


doi:10.1111/imj.13777

## Utility of photoplethysmography for heart rate estimation among inpatients

Anoop N. Koshy <sup>1</sup>, Jithin K. Sajeew,<sup>1</sup> Nitesh Nerlekar,<sup>2</sup> Adam J. Brown,<sup>2</sup> Kevin Rajakariar,<sup>1</sup> Mark Zureik,<sup>1</sup> Michael C. Wong,<sup>1</sup> Louise Roberts,<sup>1</sup> Maryann Street,<sup>1,3</sup> Jennifer Cooke<sup>1</sup> and Andrew W. Teh<sup>1,4</sup>

<sup>1</sup>Department of Cardiology, Monash University, Eastern Health Clinical School, <sup>2</sup>Monash Cardiovascular Research Centre, Department of Medicine, Monash University and Monash Heart, Monash Health, and <sup>4</sup>Department of Cardiology, The University of Melbourne, Austin Hospital Clinical School, Melbourne, and <sup>3</sup>Deakin University, Geelong, Victoria, Australia

### Key words

photoplethysmography, arrhythmias, atrial fibrillation, heart rate, accuracy.

### Correspondence

Andrew W. Teh, Department of Cardiology, Monash University, Eastern Health Clinical School, Box Hill Hospital, 5 Arnold Street, Box Hill, Vic. 3128, Australia.

Email: andrew.teh@easternhealth.org.au

Received 5 September 2017; accepted 20 November 2017.

### Abstract

The accuracy of photoplethysmography (PPG) for heart rate (HR) estimation in cardiac arrhythmia is unknown. PPG-HR was evaluated in 112 hospitalised inpatients (cardiac arrhythmias ( $n = 60$ ), sinus rhythm ( $n = 52$ )) using a continuous electrocardiogram monitoring as a reference standard. Strong agreement was observed in sinus rhythm HR < 100 and atrial flutter (bias 1 beat), modest agreement in sinus tachycardia (bias 24 beats) and complete heart block (bias -6 beats) and weak agreement with significant HR underestimation was seen in atrial fibrillation (bias 23 beats). Routine utilisation of PPG for HR estimation may delay early recognition of clinical deterioration in certain arrhythmias and sinus tachycardia.

**Funding:** This work was supported by the Eastern Health Research Foundation Grant. N. Nerlekar is supported by the National Health and Medical Research Council of Australia and National Heart Foundation Scholarship. A. W. Teh is supported by an Early Career Fellowship from the National Health and Medical Research Council of Australia.

**Conflict of interest:** None.

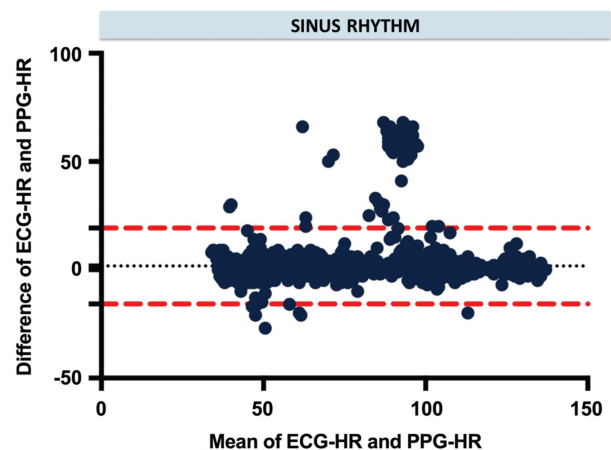
Heart rate (HR) measurement by photoplethysmography (PPG) technology has clinical appeal as a rapid, low cost alternative to a manual pulse-check or a standard electrocardiogram (ECG) in ward-based settings.<sup>1,2</sup> PPG uses an infrared light-emitting diode and photodetector to monitor blood volume changes in the microvasculature where each pulsatile signal is interpreted as an R wave.<sup>1</sup> Although current nursing guidelines recommend 60-s manual pulse counts during vital sign assessment, less

than 25% of nurses adhere to this recommendation.<sup>3</sup> HR estimation using PPG has been validated among patients in sinus rhythm but a paucity of data exists to support its use in cardiac arrhythmias.<sup>1,4</sup> With an increasing prevalence of atrial fibrillation (AF) among hospitalised patients, attaining recommended HR targets with titration of chronotropic therapies has prognostic implications especially among patients with heart failure.<sup>5,6</sup> Furthermore, early detection of significant brady or tachyarrhythmia among inpatients not on continuous telemetry monitoring may facilitate timely intervention.<sup>7</sup> The objective of this study was to compare the accuracy of HR assessment of common arrhythmias with a finger-based PPG monitor to continuous ECG monitoring as a reference standard.

