Physical Artificial Arterial Pulse System for Development and Testing of PPG-Based Sensors*

Jordan F. Hill, Josephine A. Dixon, J. Geoffrey Chase, Christopher G. Pretty

***Abstract*— A physical system to generate a PPG-mimicking signal was designed and validated using everyday low-cost components to aid in medical sensor design. The pulse waveform was created by driving a working fluid into a silicone tube and changing the pressure within it. The corresponding waveform mimics a PPG signal through an artery, is adaptable, and repeatable. The working fluid is interchangeable allowing for change of blood analyte concentrations for development and testing of PPG-based sensors. The system was validated by black ink water compared to water and air compared to water testing to confirm optical transparency of the tube. The produced PPG signal, pulse rate and pressure change were compared to that seen in subjects. Optical transparency for 660 nm – 1550 nm wavelengths of light was validated with the signal, pulse rate and total compliance matching subject data. Thus, the system can mimic arterial pulses, creating a valid PPG signal that can be detected by PPG-based sensors.**

***Clinical Relevance*— Provides a low-cost, adaptable, physical PPG signal generator for research and development of optical medical sensor technologies.**

I. INTRODUCTION

The change in arterial pressure during a cardiac cycle has a distinct pattern. This arterial pressure waveform can be detected using photoplethysmography (PPG) [1]. Different parts of the waveform indicate different parts of the pulse cycle, as outlined in Fig. 1. PPG technology is low-cost and simple to implement, lending itself well to point-of-care medical devices [2, 3].

A raw PPG signal is composed of several components originating from the arterial blood flow, thermo-regulation, respiration, and vasomotion [4]. To extract the arterial pulse, the raw PPG signal is broken into "AC" and "DC" components. The AC component, ~1% of the raw signal, is composed of frequencies greater than 0.5Hz as it is caused by cardiac pulses. Much of the DC component consists of the scattering effects and absorption of surrounding tissues and varies with subject and body composition.

Changes in the PPG waveform can indicate changes in physiology and have been utilized extensively, including pulse oximetry and cranial pressure monitoring [5, 6]. Design of optical sensors to detect blood analyte concentrations use PPG signals to isolate blood and thus analytes from surrounding tissues [7, 8, 9]. However, due to inter-subject variability, it is difficult to calculate a definitive relationship between raw sensor output and analyte concentration.

There are several methods for modelling PPG signals in silico [10, 11]. However, there are no existing physical systems to mimic PPG signals reported despite their need to develop non-invasive sensors. To eliminate variability associated with light scattering in skin and surrounding tissues, a simple, low-cost in vitro PPG system is developed.

A physical PPG system allows for further development and testing of optical sensors, specifically hand-held non-invasive glucose sensors which use PPG signals to isolate blood glucose concentrations [7, 8, 9]. The system is designed for maximum modularity over a wide range of sensor technologies and allows control of DC signal components.

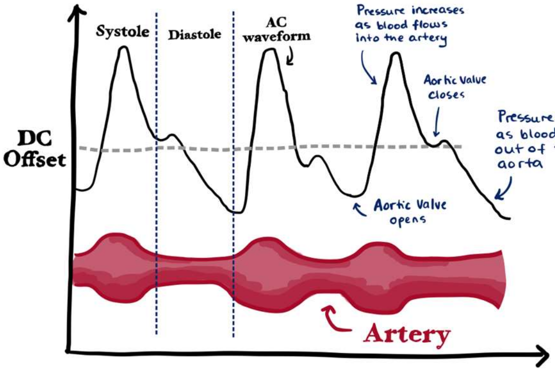

Figure 1. Three cycles of the arterial pressure waveform and the relation of the different parts of the waveform to the cardiac cycle.

II. METHODS

A. Problem definition

There are currently no available systems that provide a physical generation of a pulsatile signal for research and development of pulse-based sensors. Therefore, design objectives and specifications to create a system were developed, provided in Table I. The system incorporates compliant tubing, to mimic the artery and contains an adaptable working fluid to mimic changes in blood pressure, creating the potential for measuring changes in blood analyte concentrations. Thus, key requirements include: 1) the waveform created mimics an arterial pulse, is adaptable, and repeatable; and 2) the working fluid can be interchanged.

