Remote PPG Imaging by a Consumer-grade Camera under Rest and Elevation-invoked Physiological Stress Reveals Mayer Waves and Venous Outflow

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Keywords: Photoplethysmography, Microvasculature, Hemodynamics, Contactless, Remote, Bioimaging.

Abstract: Introduction: The photoplethysmographic (PPG) signal contains information about microvascular hemodynamics, including endothelial-related metabolic, neurogenic, myogenic, respiratory, and cardiac activities. The present goal is to explore the utility of a consumer-grade smartphone camera as a tool to study such activities. Traditional PPG is conducted using a contact method, but the resultant contact pressure can affect venous flow distribution and distort perfusion examination. This motivates us to develop a remote PPG method (rPPG) to study such activities. Methods: We used an imaging setup composed of a stand-mounted consumer grade camera (iPhone 8) with on-board LED illumination. The camera acquired 1920x1080 video data at 60 frames per second (fps); 90 second videos were captured for a hand in rest and elevated positions. Spatial averaging was performed to extract rPPG, which was filtered using continuous wavelet transform to analyse frequency ranges of interest. Results: The data demonstrated a plurality of observed patterns, which differed between rest and elevation positions. In addition to cardiac and respiratory activities, we noticed another two distinct low frequency patterns: oscillations that we conclude are likely Mayer waves, and monotonic reflection increase (gravitational venous outflow). In some cases, these two patterns are combined. Conclusions: rPPG demonstrated potential for venous compartment examinations.

1 INTRODUCTION

Photoplethysmography, or PPG, works by measuring the changes in absorption of light through tissue. The origin of the PPG signal is still a topic of active debate, but the generally accepted origins, which may also be correlated/overlapping, include changes in blood volume within the tissue, position and geometry of red blood cells, and mechanical motion of capillaries (Kyriacou & Allen, 2021). In a typical scenario, PPG measurements are collected at a single wavelength, usually within the infrared range (700-900 nm), at which hemoglobin absorbs light at a reduced level. If the tissue oxygenation is required, then two wavelengths (typically in red and infrared ranges of spectrum) are used (Wukitsch et al, 1988).

A conventional contact PPG signal can be captured using one of two acquisition modes: transmission or reflection. In transmission (most used clinically), a light emitter and receiver are positioned on either side of tissue (such as finger), and the attenuated light is captured by the receiver after transiting through the tissue. In contrast, in reflection-mode PPG, the light emitter and receiver are both situated on the same side of the tissue. Emitted light interacts with the tissue, some of which is backscattered and captured by the detector. Popularity of this contact modality is increasing in consumer applications, and can now be found in multiple smart watches and other wearable devices.

In the most common scenario for the contact PPG, pulse oxymetry, a wealth of physiological information can be extracted from this single-point measurement. In addition to the tissue oxygenation

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Burton, T., Saiko, G. and Douplik, A.
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DOI: 10.5220/0010883100003123
In *Proceedings of the 15th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2022) - Volume 2: BIOIMAGING*, pages 153-159
ISBN: 978-989-758-552-4; ISSN: 2184-4305

(Nitzan & Engelberg, 2009), several other physiological parameters can be extracted, including heart rate (Temko, 2017), heart rate variability (Lin et al., 2014), as well as respiratory rate (Daimiwa et al., 2014). From this information, other parameters, including blood pressure (Kurylyak et al., 2013), can be inferred. However, the analysis of PPG signals can be challenging, due to characteristics of biological signals in general. For example, non-stationarity, which is the time dependence of statistical properties such as standard deviation and mean in the signal, necessitates careful selection of signal processing technique to accurately quantify signal properties (Usui & Toda, 1991).

Remote PPG (rPPG) is an adaptation of transmission mode PPG in which a camera is used to capture the backscattered light from the tissue.The primary advantage of remote PPG over contact PPG lies in its contactless nature, rendering it suitable for applications with sensitive tissue (such as wounds, burns, neurological conditions, etc.) in addition to addressing other limitations of contact PPG. For instance, the contactless property means that it does not rely on robust skin-to-sensor contact, which is necessary for a strong PPG signal acquired using the contact method. Maintaining high fidelity skin to sensor contact is also made more difficult by the sensor being mechanically fixed to the skin, requiring external pressure (e.g., spring-loaded finger clip) that can have a significant effect on PPG signal quality and reproducibility. Further, contact PPG has high sensitivity to motion artifacts, and therefore requires the patient to stay very still.