Patients aged 18 years and above were prospectively recruited from the coronary care unit, intensive care unit and the emergency room. Two cohorts of patients were recruited based on underlying rhythm identified on 12-lead ECG: (i) arrhythmias; and (ii) sinus rhythm (SR). The arrhythmia cohort included patients with atrial arrhythmias and atrioventricular conduction disorders. Bradyarrhythmias and tachyarrhythmias were defined as mean heart rates <60 bpm and ≥100 bpm respectively. Exclusion criteria included implantable cardiac devices, patients in contact isolation and a mechanical inability to secure the PPG monitor. The study was approved by the institutional review board and patients provided written informed consent (ACTRN: 12616001374459). Trial Registration: Australia New Zealand Clinical Trials Registry 12616001374459.

Standard five-lead ECG telemetry system (IntelliVue; Philips, Eindhoven, The Netherlands) was utilised as the reference standard on all subjects. The electrode placement sites were prepared by standardised procedures of cleaning, shaving and skin abrading to minimise artefact and five self-adhesive electrodes were placed on right arm, left arm, right leg, left leg and a V1 unipolar precordial lead. A hospital vital sign monitor (MP5 Monitor; Philips Medical Systems, Eindhoven, The Netherlands) with a photoplethysmograph was attached to the index finger. To exclude motion artefact, participants remained supine in bed for 30-min with HR data collected every 15-s (HR/15 s) with a period of 1-min at the start of the protocol disregarded, allowing for calibration of the devices.

Continuous variables are reported as mean ± standard deviation. Bland–Altman plots with 95% upper and lower limits of agreement (LoA) were used to assess agreement between PPG-HR and ECG-HR. A narrower LoA range indicates higher agreement between the two variables. Bias indicates the mean difference between ECG-HR and SW-HR (HR/15 s). Correlation was assessed using Spearman rank correlation ( $r_s$ ) due to non-Gaussian



**Figure 1** Bland–Altman plot comparing photoplethysmography heart rate (PPG-HR) to electrocardiogram monitoring (ECG-HR) in sinus rhythm. Black dotted line represents the mean difference (bias) between the two measures and red dashed lines are the 95% limits of agreement (LoA). Measures are HR values recorded every 15 s. Plots demonstrate a bias of 1 beat with wide LoA (–16 to 19) suggesting a degree of HR variability.

distribution. Two-sided *P*-values with a significance level of <0.05 was adopted. Statistical analyses were performed using Stata 14/MP (Statacorp, College Station, TX, USA).

