The Effects of External Pressure on Multi-Wavelength Photoplethysmography Signals

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Abstract

A device consisting of a multi-wavelength photoplethysmography (MWPPG) sensor, pressure sensor and pressure generating system was developed to measure blood volume changes at different depths of the skin while changing the external pressure. The signals recorded at shorter wavelengths of light (blue and green) showed signs of blood vessel occlusion/opening at lower pressure readings than signals recorded at longer wavelengths of light (red and infrared). Similarly, the maximum oscillation amplitudes for the shorter wavelength channels occurred at lower pressure levels than for the longer wavelength channels. The oscillogram shapes and slopes also differed between the channels, shorter wavelength channels having had smaller slopes than the longer wavelength channels. In addition, the time differences between the pulse waveform feet of the different channels, computed relative to the infrared channel, increased together with the applied external pressure. The results indicate that MWPPG signals can provide new information about the vasculature by probing the tissue at different depths, and that contact pressure is a factor to consider in MWPPG applications. However, more research is needed to better understand the signals, especially how much overlapping information the longer wavelength channels carry with respect to the shorter wavelength channels.

1. Introduction

Photoplethysmography (PPG) is a well-known optical technique used to measure blood volume variations in the skin tissue. The operating principle is simple: a light source illuminates the skin and a photodetector located next to the light source registers changes in the light intensity caused by blood volume variations. Multi-wavelength PPG (MWPPG) is the use of multiple different wavelengths of light simultaneously. The benefit of MWPPG is the ability to measure blood volume variations from different depths of the skin tissue. This is possible because the penetration depth of light into the skin is depended on its wavelength [1].

The aim of this article is to study MWPPG signals while altering the external pressure in a controlled way. For this purpose, a self-made device consisting of an MWPPG sensor, pressure sensor, pressure generating mechanism and related electronics was made. Previous studies, such as [2] and [3], on MWPPG signals and external pressure have focused on occlusion pressures and shapes of the pulse waveforms. Additional interesting parameters can be obtained by ramping up and down the external pressure to create MWPPG oscillograms. These oscillograms can be used to determine, for example, the maximum oscillation amplitudes and slopes. In oscillometric blood pressure (BP) measuring method the pressure level of the maximum amplitude corresponds to the mean arterial pressure (MAP). Hence, the maximum oscillation amplitude in each MWPPG channel could hold information about the BP in different depths of the skin. Similarly in oscillometric BP measuring method, the slopes of the oscillograms are related to blood vessel stiffness [4]. This makes the slopes an interesting parameter in the case of MWPPG oscillograms, given that different blood vessels, i.e., arteries, arterioles and capillaries, dominate the signals depending on the used wavelength because of the way the different blood vessels are organized in the skin[1]. Finally, the effects of external pressure on microvasculature pulse transit times (PTT_M) computed using the pulse waveform feet are of interest because sensor contact pressure has previously been shown to have an effect on traditionally computed PTT [5].

2. Methods

2.1. Hardware Description

The MWPPG part of the device is based on the previous design in [6][2]. The sensor has five light-emitting diodes

[1] That is, the arteries are located deepest in the skin while the capillaries are closest to the skin surface.

[2] The printed circuit board (PCB) of the MWPPG sensor was, however, redesigned to be circular in shape and as small as possible, only about 9.6 mm in diameter.

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(LEDs) emitting light at different wavelengths of light[3] and a photodiode in the center of the LEDs. The MWPPG sensor PCB was installed on top of a piston-shaped object, which transmits the pressure exerted on the MWPPG sensor to an air cushion located below the piston. Inside the air cushion is an absolute barometric pressure sensor (BMP280 by Bosch Sensortec GmbH), which registers the changes in the air cushion's internal pressure when the air cushion is compressed/decompressed. Overall, the pressure sensing setup is similar to the one presented in [7] except that the pressure sensor is located inside the air cushion. The external compression force on the fingertip is generated in the same way as in [7], i.e. with a stepper motor (28BYJ-48) moving a bar down (to create a compression force) to a fingertip and up (to decrease the compression force). The setup, hence, allows to measure blood volume variations at five different wavelengths of light while simultaneously measuring the pulsations of the fingertip using a tonometric approach. The device is shown in figure 1. The PCBs were designed with Autodesk Eagle 9.5.1 and sourced from an external manufacturer. The mechanical design was created with Autodesk Inventor Professional versions 2021 and 2022, and the parts were printed with fused filament fabrication 3D printer (Creality CR-20 Pro).

