A Comparative Study on Detecting Heart Beats in Photoplethysmography Signals in Presence of Various Cardiac Arrhythmias

Loïc Jeanningros[1,2], Mathieu Le Bloa[3], Cheryl Teres[3], Claudia Herrera[3], Alessandra Porretta[3], Patrizio Pascale[3], Adrian Luca[3], Jorge Solana Muñoz[3], Giulia Domenichini[3], Jean-Marc Vesin[2], Jean-Philippe Thiran[2], Etienne Pruvot[3], Mathieu Lemay[1], Fabian Braun[1]

[1]Swiss Center for Electronics and Microtechnology (CSEM), Neuchâtel, Switzerland
[2]Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland
[3]Lausanne University Hospital (CHUV), Lausanne, Switzerland

Abstract

Cardiac arrhythmias present a significant global health concern. The advent of wearable devices utilizing photoplethysmography gives the opportunity to screen large populations, hence offering the potential for early detection of pathological rhythms and reducing risks of complications and associated medical costs. While most beat detection algorithms have been evaluated on normal sinus rhythm or atrial fibrillation recordings, their performance in patients with other cardiac arrhythmias remains unexplored to date. To address this gap, we leveraged the open-source framework PPG-beats, *developed by Charlton and colleagues, to analyse a newly acquired dataset comprising seven distinct types of cardiac arrhythmia in hospital settings.*

Among the thirteen beat detectors evaluated, the QPPG *detector performed best on atrial fibrillation (with a median F_1 score of 94.4%), atrial flutter (95.2%), atrial tachycardia (87.0%), sinus rhythm (97.7%), ventricular tachycardia (83.9%) and was ranked second for bigeminy (75.7%) behind the* ABD *detector (76.1%).*

Overall, the QPPG *beat detector achieved high performances and consistently outperformed other detectors. However, the detection of beats from wrist-PPG signals is compromised in the presence of bigeminy or ventricular tachycardia.*

1. Introduction

Cardiac arrhythmias (CAs) affect between 3.2 and 6.6% of the elderly in Europe and the US (aged 65 to 73 years) [1] and are linked to increased morbidity and mortality [2]. The asymptomatic and intermittent characteristics of some CAs during their early stages [3], [4], often lead to late diagnoses, during hospitalization for stroke or heart failure.

Photoplethysmography (PPG) measures changes in blood volume by optical means and is often integrated in wearable devices like smartwatches [5], [6]. PPG is therefore a promising technology for long-term and continuous ambulatory monitoring of heart rhythm.

Extensive research has been conducted on the detection of atrial fibrillation (AF), the most prevalent CA, mostly by analysing irregularities in inter-beat intervals (IBIs). In addition to IBIs, CAs also distort the morphology of individual PPG pulses. Pulse wave analysis (PWA) [7] has been utilized to extract such information, enhancing the detection of CAs [8], [9]. However, both IBIs and PWA heavily rely on an accurate detection of heartbeats within the PPG signal.

While beat detectors exhibit high accuracy for healthy subjects [10], their performance in the presence of different CAs has not been widely studied. Only a few studies have focused on evaluating PPG beat detection performance during AF. Harju et al. [11] reported results that correspond to an F_1 score of 96.5% on 21 subjects with AF. Väliaho et al. [12] achieved a performance equivalent to 94.5% F_1 score for pulse detection in 106 patients with AF. In a recent study by Charlton et al. [10], fifteen open-source beat detectors were compared on multiple datasets associated with various conditions. Among them, the eight detectors that performed the best achieved F_1 scores between 91.8% and 97.1% on 19 patients suffering from AF. Furthermore, Han et al. [13] developed a complex beat detector specifically designed for HR estimation in the presence of CAs. Their *SWEPD* algorithm successfully detected IBIs with an F_1 score of 97.2% in 21 patients with AF.

To the best of our knowledge, no study has compared the performance of multiple beat detectors on various types of CAs. Considering CAs beyond AF is crucial when screening large populations potentially displaying various pathological rhythms. Consequently, the choice of beat detector can significantly impact the performance of CAs classifiers based on IBIs and PWA.