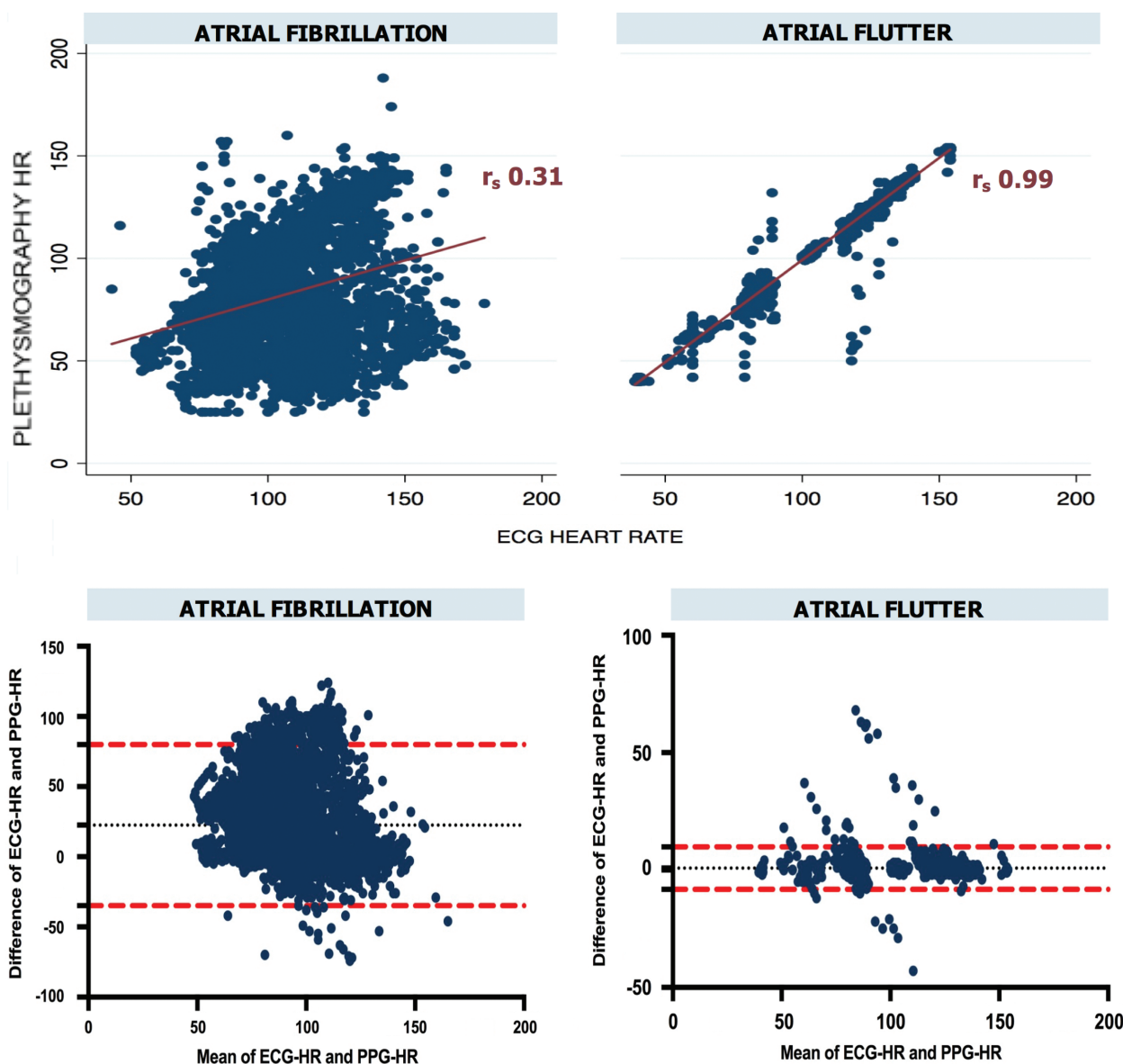
There were 112 consecutive patients recruited (65% male; mean age  $68 \pm 15$  years). Sixty patients that were included in the arrhythmia cohort analysis include: atrial fibrillation (AF,  $n = 32$ ), atrial flutter ( $n = 20$ ) and complete heart block (CHB,  $n = 8$ ). All CHB patients in the study were haemodynamically stable and monitored in coronary care prior to implantation of a permanent pacemaker. Fifty-two patients in SR, included those with persistent sinus bradycardia (HR <60,  $n = 20$ ), sinus rhythm with HR 60–99 ( $n = 20$ ) and persistent sinus tachycardia (HR ≥100,  $n = 12$ ).

Across both devices, 26 880 HR values were recorded. Overall, the SR cohort with HR within physiological range

**Table 1** Accuracy of photoplethysmography estimated heart rate

Rhythm	Correlation	Bias	95% LoA
Atrial fibrillation ( $n = 7680$ )	0.31*	23	–35 to 80
Atrial flutter ( $n = 4800$ )	0.99*	1	–8 to 10
Complete heart block ( $n = 1920$ )	0.69*	–6	–50 to 38
All arrhythmias ( $n = 14\,400$ )	0.71*	12	–39 to 62
All sinus rhythm ( $n = 12\,480$ )	0.96*	1	–16 to 19
Sinus rhythm HR <100 ( $n = 9600$ )	0.98*	3	–22 to 25
Sinus rhythm HR ≥ 100 ( $n = 2880$ )	0.69*	24	–38 to 66

\* $P < 0.01$ . Correlations are Spearman rho ( $r_s$ ) correlation co-efficient. Bias indicates heart rate difference between ECG-monitoring and Photoplethysmography, heart rates per values recorded every 15 s, with associated 95% LoA. ECG, electrocardiogram; HR, heart rate; LoA, limits of agreement.



