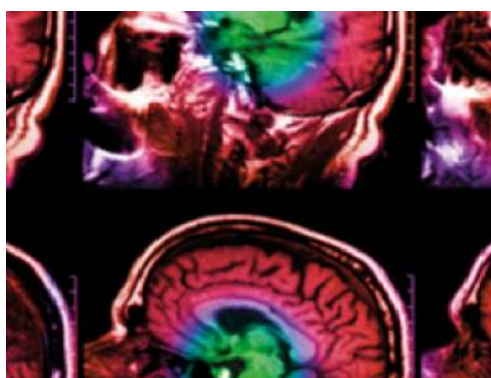


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Feasible assessment of recovery and cardiovascular health: accuracy of nocturnal HR and HRV assessed via ring PPG in comparison to medical grade ECG

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Abstract

Objective: To validate the accuracy of the Oura ring in the quantification of resting heart rate (HR) and heart rate variability (HRV). **Background:** Wearable devices have become comfortable, lightweight, and technologically advanced for assessing health behavior. As an example, the novel Oura ring integrates daily physical activity and nocturnal cardiovascular measurements. Ring users can follow their autonomic nervous system responses to their daily behavior based on nightly changes in HR and HRV, and adjust their behavior accordingly after self-reflection. As wearable photoplethysmogram (PPG) can be disrupted by several confounding influences, it is crucial to demonstrate the accuracy of ring measurements. **Approach:** Nocturnal HR and HRV were assessed in 49 adults with simultaneous measurements from the Oura ring and the gold standard ECG measurement. Female and male participants with a wide age range (15–72 years) and physical activity status were included. Regression analysis between ECG and the ring outcomes was performed. **Main results:** Very high agreement between the ring and ECG was observed for nightly average HR and HRV ($r^2 = 0.996$ and 0.980 , respectively) with a mean bias of -0.63 bpm and -1.2 ms. High agreement was also observed across 5 min segments within individual nights in ($r^2 = 0.869 \pm 0.098$ and 0.765 ± 0.178 in HR and HRV, respectively). **Significance:** Present findings indicate high validity of the Oura ring in the assessment of nocturnal HR and HRV in healthy adults. The results show the utility of this miniaturised device as a lifestyle management tool in long-term settings. High quality PPG signal results prompt future studies utilizing ring PPG towards clinically relevant health outcomes.

1. Introduction

This study evaluated the accuracy of the wearable Oura ring (figure 1) in automatic nocturnal assessment of resting heart rate (HR) and heart rate variability (HRV). The Oura ring is a multisensory wellness companion that weighs about 4 grams—depending on the ring size—and operates for 5–7 consecutive nights with one battery charge. The ring quantifies daily physical activity, night-time sleep duration, and also estimates sleep stages. Characterizing body response to lifestyle habits and related changes (Kinnunen *et al* 2016), the ring determines physiological data such as nocturnal HR and HRV. The sleep metrics provided by the first-generation Oura ring have been independently validated in a sleep laboratory setting (de Zambotti *et al* 2017).

Healthy beating hearts show remarkable variation among the time intervals between heartbeats. HRV consists of periodic and aperiodic changes in the duration of cardiac cycles, which have both clinical and practical relevance. The clinical relevance was discovered decades ago with observations on links between reduced HRV and fetal distress (Electrophysiology Task Force of the European Society of Cardiology the



Figure 1. Technical illustration of the second generation Oura ring. The ring has a titanium cover, battery, power handling circuit, double core processor, memory, two LEDs, a photosensor, temperature sensors, 6-D accelerometer, and Bluetooth connectivity to a smartphone App. Reproduced with permission from Mikko Latomäki.

