Development and Utilization of a Wireless and Portable Photoplethysmograph to Study the Post-Occlusive Reactive Hyperemic Response in a Finger

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Infrared light, when used in a narrow biological window, can be applied in such a way as to obtain blood flow measurements in vivo in tissues deeper than skin. When using light as a medium for blood flow measurement, the circulatory system's response to a stimulus such as occlusion may be a useful tool to characterize circulatory health. We developed a wireless, noninvasive device that uses photoplethysmography (PPG) in order to study pulsatile blood volume changes in the finger in both the skin and bone that occur during post-occlusive reactive hyperemia. We used this device at the top of the intermediate phalanx of the middle finger to measure a hyperemic response, which was induced mechanically with the use of a pressure cuff. Our study develops on prior work done by Näslund et al. and J. Mateus which evaluated pulsatile blood volume changes in bone with near-infrared light[1,2].

The custom built wireless reflection-mode PPG system consisted of both a visible light sensor and an infrared sensor to observe the pulsatile blood volume changes at both the surface of the skin as well as in the bone, respectively. The system utilized green and infrared LED's with peak spectral output at 568nm and 810nm. A dedicated visible light phototransistor detected the green LED light and a near-infrared phototransistor detected the near-infrared light. We specifically chose these two wavelengths because of their location near the isobestic points of blood as well as their depth of penetration into and absorption by biological tissues of interest. Each analog front end was comprised of an anti-aliasing filter, a tunable gain-stage and high and low pass active filters, which filter the analog signals from the phototransistors and restrict the PPG data to a bandwidth of .7 Hz to 4.1 Hz, covering the full range of the human pulse. We heuristically tuned the gain stage to yield a .5V peak to peak PPG waveform from both the green and infrared sensors under normal conditions with no treatments applied to the subject being studied. A microcontroller sampled data from the green and infrared sensor systems at 50 samples/sec. The device sent the data points for both channels concurrently over a single Bluetooth channel to a PC running MATLAB by time-division multiplexing the two signals.

The experiment consisted of data collection from the green and infrared PPG sensors for about ten minutes. We collected PPG data without any treatment being applied for the first two minutes. Around minute two, we inflated a pressure cuff on the bicep of the arm to 140mmHg for about three minutes in order to induce ischemia in the finger being studied. The ischemia was characterized by the absence of a pulse at the finger. At around five minutes, we deflated the cuff, inducing a hyperemic response in the finger.

We recorded eight experimental trials of the setup on one individual in MATLAB. It was not possible to obtain reliable hyperemic response data for both infrared and green PPG sensors at the same time in any of the eight trials due to the susceptibility of the sensors to motion artifact noise. Nevertheless, it was possible to obtain hyperemic response data from the sensors separately in two different trials. We used the findpeaks() and mean() functions to find the difference between the control signal amplitude recorded in the first two minutes of the trials and the hyperemic peak of the PPG signal. Comparing the control signal amplitude at the beginning of the trials to the amplitude of the PPG signal during a hyperemic response, we found that there was a 26% increase in the PPG signal amplitude of the signal from the infrared sensor and a 16% increase in the PPG signal amplitude of the green sensor. We also computed the difference between the amplitude of baseline PPG signal recorded when the arm was occluded to the amplitude of the PPG signal during a hyperemic response. We found that there was a 37% increase in PPG signal amplitude from the infrared sensor and a 31% increase in the PPG signal amplitude from the green sensor. While it is difficult in practice to isolate the infrared light being reflected off of blood in bone tissue from the light being reflected off of blood in other tissues such as skin, an effort was made to occlude the skin by holding the infrared sensor firmly to the finger.

We found that it is possible to obtain PPG data on a hyperemic response occurring within the circulatory system of a finger using both green and infrared-based PPG sensors. Further work to filter out motion artifact noise in PPG signals is needed to obtain more consistent experimental results and to increase the reliability of the data gathered.

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[1] J. Näslund, J. Pettersson, T. Lundeberg, D. Linnarsson and L. Lindberg. Non-invasive continuous estimation of blood flow changes in human patellar bone. *Med Biol Eng Comput 44(6),* pp. 501-9. 2006.

[2] J. Mateus, "Photoplethysmography for non-invasive measurement of bone hemodynamic responses to changes in external pressure," 2011.

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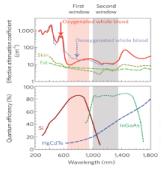
Abstract

- Blood flow measurements in tissues deeper than skin are difficult to perform noninvasively without affecting flow.
- Standard noninvasive methods involve the introduction of chemical tracers or microbeads to the bloodstream.
- Near-Infrared photoplethysmography is a noninvasive and relatively simple method that can be used to observe deep tissue blood flow such as in the bone.
- We developed a wireless, noninvasive device that uses photoplethysmography (PPG) in order to study pulsatile blood volume changes in the finger in both the skin and bone that occur during post-occlusive reactive hyperemia in the finger skin and bone.
- We used a pressure cuff to mechanically induce post-occlusive reactive hyperemia.
- Skin and bone blood flow data was sent over Bluetooth to a PC and analyzed in MATLAB.

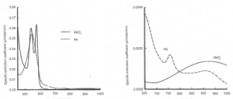
Background

- There is a "biological window" of the near-infrared (NIR) spectrum that can penetrate biological tissue deeply.



Source: Smith, Mancini and Nie. Bioimaging: Second window for in vivo imaging. *Nature Nanotechnology 4(11)*, pp. 710-711, 2009.

