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Camera-based Photoplethysmography (cbPPG) using smartphone rear and frontal cameras: an experimental study

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***Abstract*— Non-expensive methods for measuring heart rate and oxygen saturation are of great importance in the scope of the COVID-19 outbreak to follow up on the symptoms and help to control the disease.**

Smartphones are widely available and their cameras can be used to acquire relevant physiological data, such as Photoplethysmography (PPG) signals. Covering a light source and the camera sensor with a finger, it is possible to acquire the camera-based photoplethysmography (cbPPG) signal. Two methods were analyzed in this work, namely using the rear smartphone camera and the flash LED, and using the front camera and device display as a light source. The latter presents more advantages overall - in particular, greater control over the emitted light and finger detection - and better results were found when compared to a reference device.

***Clinical relevance*— This technology allows the pervasive monitoring of the PPG signal using a standard smartphone, providing a tool to evaluate the subject's heart rate and its variability, respiration, blood oxygenation, *etc*.**

I. Introduction

The COVID-19 pandemic reinforced the need for telemonitoring to evaluate patients' vital signs. The current smartphone technology and embedded cameras allow the acquisition of photoplethysmography (PPG) without the need for any external device. From the camera-based photoplethysmography (cbPPG) signal it is possible to extract important biomarkers such as heart and respiration rates, oxygen saturation and even mental states from the analysis of the heart rate variability (HRV) [1].

To acquire this signal, the smartphone rear [2], [3], [4] or front camera [5] work as a light sensor, while the device flash or display work as a light emitter, respectively. In this work, the quality of the cbPPG signal is assessed using the pulse PPG signal obtained with a validated device, the BITalino system [6]. The signals acquired simultaneously are compared and the differences are analyzed and discussed. The method using the frontal camera is of special importance in this paper. Systems using this architecture are not common in the literature because smartphones with embedded cameras in the frontal display are recent and correspond to a newer technology that is still under development.

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II. Background

In this section, some fundamental information needed to support the description of this study is provided.

A. Photoplethysmography

PPG is an optical technique that can be used to detect variations in the volume of blood vessels [7] as a result of the cardiac cycle. It relies on the principle of Beer-Lambert's law, which says that the absorbance of light at a specific wavelength can be described by:

$$I = I_0 \cdot e^{-\epsilon(\lambda)\cdot\rho\cdot d} \quad (1)$$

where $\epsilon(\lambda)$ is the specific absorptivity, characteristic of the traversed tissue and dependent of the light wavelength λ, ρ is the density of the tissue, and d is the light pathlength. The absorptivity of the body tissues is mainly affected by the hemoglobin (Hb) present in red blood cells, which is dependent on the incident light wavelength as described in Equation 1. Hb can be found in two forms: oxyhemoglobin (HbO_2), when it is bound to oxygen molecules, or deoxygenated hemoglobin (HHb), with no oxygen molecules bound. The molar extinction coefficient for each form varies differently depending on the incident light wavelength and is displayed in Figure 1. At 660 nm (light correspondent to the color red), the molar extinction coefficient of HbO_2 is greater than for HHb, which explains why arterial blood presents a more vivid red color since it absorbs less red light.

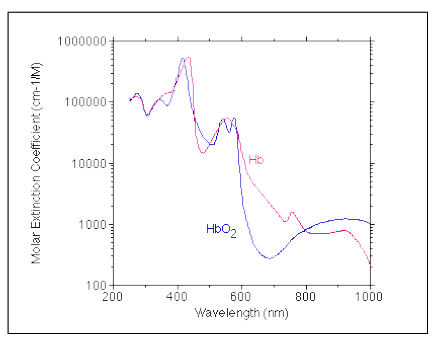

Fig. 1. Spectrum of deoxyhemoglobin (HHb) displayed as Hb, and oxyhemoglobin (HbO_2) [2].