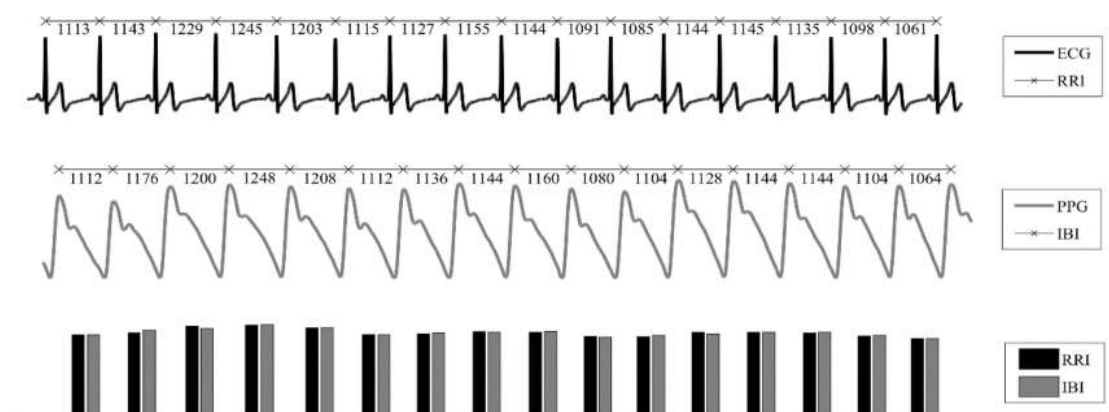


Figure 2. Derivation of beat-to-beat heart rate information from ECG and PPG signals—an example of 16 heart cycles. Top panel: ECG signal and RR-intervals (RRI), Middle panel: PPG signal and interbeat intervals (IBI). Bottom panel: RRI and IBI tachograms.

North American Society of Pacing 1996). Low HRV is also associated with higher cardiovascular mortality. Overall, normal resting HRV is an indication of cardiovascular and autonomic health as well as general fitness (Rajendra Acharya *et al* 2006). Greater nocturnal HRV has been linked with better sleep quality in healthy and clinical populations (Stein and Pu 2012). HRV also reacts to sleep phases (Xiao *et al* 2013, de Zambotti *et al* 2016). Multisensory approaches with, at minimum, an accelerometer and photoplethysmogram (PPG) sensor, have been successfully used to predict sleep quality when compared to the standard sleep laboratory polysomnogram (de Zambotti *et al* 2017, 2018, Renevey *et al* 2018).

HRV is also a practical biofeedback tool for improved relaxation, and an indicator of an athlete's recovery status and readiness to train (Kiviniemi *et al* 2007, 2010). Typically, when a person is under physical or mental stress, parasympathetic activity decreases and sympathetic activity increases. As a result, HR increases and HRV decreases. Relaxation and recovery are strongly reflected in increased high-frequency components of HRV. HRV tends to decrease with age. At a given HR, women typically have higher HRV numbers than men. HRV also responds to various stimuli, which is why it is important to standardize the measurement with regards to time of day, prior activities, and external stressors including ambient temperature, noise, and presence of other people. For the avoidance of compounding factors, night therefore provides an excellent time window for HRV evaluation.

The golden standard method to obtain HRV is an electrocardiogram (ECG). The ECG requires a good contact via adhesive pads attached on skin (electrodes). The QRS complex arises from the depolarization of the ventricles, which is followed by heart muscle contractions that pump blood to pulmonary and aortic arteries. The time between the initiations of succeeding heart beats is called the R-R interval (figure 2). Each contraction of the heart results in blood volume pulses which propagate in blood circulation. In order to get long-term data to be correlated against lifestyle changes over weeks, months, and years, there is a strong need for a comfortable measurement that does not disturb rest, since the ECG is not comfortable enough to wear for continuous use.

A related signal to the ECG, PPG signal can be obtained with a more comfortable measurement that is also suitable for long-term nocturnal use. PPG signal arises from blood volume pulses as the pulse

propagates to the peripheral arteries and capillaries. Two wavelength PPG is routinely used in hospitals to derive oxygen saturation, usually with fingertip sensors. More recently, HRV has also been estimated using pulse intervals from PPG. Its accuracy seems to vary depending on the application. The main challenge is sensitivity to motion, and studies have illustrated more noisy estimates of HRV with PPG than those measured with ECG, particularly in high-frequency parameters (Schäfer and Vagedes 2013). PPG has smoother signal characteristics than ECG, and the signal waveform also changes depending on heart stroke volume and arterial stiffness; all these factors increase the variability in the inter-beat-interval (IBI) data. The best accuracy has been obtained in nocturnal use, where wrist PPG has been reported to reach 5–6 ms mean absolute errors in the timing of a single heartbeat, corresponding to 12–15 ms standard deviation, when compared to the R-R intervals derived by the ECG method (Parak *et al* 2015). Fortunately, systematic bias can be removed mathematically. Somewhat weaker performance in elderly people have been reported. Finger PPG seems to have potential for better beat-to-beat detection accuracy than wrist PPG (Harju *et al* 2018) which could be related to the proximity of arteries on the palmar side of the finger. Prior to this study, the accuracy of nocturnal HR and HRV evaluation with the first-generation Oura ring has been reported as a conference abstract in a relatively narrow sample (Kinnunen and Koskimäki 2018).