 ISSN: 2325-887X DOI: 10.22489/CinC.2023.119

In this study, we employed the open-source *PPG-beats* framework by Charlton et al. [10] to assess the performance of thirteen open-source beat detectors. The framework was applied to a recently acquired dataset containing seven distinct types of CAs. The main objectives of this research are twofold: 1) to evaluate the effectiveness and reliability of beat detectors in the presence of various types of CAs, and 2) to identify specific CAs for which heartbeat detection from wrist-PPG signals is limited.

2. Material and Methods

2.1. Dataset

58 patients referred for diagnostic or therapeutic electrophysiological procedures at the Lausanne University Hospital (CHUV) were included. This study received approval from the local ethics committee of Lausanne (CER-VD, Project-ID 2021-00586) and has been registered on ClinicalTrials.gov (NCT04884100).

PPG signals were recorded at 100 Hz from a proprietary wrist-bracelet (CSEM, Neuchâtel, Switzerland). Simultaneously, 12-lead ECG signals were acquired with the Axiom Sensis XP® System (Siemens®, Munich, Germany) at a sampling frequency of 2 kHz and bandpass filter settings of 0.5-200 Hz. The system provided R-peak annotations, indicating the occurrence of heartbeats.

ECG signals were manually annotated by a medical expert to identify CAs. Both atrial and ventricular bigeminy, as well as trigeminy and quadrigeminy, or any combination of these rhythms, were indistinctly labeled as bigeminy. The label AVRT included both atrioventricular reetrant tachycardia and atrioventricular nodal reentrant tachycardia. Finally, single atrial and ventricular premature contractions were not considered as CAs and were therefore ignored in this study.

2.2. PPG Beat Detector Evaluation

The *PPG-beats* framework[1] provided by Charlton and colleagues [10] was utilized for this study. The performance evaluation methods are identical to those in the original paper [10], with the exception of the *SPAR* and *PWD* detectors, which were removed due to runtime errors for several signals.

The essential steps are summarized as follows: First, the PPG signals were bandpass filtered between 0.67 and 8.0 Hz. Next, beats were detected using the thirteen open-source detectors. To apply PPG beat detection, the PPG signals were segmented into 20-s windows with a 5-s overlap and duplicate beats within overlapping segments were removed. For each detector, the timings of detected beats were used to determine the corresponding middle-amplitude point of systolic upslope, which was used for analysis. To synchronize PPG beats with reference ECG beats, the lag associated with the maximum number of correctly identified ECG beats was used. ECG beats were considered correctly identified if they were within 150 ms of at least one PPG beat. The performance of the beat detectors was evaluated based on the number of correctly identified beats, false-negative, and false-positive detections to calculate sensitivity, positive predictive value (PPV) and F_1 score. Finally, beats were included in our analysis only if they belonged to a homogeneous rhythmic event lasting for at least 25 s.

[1] https://github.com/peterhcharlton/ppg-beats

3. Results

3.1. Dataset

Table 1 provides a comprehensive overview of the eight types of CA recorded, along with their occurrence frequency. Out of the 58 subjects involved in the study, 40 were men, and the mean age was 56±16 years.

Table 1 List of cardiac arrhythmias

	Cardiac arrhythmia	Subjects	Duration (h)
		58	*81.4*
AF	Atrial fibrillation	12	5.4
AFL	Atrial flutter	9	7.8
AT	Atrial tachycardia	3	1.2
AVB	Atrioventricular block	2	0.5
AVRT	Atrioventricular reentrant tachycardia	8	0.3
Bi	Bigeminy (atrial or ventricular)	10	4.6
SR	Sinus rhythm (normal)	58	58.8
VT	Ventricular tachycardia	10	2.9

