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2005 Physiol. Meas. 26 531

(http://iopscience.iop.org/0967-3334/26/4/017)

INSTITUTE OF PHYSICS PUBLISHING PHYSIOLOGICAL MEASUREMENT

Physiol. Meas. **26** (2005) 531–544 doi:10.1088/0967-3334/26/4/017

Variability in time delay between two models of pulse oximeters for deriving the photoplethysmographic signals

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Received 3 February 2005, accepted for publication 22 April 2005
Published 10 May 2005
Online at stacks.iop.org/PM/26/531

Abstract

Pulse oximetry is commonly used as an arterial blood oxygen saturation (SaO_2) measure. However, its other serial output, the photoplethysmography (PPG) signal, is not as well studied. Raw PPG signals can be used to estimate cardiovascular measures like pulse transit time (PTT) and possibly heart rate (HR). These timing-related measurements are heavily dependent on the minimal variability in phase delay of the PPG signals. Masimo SET® Rad-9™ and Novametrix Oxypleth oximeters were investigated for their PPG phase characteristics on nine healthy adults. To facilitate comparison, PPG signals were acquired from fingers on the same hand in a random fashion. Results showed that mean PTT variations acquired from the Masimo oximeter (37.89 ms) were much greater than the Novametrix (5.66 ms). Documented evidence suggests that 1 ms variation in PTT is equivalent to 1 mmHg change in blood pressure. Moreover, the PTT trend derived from the Masimo oximeter can be mistaken as obstructive sleep apnoeas based on the known criteria. HR comparison was evaluated against estimates attained from an electrocardiogram (ECG). Novametrix differed from ECG by $0.71 \pm 0.58\%$ ($p < 0.05$) while Masimo differed by $4.51 \pm 3.66\%$ ($p > 0.05$). Modern oximeters can be attractive for their improved SaO_2 measurement. However, using raw PPG signals obtained directly from these oximeters for timing-related measurements warrants further investigations.

Keywords: pulse oximeter, photoplethysmography, heart rate variability, pulse transit time

Introduction

Since its introduction, pulse oximetry has become an increasingly popular instrumentation used in the practice of medicine (Salyer 2003, Trivedi *et al* 1997). Currently, the oximeter is commonly used as a standard non-invasive arterial blood oxygen saturation (SaO_2) measure (Perkins *et al* 2003, Trang *et al* 2004, van Oostrom and Melker 2004). Studies have shown that modern oximeters have the advantages of being accurate, reliable and having good response time for this measure (Goldman *et al* 2000, Trivedi *et al* 1997, Perkins *et al* 2003). Advances in signal processing techniques and data rejection algorithms have claimed improvements in SaO_2 measurement (Goldman *et al* 2000, Trang *et al* 2004). In particular, the newer generation of oximeters like those incorporated with the signal extraction technology (SET®) from the Masimo Corporation (Irvine, California, USA) shows promising results (Salyer 2003, Trivedi *et al* 1997). However, conflicting reports on their performance do exist (Robertson and Hoffman 2004, Bohnhorst *et al* 2000). Although an accurate SaO_2 measure from modern oximeters may be achieved, the characteristics of its other serial output signals like the photoplethysmography (PPG) have yet to be examined.

Besides its primary role as a SaO_2 measure, oximeters are also increasingly used in other cardiovascular measurements like pulse transit time (PTT) and possibly heart rate (HR). This generally involves using raw PPG signals obtained directly from the oximeters (Singham *et al* 2003, Katz *et al* 2003, Pitson *et al* 1994). PTT is a recent, simple and non-invasive technique that uses the PPG signals in its timing derivation. The use of PTT has also been well documented in respiratory sleep studies (Pitson and Stradling 1998, Smith *et al* 1999, Katz *et al* 2003). The present literature defines PTT as the interval between ventricular electrical activity and the appearance of a peripheral pulse waveform (Singham *et al* 2003). For the convenience of prolonged monitoring, the R-wave of the electrocardiogram (ECG) is generally used to indicate the start of the PTT computation (Katz *et al* 2003, Pitson *et al* 1994). Studies have established accurate estimation of the pulse arrival at the periphery by the direct derivation of raw PPG signals from oximeters (Katz *et al* 2003, Singham *et al* 2003, Pitson and Stradling 1998). Documented evidence suggested that the PTT baseline value at resting heartbeat for healthy adults is approximated to be 250 ms (Pitson *et al* 1994, Smith *et al* 1999, Singham *et al* 2003). As PTT is a semi-quantitative measure, it is recommended that fluctuations from its baseline be used instead (Katz *et al* 2003, Smith *et al* 1999). Studies have also shown that an equivalent relationship between blood pressure (BP) and PTT can be drawn. A change of 1 ms in PTT can be considered as a corresponding change of 1 mmHg in BP (Pitson and Stradling 1998, Pitson *et al* 1994). On the other hand, HR measurement is useful to predict cardiovascular morbidity in a non-invasive manner. The exact definition of the conditions under which HR is measured appears to be as crucial as the determination of blood pressure or plasma catecholamine (Reunanen *et al* 2000, Seccareccia *et al* 2001). In clinical monitoring, the principal interest for PTT and HR measures is in their relative changes from the baseline value in response to clinical events.

