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2010 Physiol. Meas. 31 N79

(http://iopscience.iop.org/0967-3334/31/11/N01)

IOP PUBLISHING PHYSIOLOGICAL MEASUREMENT
Physiol. Meas. **31** (2010) N79–N83 doi:10.1088/0967-3334/31/11/N01

NOTE

Investigating a smartphone imaging unit for photoplethysmography

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Received 8 April 2010, accepted for publication 3 September 2010
Published 24 September 2010
Online at stacks.iop.org/PM/31/N79

Abstract
Current-generation smartphones boast a video unit comprising a camera next to a white light emitting diode and this configuration would be suitable for reflection-mode bio-optical sensing and imaging applications. We demonstrate reflection photoplethysmographic (PPG) imaging using this technology on the index finger of a male volunteer during rest and immediately after performing a short run. The returned signals carry useful PPG signals and were used, for example, to compute change in heart rate. Our results are encouraging, especially in the area of personal and home-based care applications.

Keywords: photoplethysmography, smartphone, visible light, heart rate detection

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recently, cellular phone technology has been enrolled in innovative approaches to advance healthcare services and solutions, as well as to mitigate the growing healthcare concerns (Granot *et al* 2008, Breslauer *et al* 2009). Combining cellular phones and inexpensive, commonly available sensor devices also creates opportunity in the area of personal and home-based care applications. Since cellular phones are primarily communication devices, medical applications have exploited these devices as data conduits between a data acquisition unit and a processing station. Current-generation phones feature a video imaging unit comprising a practical camera next to a white light emitting diode (WLED) as an illumination source. This configuration supports exploring reflection-mode bio-optical imaging where the cellular

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(a) (b)

Figure 1. Smartphone-based visible light PPG. (a) Video unit comprising a camera (CA) next to a WLED. (b) Index finger placed across the LED and camera.

phone white light source illuminates target tissue and the re-emitted signal is detected by the phone camera. Based on this approach, in this note we present study results from using a cellular-phone imaging unit for reflection photoplethysmographic imaging.

Photoplethysmography (PPG), dating back to the 1930s, is a non-invasive technique for detecting blood volume changes during a cardiac cycle at selected body locations (Hertzman 1938, Mendelson 1992). Clinical PPG applications range from monitoring of blood pressure, heart and respiration rate, blood oxygen saturation, to detection of peripheral vascular diseases. The technique functions by illuminating skin with penetrating optical radiation usually from a light emitting diode and detecting the transmitted signal in the case of transmission mode PPG, where the photodetector is positioned directly across from the light source, or the reflected signal, for the case of reflection mode PPG achieved by locating the photodetector next to the light source (Harness and Marjanovic 1989, Stojanovic and Karadaglic 2007). The modified Beer–Lambert law suffices in explaining the origin of the PPG waveform (Shelley 2007). Reflection mode PPG is a more useful configuration than transmission mode because of the shallow penetration depth of optical radiation. Replacing the photodetector with a camera, the technique ceases to be limited to single-point measurement and PPG imaging is realized. PPG imaging is an emerging area offering advantages of improved sensitivity and real-time large surface area measurement useful also in mapping applications (Zheng and Hu 2007, Verkruysse *et al* 2008).

2. Experiment details

A consumer grade (Nokia model E63) cellular phone was used in this study. Figure 1(a) is a photo-image of the phone imaging unit. The unit consists of a WLED as the illumination source next to a 2.0 megapixel camera at a centre-to-centre separation of around 10 mm. The phone supports colour video recording at about 15 frames per second at three user-selectable resolutions of 128×96, 176×144 and 320×420 pixels. For this study the maximum resolution setting was chosen. The experiment involved a volunteer human subject (also the first author of this communication) of African origin after obtaining informed consent. A colour video of the volunteer's index finger placed across both the WLED and camera aperture as shown in the photo-image in figure 1(b) was recorded in MPEG-4 format onto the phone memory. In addition to recording movies while at rest, the subject was also requested to perform a short run for about 3 min immediately before commencing recording and during recording, to inhale deeply and hold breath for as long as was comfortable.