3.2. Beat Detector Performance

Figure 1 shows the F_1 scores obtained during the performance evaluation of beat detectors. Sensitivity and PPV metrics are not shown. The medians of F_1 scores on normal sinus rhythm range from 89.6% to 97.7%, with five beat detectors showing similar high scores (>97.3%): *QPPG*, *ABD*, *MSPTD*, *AMPD* and *ERMA*. The drop in accuracy when detecting beats during AF or atrial flutter is noticeable. *QPPG* and *MSPTD* stand out as the best detectors during AF, achieving median F_1 scores of 94.4% and 94.1%, respectively. For atrial flutter, the variability in beat detection across subjects is more pronounced, with *QPPG* outperforming other detectors with a median F_1 score of 95.2%. Atrial tachycardia and ventricular tachycardia obtain the most spread-out performances among the beat detectors. *QPPG* (87.0%) and *MSPTD* (85.1%) slightly outperformed other detectors in atrial tachycardia. In the case of ventricular tachycardia, performances vary significantly across subjects, with some very inaccurate detections. *QPPG* once again ranks at the top with 83.9% median F_1 score. Bigeminy beats often remain undetected, depending on the subject. Notably, bigeminy shows the worst performance, with the best detectors being *ABD* and *QPPG* with median F_1 scores of 76.1% and 75.7% respectively. Finally, the top-ranked beat detectors achieve high performance for both atrioventricular blocks and atrioventricular reentrant tachycardias. *QPPG*, *ABD* and *WFD* show medians F_1 scores between 97.2% and 97.9% for AV blocks. For AVRT, *MSPTD* emerges as the best detector with a median F_1 scores of 93.5% closely followed by *PDA*, *QPPG*, *ABD*, *AMPD* and *PULSES* (>92.1%).

4. Discussion and Conclusion

ABD, *MSPTD* and *QPPG* detectors consistently ranked among the top detectors for the different types of CA showing no failure on any specific CA. These findings align with the study by Charlton and colleagues [10], which concluded that *MSPTD* and *QPPG* detectors were performing best within various conditions (including hospital, daily-life, and atrial fibrillation). Our analyses emphasized the superiority of the *QPPG* beat detector's performance in hospital conditions. This can be attributed to its good sensitivity, which allows it to detect beats occurring early in the cardiac cycle. Consequently, *QPPG* provides a clear advantage for detecting beats during CAs such as atrial and ventricular tachycardias, atrial flutter and AF. Unlike other detectors, *QPPG* also maintains a