In the most typical acquisition scenario, rPPG is used to capture a single PPG signal over a whole tissue area, such as the palm (Zheng et al., 2008) or face (Zheng et al., 2009). However, the utility of rPPG goes beyond tissue oxygenation. For example, several PPG devices placed on the skin can be used to extract pulse wave velocity (PWV), which demonstrates a significant clinical value (e.g. baPWV (Katakami et al., 2014)).

With a large enough field of view, the same data can be collected using video rPPG, which registers rPPG signals for segments of the field of view (in contrast to a single signal from the entire field of view). Several recently proposed imaging modalities take advantage of the multi-pixel nature of rPPG and aim to extract additional physiological information from spatially resolved rPPG signals. For example, (Saiko et al., 2021) used a high frame rate camera to analyze pulse wave velocity in peripheral blood vessels. Similarly, (Burton et al., 2021) used spatially resolved PPG signal to extract information about tissue perfusion.

However, as we go beyond typical PPG utility, complexity rises. The hemodynamics of the microcirculation are extremely complex, with multiple autoregulatory systems at play.

The predominant signal source in the PPG is the cardiac pulsation caused by the ejection of blood from the left ventricle during cardiac systole, which affects the origins previously described. Heart rate for normal subjects at rest varies from 60-100 beats per minute (bpm) (John Hopkins Medicine, 2021). Conservatively extending the lower bound to 50pm to consider lower resting heart rates that can occur in certain people, such as athletes (Doyen et al., 2019), then the corresponding frequency range is 0.83-1.67Hz. As previously mentioned, respiration can also be extracted from PPG signals. The normal respiration rate for a healthy subject is 12 to 20 breaths per minute (Cleveland Clinic, 2021), corresponding to a frequency range of 0.20Hz-0.33Hz.

The amplitude of PPG signals is known to be low, which is attributed to a significant depth from the originating tissue to the surface of the skin, which photons must travel to register on the detector (Moço et al., 2018). In particular, (Moço et al., 2018) simulated photon propagation in a multi-layered turbid media, configured to represent the optical properties of six layers of skin in the palm or finger pad, and found that the depth origin of the PPG signal was from approximately 1.5-2mm under the surface of the skin. This low amplitude signal further contains oscillations in 0.01-0.02Hz, 0.02-0.06Hz, 0.06-0.15Hz ranges corresponding to endothelial related metabolic, neurogenic, and myogenic activities, respectively (Li, 2006).

Finally, a lesser discussed signal which may be present in the PPG are Mayer waves, which are oscillations in blood pressure that typically occur at a frequency of 0.1Hz (Julien, 2006). The mechanism for Mayer waves is subject to active debate, but recent findings advocate that the oscillations are produced by a sympathetic baroreceptor response to hemodynamic disturbances (Julien, 2006). Further, Mayer waves have been demonstrated to have clinical utility in prediction of hypertension. In a longitudinal study, Mayer waves were extracted from electrocardiograms (ECG) and their characteristic frequency quantified. Five years after ECG acquisition, investigators followed up with subjects and observed that lower frequency Mayer waves corresponded to an increased risk of primary hypertension (Takalo et al., 1999). A related mechanism for blood pressure regulation is the myogenic vascular response (MVR), which is a nonsympathetic vascular contraction in response to a localized increase in blood pressure (Estañol et al., 2016). As mentioned previously, MVR presents at a similar frequency range to Mayer waves (0.06-0.15Hz), presenting difficulty in distinguishing between these two mechanisms.