Presently, no study has yet been performed to investigate the phase coherence of raw PPG signals when different models of oximeter are used. In medical practices, both the PTT and HR measure are becoming more frequently used as diagnostic tools. HR measurement is used to monitor the cardiovascular status of in-hospital patients and the use of PTT has been marketed beyond its application of respiratory sleep studies in a growing trend (Singham *et al* 2003, Mahmud and Feely 2004, Naschitz *et al* 2004). With the clinical roles both PTT and HR measures play, it is important to assess the accuracy of raw PPG signals in their timing derivations. It is understood that due to the inherent computational overheads in oximeters, phase delays in the PPG signals are expected. However, undesirable variability induced

in these phase delays can affect the accurate timing derivations from the peripheral pulse waves.

Hence, this was a clinical observation on the raw PPG signals when they were used in timing-related measurements with the following objectives: (1) to test the signal heuristic performance and agreement between different oximeters, (2) to evaluate their potential to estimate PTT values in a coherent manner and (3) to assess their reliability when their relative beat-to-beat (B–B) estimates were used to derive HR.

Methods and Materials

Subject

This study involved the participation of nine healthy adults (five were male and four were female) with a mean age of 32.2 $\pm$ 8.7yr (range 22 to 46yr). Only adults with no clinically apparent arterial diseases, physical abnormalities, or observable injury of the peripheries on medication or strenuous exercise 24 h prior were recruited. All measurements were performed in a typical sleep laboratory in a tranquil environment at an ambient temperature of 25 °C from 2 pm to 5 pm. Before the test activity, all subjects were habituated to the surrounding for at least 10 min for cardiovascular stability.

Materials used

In this study, a blinded side-by-side comparison was conducted on two different generations of oximeter with a serial PPG signal output. The first selected oximeter was a recent model of SET® Rad-9™ from the Masimo Corporation. The signal processing capabilities of this oximeter differed from its conventional counterpart as it was equipped with a combination of adaptive filtering and a discrete saturation transformation process. The second was a conventional oximeter equipped with an auto-gain feature, Oxypleth model 520A (Novametrix Medical Systems Inc, Wallingford, USA). Both oximeters used a two-wavelength pulsatile system to distinguish between oxygenated and deoxygenated blood. The light sources of red (660 nm) and infrared (940 nm for Novametrix or 905 nm for Masimo) light-emitting diodes (LED) were used to derive the pulsatile cycles from the measured periphery. The Novametrix oximeter had a pulse rate (PR) accuracy ranging from 30 to 250 beats per minute (bpm) with a resolution of 1 bpm. Similarly, the Masimo oximeter had PR accuracy between 25 and 240 bpm at 1 bpm resolution. Further technical specifications were not included in this study to avoid violations of manufacturers' proprietary rights. In order to facilitate comparison, both devices were set to the 8 s averaging mode and proprietary reusable finger probes (Masimo LNOP DCI and Novametrix OxySnap) were used accordingly. PPG signals obtained from the two oximeters were fed continuously into an 8 channel analogue-to-digital converter (ADC) system and recorded in its proprietary software, Chart version 3.5 (ADInstruments Corporation, Sydney, Australia).

The R–R estimates obtained from a single-lead ECG machine (S&W Medico, Teknik, Denmark) were used to quantify PTT estimations and HR comparison. In order to compare PTT measurement in this study, a custom-made battery-operated PPG device was constructed using discrete electronic devices. It was tested for its compliance of introducing less than 90° phase lag per measured period from 0 to 2 Hz. This custom PPG device had no signal processing capability and a signal bandwidth from 0 to 17.3 Hz. The finger probe housed only a red LED with a nominal wavelength of 660 nm and a photo-detector. The basic block diagram of the said PPG device is given in figure 1. The inclusion of the custom PPG device

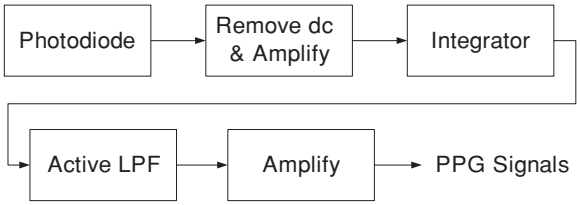

Figure 1. Block diagram of the custom-made PPG device where LPF denotes low-pass filter.

was for its known output phase performance and only for comparison purposes within the context of this study. A total of four continuous measure outputs were fed simultaneously into the ADC system and recorded at a rate of 400 samples per second for further analysis. No post-signal processing was applied to either the PPG or ECG signals.

Experimental protocol

Raw PPG timing characteristics were obtained directly from the serial port provided by the manufacturers and were assessed on the tidal breathing of the subjects in their wakeful state. In order to minimize possible timing differences, PPG signals were acquired from different fingers on the right-hand side. The measuring probes from the Masimo, Novametrix and custom PPG devices were placed on the index, middle and ring fingers of the subjects randomly. After the ECG leads were placed on the chest, the subject was familiarized with the measuring apparatus for another 5 min in the sitting posture. The subject was then asked to sit as still as possible with the measured right arm resting on the subject's right thigh for a minimum recording period of 60 s. The ECG signals were also recorded in conjunction with the PPG signals. Thereafter, the same sequence was applied to ensure all the three devices acquired PPG signals from all three fingers in a random fashion for no less than 60 s. Moreover, an interval of 5 min rest was given between each successive PPG recording.

