Investigating a smartphone imaging unit for photoplethysmography

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LETTER

Cellular phone-based photoplethysmographic imaging

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We present study results on visible light reflection photoplethysmographic (PPG) imaging with a mobile cellular phone operated in video imaging mode. PPG signal components around 0.1 Hz attributed to the sympathetic component of the heart rate, 1 Hz as the heart rate and 2 Hz as heart rate high order harmonic were quantified on the index finger of a healthy volunteer. The green channel reported PPG signals throughout the sampled area. The blue and red channel returned plethysmographic information, but the signal strength was highly position specific. Our results obtained with a cellular phone as the data acquisition device are encouraging, especially in the broad context of personal or home-based care and the role of cellular phone technology in medical imaging.

Cellular phone-based visible light PPG imaging.

1. Introduction

Reflection photoplethysmography (PPG) is a non-invasive technique for detecting relative blood volume changes due to the cardio-vascular pulse travelling throughout the body from the heart. The technique, first reported in the 1930s by Hertzmann [1], exploits the fact that blood absorbs light more than surrounding tissue and variations in blood volume affect the transmitted and reflected signal components of a suitable optical probe. Clinical PPG applications span monitoring of blood pressure, cardiac output, oxygen saturation (pulse oxymetry), heart (HR) and respiration (RR) rates to assessment of autonomous functions and detection of peripheral vascular diseases. PPG systems combine a dedicated light source operating in the red and/or infra-red (IR) wavelength range and a photo detector assembled into a compact skin irradiation probe for single spot measurement. Here, the focus is PPG imaging an emerging area [2–4] realised by replacing the photodiode with a camera, offering the advantages of real-time large area measurement and sensitivity.

In this letter, a PPG imaging system designed around a cellular phone video imaging unit is presented. Due to technological advances, present day mobile cellular phones feature a practical video imaging unit, comprising a white light source in the form of a white light emitting diode (WLED) and a camera, that supports a frame rate of around 30 fps suitable for near real-time imaging applications. We explore this development for visible light PPG imaging and also in the broad context of medical imaging and personal and/or home based care applications.

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Figure 1 (online color at: www.biophotonics-journal.org) Photo-image of the cellular phone showing position of the video unit comprising a white light emitting diode (WLED) and camera.

2. Experimental

2.1 Materials and set-up

A consumer grade (Sony-Ericsson model W705 with 4 GB memory card) mobile cellular phone was used for this study. The phone video unit comprises a white light emitting diode (WLED) located beside a 3.2 megapixel camera at a centre-to-centre separation distance of around 10 mm (Figure 1). The phone supports colour video recording at around 30 fps and pixel resolution of 320×240. PPG signals were acquired from the index finger of a healthy volunteer of African descent. The WLED was turned on and the phone was set to movie mode. A colour movie of the volunteer's index finger covering both the WLED and camera objective, as shown in the photo-image in Figure 2, was recorded and saved as a MPEG-4 file into the phone memory.

Figure 2 (online color at: www.biophotonics-journal.org) Visible light PPG imaging of the index finger positioned to cover the cellular phone video unit.

2.2 PPG Signal extraction and processing

The MPEG-4 file was transferred from the cellular phone memory to a laptop computer via Bluetooth(TM) connection for further processing. The file was first converted to RGB JPEG frames using freeware downloaded (http://www.dvdvideosoft.com) from the internet. The frames were opened as an RGB stack in ImageJ (NIH, USA) for colour histogram and distribution analysis (CHDA). On the basis of the CHDA results, three regions of interest (ROI) that is, cells measuring 8x8 pixels, along a left diagonal were selected for processing and analysis with a custom designed Matlab (Mathworks Inc., USA) program. The Matlab program computed the mean intensity values as the raw *PPG signal*, $PPG_{raw}(MV_{cr}, t)$, where MV_{cr} is the cell mean pixel value and subscript c identifies the colour channel ($c = r$, g or b for red, green, blue channel respectively) and $r (= 1, 2, 3)$ is the ROI cell number; t is the time stamp for the frame. Signal processing included filtering with a Butterworth band pass filter of order 8 and frequency pass band 0.08 to 7 Hz. The pass band filter simultaneously removes any high frequency noise that might be present in the signal while also suppressing quasi-DC signal due, for example, to finger movement or changes in venous pressure. Fast Fourier Transform (FFT) spectral and power spectral density (PSD) analysis was performed on the data.

3. Results and discussion

Figure 3 shows a sample raw green channel PPG signal extracted from a 25 second movie of the index finger.

