actual triggers. While lying on the left side can be reliably detected when a chest sensor is used, validating physical exertion or psychophysiological stress is more challenging. These triggers are mostly subjective and may not consistently align with the effects observed in biosignals.

5 CONCLUSIONS

This paper explores the potential of long-term ECG- and PPG-based monitoring to identify suspected triggers of AF episodes in patients with paroxysmal AF. The relational strength between suspected triggers and AF episode occurrences, as detected by ECG- and PPG-based AF detectors, differs from manual annotation by an average of 0.03 and -0.21, respectively. While wearable biosignals show promise for personalized identification of suspected AF triggers, challenges such as non-wear periods and poor PPG signal quality must be addressed to enable clinical application.

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