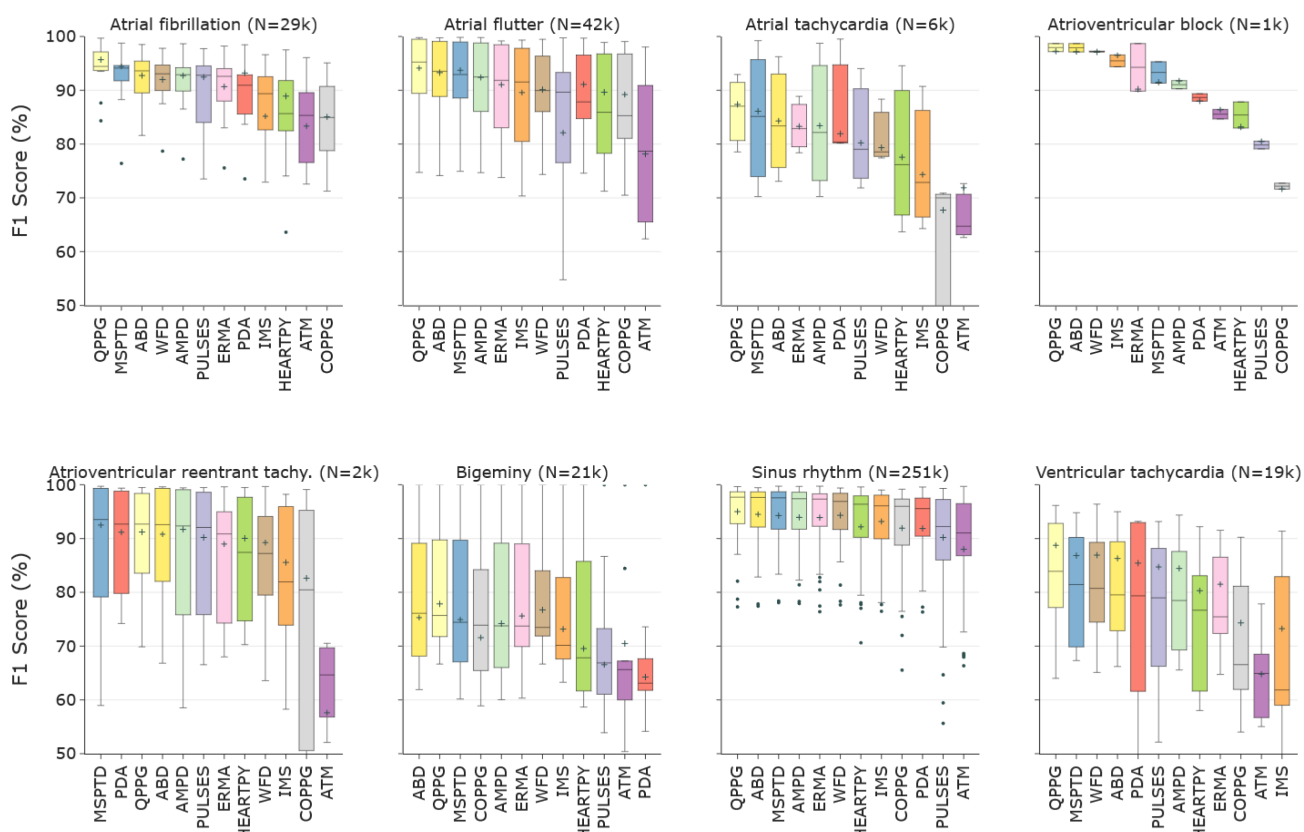

Figure 1 Beat detector performance (F_1 score) comparison by cardiac arrhythmia. The number of reference beats (N) per CA is written next to each subtitle in thousands (k). Black dots represent outlier subjects, boxes show the median, 1st and 4th quartiles, 10th and 90th percentiles of F_1 scores obtained per subjects while the black cross indicates F_1 score calculated across all subjects. Detectors are ordered by decreasing median of F_1 score.

high PPV even during bigeminy.

The detection of bigeminy beats was particularly poor compared to other CAs. This is due to premature contractions that occur very early in the cardiac cycle, such heartbeats do not necessarily generate a pressure wave. The resulting changes in the PPG signal - reflecting blood volume changes in the peripheral arteries - are minimal, comparable to that of a dicrotic notch. It is therefore rather an intrinsic physiological limitation for the detection of heartbeats from blood volume variations in the peripheral vascular system. However, one possibility would be an in-depth analysis of the PPG waveform, to characterize it as typical bigeminy and deduce that it contains a hidden premature contraction.

All beat detectors showed lower sensitivity in presence of ventricular tachycardia (VT). VT beats are particularly rapid and result either in PPG waves of decreased amplitude or hidden waves comparable to those of bigeminy. Such beats are very difficult to detect without triggering false positives in return.

Our work is limited by the number of arrhythmic events of atrioventricular block (of any degree) and atrioventricular (nodal or not) re-entrant tachycardia, which is too small to draw any meaningful conclusions for these two groups of CA.

In this study, we assessed the performance of thirteen open-source PPG beat detectors under various CAs. Our findings demonstrated that *QPPG* achieved the highest performance. Additionally, our evaluation shed light on the challenges faced by beat detectors in detecting beats during bigeminy and ventricular tachycardia.

The results obtained from this investigation offer strong support for selecting an appropriate beat detector for continuous monitoring of CAs.

Acknowledgments

This research was funded by the Swiss National Science Foundation: ENHEART project (205321_192020).

References

[1] S. Khurshid *et al.*, "Frequency of Cardiac Rhythm Abnormalities in a Half Million Adults," *Circ Arrhythm Electrophysiol*, vol. 11, no. 7, Jul. 2018, doi: 10.1161/CIRCEP.118.006273.