Analysis results are summarised as Figure 4. In Figure 4a.i and a.ii results of the colour histogram and distribution analysis are presented. Figure 4a.ii is a RGB profile along an observation line marked AB on Figure 4a.i with position A towards the WLED position. It can be observed that while the green channel signal could be detected at each pixel position in each frame but at reduced strength away from the light source position, the blue channel signal was detected only in a small region towards the light source position and, finally, the red channel signal was available at pixels positions furthest from the light source after what appears to be shunting effect up to a distance of around 220 pixels from the light source position. First, these observations conform to the known interdependence of penetration depth and wavelength, with the former increasing with a wavelength shift from blue to red, and can be exploited for depth discrimination and as a solution

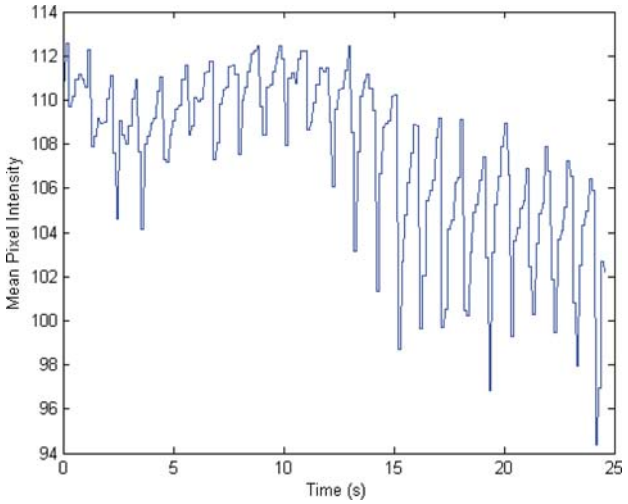

Figure 3 (online color at: www.biophotonics-journal.org) Example green channel PPG signal.

towards the challenge of probe depth ambiguity. Second, this behaviour is as expected when considering the relationship between wavelength and source detector separation where the interaction distance to retrieve useful information increases for photon wavelength ranging from short (blue) to long (red) wavelength [5]. More importantly, the result also confirms the green wavelength [2, 6] as a good compromise between practical penetration depth and useful signal strength when PPG is to be used to also probe superficial microvasculature rather than deeper vasculature which has always been the focus of pulse oxymetry [7, 8].

The PPG ac signals, FFT spectral and PSD analysis results are presented in Figure 4b, c, and d respectively. Apart from differences in signal amplitude and extent of spurious peaks, the FFT spectra conform to expected results for normal subjects, namely, a signal peak around 0.1 Hz due to the sympathetic pacing of the heart [8] and 1 Hz as the heart