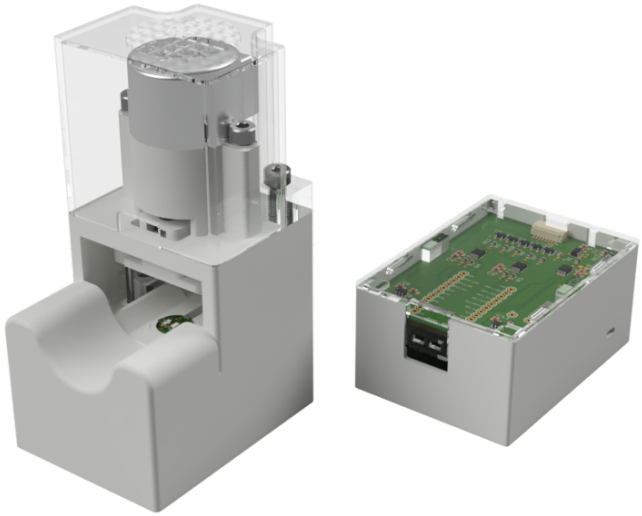

Figure 1. Rendered picture of the developed device with some of the parts intentionally made transparent for illustration purposes.

2.2. System Operation

The device is controlled with a graphical user interface (GUI) written in Python programming language. The application allows the user to change the settings of the device, observe the incoming data from real-time graphs, and initiate a measurement. Once a measurement process is initiated, the firmware (written in C programming language using the nRF5 SDK) of the device sends a command to the stepper motor to start lowering the bar on the fingertip. The MWPPG and pressure sensors simultaneously record signals at sampling rates of 500 Hz (for each channel) and 100 Hz, respectively. The bar is lowered until the maximum allowed external pressure (set above the systolic blood pressure) is reached, after which the stepper motor is reversed to decrease the external pressure.

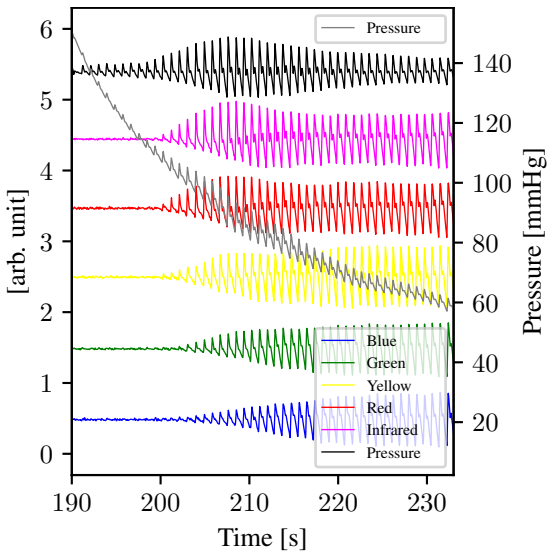

Figure 2. The AC components of pressure and MWPPG signals during a pressure release.

2.3. Algorithms

The recorded data was analysed offline with algorithms written in Python programming language. The pressure signal was upsampled to 500 Hz to match the sampling frequency of the MWPPG signals. All of the signals were then band-pass filtered using a Butterworth filter with a lower cutoff frequency at 0.5 Hz and a higher cutoff frequency at 8.0 Hz. The amplitude envelopes were computed using the Hilbert transform, after which the envelope peaks were identified with a peak detection algorithm. Finally, a least squares polynomial fit was computed on the peaks.