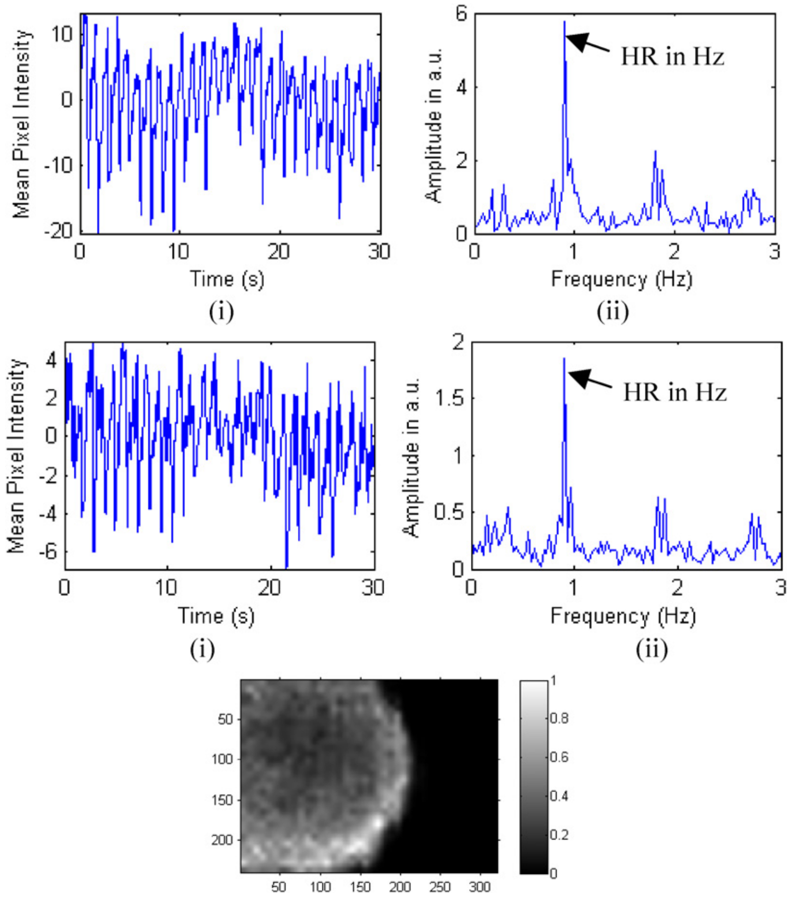

Figure 2. Male subject at rest. (a) Green channel: (i) PPG waveform and its (ii) corresponding FFT spectrum. (b) Red channel: (i) PPG waveform and its (ii) corresponding FFT spectrum. (c) Green channel PPG image measuring 320 × 240 pixels. HR is heart rate.

3. PPG waveform and processing

The MPEG-4 files were transferred from cellular phone memory via Bluetooth to a laptop computer for further processing. The videos were first converted to RGB JPEG frames with freeware program available at http://www.dvdvideosoft.com/ on the internet.

PPG waveform extraction and processing was performed for the green and red channel signals with a custom-designed Matlab (Mathworks Inc., USA) program. A central region of interest (ROI) measuring 10 × 10 pixels was selected arbitrarily with spatial resolution in mind. The PPG signal was extracted as PPG = MV(f, t) MINUS MV(dc), where MV(dc) is the mean intensity for the ROI stack, MV(f, t) is the individual cell mean intensity, f is frame number and t is the time stamp of the frame. Waveform processing included filtering with a Butterworth band pass filter of order 8 and frequency pass band 0.08 to 7 Hz. Band pass filtering simultaneously suppress high frequency noise in the signal and quasi-dc signal due, for example to finger movement or changes in venous pressure. Thereafter fast Fourier transform (FFT) spectral and power spectral density (PSD) analyses were performed on the data.