To meet these requirements, the solution uses two sub-systems: 1) PPG signal creation; and 2) working fluid containment. The physical system creates an artificial pulse through increasing/decreasing tube pressure.

Sub-system 1: A stepper motor connected to a lead screw via a flexible coupling drives the syringe plunger (Fig. 2). This working fluid motion changes the pressure, and so volume in the tube, causing it to dilate and contract. An

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Arduino Nano controls input motion, and thus the waveform, creating a controllable pressure waveform.

Sub-system 2: Interchanging of the working fluid is vital for validation of the system and aids sensor testing. Working fluid was contained in the 5 mL medical syringe and unstressed 5mm diameter tube volume. The syringe and tube were sealed with a clip for ease of changing the working fluid. Mounts were designed to hold and align the plunger, motor, and sensor board. All mounts were 3D printed and can be adapted for alternative sensor architectures. The tube threaded through the mounts and sat directly on the sensors surface.

TABLE I. Design requirements for the PPG system.

PPG System Design Requirements	
1	Mimic a pulse wave through an artery (create a PPG waveform).
2	Adaptable to various sensor layouts/architectures.
3	The ‘artery’ can be placed directly onto the surface of the sensor.
4	The ‘artery’ is optically transparent for visible to near-infrared (NIR) wavelengths of light.
5	The ‘artery’ dilates/contracts with typical physiological pressure (<140 mmHg [12]).
6	Working fluid can be interchanged without disassembly of entire system.
7	Able to capture and present PPG waveform data in near-real time.
8	Easy to handle and operate for all users.

The system was designed for development of optical sensors which use PPG signals. The sensor used in this experiment uses light emitting diodes (LEDs) for emission and detection. The tube was in direct contact with the LEDs. Black tape was placed over the tube and LEDs to prevent ambient light contaminating results (Fig. 2f). The tape is not required for non-optical PPG-based sensors.

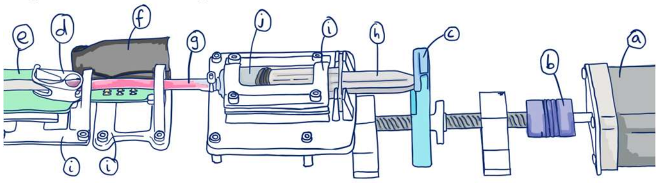


Figure 2. Physical system design. a) stepper motor, b) flexible coupling, c) lead screw slider and clip, d) tube clip, e) sensor, f) ambient light covering, g) silicone tube, h) syringe, i) mounts, j) working fluid.

The silicone tubing was selected to have similar properties to the human vascular system to best mimic arterial compliance. The compliance of the tube was calculated using (1) adapted from Celant et al. [13]:

$$TC = \frac{V - V_u}{MCFP} \qquad (1)$$

Where: TC is the total compliance, V is the total tube volume, V_u is the unstressed tube volume, and $MCFP$ is the mean filling pressure.

A graphical user interface (GUI) plots and saves sensor data. The GUI was designed in the MATLAB 2021 inbuilt app designer and is shown in Fig. 3 [14]. The design requires several user inputs for time to record the data, and patient details for the saved files. Each LED sensor output is live plotted, presenting near-real time PPG waveforms.

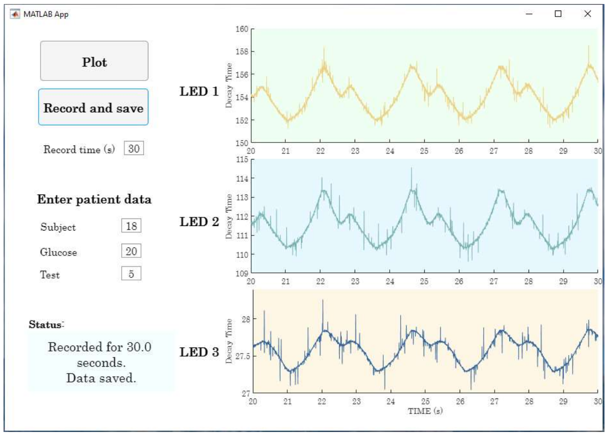
B. Experimental validation

The system was evaluated against the design specifications (Table I). Four validation experiments were performed to aid evaluation: comparison of black ink water, and air to plain water, visualisation of the produced signal, pulse detection, and total compliance.