The methodology of HRV has been presented in a Task Force committee report (Electrophysiology Task Force of the European Society of Cardiology the North American Society of Pacing 1996). Several different HRV parameters are used in research and practical applications. The most used parameter rMSSD is a time domain parameter which is an estimate of short-term components of HRV that mostly reflect the parasympathetic activity of the autonomic nervous system. In research use, 5 min has become a standard duration for short-term measurements since shorter durations increase the probability of unstable results.

Wearable devices have become more and more comfortable, lightweight, and technologically advanced. Measurements performed at rest have shown proof of concept in personal recovery, sleep, and health-related monitoring. At present, they have enabled highly motivated individual users to adjust their lifestyle and training volumes and pay attention to stress factors by following their autonomic nervous system responses via changes in their resting HR and HRV. In the future, continuous wearable-based monitoring may provide a cost-effective method to avoid elevated stress levels and enable an early warning system that could allow medical interventions at the earliest stages of disease. However, their accuracy should be proven before larger scale studies can be started to test their suitability for these purposes.

The aim of this study is to determine the accuracy of the Oura ring in assessing resting HR and HRV, and to discuss the potential of wearable devices for cardiovascular health solutions. This study is novel since data collection is performed with a comfortable and light-weight wearable ring that can enable evaluation of night-by-night variations in autonomic nervous system balance in response to daily health-related behaviors over extended periods of time.

2. Subjects and methods

2.1. Dataset description and consent to study

The study enrolled 60 voluntary, apparently healthy subjects with no self-reported clinical history of any established disease, or any symptoms. Participants were ≥ 15 years old and represented different levels of physical activity (40 female, 20 male, mean \pm sd age 31.6 ± 11.8 and range 15–72 years). In addition to inactive and moderately active female and male (15 and 20, respectively) participants, 25 highly physically active young females participated. People with low HRV can test if the PPG based method works even if the ECG method indicates low HRV, and people with high HRV have capacity to test if the device can differentiate exceptionally high HRV from motion artefacts or other abnormalities. Young athletes sometimes have pronounced respiratory sinus arrhythmia as part of their normal rhythm.

This study conforms to the principles outlined in the Declaration of Helsinki. Prior to their enrolment, the subjects were informed of the overnight ECG recording and use of the ring, and they gave their written consent to participate. They were also advised of their right to withdraw from the investigation at any time. The measurement was performed as a part of their normal life, and the risk to participants was minimal. Researchers adhered to the principles of research integrity and ethics, and the responsible conduct of research guidelines in Finland.

Subjects received the Oura ring and an ECG monitoring device with instructions in the afternoon prior to the recording. The recording was performed at home. ECG was successfully recorded from 58 subjects; two dropouts were due to subjects' failure to initiate the measurement. Oura ring data was successfully retrieved from 54 out of the remaining 58 subjects. The dropouts were due to ring short-term memory issues as two subjects did not open the associated Oura App for data download within two days (memory limitation), too low battery charge status prior to the recording in one ring, and one unknown technical issue. Finally, five subjects had frequent ectopic beats, as analyzed with MARS ambulatory ECG system (Software version 8, GE

Healthcare) and confirmed by a cardiologist, in such amounts that reliable reference HRV could not be achieved from the ECG. Thus, our final dataset consisted of 49 whole night recordings from as many subjects.

The time period where the Oura ring detected users as being in bed was selected for analysis—the ring determination of time spent in bed is based on subject immobility and high skin temperature.

2.2. R-peak detection and HRV from the ECG

Reference data was obtained from single-lead ECG data collected with medical grade ECG devices: Somnologica (Somnomedics GmbH, Randersacker, Germany, Fs 256 Hz, $N = 33$), Faros 90 (Bittium Oy, Oulu, Finland, Fs 250 Hz, $N = 9$), and Faros 180 (Fs 1000 Hz, $N = 8$). Firstly, the ECG signal was detrended using smoothness prior approach; secondly, preliminary timing of R peaks was determined using Pan–Tompkins R-peak detector (Pan and Tompkins 1985), and thirdly, final timing from the local maximum of the original ECG in the proximity of the preliminary R peak was determined. With 250 and 256 Hz sampling frequencies, an inverted parabola was fitted to three highest ECG samples, and one-millisecond resolution was used in the final peak detector.