All the obtained data were imported into the Matlab version 6.5 environment (MathWorks Inc, Natick, USA) and had a recorded resolution of 2.5 ms. To optimally estimate the corresponding PTT and HR values from the raw PPG signals, the 25% of its peak amplitude was used as suggested by others (Smith *et al* 1999, Katz *et al* 2003, Singham *et al* 2003). A test program that predicted each corresponding PPG peak was written in the Matlab environment. Firstly, a slope detection algorithm was used to indicate the rising edge of the PPG signals and a differentiator then detected their corresponding peak. Thereafter, a window of 100-recorded data following this detected peak was used to determine its validation. This was to minimize the false locating of peaks induced by ripples riding on the PPG signals. After that, the corresponding 25% point was located and recorded. Likewise, the peak of the ECG R-waves was used as the marker in both the PTT and HR estimations (Smith *et al* 1999, Katz *et al* 2003, Singham *et al* 2003).

Statistical analyses

Due to the possible differences in arterial compliance, absolute PTT values by themselves cannot be quantified (Katz *et al* 2003, Pitson *et al* 1994, Smith *et al* 1999). In this study, PTT measurements were assessed in two methods. Firstly, in order to appreciate the significance of PTT variations from its baseline, the suggested relationship between BP and PTT (Pitson and Stradling 1998, Pitson *et al* 1994) was adopted. Particularly, the magnitudes of PTT variations or the corresponding BP variability were examined. In order to minimize inter-subject variability, the mean PTT from each subject was subtracted from all PTT data

for that subject. This effectively removed inter-subject differences in PTT values and gave a mean PTT of zero for all data. Secondly, the trend of PTT variations was then tested for its compliance within the boundary of 15 ms from its baseline. Exceeding this boundary by more than a 5 s period was defined as the occurrence of obstructive sleep apnoea (OSA) in respiratory sleep studies (Pitson and Stradling 1998, Katz *et al* 2003).

HR comparison was derived as a relative ratio of B–B with respect to its corresponding R–R estimate from the ECG signals. The latter also served as the reference for any phase assessment in this study. This ratio comparison was adopted to minimize the possible effects of inter-subject HR differences on the result accuracy and the equation used was as follows:

$$\text{Ratio}(\%) = \left| \frac{(\text{R–R}) - (\text{B–B})}{(\text{R–R})} \right| \times 100\%. \tag{1}$$

The analysis with correlations and least squares linear regression or calibration statistics was found to be fundamentally limited. It was recommended that a statistical method for assessing the agreement between two methods of measurement be used (Bland and Altman 1999, Mantha *et al* 2000). Hence, the Bland–Altman plot was employed to compare the level of agreement in HR estimates between the three PPG devices and the ECG. Statistical analysis was performed using SPSS for Windows Student version 11 (SPSS, North Chicago, Illinois, USA) and the Excel XP (Microsoft Corporation, Seattle, USA) package. Descriptive statistics was performed on all data including the ECG readings. Paired Student's *t*-test assuming equal variance was used to test for significant differences and correlations for discrete data among the two oximeters against the ECG data. In this study, a value of $p < 0.05$ was considered statistically significant.

Results

From the obtained results, it can be observed that mean PTT estimates from the Novametrix oximeter had a range from 238.8 to 278.4 ms with a window difference of 39.6 ms, whereas mean PTT estimated by the custom-made PPG device had a range of 241.1 to 298.9 ms with a window difference of 57.8 ms. However, the Masimo oximeter estimated mean PTT ranged from 185.4 to 326.7 ms with a window difference of 140.3 ms for the same pool of subjects. Interestingly, the Masimo oximeter estimated a much wider mean PTT range when compared to the other two devices as given in table 1. From the same table, it can be seen that PTT variations for each subject obtained from the Masimo were also observably greater. Intra-subject mean PTT variation obtained from the Novametrix oximeter was 5.66 ms and custom PPG was 9.58 ms while the Masimo oximeter registered 37.89 ms. With the known equivalent relationships with BP, this can be interpreted as variability of 5.66 mmHg, 9.58 mmHg and 37.89 mmHg respectively. It can be seen from figure 2 that the PTT values estimated by the Novametrix oximeter and custom PPG device were fluctuating close to its baseline and within the 15 ms limits. However, a period of approximately 6 s with more than 15 ms variations can be observed in PTT estimates derived from the Masimo oximeter as given in figure 2. This can be mistakenly regarded as an OSA event in respiratory sleep studies as described by others. It is worth noting that the entire study was conducted with the subjects in their tidal breathing and wakeful state.

From table 2, it can be seen that HR estimates derived from the raw PPG signals of the Novametrix and custom PPG devices were significantly correlated ($p < 0.05$) with those obtained from R–R estimates of the ECG. However, HR estimates from the Masimo PPG signals were not considered significantly correlated ($p > 0.05$) in all subjects. The Bland–Altman plots in figures 3–5 can better demonstrate the level of agreement in HR

Table 1. Results showed that mean PTT derived from the Masimo oximeter had a wider range when compared to the Novametrix oximeter or custom PPG device. Furthermore, the observably larger PTT variations obtained using the Masimo oximeter may be interpreted as abrupt BP variations. This table also shows that possible false alarms of OSA events occurred when the Masimo oximeter was used on some of the subjects even in their tidal breathing and wakeful state.