3. Results

The device was tested on three volunteers (one woman) by recording simultaneous MWPPG and pressure signals from the index finger of the right hand. Three measurements were performed on each volunteer. After each mea-

[3]The LEDs emit light at the following wavelengths: 465 nm (blue), 515 nm (green), 590 nm (yellow), 640 nm (red), and 880 nm (infrared).

surement a reference blood pressure measurement was taken from the right hand with a digital blood pressure monitor (Omron M3).

Figure 2 shows an example of band-pass filtered AC components for each sensor channel, stacked on top of each other during a pressure release. The figure shows a typical observation during the measurements in that the blue and green channels show signs of occlusion/opening at lower pressure levels than the rest of the MWPPG channels. This observation is in line with the results in [2] where shorter wavelength channels occluded before the longer wavelength channels. However, the phenomenon was not always very clear, possibly due to pressure-induced vasodilation. Another possible explanation could be the enhanced penetration depth of light into the skin due to skin compression [8]. That is, the shorter wavelength channels start to probe deeper into the skin as the pressure increases.

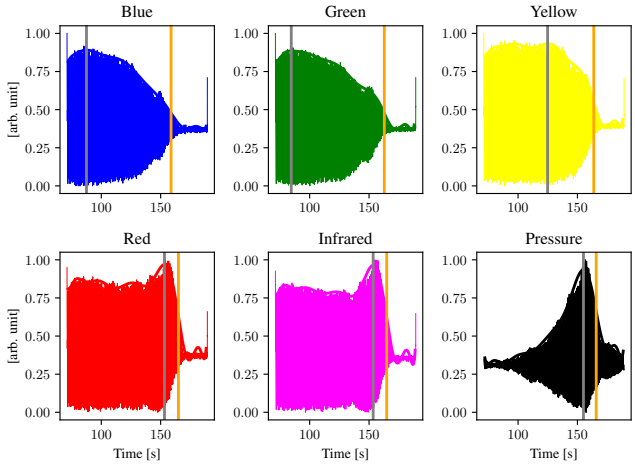

Figure 3. An example of oscillogram amplitude envelopes together with polynomial fittings for each channel during increasing pressure. The vertical orange lines mark the positions of the greatest slopes for the polynomial fittings while the grey vertical lines mark the positions of the maximum oscillation amplitudes.

The oscillograms of the infrared and red channels are typically very similar and share a notable "peaking" similar to the pressure oscillogram, especially during increasing pressure. This "peaking", shown in figure 3, occurs at the same pressure levels as pressure oscillogram's maximum amplitude, shown in the table 1. In addition, the slopes, shown in table 2, between the red, infrared and pressure channels are close to each other. The measurements, hence, imply that longer wavelengths of light penetrate into the arteries. The blue and green channels tend to form another pair, sharing a less notable shape and having maximum amplitudes at lower pressure levels and slopes less than in the case of red and infrared channels. The yellow channel is between the two pairs. These results indicate that the different channels probe different depths of the skin, and hence could reveal information about the different blood vessels (i.e., capillaries, arterioles and arteries) in the skin.

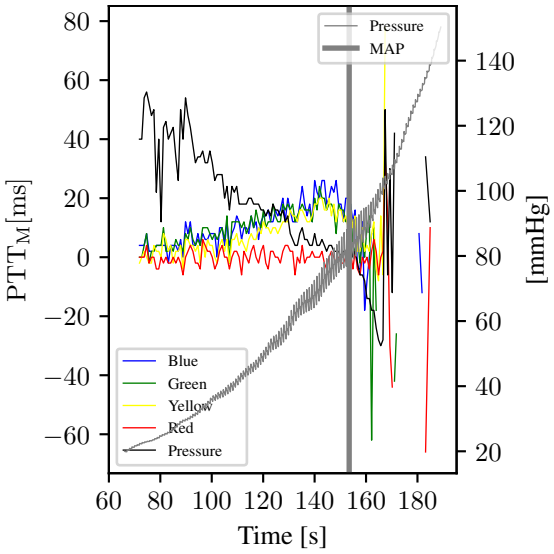

Figure 4. PTT_M values computed during increasing pressure. The values have been computed against the infrared channel.