To measure the PPG signal, a light emitter and a light sensor are required. These can be placed on each side across the tissue (transmissive PPG) or side-by-side, in such a way that the light sensor measures the light scattered

[2]Scott Prahl. Optical Absorption of Hemoglobin. URL: `https://omlc.org/spectra/hemoglobin/` (visited on 2021-02-21)

by the tissues (reflective PPG). In camera-based methods, reflective PPG is typically used. The measured signal is constituted by a non-pulsatile (DC) component, resulting from the surrounding tissues and the basal blood volume, and a pulsatile component (AC) caused by the increase of blood flowing through the vessels during the cardiac cycle [7]. The PPG signal is usually represented only by the pulsatile component and is inverted [7], [8]; hence the peaks of the signal (corresponding to an increase of blood flow), in reality, correspond to a decrease in the light detected, caused by an increase of absorption by the circulating blood.

B. Smartphone Camera

Smartphones are evolving and becoming more powerful. One consequence of the evolution of smartphone technology is that front-facing cameras are getting smaller and having higher resolution. Screens, on the other hand, are becoming wider and with thinner bezels, with front-facing cameras seamlessly integrated into them. Having the front-facing camera surrounded by the device screen makes the use of the display a good light source for cbPPG since the light source and light sensor are side-by-side.

When using camera-based approaches for PPG acquisition, it is important to understand the light principles behind camera exposure, as these will greatly impact the measured signal and its quality. If the video is underexposed, it will present a small signal-to-noise ratio (SNR), while an overexposed video will saturate the camera sensor, also resulting in a small SNR.

Three settings are important to control in the smartphone camera to obtain a good PPG signal: ISO, shutter speed, and white balance.

1) ISO: Usually described as the sensitivity of the camera sensor, the ISO controls the brightness of the camera image [9]. A smaller value will return darker images and a higher value will return brighter images. However, increasing the ISO value has the consequence of increasing the gain of the camera sensor and, therefore, the noise of the image.

2) Shutter Speed: This setting controls how long the camera sensor is exposed to light [9]. Increasing the shutter speed will result in brighter images since the camera sensor is exposed to light for a longer period of time. The shutter speed determines the camera frame rate, *i.e.*, sampling rate.

3) White Balance: White balance is associated with color temperature [9], which is measured in Kelvin and is a physical property of light. When a color temperature value is selected, the camera compensates by adding the opposite color in an attempt to bring the color temperature of the image back to neutral [9].

C. Camera-Based Photoplethysmography

Smartphones are nowadays ubiquitous devices with high computational and sensory capacity. The sophistication and high resolution of their embedded cameras allow them to develop complex and computationally demanding applications. The acquisition of PPG and its analysis in real-time is one of these cases that we describe in this article.

cbPPG uses a reflective PPG sensing principle and, currently, can be based on two methods: one in which the subject covers the light source and detector (camera) with an indicated body part (typically a finger) [2], [3], [4], [5], and another where the camera and light source are not in contact with the subject, e.g. Eulerian Video Magnification (EVM) [10]. The first is the most common method for acquiring this signal - since the finger is directly in contact with the light emitter and sensor, it is less susceptible to noise from small movements of the subject or external light sources. The second method is more susceptible to noise and artifacts, however, it allows the contactless acquisition of the PPG signal. Noise removal methods are essential to isolate the PPG signal.

In this work, the first method was studied, since it is the most robust for free-living usage. The typical approach in smartphones uses the flash LED as a white light source and the back camera as a light detector [2], [3], [4], as shown in Figure 3 (left). Another approach uses the screen as a light source and the front-facing camera as a light sensor [5], Figure 3 (right). Unlike the flash LED method that emits all wavelengths in the visible range, using the display as light source results in a narrower band of emitted wavelengths.

In both approaches, the person must place a finger over the light source and sensor (reflective PPG), and an average pixel intensity is extracted from the video feed. This intensity will vary according to the blood volume flowing through blood capillaries, corresponding to the PPG signal. The green color channel is commonly used since hemoglobin presents a higher absorbance for this wavelength.

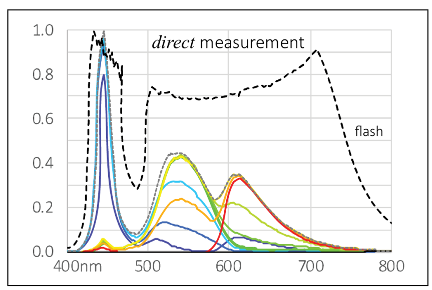

Fig. 2. Spectral distribution of intensities of the smartphone LCD display under different illumination colors compared with the smartphone flash LED [5].