	Mean PTT (ms)			PTT variations (ms)			No of mistaken OSA		
Subject	Novametrix	Masimo	Custom	Novametrix	Masimo	Custom	Novametrix	Masimo	Custom
1 (M)	272.2 ± 5.8	302.4 ± 42.1	276.9 ± 7.0	4.60 ± 3.56	30.02 ± 27.44	5.80 ± 3.94	0	4	0
2 (F)	266.0 ± 6.8	314.6 ± 43.2	287.0 ± 11.3	5.79 ± 3.55	34.86 ± 22.18	9.37 ± 7.40	0	3	0
3 (M)	270.2 ± 5.9	326.7 ± 35.1	290.4 ± 13.5	4.74 ± 3.36	27.71 ± 19.51	11.14 ± 7.71	0	0	0
4 (M)	256.0 ± 8.1	185.4 ± 69.4	253.7 ± 8.4	6.42 ± 4.88	50.32 ± 31.99	6.58 ± 5.26	0	5	0
5 (M)	273.8 ± 6.8	204.8 ± 50.3	241.1 ± 17.6	5.19 ± 4.47	39.62 ± 29.71	14.36 ± 9.57	0	2	0
6 (F)	238.8 ± 9.7	199.7 ± 26.3	267.5 ± 10.0	7.19 ± 6.51	21.40 ± 14.35	7.46 ± 6.58	0	4	0
7 (F)	254.2 ± 10.3	295.4 ± 31.1	263.8 ± 17.0	8.83 ± 5.25	23.67 ± 20.15	15.88 ± 12.08	0	0	0
8 (M)	278.4 ± 6.2	326.2 ± 30.0	298.9 ± 6.4	4.82 ± 3.73	24.13 ± 17.16	5.08 ± 3.59	0	3	0
9 (F)	266.9 ± 4.7	308.8 ± 47.5	281.8 ± 7.8	3.94 ± 2.54	39.49 ± 26.43	6.42 ± 4.41	0	2	0
		Mean ± SD		5.66 ± 4.44	37.89 ± 38.28	9.58 ± 10.41	0	23	0

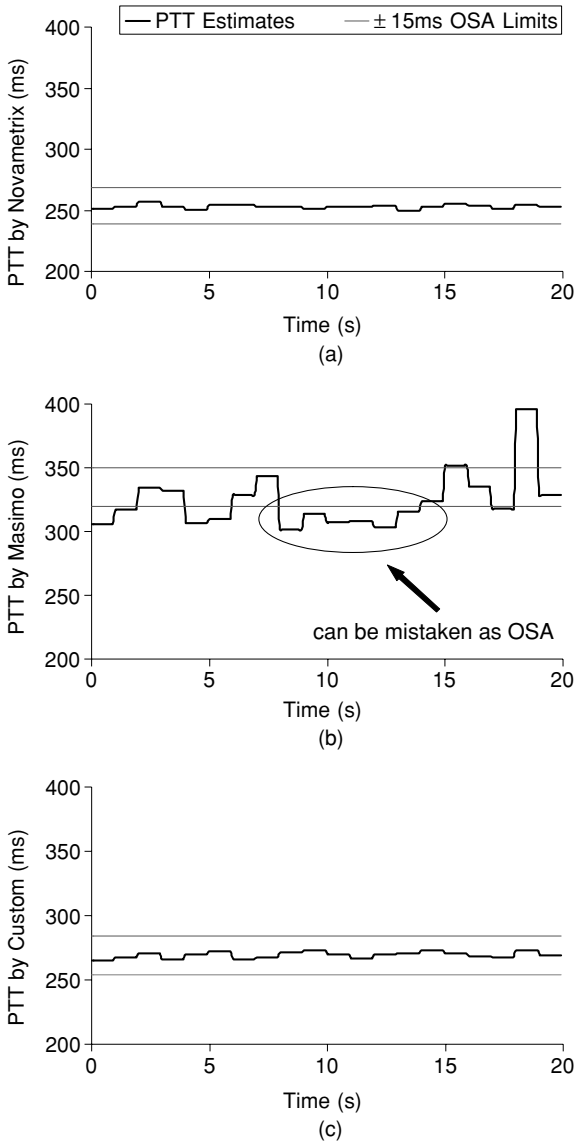

Figure 2. (a) Mean PTT and variations estimated by the Novametrix oximeter at resting heartbeats. It can be seen that the PTT values are fluctuating within the 15 ms boundary that was used as an indication of OSA occurrence. (b) Much wider PTT variations estimated by the Masimo oximeter on the same subject can be seen. It is observed that a period of 6 s with more than 15 ms variations has occurred and this can be mistaken as the occurrence of OSA in respiratory sleep studies. Furthermore, such variations may be interpreted as abrupt BP variability on a beat-to-beat basis. These incidences can cause false alarms and clinical diagnosis can be compromised. (c) Similar PTT variations estimated by the custom PPG device when compared to the Novametrix oximeter at resting heartbeats. Its estimated PTT values are also fluctuating within the 15 ms OSA occurrence boundary.

estimates from the three devices when compared to the ECG. Similarly, this can be suggestive that HR estimates from the Masimo device may not reflect the cardiovascular status of the subjects accurately even during resting heartbeat.