[2] C. W. Tsao *et al.*, "Heart Disease and Stroke Statistics—2023 Update: A Report From the American Heart Association," *Circulation*, vol. 147, no. 8, pp. e93–e621, Feb. 2023, doi: 10.1161/CIR.0000000000001123.

[3] R. W. Rho and R. L. Page, "Asymptomatic Atrial Fibrillation," *Progress in Cardiovascular Diseases*, vol. 48, no. 2, pp. 79–87, Sep. 2005, doi: 10.1016/j.pcad.2005.06.005.

[4] B. Gorenek (chair) *et al.*, "Device-Detected Subclinical Atrial Tachyarrhythmias: Definition, Implications and Management—an European Heart Rhythm Association (EHRA) consensus document, endorsed by Heart Rhythm Society (HRS), Asia Pacific Heart Rhythm Society (APHRS) and Sociedad Latinoamericana de Estimulación Cardíaca y Electrofisiología (SOLEACE)," *EP Europace*, vol. 19, no. 9, pp. 1556–1578, Sep. 2017, doi: 10.1093/europace/eux163.

[5] J. Allen and P. A. Kyriacou, *Photoplethysmography: Technology, Signal Analysis and Applications*. Academic Press, 2021.

[6] M. Lemay *et al.*, "Applications of Optical Cardiovascular Monitoring," in *Wearable Sensors*, 2nd ed., E. Sazonov, Ed., London, United Kingdom: Elsevier, 2020, pp. 487–517. doi: 10.1016/B978-0-12-819246-7.00018-8.

[7] M. Proença *et al.*, "Pulse Wave Analysis Techniques," in *The Handbook of Cuffless Blood Pressure Monitoring: A Practical Guide for Clinicians, Researchers, and Engineers*, J. Solà and R. Delgado-Gonzalo, Eds., Cham: Springer International Publishing, 2019, pp. 107–137. doi: 10.1007/978-3-030-24701-0_8.

[8] L. Jeanningros *et al.*, "Pulse Wave Analysis of Photoplethysmography Signals to Enhance Classification of Cardiac Arrhythmias," in *CinC 2022*, Tampere, Finland, Sep. 2022. [Online]. Available: https://cinc.org/2022/Program/accepted/23.html

[9] M. Basza *et al.*, "Photoplethysmography Wave Morphology in Patients with Atrial Fibrillation," *Physiol. Meas.*, vol. 44, no. 4, p. 045001, Apr. 2023, doi: 10.1088/1361-6579/acc725.

[10] P. H. Charlton *et al.*, "Detecting Beats in the Photoplethysmogram: Benchmarking Open-Source Algorithms," *Physiol. Meas.*, vol. 43, no. 8, p. 085007, Aug. 2022, doi: 10.1088/1361-6579/ac826d.

[11] J. Harju, A. Tarniceriu, J. Parak, A. Vehkaoja, A. Yli-Hankala, and I. Korhonen, "Monitoring of Heart Rate and Inter-Beat Intervals with Wrist Plethysmography in Patients with Atrial Fibrillation," *Physiol. Meas.*, vol. 39, no. 6, p. 065007, Jun. 2018, doi: 10.1088/1361-6579/aac9a9.

[12] E.-S. Väliaho *et al.*, "Wrist Band Photoplethysmography in Detection of Individual Pulses in Atrial Fibrillation and Algorithm-Based Detection of Atrial Fibrillation," *EP Europace*, vol. 21, no. 7, pp. 1031–1038, Jul. 2019, doi: 10.1093/europace/euz060.

[13] D. Han *et al.*, "A Real-Time PPG Peak Detection Method for Accurate Determination of Heart Rate during Sinus Rhythm and Cardiac Arrhythmia," *Biosensors*, vol. 12, no. 2, Art. no. 2, Feb. 2022, doi: 10.3390/bios12020082.

Address for correspondence:

Fabian Braun.
CSEM, Rue Jacquet-Droz 1, 2000 Neuchâtel, Switzerland.
fabian.braun@csem.ch