To assess the optical transparency of the silicone tube, the system was tested using a red-light (660 nm) sensor, and a NIR (1200 nm, 1450 nm and 1550 nm) sensor comparing plain tap water and a black ink water mixture as the working fluid. A black permanent marker was left in 100 mL of water for one hour to create the black ink mixture. Black ink absorbs predominantly in the visible spectrum and minimally in the NIR spectrum. To validate NIR optical transparency, air was also compared to water in place of the black ink.

Fluid was drawn up through the silicone tube and syringe (3.0 mL). Care was taken to avoid air bubbles in the tube. The free end of the tube was secured according to the set-up design. The sensor was turned on for 5 minutes allowing the LEDs to heat up and reduce effects of temperature-related drift [7, 8, 9].

Once warm, the system was run for 5 x 30 second trials. The motor ran constantly across all trials. The raw data was collated and filtered using a simple finite impulse response (FIR) lowpass window filter (cut-off frequency, $f_c = 20.0$ Hz) in MATLAB to remove noise [14]. Mean sensor output across the 5 trials was determined for both working fluids.



Record time (s) 30

Subject 18

Glucose 20

Test 5

Recorded for 30.0 seconds.
Data saved.

Figure 3. GUI displaying live plot of the sensor data and user inputs for recording time and patient data.

Aurdino code drove the system in a series of forward- and back movements to create a PPG-like shape at a pulse-rate of ~30 bpm. The pulse shape and rate were validated using the GUI (Fig. 3) and compared to a real PPG signal shape (Fig. 1). The system pulse output was also validated using a Shenzhen Yimi Life Technology pulse oximeter (Shenzhen, China). The silicone tube was threaded through the oximeter and secured, ensuring sensor contact to measure a ‘pulse’.

The physiological pressure was measured using the pressure gauge from an Accoson sphygmomanometer

(Ayrshire, United Kingdom). The empty syringe was attached to the gauge to determine the pressure change over the known syringe + unstressed tube volume (3.0 mL + 1.5 mL). The pressure change corresponded to the mean filling pressure to determine total tube compliance.

III. RESULTS

The black ink water absorbed a greater fraction of light than plain water, increasing sensor output by 9.5 % from 33.8 to 37.0 for this particular sensor setup, validating optical transparency of the silicone tube for 660 nm (Fig. 4).

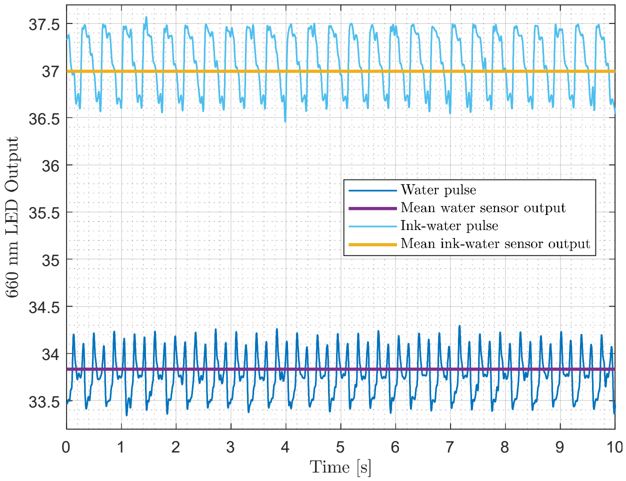


Figure 4. Varying pulse wave patterns for black ink water vs. water mean sensor output.

Black ink water absorbed a greater fraction of light than water for all wavelength LEDs. As seen in Fig. 5, the mean sensor output for black ink water is greater than the mean sensor output for water for all LEDs in all trials.