Table 2. The entries show the results of relative B–B differences of the two oximeters and custom PPG device at resting heartbeats when compared to the ECG. Each device compares its derived HR as a percentage against that attained from the ECG machine. A (#) sign indicates that data were not significantly correlated. Similarly, it can be seen that the Masimo oximeter had an uncorrelated result ($p > 0.05$) with the ECG.

		Novametrix			Masimo			Custom		
Subject	n	Ratio (%)	r^2 value	p value	Ratio (%)	r^2 value	p value	Ratio (%)	r^2 value	p value
1 (M)	238	0.71 ± 0.68	0.967	<0.05	4.19 ± 3.38	0.464	>0.05#	0.48 ± 0.40	0.985	<0.05
2 (F)	189	0.73 ± 0.59	0.946	<0.05	3.21 ± 2.76	0.633	>0.05#	1.16 ± 0.91	0.931	<0.05
3 (M)	241	0.69 ± 0.50	0.979	<0.05	3.50 ± 2.85	0.599	>0.05#	1.18 ± 0.80	0.943	<0.05
4 (M)	186	0.75 ± 0.57	0.992	<0.05	6.85 ± 5.13	0.411	>0.05#	0.80 ± 0.54	0.996	<0.05
5 (M)	171	0.78 ± 0.61	0.971	<0.05	4.09 ± 2.84	0.502	>0.05#	0.92 ± 0.62	0.948	<0.05
6 (F)	168	0.59 ± 0.48	0.988	<0.05	4.72 ± 3.51	0.394	>0.05#	1.09 ± 0.87	0.907	<0.05
7 (F)	214	0.68 ± 0.52	0.965	<0.05	2.69 ± 2.42	0.645	>0.05#	1.42 ± 1.23	0.879	<0.05
8 (M)	243	0.57 ± 0.47	0.985	<0.05	3.94 ± 3.01	0.435	>0.05#	0.68 ± 0.57	0.968	<0.05
9 (F)	222	0.64 ± 0.42	0.976	<0.05	3.84 ± 2.38	0.487	>0.05#	0.92 ± 0.75	0.957	<0.05
Total	1872	0.71 ± 0.58	0.972	<0.05	4.51 ± 3.66	0.704	>0.05#	0.89 ± 0.71	0.944	<0.05

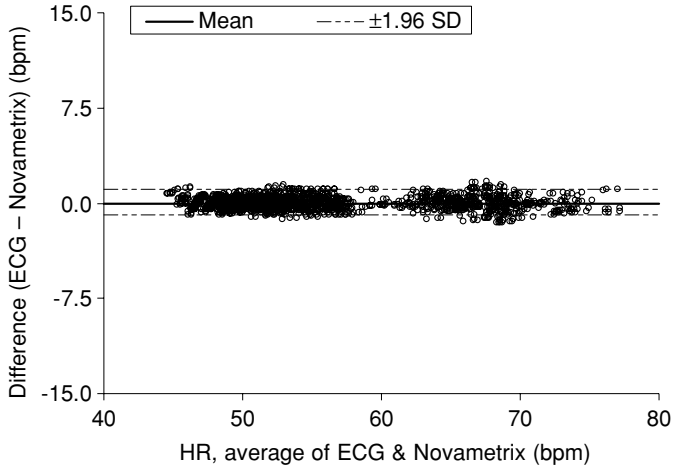

Figure 3. Bland–Altman plot of HR difference between the ECG and Novametrix oximeter versus the average of the two respective readings with 95% limits of agreement. This showed a better level of agreement between the two relative to that of the Masimo oximeter.

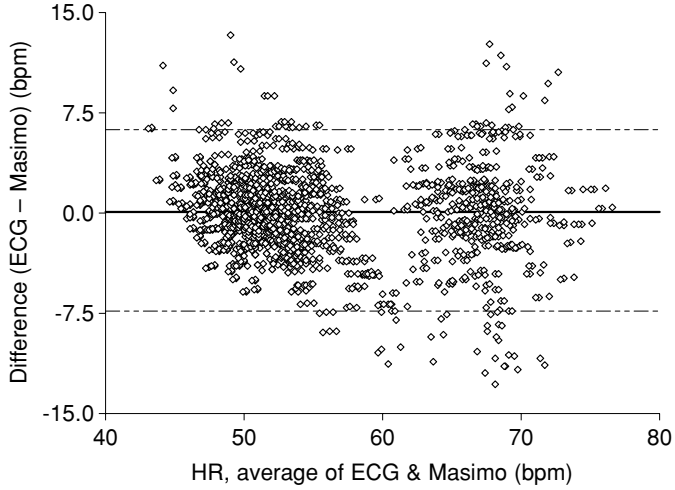

Figure 4. Bland–Altman plot of HR difference between the ECG and Masimo oximeter with wider differences from the ECG when compared to the Novametrix oximeter.