The similarity/dissimilarity of the different MWPPG channels is also visible in the PTT_M values calculated based on the pulse waveform feet. When the values are computed against the infrared channel, the red channel is close to zero, meaning that the waveform feet are closely aligned timing-wise with the infrared waveform feet. The blue and green channels show the greatest time differences with regard to the infrared channel whereas the yellow channel is somewhere in between. Excluding the red channel, the PTT_M values for the other MWPPG channels increase as the external pressure increases, peaking at around the MAP. The pulse waveforms, especially for the shorter wavelengths of light, tend to distort after the MAP, making automatic computations less reliable. The pressure waveform feet tend to show the opposite behaviour, getting closer to the infrared waveform feet as the pressure increases, zeroing at around the MAP (i.e., at zero transmural pressure).

4. Conclusions

The results show that an MWPPG sensor combined with an external pressure generating and sensing system can probe different depths of the skin and, hence, different blood vessels (i.e., arteries, arterioles and capillaries), or-

Table 1. Computed blood pressure values (mean (standard deviation) mmHg) based on the oscillograms.

Subject	Reference device [mmHg]			Pressure	Developed device [mmHg]					
	SBP	DBP	MAP		Blue	Green	Yellow	Red	Infrared	Pressure
1	119.0 (3.6)	67.6 (2.9)	84.8 (2.9)	Increasing	28.1 (4.6)	27.5 (4.9)	54.4 (4.7)	80.8 (1.3)	81.3 (1.1)	83.9 (1.2)
				Decreasing	34.6 (7.2)	36.1 (8.4)	51.1 (11.3)	85.5 (1.1)	85.7 (1.2)	85.9 (0.7)
2	124.3 (0.6)	83.3 (1.2)	97.0 (0.6)	Increasing	57.7 (2.5)	60.0 (2.9)	68.2 (1.5)	89.7 (2.6)	89.9 (2.6)	93.4 (2.5)
				Decreasing	63.1 (1.8)	66.0 (7.8)	81.7 (3.3)	94.7 (3.1)	96.0 (3.3)	99.1 (3.1)
3	130.0 (1.7)	90.7 (2.1)	103.8 (1.8)	Increasing	54.8 (7.5)	56.1 (10.8)	83.0 (20.8)	95.5 (3.2)	94.6 (4.1)	100.1 (2.1)
				Decreasing	64.8 (13.8)	63.2 (15.9)	82.1 (20.0)	96.5 (2.6)	96.5 (2.9)	104.4 (4.0)

Table 2. Computed maximum oscillogram slopes (mean (standard deviation)) relative to the pressure channel.

Subject	Pressure	Relative slope				
		Blue	Green	Yellow	Red	Infrared
1	Increasing	0.33 (0.03)	0.38 (0.02)	0.60 (0.07)	1.06 (0.14)	1.11 (0.14)
	Decreasing	0.49 (0.09)	0.52 (0.06)	0.64 (0.07)	0.95 (0.09)	1.12 (0.06)
2	Increasing	0.65 (0.06)	0.71 (0.12)	0.61 (0.11)	1.07 (0.29)	1.12 (0.29)
	Decreasing	0.42 (0.06)	0.50 (0.06)	0.50 (0.06)	0.63 (0.03)	0.76 (0.03)
2	Increasing	0.36 (0.06)	0.36 (0.04)	0.94 (0.11)	1.14 (0.09)	1.18 (0.09)
	Decreasing	0.41 (0.01)	0.40 (0.06)	0.72 (0.04)	0.88 (0.10)	0.87 (0.12)

ganized in a layer-like structure, in the skin. Many interesting parameters can, hence, be extracted from the signals by varying the amount of external pressure. However, more research is needed to better understand these parameters, and a possible key to it is to understand the penetration depth dependency of the different channels in more detail and how much other factors, such as pressure-induced vasodilation, affect the signals. The former could perhaps be studied with a detailed simulation model describing the passage of photons within the fingertip. Gathering more data from subjects with wide variety of backgrounds (e.g., age, gender and diseases) is also required to further understand the signals.

Acknowledgements

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