2.3. Heartbeat intervals and HRV using the ring

We analyzed nocturnal continuous heart beat interval data evaluated by the Oura ring. The Oura ring automatically determines IBI data from the PPG (Fs 250 Hz) using infrared light (900 nm) during the nightly sleep, and stores them into memory. To derive IBI data, firstly, a real-time moving average filter is applied to locate local maximum and minimum values to denote the timing of each heartbeat. The algorithm implemented in the Oura ring labels each IBI as normal or abnormal using median filters: deviation by more than 16 bpm from the 7-point median IBI in its' immediate neighborhood is marked as abnormal (Kinnunen 1997). Secondly, any IBI is included for the calculation only if five consecutive IBI values are labeled as normal, i.e. two before and two after each are acceptable IBI. Each 5 min sample is processed if a minimum of 30% of the intervals are accepted by this criterion. Finally, the ring determines the HR and HRV for each 5 min segment and whole night averages ($HR_{ring_5\ min}$, $rMSSD_{ring_5\ min}$, HR_{ring} , $rMSSD_{ring}$). The ring PPG measurement is automatically stopped after two minutes of activity if the intensity exceeds or corresponds to that of slow walking. IBI data and the derived HR and HRV numbers download via Bluetooth to the accompanying smartphone application.

2.4. Statistical analysis

Regression and Bland–Altman analysis of nocturnal HR and HRV readings between PPG and ECG methods were performed using Matlab software (Mathworks Inc. MA, USA). A Spearman correlation was used in the regression analysis, and a t -test was used to test the null hypothesis of zero difference between the methods.

3. Results

3.1. Whole night average HR and HRV

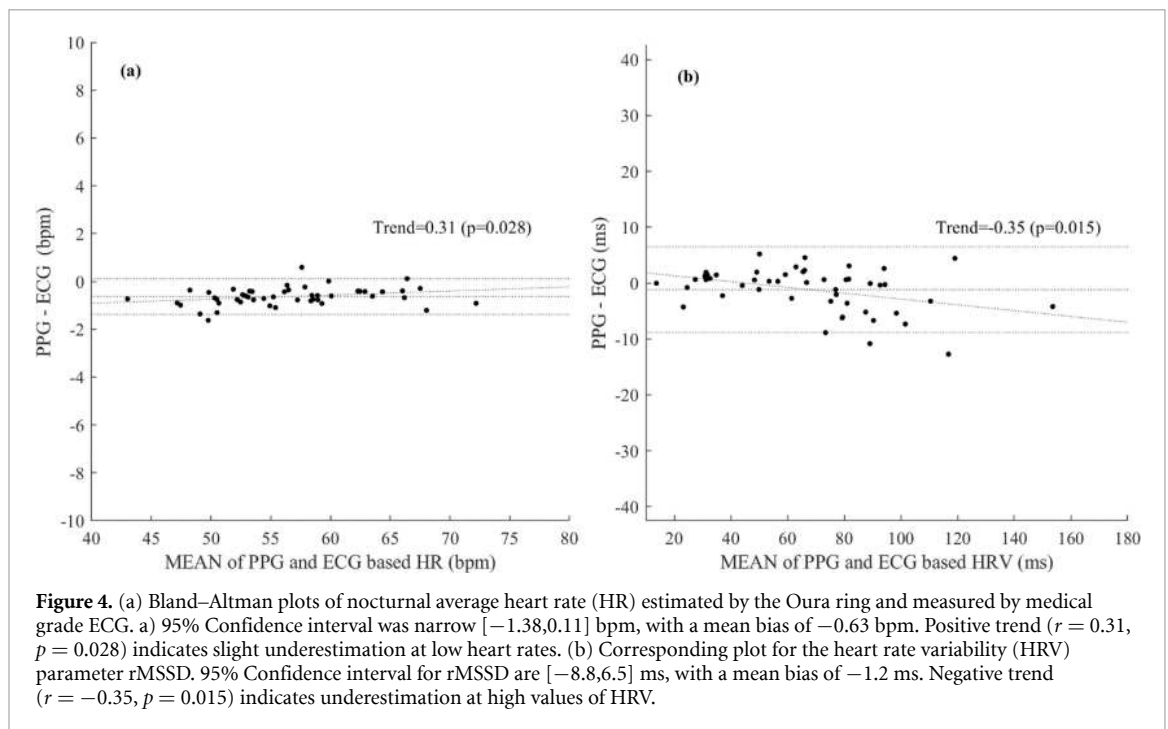
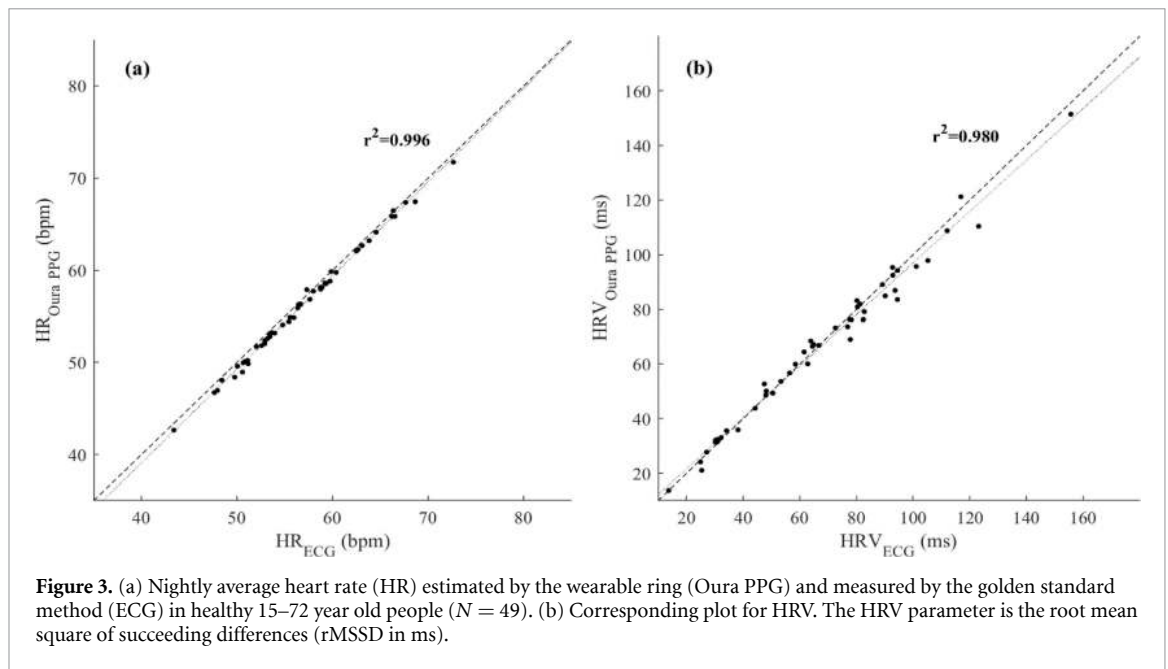
Very high agreement between the ring and ECG was observed for HR and rMSSD ($r^2 = 0.996$ and 0.980 , respectively); see figure 3. Bland–Altman analysis indicated a narrow 95% Confidence interval between $[-1.38, 0.11]$ bpm with a mean bias of -0.63 bpm for HR, and 95% Confidence interval of $[-8.8, 6.5]$ ms for rMSSD with a mean bias of -1.2 ms, see figure 4. Despite near perfect agreement between the methods, the ring slightly but significantly underestimated high values of rMSSD as indicated by negative trend in Bland–Altman analysis ($r = -0.35$, $p = 0.015$).