As the ECG by itself is not variable in the same manner with the PPG signal, its corresponding peaks from all the three PPG devices were further compared. In table 3, the absolute timing differences of the PPG signals among all three devices are tabulated. It can be seen that the mean timing difference between Novametrix and Masimo oximeters was 35.83 ms, Novametrix and custom was 11.31 ms while Masimo and custom was 37.85 ms. Figure 6 shows that raw PPG signals from the Masimo oximeter may have a varying phase output. From the same figure, it can be observed that the Novametrix oximeter, the custom PPG device and the ECG had observably negligible phase variability when they were compared against one another. In the upper plot, using the R-wave as a guide, it can be observed that the Masimo PPG signal was lagging for its first three estimates compared to those from the

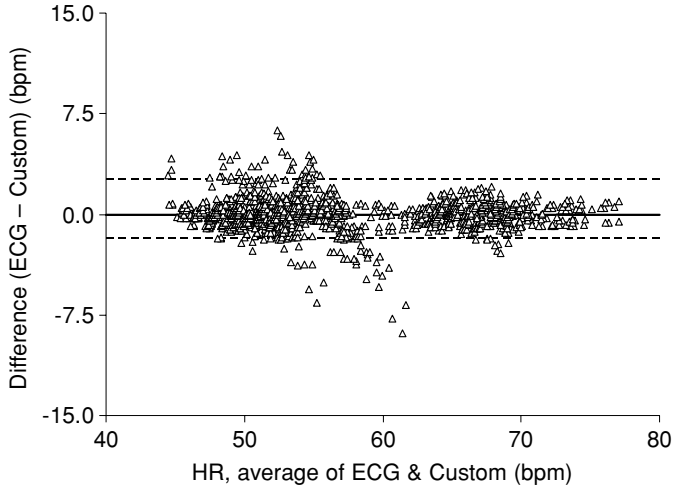

Figure 5. Bland–Altman plot of HR difference between the ECG and custom PPG device.

Table 3. In comparison with each successive peak of the PPG signals, the results showed that the Masimo oximeter had the most distinctive timing differences among the three devices.

	Differences in respective PPG peaks (ms)		
Subject	Novametrix and Masimo	Novametrix and custom	Masimo and custom
1	30.60 ± 30.16	6.38 ± 5.57	31.38 ± 30.38
2	44.70 ± 32.72	11.04 ± 10.27	49.37 ± 35.65
3	33.63 ± 24.58	12.00 ± 8.04	34.74 ± 23.69
4	42.77 ± 33.75	11.71 ± 9.52	50.14 ± 31.07
5	54.62 ± 42.03	7.50 ± 7.96	54.63 ± 42.48
6	23.84 ± 18.74	7.77 ± 5.25	22.46 ± 17.42
7	20.75 ± 15.84	12.19 ± 9.63	28.65 ± 25.38
8	22.69 ± 15.24	8.24 ± 7.34	24.06 ± 16.99
9	34.64 ± 23.49	8.00 ± 7.79	34.19 ± 21.95
Mean	35.83 ± 32.50	11.31 ± 10.94	37.85 ± 32.20

Novametrix and custom devices. However, it attained phase coherence for the next two before leading on its fifth to seventh estimates. The nature of this cycle was unknown at this stage. Alternatively, it can be seen that the intervals between PPG signals from the Masimo oximeter and the R-wave shortened with the progression of time in the middle plot of figure 6. The lower plot illustrates that phase variability between the PPG signals from the Novametrix or custom device was observably negligible between the two.

Discussion

The present study was undertaken to analyse the differences in timing-related measurements when raw PPG signals acquired from different commercial devices were used. With the inclusion of the custom-built PPG device, it provides a platform for comparison only for the purpose of the present study as its output phase delay and signal processing capability are known. The results obtained here demonstrate that PPG phase characteristics attained from different oximeters diverge in a significant manner. Present commercial efforts are generally

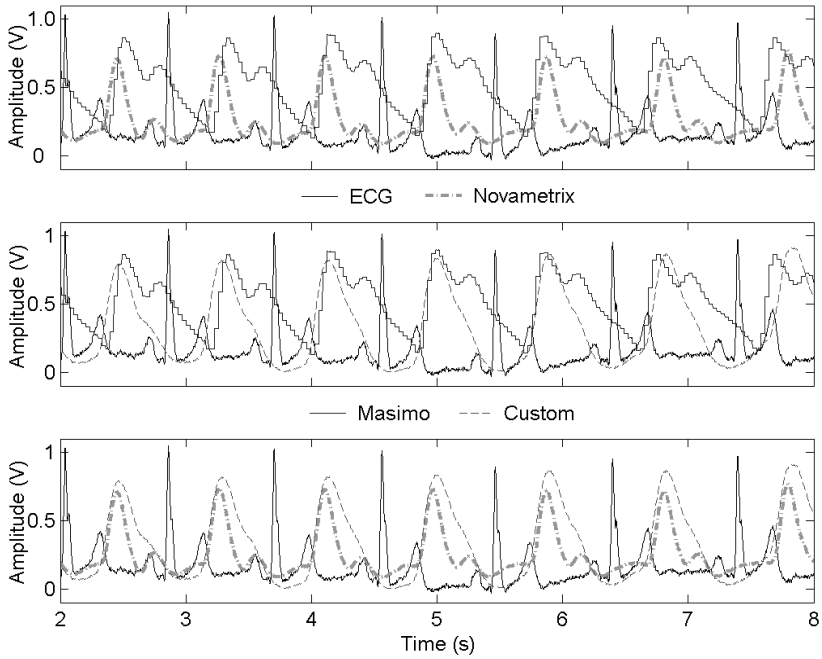

Figure 6. This figure illustrates that raw PPG signals from the Masimo oximeter had variable phase delays when compared to the ECG, Novametrix oximeter or custom PPG device. It can also be seen that the intervals between Masimo PPG signals and the R-wave shortened with the progression of time. The phase variability among the other three devices was observably negligible. In timing-related measures like PTT and HR, such variability in phase delay can lead to wider variations and inaccurate measurements can occur.

focused on improving the SaO_2 measure but other serial outputs like the PPG signals may yet attract similar interest. Although the signal processing algorithms used to derive the SaO_2 and PPG measure within the same oximeter are often different, the characteristics of the latter are frequently overlooked. In this study, only raw PPG signals were evaluated based on two cardiovascular measures of PTT and HR during tidal breathing of subjects in their wakeful state. The results herein indicate that detailed investigations are necessary before employing any raw signals from the oximeters for purposes other than what they were designed for.