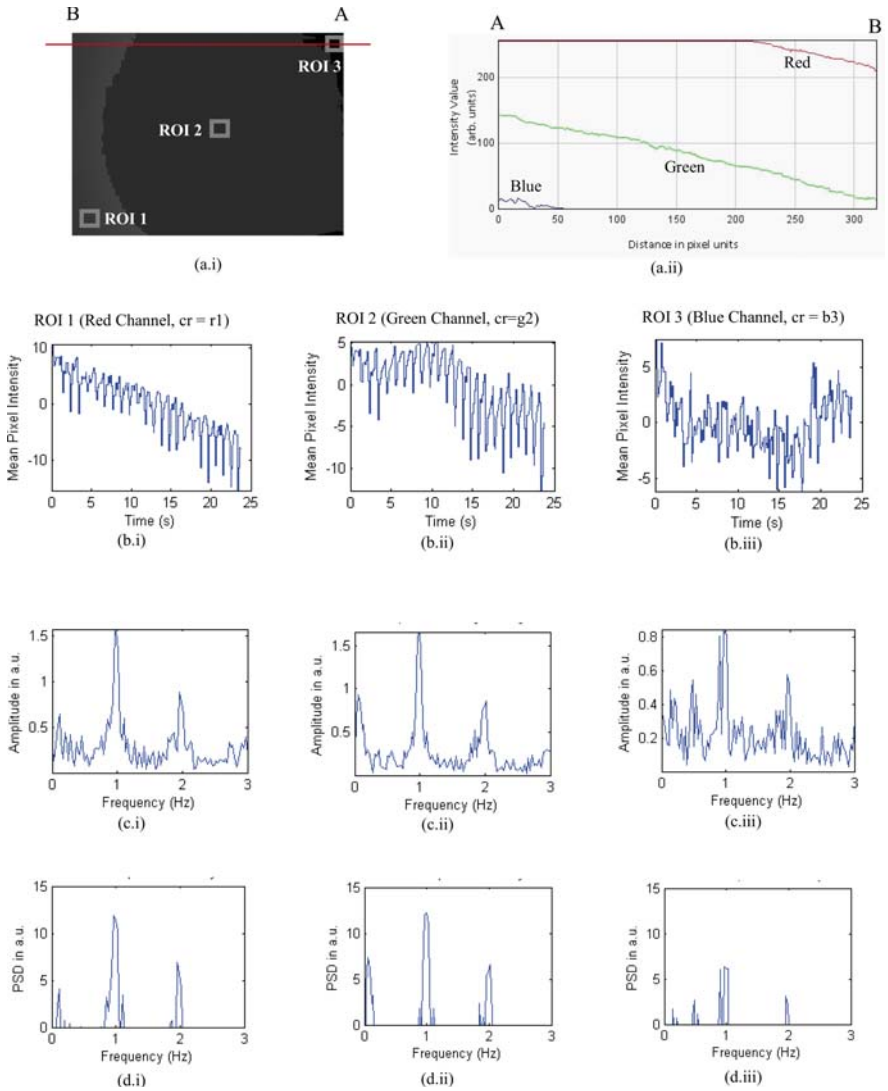

Figure 4 (online color at: www.biophotonics-journal.org) PPG ac signal processing results. (**a.i**) Typical single frame measuring 320×240 pixels showing selected 3 ROI's (grey squares) along a left diagonal. (**a.ii**) RGB profiling along observation line (in red) marked AB where A is towards the WLED position confirming green channel signal can be detected throughout the imaging area while red and blue channels detected in marked zones. (**b**) Raw PPG signal traces, (**c**) FFT spectra and (**d**) PSD spectra for (i) ROI 1 Red, (ii) ROI 2 Green and (iii) ROI 3 Blue channels.

Table 1 Comparison between the mean heart rate measurement using the PPG method and a commercial instrument.

PPG Method	62	66	60	63	64
Commercial Instrument	62	65	60	65	66

rate as well as another peak around 2–2.5 Hz, being the higher harmonic of the cardiac output. The PSD estimate showed similar frequency components as the FFT, where the 1 Hz components was stronger than the 0.1 Hz components. The 1 Hz mean heart rate (60 beats per minute) compared very well to the 62 beats per minute measured with a commercial fully automatic blood pressure monitor (model BPM1C, Kinetic Medical Devices, UK). Additional results confirming that the PPG measurements compare very well with the commercial instrument are presented in Table 1.

Following the approach in [2], Figure 5 presents PPG images from plotting the PPG signal amplitude at the mean 1 Hz heart rate frequency for each colour channels along the lines. As already discussed the red (Figure 5a) and blue (Figure 5c) channels report PPG signals only at specific locations while the green channel signal is generally available throughout the observed area measuring 320 by 240 pixels. The origin of the signal bands clearly evident in Figure 5b warrants further investigation.

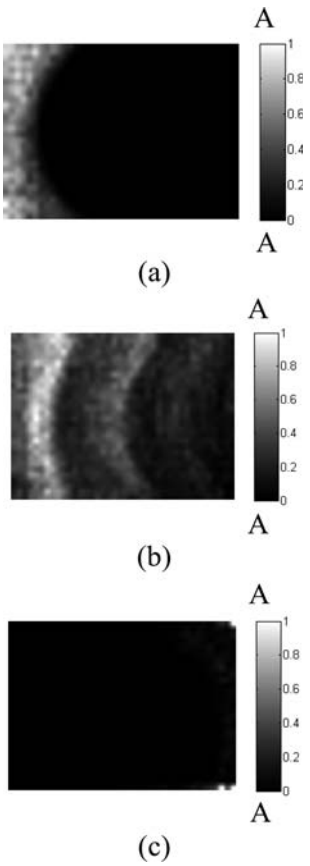

Figure 5 PPG signal amplitude maps for the (**a**) red channel, (**b**) green channel and (**c**) blue channel. Mark AA is towards the WLED position.

The study results show that movies of a human finger recorded with a cellular phone operating in the video mode using its WLED as the PPG probe source contain useful reflectance PPG signals. The green channel was useful for mapping the PPG signal throughout the observation area when compared to the blue and red channel signals. Our work contributes to a new concept of medical imaging using cellular phone technology, for example, Granot et al. [10]. However, our study is different from the approach adopted by Granot and others where the cellular phone was used as a data conduit in that here the cellular phone function both as the data acquisition device in addition to data storage and transmission.

4. Conclusion

We have demonstrated the usefulness of a cellular phone technology for white light PPG imaging. Cellular phone application in medical imaging is an emerging area and for the task at hand the technology is exploited for data acquisition as well as a data conduit.

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