In summary, rPPG can embed a variety of signals. The aim of this project is to understand the utility of consumer-grade cameras as a remote PPG tool for microvascular hemodynamics investigations. For these purposes, we designed a test where PPG signals are captured with hands placed on a table (baseline) and hands elevated (elevation stress). In the first case (baseline), we expect that the hand will be in physiological equilibrium. Thus, the normal physiological autoregulation systems will be at play. In the second test, we captured video of the hand raised from the sitting position, immediately after that raise. In this case, we expect that the system will be out of equilibrium (elevation stress), and some transient changes will occur. As a result, we collected pilot rPPG data under rest and elevation stress from a group of healthy subjects.

2 METHODS

2.1 Imaging Setup

In the present work, we used an imaging setup composed of a stand-mounted consumer grade camera (iPhone 8). Illumination was provided by the on-board LED. The camera was configured to acquire 1920x1080 video data at 60 frames per second (fps), with auto-exposure and auto-focus locked to disable automated adjustments during acquisition. In the rest scenario, subjects were seated, and hand placed on a table. The acquisition was repeated for each hand. The camera was positioned about 10cm above the subject's hand, and video captured for 90 seconds. In the elevation stress scenario, the subject was seated with the chair positioned perpendicular next to a wall. For the right hand, the right side of the body was next to the wall, and opposite for the left hand. The subject then reached the hand as high as possible and placed it on the wall. Data was then acquired for 90 seconds, then repeated for the next hand. Some acquisitions were also performed while subjects were holding their breath to investigate the effect of respiration.

2.2 Data Processing

A region of interest (ROI) was manually chosen in each video to exclude any non-anatomical features in the video (i.e., the wall or table). Pixels outside of the ROI were removed from the analysis, and every second pixel (both row-wise and column-wise) were removed for memory purposes (post-removal still provided desired spatial resolution). To calculate the rPPG, the pixel values were averaged across the ROI for each frame, creating 60Hz time series for each of the three colour channels (red, green and blue) spanning the 90 seconds of acquisition. Filtering with continuous wavelet transform (MATLAB functions *cwt* and *icwt*) was performed from 0.075-0.125Hz to isolate signal components that correspond to Mayer waves and MVR, from 0.83-1.67Hz for cardiac pulsations, and 0.20-0.33Hz for respiration. As previously discussed, biological signals such as PPG are typically non-stationary, meaning that signal statistics such as mean and standard deviation vary over time. Therefore, to accurately capture amplitude at a specific frequency while minimizing time sensitivity (since some frequency content may only be transient and therefore not of interest), an envelope methodology was used. An envelope traces the extremes of a signal, as defined by specific criteria (Johnson, Sethares & Klein 2011); in this case, moving minimum and maximum, for the lower and upper envelopes, defined by the lower range of the frequency band of interest. Once the envelopes are evaluated, then the point-wise difference between the upper and lower envelopes define the instantaneous amplitude at any given time point. Evaluating the median amplitude across the signal reduces sensitivity to any transient changes in the amplitude. This method was implemented using the k-point moving maximum (MATLAB function *movmax*) and k-point moving minimum (MATLAB function *movmin*). k was configured to be proportional to the lower bound of the filtering range with the relationship (1/frequency)*fps. Therefore, k=800 in the case of the Mayer wave / MVR signal, k=72 for the cardiac signal and k=300 for respiration.

2.3 Subjects

As an initial pilot investigation, data was collected as described from 6 healthy subjects (5 male, with 1 over the age of 30, and 1 female under the age of 30) under approval from the Ryerson University REB.

The videos were captured on both hands, with hands placed on a table (baseline) and hands elevated (elevation stress) for a total of 24 videos. 2 additional videos were captured to assess impact on the signal of breath holding.

3 RESULTS

In the elevation stress signals, 3 of the 6 subjects exhibited clear visually recognizable low-frequency waves (see Figure 1).