It is recognized that due to the inherent computational overheads in oximeters, phase lags are expected in the raw output PPG signals. However, variability in these phase lags is undesirable especially when such variability can compromise the accuracy of timing-related measurements as demonstrated in this study. It is common that raw PPG signals are used directly from oximeters (Katz *et al* 2003, Singham *et al* 2003, Pitson *et al* 1994) and devices that incorporate PPG output (Smith *et al* 1999, Naschitz *et al* 2004) in clinical studies. It is therefore prudent to understand the possible complications these raw signals may have before applying them for specific purposes. The findings obtained here may also indicate that some commercial devices may not be designed to output laboratory grade PPG waveforms that can be used directly for detailed physiologic analysis.

In figure 6, it was shown that the raw PPG signals from the Masimo oximeter seem to have a moving characteristic in phase. It can produce leading PPG signals at certain intervals while lagging at others even for the same subject at resting heartbeats. This phase observation is done with respect to two commercial devices (the ECG machine and Novametrix oximeter)

and a custom-made PPG device with a known maximum phase lag of 90°. However, the occurrence of this phenomenon is unclear and warrants further investigations. From the same figure, it appears that Masimo oximeter may also have a lower sampling rate or less resolution than both the Novametrix oximeter and custom PPG device. This lower resolution signal may also account for the observed inaccuracy in its timing determination. Furthermore from the Bland–Altman plots, it is clear that there is a lower level of agreement in HR estimates between the Masimo oximeter and the ECG. The implications of these figures do indicate that accuracy of timing-related measures can be compromised if raw PPG signals with variability in phase delay are used directly in timing-related derivations.

In cardiovascular measurements, abrupt changes from PTT or HR baseline values are generally used as a non-invasive indicator of clinical events. Previous studies demonstrated that a change of 1 ms in PTT can be considered equivalent to a 1 mmHg variation in BP (Pitson and Stradling 1998, Pitson *et al* 1994). With this correlation, the wider PTT variations registered by the Masimo oximeter can give a false indication of the number of BP changes. Previous studies have suggested that BP variability may be an independent risk factor for cardiovascular morbidity, on the grounds that biological materials are more susceptible to damage by changes of pressure than steady-state levels (Pickering *et al* 2005, Parati *et al* 1995, Hata *et al* 2002). Although some of these studies support a pathological role of increased BP variability, the extent of such adverse effects remains unclear (Parati *et al* 1995, Hata *et al* 2002). The wider PTT variations acquired from the Masimo oximeter as seen in the present study can be misinterpreted as the occurrences of clinical events. However, the exact clinical implications of such variations warrant further examinations.

In respiratory sleep studies, a notable shift in mean PTT baseline can occur during episodes of upper airway collapse during sleep (Pitson *et al* 1994, Smith *et al* 1999). Previous studies defined the occurrences of OSA as variations from the PTT baseline by more than 15 ms for a given period of longer than 5 s (Pitson and Stradling 1998, Katz *et al* 2003). By this definition, PTT estimates from the Masimo oximeter may not be able to portray OSA events in a faithful manner as its variations during tidal breathing are already likely to exceed this limit as illustrated in figure 2. Studies have suggested that monitoring HR is not only an indicator of pre-existing illness but also an independent predictor of fatal events. A positive association between HR and cardiovascular diseases like coronary diseases and sudden death has been established (Reunanen *et al* 2000, Seccareccia *et al* 2001). As the diagnosis of these sufferers is highly dependable on these relative indications, it is essential that such clinical events are reflected appropriately.

There are some limitations for this study. Firstly, it is known that PPG signal characteristics may be distinct on different peripheries due to the possible variations in pigmentation, perfusion and vascular compliance. The PPG signals in this study were attained from the index, middle and ring fingers on the same hand in a random fashion. Based on this understanding, the differences in the PPG phase characteristics among the three sets of recordings should have been averaged out. Secondly, it is acknowledged that the proprietary finger probes used in this study can have different transmission mode sensors with distinctive application pressure on the measured fingertip. However, these probes are commercially produced and can be easily regarded as equivalent unless proved otherwise. Thirdly, both pulse oximeters and their accessories are commercial instruments whereas the custom PPG device was yet to be calibrated to any industrial standard. Nevertheless, its sole purpose is for comparison within the context of this study only as its output characteristics are known. Lastly, it is also recognized that the various frequency bands of the PPG signals can contribute to the observed variations in a different manner. Hence, this warrants a further investigation as a continual study to understand their individual contributions to the overall fluctuations of PPG signals.