**Figure 2** Top: Spearman rho correlations ( $r_s$ ) between photoplethysmography heart rate (PPG-HR) and five-lead electrocardiogram HR (ECG monitoring) and for atrial fibrillation (AF) and atrial flutter. Measures are HR values recorded every 15 s. Bottom: Bland-Altman plots comparing PPG-HR to ECG monitoring (ECG-HR) in AF and atrial flutter. Black dotted line represents the mean difference (bias) between the two measures and red dashed lines are the 95% limits of agreement. Measures are HR values recorded every 15 s. Plots demonstrate smaller bias in atrial flutter (1 beat) compared to AF (23 beats) with small limits of agreement (LoA) (–8 to 10 vs –35 to 80). (●), PPG-HR; (—), Fitted values.

(HR < 100) demonstrated strong agreement with ECG-HR with a mean bias of 1 beat and  $r_s$  0.96 ( $P < 0.001$ ) (Fig. 1). Despite the low overall mean bias observed in this cohort, wide LoA (–22 to 25 beats) observed suggests a degree of imprecision that may have been influenced by outlier results as seen on the Bland-Altman plot. HR assessment in sinus tachycardia (HR  $\geq 100$  bpm), demonstrated a mean bias of 24 beats with wider LoA (–38 to 66 beats), suggesting marked HR underestimation with PPG.

Presence of any arrhythmia led to reduced agreement when compared with sinus rhythm (Table 1). Subgroup arrhythmia analysis demonstrated the highest agreement for atrial flutter (bias 1 beat, 95% LoA –8 to 10, ( $r_s$  0.99,  $P < 0.001$ )). AF in particular, demonstrated poor agreement with a mean bias of 22 beats with wide LoA –34 to 80 beats suggesting HR underestimation and weak correlation ( $r_s$  0.31,  $P < 0.001$ ) (Fig. 2). CHB subjects demonstrated a mean bias of –6 beats, with poor agreement as demonstrated by the wide LoA of –49 to 38 beats.

## Discussion

Our findings demonstrate three key findings: (i) sinus rhythm with HR < 100 and atrial flutter demonstrated minimal bias and strong correlation with ECG HR; (ii) CHB and sinus tachycardia demonstrated only moderate agreement with ECG-derived HR with wider LoA; and (iii) poor agreement, with significant HR underestimation was noted in AF.

Despite widespread adoption of PPG-based HR monitoring in hospitals, this is the first study evaluating their accuracy in arrhythmias. The difference in accuracy between AF and atrial flutter is not unexpected. Beat-to-beat variability in AF and reduced perfusion of the microvasculature can impair signal recognition and HR computation similar to the clinical concept of a 'pulse deficit'.<sup>4,8</sup> In contrast, atrial flutter being a re-entrant tachycardia would have minimal variability in HR and stroke volume, thereby attenuating HR underestimation due to device filtering algorithms.<sup>9</sup> Findings of a wide LoA in CHB patients suggest a degree of variability with the PPG HR estimation in this cohort. The generalisability of this finding, however, is limited by the small sample size.

The reduced HR agreement in sinus tachycardia is a novel finding, as patients in this study were evaluated at rest. HR underestimation during sinus tachycardia has been reported previously in laboratory-based exercise settings where motion artefact and impaired skin contact during peak exercise were thought primarily to affect HR computation.<sup>10,11</sup> Our results taken in resting subjects suggest that tachycardia in itself may contribute to inherent inaccuracies in PPG-based HR estimation due to effects on sampling frequency or signal filtering of the device. Alternatively, sinus tachycardia which often coexists in the context of sepsis, inotrope use or metabolic derangement could increase systemic vascular resistance and impair peripheral perfusion, thereby affecting HR computation of the photoplethysmograph.

Our results demonstrate that routine use of PPG in a hospital setting for estimating HR may produce inconsistent results. HR is currently incorporated in the Medical Emergency Team (MET) activation platform, which has reduced the incidence and mortality from in-hospital cardiac arrests.<sup>7</sup> Given that tachycardia and arrhythmias

including AF account for over 20% of MET activations, utilisation of PPG alone might delay early identification of the deteriorating patient with tachycardia or AF.<sup>12</sup> Furthermore, clinician decisions on titration of chronotropic agents are made based on HR trends documented in a patient's vital sign measurements. Inappropriate or inadequate alterations in pharmacotherapy based on PPG-derived HR readings could therefore also predispose to suboptimal HR control or result in premature discharge of a patient with an underlying tachyarrhythmia.