3.2. Accuracy within 5 min segments

Figure 5 displays combined 5 min HR and HRV data as a scatter plot from all users ($r^2 = 0.972$ and 0.943 , respectively). High agreement was also observed across 5 min segments within individual nights between the ring and ECG in HR and HRV ($r^2 = 0.869 \pm 0.098$ and 0.765 ± 0.178 , respectively). Figure 6 displays data from three individual subjects. In Oura ring data, $2.7 \pm 5.1\%$ of 5 min segments did not have enough reliable IBI data according to the criteria presented in chapter 2.3. and were excluded from analysis.

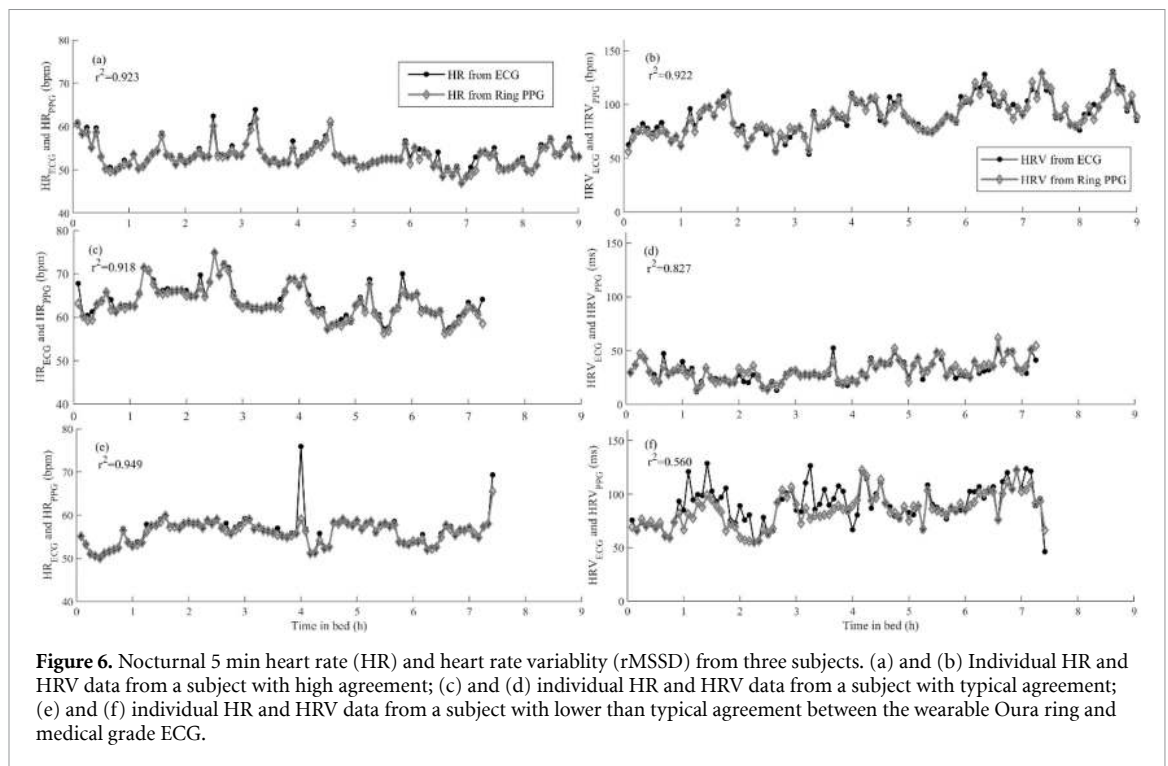
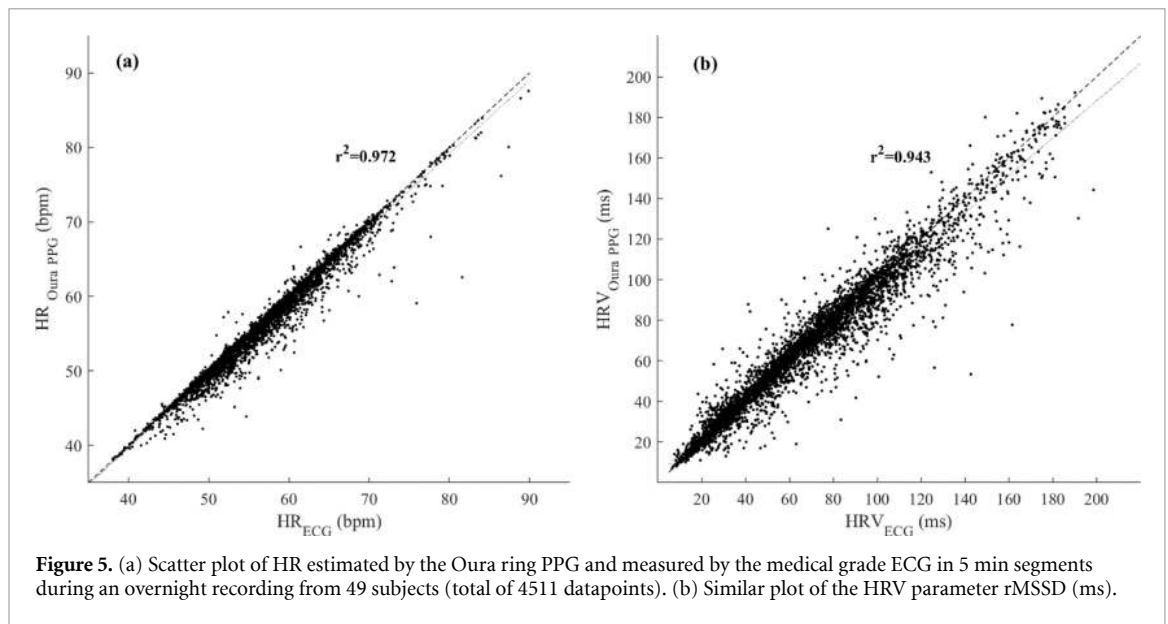
4. Discussion: present and future wearable solutions for cardiovascular health