Conclusions

A recent innovative approach that adopts advanced signal processing algorithms may have shown promising results pertaining to the accuracy and noise immunity of the SaO_2 measure from pulse oximetry. However, other serial outputs derived from these modern oximeters like the raw PPG signals have yet to be well studied. From the present study, one possible limitation of these oximeters is the inherent variability in phase delay their PPG signals are subjected to. Phase delays may be common in commercial devices but it is clear that variability in these phase delays can compromise clinical interpretations of timing-related measures, like PTT and HR estimates. Documented evidence has demonstrated that abnormal variations in PTT can indicate the presence of clinical events in respiratory sleep studies and possibly cardiovascular studies. The devices used in these clinical studies must be able to abide by such boundaries. Oximeters from different models or manufacturers may output their PPG signals in a divergent manner. Hence, data from different oximeters may deviate and caution should be applied when they are used directly for timing-related measurements. It is then important that clinical investigations are conducted to understand the contextual PPG performance from these oximeters before applying them directly for specific purposes or measurements.

References

Bland J M and Altman D G 1999 Measuring agreement in method comparison studies *Stat. Methods Med. Res.* **8** 135–60

Bohnhorst B, Peter C S and Poets C F 2000 Pulse oximeters' reliability in detecting hypoxemia and bradycardia: comparison between a conventional and two new generation oximeters *Crit. Care Med.* **28** 1565–8

Goldman J M, Petterson M T, Kopotic R J and Barker S J 2000 Masimo signal extraction pulse oximetry *J. Clin. Monit. Comput.* **16** 475–83

Hata Y *et al* 2002 Office blood pressure variability as a predictor of acute myocardial infarction in elderly patients receiving antihypertensive therapy *J. Hum. Hypertens.* **16** 141–6

Katz E S, Lutz J, Black C and Marcus C L 2003 Pulse transit time as a measure of arousal and respiratory effort in children with sleep-disordered breathing *Pediatr. Res.* **53** 580–8

Mahmud A and Feely J 2004 Effects of passive smoking on blood pressure and aortic pressure waveform in healthy young adults—influence of gender *Br. J. Clin. Pharmacol.* **57** 37–43

Mantha S, Roizen M F, Fleisher L A, Thisted R and Foss J 2000 Comparing methods of clinical measurement: reporting standards for Bland and Altman analysis *Anesth. Analg.* **90** 593–602

Naschitz J E *et al* 2004 Patterns of cardiovascular reactivity in disease diagnosis *Q. J. Med.* **97** 141–51

Parati G, Saul J P, Di Rienzo M and Mancia G 1995 Spectral analysis of blood pressure and heart rate variability in evaluating cardiovascular regulation. A critical appraisal *Hypertension* **25** 1276–86

Perkins G D, McAuley D F, Giles S, Routledge H and Gao F 2003 Do changes in pulse oximetry oxygen saturation predict equivalent changes in arterial oxygen saturation? *Crit. Care* **7** R67–71

Pickering T G, Hall J E, Appel L J, Falkner B E, Graves J, Hill M N, Jones D W, Kurtz T, Sheps S G and Roccella E J 2005 Recommendations for blood pressure measurement in humans and experimental animals. Part 1: blood pressure measurement in humans: a statement for professionals from the subcommittee of professional and public education of the American heart association council on high blood pressure research *Circulation* **111** 697–716

Pitson D, Chhina N and Knijn S 1994 Changes in pulse transit time and pulse rate as markers of arousal from sleep in normal subjects *Clin. Sci.* **87** 269–73

Pitson D J and Stradling J R 1998 Value of beat-to-beat blood pressure changes, detected by pulse transit time, in the management of the obstructive sleep apnoea/hypopnoea syndrome *Eur. Respir. J.* **12** 685–92

Reunanen A, Karjalainen J, Ristola P, Heliovaara M, Knekt P and Aromaa A 2000 Heart rate and mortality *Intern. Med. J.* **247** 231–9

Robertson F A and Hoffman G M 2004 Clinical evaluation of the effects of signal integrity and saturation on data availability and accuracy of Masimo SET® and Nellcor N-395 oximetry in children *Anesth. Analg.* **98** 617–22

Salyer J W 2003 Neonatal and pediatric pulse oximetry *Respir. Care* **48** 386–96

Seccareccia F, Pannozzo F, Dima F and Minoprio A 2001 Heart rate as a predictor of mortality: the MATISS project *Am. J. Public Health* **91** 1258–63

Singham S, Voss L, Barnard J and Sleigh J 2003 Nociceptive and anaesthetic-induced changes in pulse transit time during general anaesthesia *Br. J. Anaesth.* **91** 662–6

Smith R P, Argod J, Pepin J L and Levy P A 1999 Pulse transit time: an appraisal of potential clinical applications *Thorax* **54** 452–8

Trang H, Boureghda S and Leske V 2004 Sleep desaturation: comparison of two oximetry *Pediatr. Pulmonol.* **37** 76–80

Trivedi N S, Ghouri A F, Lai E, Shah N K and Barker S J 1997 Pulse oximeter performance during desaturation and resaturation: a comparison of seven models *J. Clin. Anesth.* **9** 184–8

van Oostrom J H and Melker R J 2004 Comparative testing of pulse oximetry probes *Anesth. Analg.* **98** 1354–8