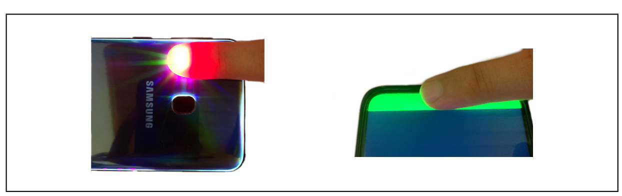

Fig. 3. Flash as light source and rear camera as light detector (left) and display as light source and front camera as light detector (right).

III. METHODS

A. Camera Settings

Using a camera-based approach requires the setup of the exposure (ISO and shutter speed) and color balance (white balance) settings of the camera, avoiding unwanted fluctuations of the measured values. The white balance value *Daylight* was chosen taking into account the color temperature of the flash LED and smartphone display. The resolution of the video feed was set to its minimum value to reduce the computational load.

B. Back camera + flash light

When using the back camera as a light detector and the flash LED as a light source, the user must place both these parts with his finger. A Region-Of-Interest (ROI) can be defined in the video area closest to the light source, increasing the overall gain of the signal. The exposure settings will determine in which wavelength the PPG is acquirable. If settings are defined to obtain a lower exposure of the camera, the video feed will mainly contain the PPG signal in the red channel, corresponding to wavelengths in the range of red light, for which Hb is highly reflective. These settings are evaluated in the next section.

C. Front camera + screen

When using the front camera as a light detector and the screen as a light source, it is better if the camera is surrounded by the display as it happens in more recent smartphone models like the one used, Xiaomi Redmi Note 9S. The screen brightness must be set to its maximum value and color is displayed in the display area surrounding the camera. In this experiment, the green color was used. Since the light intensity of the screen is lower than the one of the flash LED, it is very important to select a region of interest (ROI) where the PPG signal presents the higher SNR. In the setup where the front camera is surrounded by the display, this region corresponds to the corners of the captured video.

D. Benchmarking Device

In this work, we evaluated the performance of the described cbPPG approaches using as a reference setup a BITalino device and the widely used PulseSensor[3]. The BITalino device is a scientifically validated biomedical data acquisition system [6] that allows the connection of specialized sensors (*e.g.* PPG), and has Bluetooth connectivity to devices such as the smartphone. This setup makes possible the acquisition of a cbPPG time-series synchronized with a standard PPG time-series in a mobile application (described next), hence leading to a more accurate comparison.

E. Experimental Setup

The smartphones used in this work were the Redmi Note 9S and the Samsung Galaxy A40.

An application was developed to acquire both the cbPPG camera feed and also the BITalino PPG time series. The cbPPG acquisition method (back camera + flash / front camera + screen) can be selected within the application. A Flutter plugin was also developed, *bitalino_plugin*[4], for the communication between Android/iOS smartphones and BITalino devices. The two smartphones were used simultaneously, the Redmi recording cbPPG at the index finger using the front camera + screen mode together with the BITalino device recording PPG at the middle finger using the PulseSensor, and the Samsung recording cbPPG at the ring finger with the back camera + flash mode. The three acquisitions were started at the same time, with the BITalino recording data at 100 Hz and the cbPPG recorded at 30 Hz. Signals of 30 seconds were obtained and aligned using the first pulse peak.

[3]World Famous Electronics LLC. Heartbeats in Your Project, Lickety-Split. URL: `https://pulsesensor.com/` (visited on 2021-02-26)

[4]ScientISST. bitalino — Flutter Package. URL: `https://pub.dev/packages/bitalino` (visited on 2021-02-26)

IV. RESULTS

In this section, the experimental results using both cbPPG methods are described and compared with the PPG acquired with the benchmarking device. The experimental procedures involved exclusively team members hence did not require approval by the Institutional Review Board.