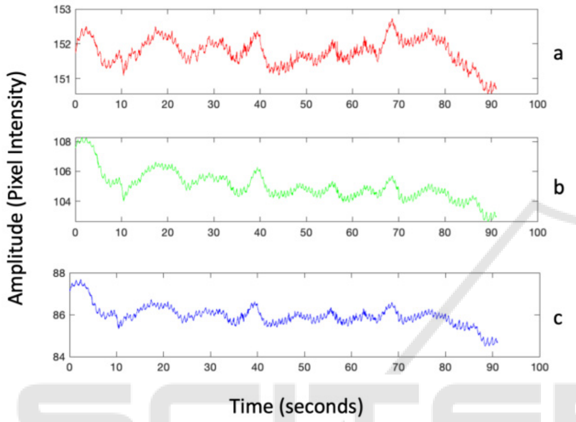

Figure 1: An example of low frequency waves observed in the raised hand position. Each subplot represents raw data collected by red (a), green (b), and blue channels (c), respectively.

In the elevation stress signals, 4 of the 6 subjects exhibited a signal baseline change, specifically an increasing amplitude (Figure 2).

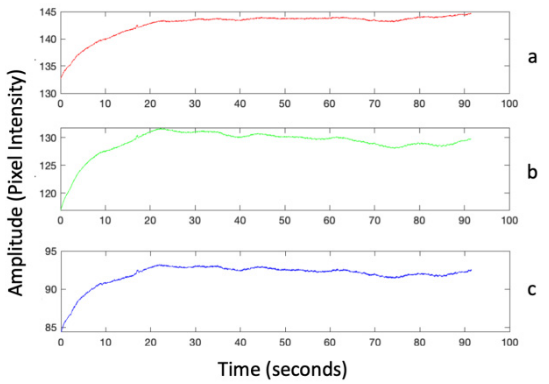

Figure 2: An example of a monotonic reflection increase observed in the raised hand position. Each subplot represents raw data collected by red (a), green (b), and blue channels (c), respectively.

2 subjects exhibited both low frequency waves and monotonic reflection increase in their elevation stress signals and are included in previous counts (Figure 3).

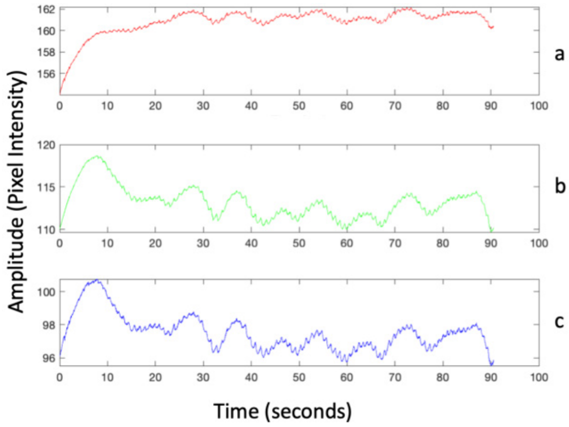

Figure 3: An example of a hybrid behavior (a monotonic reflection increases plus low frequency oscillations) observed in the raised hand position. Each subplot represents raw data collected by red (a), green (b), and blue channels (c), respectively.

3 subjects exhibited baseline signals without any distinguishing characteristics, as was expected during physiological equilibrium. However, in the remaining three subjects, an unknown high-amplitude signal dominated the rPPG, which could either be of either physiologic or external origin. Due to the unknown providence of this signal, these abnormal signals were excluded from the upcoming analyses.

One possible explanation for the observed low frequency waves is respiration. As previously described, the expected respiration frequency is 0.20Hz-0.33Hz. While the frequency of these waves appears to be lower frequency than this range, we wanted to exclude their effect explicitly. For this purpose, 2 subjects performed 30-second breath holding in the elevated stress position. The low frequency waves did not appear to be affected by breath holding, leading us to exclude respiration in favour of Mayer/MVR mechanism.

Figure 4 shows the variation in rPPG amplitudes for respiration, Mayer/MVR and cardiac pulsations, both at rest (3 subjects, each with 2 signals) and elevation (6 subjects, each with 2 signals), across the RGB channels. As would be expected, the green colour channel generated the highest-amplitude signals in the majority of cases, since it is most sensitive to changes in oxygenated haemoglobin concentration as compared to red and blue channels.