Previous studies have reported the auscultatory method for 60-s to be superior to a radial pulse-check in AF or when HR exceeds 100 beats per minute.<sup>3,13</sup> A comparison of a manual pulse-check to PPG-derived HR, however, is lacking. New machine learning algorithms that utilise granular PPG data have shown promise in differentiating sinus rhythm from arrhythmias.<sup>10</sup> Although incorporating these into conventional PPG monitors could improve their accuracy, this is yet to be proven. The widespread availability of smart watches and fitness trackers are an attractive prospect for estimation of HR using consumer-derived biometric data. However, given the poor accuracy of PPG which uses similar technology, patients should be cautioned on utilising these until further validation studies are conducted.

First, only one brand of a medical-grade photoplethysmograph was assessed in this study and this may limit the generalisability of our findings. Second, the HR values were assessed when patients were immobile in bed and may not be representative of ambulant patients, where exercise and movement may exaggerate contact artefact.<sup>2,11</sup> This methodology, however, was deliberately chosen to assess HR accuracy without confounding from movement artefact.

PPG has excellent agreement to ECG-HR in sinus rhythm (HR < 100) and atrial flutter, but significantly underestimates HR in AF and sinus tachycardia. Accurate assessment of HR is critical among any cohort of hospitalised patients, irrespective of their cardiac rhythm. As such, PPG should not replace a manual pulse assessment or ECG in assessing HR in patients that are not on continuous cardiac monitoring.

## References

- Allen J. Photoplethysmography and its application in clinical physiological measurement. *Physiol Meas* 2007; **28**: R1–39.
- Sinex JE. Pulse oximetry: principles and limitations. *Am J Emerg Med* 1999; **17**: 59–67.
- Hollerbach AD, Sneed NV. Accuracy of radial pulse assessment by length of counting interval. *Heart Lung* 1990; **19**: 258–64.
- Carrara M, Carozzi L, Moss TJ, de Pasquale M, Cerutti S, Ferrario M *et al.* Heart rate dynamics distinguish among atrial fibrillation, normal sinus rhythm and sinus rhythm with frequent ectopy. *Physiol Meas* 2015; **36**: 1873–88.
- Zoni-Berisso M, Lercari F, Carazza T, Domenicucci S. Epidemiology of atrial fibrillation: European perspective. *Clin Epidemiol* 2014; **6**: 213–20.
- Nikolovska Vukadinovic A, Vukadinovic D, Borer J, Cowie M, Komajda M, Lainscak M *et al.* Heart rate

- and its reduction in chronic heart failure and beyond. *Eur J Heart Fail* 2017; **19**: 1230–41.
- 7 Buist MD, Moore GE, Bernard SA, Waxman BP, Anderson JN, Nguyen TV. Effects of a medical emergency team on reduction of incidence of and mortality from unexpected cardiac arrests in hospital: preliminary study. *BMJ* 2002; **324**: 387–90.
  - 8 Halmos PB, Patterson GC. Effect of atrial fibrillation on cardiac output. *Br Heart J* 1965; **27**: 719–23.
  - 9 Samet P. Hemodynamic sequelae of cardiac arrhythmias. *Circulation* 1973; **47**: 399–407.
  - 10 Zhang Z, Pi Z, Liu B. TROIKA: a general framework for heart rate monitoring using wrist-type photoplethysmographic signals during intensive physical exercise. *IEEE Trans Biomed Eng* 2015; **62**: 522–31.
  - 11 Iyriboz Y, Powers S, Morrow J, Ayers D, Landry G. Accuracy of pulse oximeters in estimating heart rate at rest and during exercise. *Br J Sports Med* 1991; **25**: 162–4.
  - 12 Jones D, Duke G, Green J, Briedis J, Bellomo R, Casamento A *et al*. Medical emergency team syndromes and an approach to their management. *Crit Care* 2006; **10**: R30.
  - 13 Sneed NV, Hollerbach AD. Accuracy of heart rate assessment in atrial fibrillation. *Heart Lung* 1992; **21**: 427–33.
-