A. Camera Exposure

It is important to manually set the correct camera exposure, guaranteeing the signal is correctly captured. Increasing the camera ISO will increase the gain of the light sensor, resulting in an increase of measured signal amplitude, however, it may also increase the amount of noise captured. Decreasing the shutter speed, increases the amount of light reaching the sensor, therefore, increasing the signal quality, however, it directly affects the sampling rate. It is necessary to find a good balance between these settings.

When using the flash as the light source, it is possible to measure the PPG in the red, green, and blue wavelengths. Different camera settings allow the acquisition of these wavelengths. With the shutter speed fixed to 30 Hz, the Figure 4 shows that for low ISO values, the red channel is practically saturated, presenting intensity values around 250 (max=255). As seen in Figure 1, Hb is highly reflective of red wavelengths, explaining the higher intensity values for the red channel. With a lower ISO value, the gain of the sensor is not sufficient to acquire a valid PPG in the blue color channel. This is consistent with the spectrum of Figure 1, where it is showed a higher absorbance of Hb for blue wavelengths, hence resulting in a smaller amount of reflected light reaching the camera sensor. Once the ISO increases, the blue PPG amplitude also increases and it becomes detectable.

A similar effect of varying the shutter speed is showcased for the front camera and screen in Figure 5, where the ISO was fixed to 50 and the display was showing the green color (the PPG signal was measured in the green color channel).

B. Back Camera + Flash vs Front Camera + Screen

A signal of 30 seconds was acquired simultaneously using cbPPG with the back and front cameras, and a pulse sensor connected to a BITalino device. The three PPG signals were synchronized, normalized, and are displayed in Figure 6. To evaluate the similarity between these signals, the Mean Square Error (MSE) and standard deviation of the differences (STD) was calculated. The results show that the signal

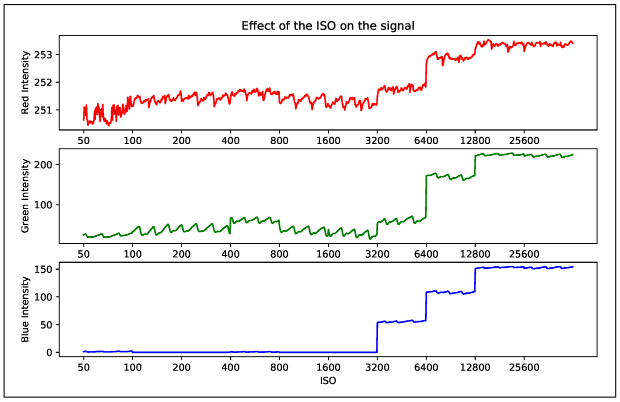

Fig. 4. Effect of the ISO value on the average intensity of the different colors channels over time. Each segment was recorded for 5 seconds and the ISO value was increased in powers of 2.

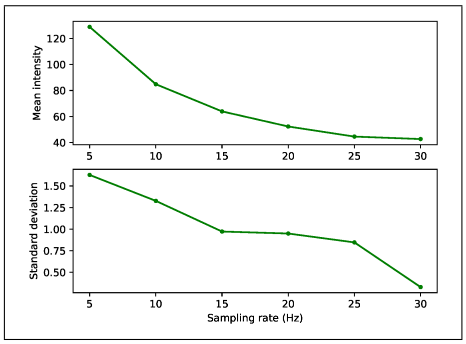

Fig. 5. Effect of the shutter speed value on the average intensity of the different colors channels.

obtained with the screen light is more similar to the BITalino PPG signal, having an MSE of 0.100 and STD of 0.316, while the flash signal has an MSE of 0.102 and STD of 0.319. These apparent small differences between both methods do not reflect the better quality of the cbPPG acquired with the frontal camera with respect to the rear+flash method as shown in Fig. 4.

Using the phone display allows for greater control over the emitted light because unlike the flash that excites Hb with the whole visible spectrum, the light emitted is restricted to a narrower band around the wavelength of a selected color (red, green, or blue), thus capturing a better PPG signal on the corresponding color channel.

V. CONCLUSION

The results reflect the importance of manually setting the right camera parameters. The inability to correctly set these may result in underexposure of the camera, in which the PPG signal is not detected due to its low SNR, or overexposure, in which the color channels of the camera are completely saturated and no PPG signal can be extracted from them. When using the flash LED as a light source, the camera exposure also affects the measured wavelength, *i.e.*, if the cbPPG signal is measured in the green color channel, the camera must be correctly exposed to capture this wavelength.