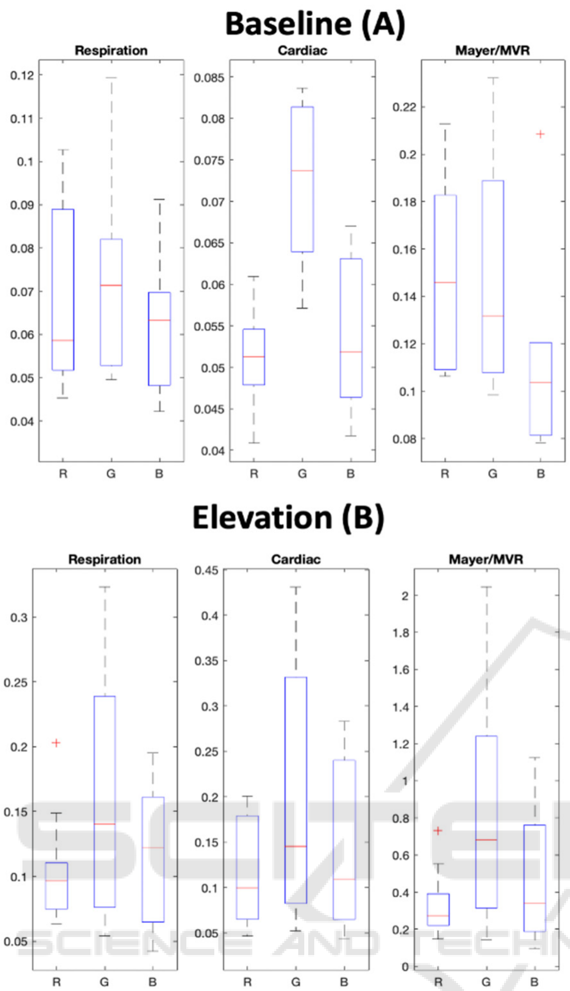

Figure 4: rPPG amplitudes of respiration, Mayer/MVR and cardiac pulsations at rest (3 subjects, each with 2 signals) and elevation (6 subjects, each with 2 signals). The median is represented by the red line, and the 25th and 75th percentiles by the bottom and top of the box, respectively. The whiskers extend to the furthest non-outlying points (75th percentile + 1.5 x interquartile range and 25th percentile - 1.5 x interquartile range), and the + symbol represents outliers.

This observation corresponds with previously published results (Verkruysse, 2008), serving as a confirmation of the validity of the approach used herein.

Figure 5 extends this analysis by directly comparing the signal amplitudes across the rest and elevation conditions (N=3, excluding the subjects with abnormal baseline signals). The ranges corresponding to cardiac, respiration and Mayer/MVR all increase in amplitude during elevation as compared to rest, with Mayer/MVR exhibiting the largest increase.

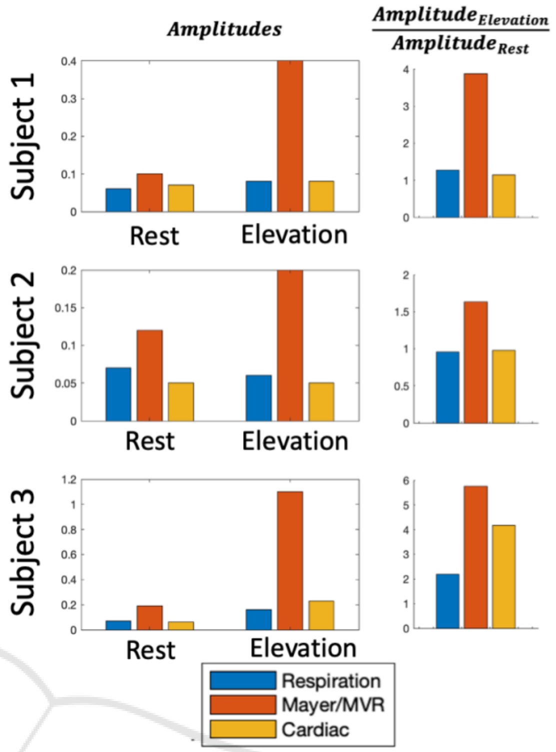

Figure 5: Comparison of rPPG amplitudes at frequencies corresponding to respiration, Mayer waves and cardiac pulsations at rest and elevation across three subjects. Amplitudes are shown on the left, and ratios comparing elevation to rest on the right.