The results of this study revealed close to perfect agreement between the Oura ring estimates and the ECG measurements in nocturnal average HR and beat-to-beat HRV. Combining comfort and accuracy of the IBI measurement, the ring can be regarded as a feasible tool for a long-term follow-up of autonomic nervous system responses between nights. Within-night analysis across 5 min segments between the wearable and ECG also showed high agreement, which is promising for analysis of the recovery process during the night,



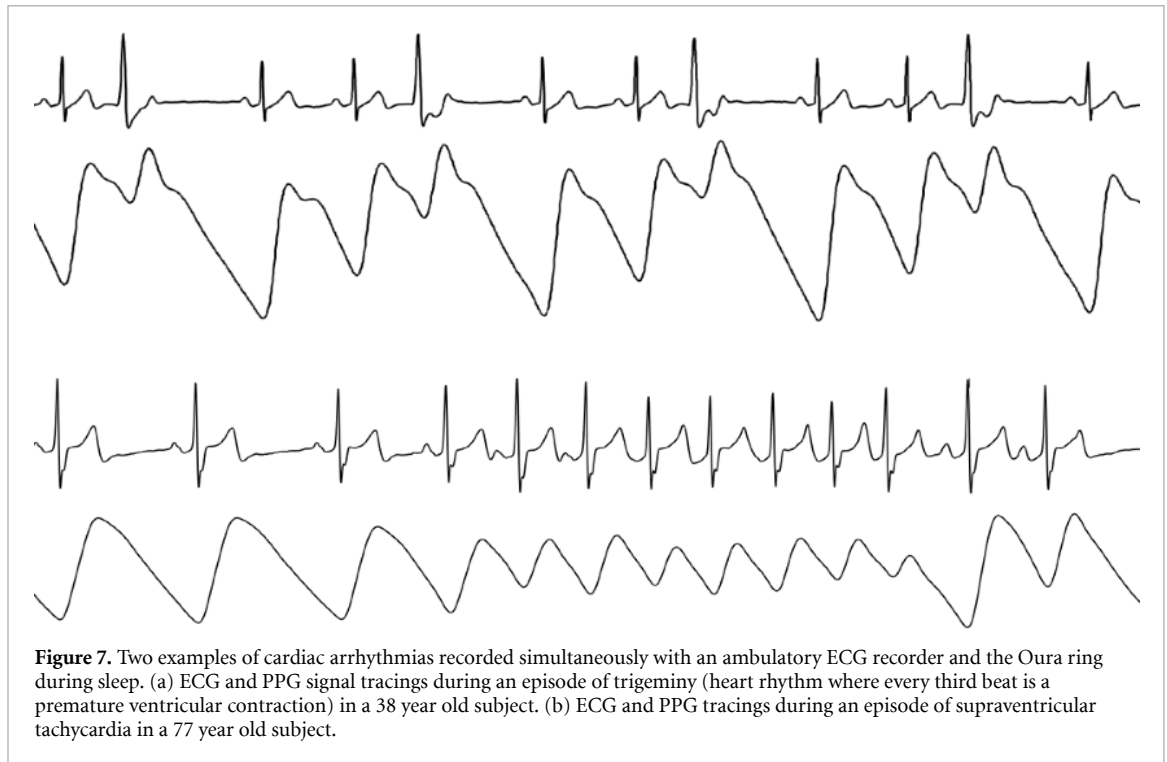
for example to display heartbeat dynamics induced by evening activities, nutrition, alcohol, shift work, or other circadian misalignment. Most optical heart rate monitoring devices do not supply beat-to-beat detection accuracy nor heartbeat interval output so there are very few studies available for comparison. However, the present results compare well, for example to an earlier smaller scale study ($N = 10$) where a novel wrist mounted device was used (Parak *et al* 2015).

The significance of a single numeric value of whole night HR or HRV average per se is limited in a clinical sense, even though low resting heart rate has been associated with longevity and overall good physical health and lower cardiovascular risk (Johansen *et al* 2013, Palatini *et al* 2013). However, long-term trends and how the heart rate changes from night to night has the capacity to provide interesting insights into the health status of subjects. For example, nights following consumption of alcohol will increase the average nocturnal heart rate significantly. Similarly, heavy exercise, pregnancy, sleep disorders, or fever increase the nighttime average HR. From a clinical perspective, we can therefore see future potential use cases in a supportive role: pregnancy follow-up, post-operative care, Parkinson disease status, and avoidance of sleep-related side effects of medication, and so on.