It was verified that the cbPPG acquired with the smartphone front camera and its display allows for better control

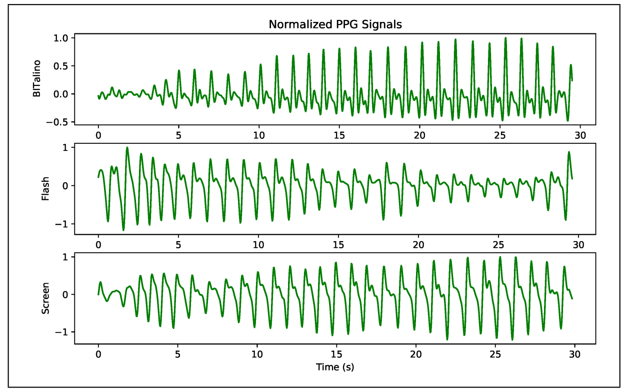

Fig. 6. 30 seconds normalized PPG signals acquired using a pulse sensor + BITalino, back camera + flash, and front camera + screen.

over the emitted light, improving the acquired signal quality. Using the display comes with some extra and useful features, such as detecting the finger's presence and its movements, which can be used for evaluating the acquisition conditions and determine if these are acceptable.

The described cbPPG approaches provide simple, low-cost, and effective methods to remotely monitor patients' vital signs, constituting an important tool in telemedicine. Taking into account the evolution path of smartphone displays and cameras, the front camera PPG can constitute a valuable method for acquiring various physiological signals.

REFERENCES

[1] M. Malik and C. et al., "Heart rate variability. standards of measurement, physiological interpretation, and clinical use," *European Heart Journal*, vol. 17, no. 3, pp. 354–381, 1996.

[2] C. Scully, J. Lee, J. Meyer, A. Gorbach, D. Granquist-Fraser, Y. Mendelson, and K. Chon, "Physiological parameter monitoring from optical recordings with a mobile phone," *IEEE transactions on bio-medical engineering*, vol. 59, pp. 303–6, 07 2011.

[3] A. Kanva, C. Sharma, and S. Deb, "Determination of SpO2 and heart-rate using smartphone camera," *International Conference on Control, Instrumentation, Energy and Communication, CIEC 2014*, pp. 237–241, 11 2014.

[4] B. Yan, C. Chan, C. Li, O. To, W. Lai, G. Tse, Y. Poh, and M.-Z. Poh, "Resting and postexercise heart rate detection from fingertip and facial photoplethysmography using a smartphone camera: A validation study," *JMIR Mhealth Uhealth*, vol. 5, p. e33, 03 2017.

[5] C. Holz and E. Ofek, "Doubling the signal quality of smartphone camera pulse oximetry using the display screen as a controllable selective light source," *Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference*, vol. 2018, pp. 1–4, 07 2018.

[6] D. Batista, H. P. da Silva, A. Fred, C. Moreira, M. Reis, and H. A. Ferreira, "Benchmarking of the bitalino biomedical toolkit against an established gold standard," *Healthcare Technology Letters*, vol. 6, 2019.

[7] J. Allen, "Photoplethysmography and it application in clinical physiological measurement," *Physiological measurement*, vol. 28, pp. R1–39, 04 2007.

[8] V. Hartmann, H. Liu, F. Chen, Q. Qiu, S. Hughes, and D. Zheng, "Quantitative comparison of photoplethysmographic waveform characteristics: Effect of measurement site," *Frontiers in Physiology*, vol. 10, mar 2019.

[9] B. Peterson, *Understanding Exposure, 3rd Edition*. Potter/Ten Speed/Harmony/Rodale, 2010.

[10] H.-Y. Wu, M. Rubinstein, E. Shih, J. Guttag, F. Durand, and W. Freeman, "Eulerian video magnification for revealing subtle changes in the world," *ACM Transactions on Graphics*, vol. 31, pp. 1–8, 8 2012.