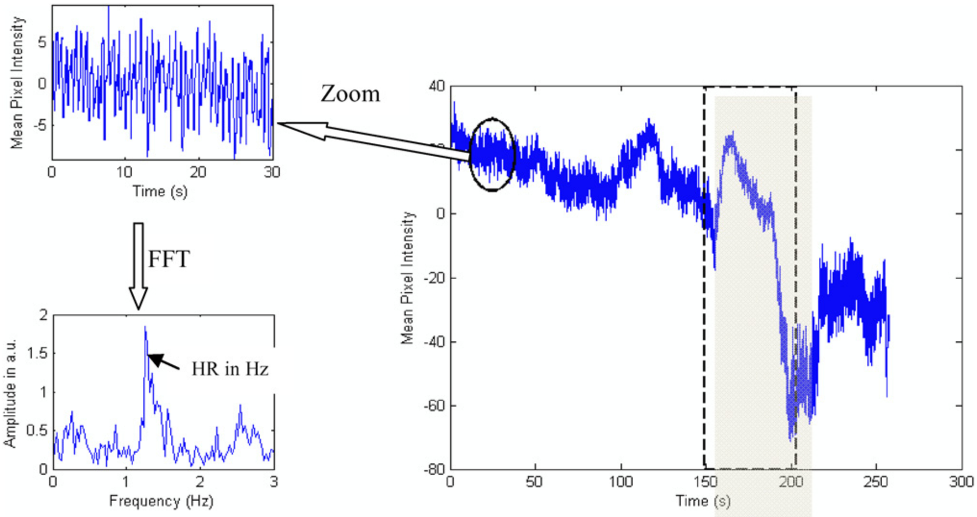

Figure 3. Main figure showing the green channel PPG trace captured after a short run. The portion of the waveform that was extracted and analysed by FFT is marked with an ellipse. The grey rectangle corresponds to breath holding. HR is heart rate.

4. Results and discussion

The raw PPG waveform and the corresponding FFT spectrum for the subject at rest for the selected ROI are shown in figures 2(a) and (b) for the green and red channels, respectively. For the selected ROI, the green channel returned a stronger PPG signal than the red channel as shown in figures 2(a(i)) versus (b(i)). This observation may be explained in terms of the dependence of the number of scattering events on a wavelength for a fixed probe depth, where the former decreases with a shift in wavelength from blue to red. Despite the difference in amplitude, both channels contain PPG information as revealed in their FFT spectra presented in figures 2(a(ii)) and (b(ii)). The spectra conform to expected results, namely signal peaks in the frequency bands around 0.1 Hz due to autonomic nervous activities, 1 Hz due to the pumping action of the heart as well as around 2 Hz and 3 Hz being higher order harmonics of the cardiac output (Phillips *et al* 2008, Cennini *et al* 2010). An example PPG image measuring 320 $\times$ 240 pixels from plotting the PPG signal amplitude at the mean 0.9 Hz heart rate frequency for the green channel is show in figure 2(c). As a result of limited penetration in tissue the green channel signal is suitable for probing superficial vasculature (Verkruysse *et al* 2008).

Figure 3 shows measurement results immediately after a short run. The main figure is the raw PPG trace extracted from the green channel also showing the region (ellipse) for FFT analysis as well the effect of breath and hold (dotted rectangle) on the PPG waveform. The effect of the short run on the heart rate can be quantified by comparing between FFT spectra in figures 2(a(ii)) and 3. In figure 2(a(ii)) the heart rate is around 0.9 Hz (or 54 beats per minute) while for figure 3 it is around 1.25 Hz (or 75 beats per minute), clearly showing the increased heart rate in response to the exercise.

5. Conclusion

The objective of our study was to demonstrate the usefulness of a smartphone video unit for reflection bio-optical imaging applications and here we demonstrate the reflection mode PPG technique. Our results show that movies of a human finger recorded with a cellular phone operating in the video mode and using its WLED as illumination contain useable reflection PPG signals. For example, we were able to detect change in heart rate in a subject. Our work contributes to the area of medical imaging in the context of personal and home-care applications. In this study the ROI was chosen arbitrarily and investigating the effect of ROI shape and size will be conducted in future studies which will also include comparing our technique to established clinical devices. In these studies we will also investigate if our technique can detect PPG signals at other body surfaces that are easily accessible, such as the wrist.

Acknowledgments

The authors are grateful for funding from the Irish government under the national development plan (NDP) 2007-13 HEA PRTLI IV and the National Biophotonics and Imaging Platform Ireland (NBIPI).

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