Automatic detection of measurement errors and ectopic beats plays an important role in HRV analyses, since HRV is vulnerable to errors, and visual verification and manual correction of the long-term ECG can be extremely time-consuming (Malik *et al* 1993). Since PPG signal is sensitive to motion, elimination of motion artefacts is very crucial. Night as the measurement time window has a clear benefit thanks to subject immobility during sleep. In our analysis, an average amount of 2.7% of 5 min segments had to be excluded because of excess number of deviating IBI values, usually associated with motion.

The fact that Oura underestimated very high values of HRV can arise from the fact that automatic elimination of extraordinarily large beat-to-beat differences excluded some of them from the PPG-based HRV data but not from the corresponding ECG-based HRV numbers since visual verification of the ECG confirmed them as respiratory sinus arrhythmia. The filtering of abnormal beats and motion artefacts in the Oura ring is based on the timing of heartbeats. As a result, future studies should examine if PPG waveform analysis could be linked to the elimination of errors and detection of arrhythmia (figure 7). Five subjects were excluded entirely from our HRV analysis due to frequent ectopic beats. Automated detection and



elimination of frequent ectopic beats using both ECG and PPG waveform is certainly worth another study, with goals to characterize the underlying autonomic nervous system activity.

The present study only included healthy and high-performing individuals. The strength of the present study is that it also included young athletes whose data may include extremely high HRV—usually as respiratory sinus arrhythmia but sometimes also as nodal rhythm or other form of ectopy. Future studies should validate the ring evaluations in various patient populations where extra beats can be prevalent while normal HRV can be very low. High agreement with the most used time domain parameter (rMSSD) is also encouraging with regards to other HRV parameters, including frequency-domain. rMSSD quantifies the highest frequencies found in HRV and thus includes all excess variability in heartbeat timing that is found in PPG over ECG. It is fair to assume that different calibration methods will be needed for removal of bias between PPG and ECG in each HRV parameter, and the bias can be expected to be smaller the lower the frequency bands being examined.

Feasible and accurate detection of heart beat dynamics also benefits research and application development around various dimensions of sleep health. High parasympathetic and low sympathetic autonomic nervous system activity are generally associated with improved sleep quality, particularly deep/N3 sleep (Penzel *et al* 2016). Literature presents several HRV parameters that correlate with sleep stages, including parameters that are superior to rMSSD in this respect (Xiao *et al* 2013). Several of the most promising HRV parameters in sleep assessment link to respiration. For example, changes in cardiorespiratory coupling, which is the highest in deep sleep and the weakest in REM sleep, can be observed via some parameters.

Over the past few years, wearable devices have become tools for personal wellness, performance, and recovery optimization. In real life practical applications, by following the autonomic nervous system responses via nocturnal HR and HRV, active wearable device users can make lifestyle changes that help them in maintaining balance between mental and physical load and recovery. Right now, wearable technology is also undergoing a shift from tracking users' activity and wellness metrics towards offering relevant real-time health metrics. This shift is further fueled by the advancements in computer technology and machine learning. The comfort and unobtrusiveness of wearable devices, such as the Oura ring, enable the accumulation of unique long-term data, which opens new horizons for healthcare applications and practitioners. Moreover, the accurately and conveniently achieved values will help us as a society to understand human behavior and physiology at a population scale, like in this study which quantified the relationship between sleep consistency and sleep quality (Koskimäki *et al* 2018) or another recent one which illustrated resting HR dynamics in 57 000 people in relation to seasonality, behavioral, and societal factors (Koskimäki *et al* 2019). In the future, wearables can be used for continuous monitoring of people at high risk of developing disease thus providing a cost-effective, early warning system that allows medical interventions

at the earliest stages of disease (Goodday and Friend 2019). For instance, various cardiac arrhythmias and total arrhythmia burden could be assessed with the help of long-term monitoring provided by wearable devices, especially during sleep when body movements are minimized, skin temperature is high, peripheral vascular resistance low, and subsequently, peripheral PPG signal quality is optimal.

5. Conclusions

Present findings indicate high validity of the novel biomedical instrument, the Oura ring, in the assessment of nocturnal HR and HRV in a healthy, adult population. The results are promising for the ring as a new wearable form-factor with various practical applications in lifestyle management. High-quality nocturnal PPG signals that can be achieved by just wearing a ring also prompt future work to discover clinically relevant biomarkers that can be derived from the wearable data to indicate health status and early stage diseases.

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Conflicts of Interest

Oura Health Ltd, full-time or part-time employer of several authors, supported the study by providing salary to the authors, measurement equipment, and associated software but had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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