4 DISCUSSION

Here, we present an initial pilot investigation of the microvasculature hemodynamics captured by a smartphone camera. Data was collected as described from six healthy subjects.

The collected data demonstrate the plurality of observed patterns. In particular, in addition to cardiac and respiratory activities two distinct patterns; low frequency oscillations (Figure 1) and monotonic reflection increase (Figure 2) are clearly noticeable. In some cases, both these patterns are combined (Figure 3).

We hypothesize that the low frequency oscillations can be attributed to Mayer waves. While Mayer waves share the same frequency range as myogenic activities (0.06-0.15Hz), their origins are different. Mayer waves are the sympathetic activity with baroreflex activation. MVR is local and independent of the sympathetic nervous vasoconstriction. The elevation scenario performed here is similar to a simulation performed by

(Hammer & Saul, 2005), which found that a reduction in blood volume (such as that which occurs due to limb elevation) can perturb the baroreflex (normally stable), and lead to the blood pressure oscillations known as Mayer waves. Therefore, we believe that it is more likely that the observed low frequency waves are Mayer rather than MVR, and the amplitude increase during elevation stress represents a sympathetic response to the reduction in blood volume. The increase in cardiac amplitude during elevation stress further confirms the effectiveness of the stressor, since it matches previously published results (Hickey, 2015).

Speaking of the monotonic reflection increase (Figure 2) mechanism, we hypothesize that it is connected with gravitational venous outflow from the raised hand. A decreasing concentration of venous blood leads to decreased light absorption and therefore increased light reflection and captured signal intensity. It is particularly visible in the red channel Figure 3). In this wavelength range, the absorption of deoxyhemoglobin dominates over that of oxyhemoglobin. Thus, we expect that this signal is indicative of gravitational venous outflow.

It is typically assumed that the volume of bloodheld in the venous compartment stays relatively constant, leaving the major portion of the PPG signal coming from the arterial side. However, our experiments confirm the notion that in some cases venous blood redistribution can be significant and contribute to the PPG signal. It was also observed in experiments with the occluded body parts (see, for example, (Burton et al., 2021)), where the oxyhemoglobin can be gradually converted into deoxyhemoglobin; thus, increasing absorption and decreasing the reflectance in the red range of spectrum.

It also should be noted that blood redistribution effects can be significant and may take up to 30 seconds, even in simple experiments. Thus, a reasonable equilibration time should be properly incorporated while planning experiments.

It should be noted that the current study involved a very small number of subjects. Given the multitude of observed patterns, these results are very preliminary. Much broader studies are required to come to meaningful conclusions, which will be the focus of our future work. Further, including a conventional contact PPG sensor on the non-elevated hand will be considered in the future, as a reference signal. Extension of our methodology to imaging PPG, where maps visualize characteristics of local PPGs across an area of tissue (Kyriacou & Allen, 2021), may also be beneficial to explore the observed effects.

5 CONCLUSIONS

Remote PPG is a versatile tool, which can be used in hemodynamic analysis.

PPGs can not only capture changes in arterial blood, as previously asserted, but can also capture changes in venous blood volume. As venous outflow from tissue occurs, such as due to gravity when the tissue is elevated, the volume of venous (deoxygenated) blood is getting lower. Thus, the absorption of the tissue decreases, resulting in more reflection and therefore higher intensity registered by rPPG. This result was clearly observed in several volunteers (venous outflow pattern).

Such as skin pressure induced by the contact PPG can affect venous flow distribution, the noncontact nature of rPPG makes it an ideal tool for venous compartment investigations.

ACKNOWLEDGEMENTS

The authors thank all the members of the Ryerson photonics group for their support. The authors acknowledge funding from NSERC Alliance (Douplik & Saiko), NSERC Personal Discovery (Douplik), NSERC RTI (Douplik), and Ryerson Healthy Fund (Douplik).

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