- Selecting isobestic points of blood with respect to light wavelength ensures that light reflected off of blood is equal for both deoxygenated and oxygenated blood. We selected 568nm and 810nm emitting LEDS for this reason.



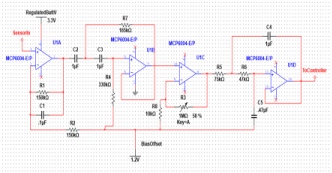
Source: Booth, Dukatz, Ausman and Wider. Cerebral and somatic venous oximetry in adults and infants. *Surgical Neurology International 1(75)*, pp. 75. 2010.

- Visible green light at around 560nm is able to penetrate biological tissue 1-2mm deep, making it useful for skin. Infrared light at around 800nm can penetrate tissue up to 13mm deep. Bone is nearly transparent at 800nm making it an ideal wavelength to observe blood flow in bone.

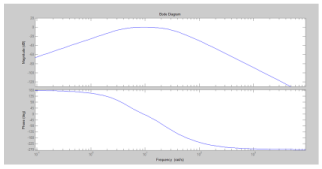
PPG Sensor Design

- Two reflection-mode PPG sensors: a skin blood flow PPG sensor and a bone blood flow PPG sensor. The skin PPG sensor was located at the fingertip and the bone PPG sensor was located at the top of the middle segment of the finger.
- Each PPG sensor consisted of a phototransistor and an LED.
- We selected phototransistors due to their cost, their availability and their inherent gain on the signal being detected.
- We embedded PPG sensor components in a finger splint using insulating rubber putty.

Analog Front End Design



- 4 Stage Analog Front End: Input 1st order 10Hz low pass filter with a gain of 2, 2nd Order Butterworth high pass filter, variable gain stage and 2nd Order Butterworth low pass filter. Identical for both channels.
- The use of Butterworth filters ensured an optimally flat passband. The bandwidth is restricted from .7Hz to 4.1Hz or 42 to 246 BPM.



- A Bode plot of the analog front end depicts a reasonably flat passband. The Bode plot does not depict the gain, which we heuristically tuned to yield .5V peak-to-peak PPG waveforms for each channel.

Hardware Overview

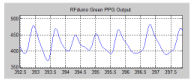
Notable Components and IC's	Quantity Used
RFduino Arduino-Based Bluetooth-Enabled Microcontroller	1 as transmitter, 1 as receiver.
MCP6004 Quad-Packaged Low-Power Op Amp	2
MCP1700 Low Power LDO Linear Regulator	1
LM4041 Precision 1.2V Voltage Reference	1
MTE1081C 810nm Near-Infrared LED	1
565nm Green LED	2
RPT-37PB3F Near-Infrared phototransistor	1
TEPT5700 Ambient-Light Phototransistor	1
2N3904 Transistor for LED Driver Circuit	2

Experiment Setup

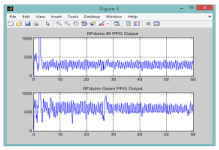
- We affixed the sensor head of the device middle finger (pictured here on the index finger).
- We used a Velcro strap to hold the device in place.
- We placed a pressure cuff on the arm and inflated to 140mmHg at about two minutes into the experiment.
- At about five minutes we deflated the cuff, triggering a hyperemic response.
- The sensor system sent data wirelessly over a Bluetooth connection to a PC.

Data Collection

- An Arduino-based, Bluetooth-capable microcontroller sampled PPG waveform data from the analog front end outputs of both the green and NIR sensor at 50 samples/sec each.
- A 10-sample wide moving average filter processed each channel's data and time-division multiplexed (TDM'd) the each channel's data stream in order to send it over the single Bluetooth channel.

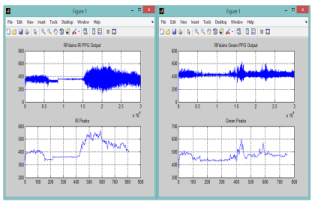


- We implemented TDM by appending a character to each data point, identifying it as green or NIR sensor data.



Results

- We conducted eight experimental runs. Motion artifact noise at the finger made collecting PPG data from both channels during a hyperemic response difficult. However, we observed a hyperemic response using PPG in both sensors from two different experimental trials.



- We quantified the control signal by taking the mean value of the PPG signal for the IR sensor and the Green sensor from 40s-80s. We found this to be 403.1 for the IR sensor and 489.6 for the green sensor.
- Taking the mean of the hyperemic peak between from 460s to 520s for the IR sensor yielded a mean hyperemic peak value of 509.4. Taking the mean of the hyperemic peak between 430s and 440s yielded a value of 569.7 for the Green sensor.
- Taking the percent difference from the control signal value compared to the mean hyperemic peak value of the PPG signals yielded a 26% increase in the amplitude of the IR PPG signal and a 16% increase in the amplitude of the Green PPG signal.
- We quantified the signal baseline by taking the mean value of the PPG signal for the IR sensor from 300s to 400s and 200s to 300s for the Green sensor. We found this to be 370.6 for the IR sensor and 434.5 for the green sensor.
- Taking the percent difference from the baseline compared to the mean hyperemic peak value of the PPG signals yielded a 37% increase in the IR PPG amplitude and a 31% increase in the Green PPG waveform.

Summary

- We developed a wireless PPG sensor system to observe hyperemic responses in both skin and bone blood flow at the middle finger.
- We carefully selected components and used Butterworth filtering in order to obtain minimally attenuated PPG signals from the skin and bone of a finger during a hyperemic response.
- More work can be done to decrease the motion artifact noise in the PPG signal to improve signal clarity.