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Utility of Photoplethysmography for Heart Rate Estimation among Inpatients

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Abstract

The accuracy of photoplethysmography (PPG) for heart rate (HR) estimation in cardiac arrhythmia is unknown. PPG-HR was evaluated in 112 hospitalized 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.

Introduction

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.^{1,2} 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.¹ Although current nursing guidelines recommend 60-second manual pulse-counts during vital sign assessment, less than 25% of nurses adhere to this recommendation.³ 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.^{1,4} With an increasing prevalence of atrial fibrillation (AF) among hospitalized patients, attaining recommended HR targets with titration of chronotropic therapies has prognostic implications especially among patients with heart failure.^{5,6} Furthermore, early detection of significant brady or tachyarrhythmia among inpatients not on continuous telemetry monitoring may facilitate timely intervention.⁷ 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.

Methods

Patients aged 18 years and over 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: a) Arrhythmias b) 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).

Standard five-lead ECG telemetry system (IntelliVue, Phillips, The Netherlands) was utilized as the reference standard on all subjects. The electrode placement sites were prepared by standardized procedures of cleaning, shaving and skin abrading to minimize artifact 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, Phillips Medical Systems, The Netherlands) with a photoplethysmograph was attached to the index finger. To exclude motion artefact, participants remained supine in bed for 30-minutes with HR data collected every 15-seconds (HR/15s) with a period of 1-minute at the start of the protocol disregarded, allowing for calibration of the devices.

Continuous variables are reported as mean \pm 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/15s). Correlation was assessed using Spearman rank correlation (r_s) due to non-Gaussian 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, Texas, USA).

Results

There were 112 consecutive patients recruited (65% male; mean age 68 ± 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 ($HR \geq 100$, $n=12$).

Across both devices, 26,880 HR values were recorded. Overall, the SR cohort with HR within physiological range ($HR < 100$) demonstrated strong agreement with ECG-HR with a mean bias of 1 beat and $r_s 0.96$ ($p < 0.001$) (**Figure 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 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**). 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 ($r_s 0.31$, $p < 0.001$) (**Figure 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 two key findings: 1) Sinus rhythm with HR<100 and atrial flutter demonstrated minimal bias and strong correlation with ECG HR; 2) CHB and sinus tachycardia demonstrated only moderate agreement with ECG derived HR with wider LoA; 3) 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'.^{8,9} In contrast, atrial flutter being a reentrant tachycardia would have minimal variability in HR and stroke volume, thereby attenuating HR underestimation due to device filtering algorithms.¹⁰ Findings of a wide LoA in CHB patients suggests a degree of variability with the PPG HR estimation in this cohort. The generalizability 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 to primarily affect HR computation.^{11,12} Our results taken in resting subjects suggests 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.⁷ Given that tachycardia and arrhythmias including AF account for over 20% of MET activations, utilization of PPG alone might delay early identification of the deteriorating patient with tachycardia or AF.¹³ 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 sub-optimal HR control or result in premature discharge of a patient with an underlying tachyarrhythmia.

Previous studies have reported the auscultatory method for 60-seconds to be superior to a radial pulse check in AF or when HR exceeds 100 beats per minute.^{3,14} A comparison of a manual pulse-check to PPG derived HR however, is lacking. New machine learning algorithms that utilize granular PPG data have shown promise in differentiating sinus rhythm from arrhythmias.¹¹ 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 utilizing these until further validation studies are conducted.

Limitations

Only one brand of a medical-grade photoplethysmograph was assessed in this study and this may limit the generalizability of our findings. Secondly, 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 artifact.^{2,12}. This methodology however, was deliberately chosen to assess HR accuracy without confounding from movement artifact.

Conclusion

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 hospitalized 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.

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Figure Legend

Figure 1: Bland-Altman plot comparing PPG-HR to ECG 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. Measures are HR recorded every 15 seconds. Plots demonstrate a bias of 1 beat with wide LoA (-16 to 19) suggesting a degree of HR variability.

Figure 2:

Top: Spearman rho correlations (r_s) between Photoplethysmography Heart Rate (PPG-HR) and 5-Lead Electrocardiogram HR (ECG Monitoring) and for AF and Atrial Flutter. Measures are HR values recorded every 15 seconds.

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 recorded every 15 seconds. Plots demonstrate smaller bias in atrial flutter (1beat) compared to AF (23 beats) with small LoA (-8 to 10 vs -35 to 80).

Table 1: Accuracy of Photoplethysmography Estimated Heart Rate

Rhythm	Correlation	Bias	95% LOA
Atrial Fibrillation (n=7,680)	0.31*	23	-35 to 80
Atrial Flutter (n=4,800)	0.99*	1	-8 to 10
Complete Heart Block (n=1,920)	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= 9,600)	0.98*	3	-22 to 25
Sinus Rhythm HR ≥ 100 (n= 2,880)	0.69*	24	-38 to 66

*indicates $p < 0.01$. 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 seconds, with associated 95% limits of agreement (LOA)