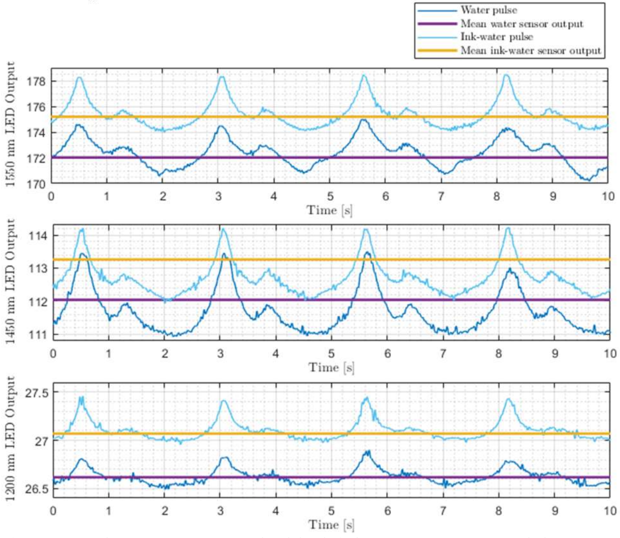


Figure 5. Pulse wave patterns for black ink water vs water and the mean LED output for each tested wavelength of light.

Mean sensor output and percent change for each tested LED wavelength is seen in Table II. The increase in mean output with positive percent change validates the optical transparency of the silicone tube for all tested wavelengths of light.

TABLE II. Mean sensor output and percent change for LED wavelengths for black ink water compared to water.

LED wavelengths [nm]	**Mean sensor output**		**% Change**
	Water	**Ink-water**	
660	33.8	37.0	9.5
1200	26.6	27.1	1.9
1400	112.0	113.3	1.1
1550	172.0	175.2	1.8

The same test was conducted with air compared to water on the NIR wavelength sensor. Table III provides the mean sensor output and percent change for each wavelength. Air absorbs less light than water, decreasing sensor output. Hence, the percent change reported is a reduction.

TABLE III. Mean sensor output and percent change for LED wavelengths for air compared to water.

LED wavelengths [nm]	**Mean sensor output**		**% Change**
	Water	**Air**	
1200	26.6	23.9	-10.5
1400	112.0	81.7	-27.1
1550	172.0	116.3	-32.4

The waveform produced has distinct systolic and diastolic regions with clear peaks (Fig. 6) and is comparable to a typical PPG waveform, as shown in Fig. 1. The oximeter detected a pulse of 30 bpm, with the PPG signal waveform consistent across all trials for each wavelength. The pulse rate was confirmed with the signal repeating every ~2.0 seconds on the GUI. A mean filling pressure of ~120 mmHg and a stressed tube volume of 1.8 mL was measured. Using (1), the total compliance of the silicone tube was 2.5 mL/mmHg.

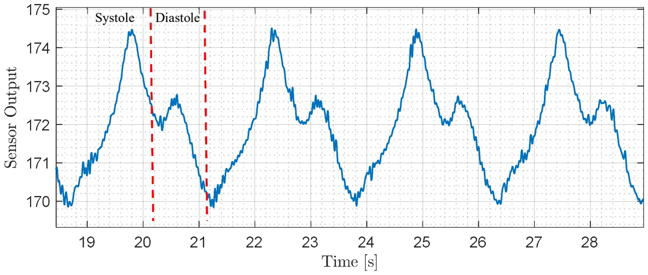


Figure 6. Filtered waveform shape produced by the system with PPG phases labeled.

IV. DISCUSSION

A. *System Design Performance*

Black ink absorbs more light than water in the visible spectrum resulting in a 9.5 % increase of sensor output at 660 nm. The smaller sensor output of 1.1 - 1.9 % for NIR light was expected as absorption by black ink is minimal for the NIR wavelengths.

Air absorbs less light than water in the NIR spectrum. Comparing air to water for the NIR wavelengths confirmed the silicone tube was not absorbing infrared light, with 10.5 - 32.4 % sensor output reductions.

Development of hand-held non-invasive sensors similarly use light absorption to calculate blood analyte concentrations. For the sensor used in experiments, greater absorption by the molecule decreases the amount of light getting back to the sensor. Therefore, more time is required for the voltage to drop past the set threshold, increasing sensor output. When the molecule absorbs less light, the opposite occurs with sensor output decreasing.

Sensor output varies with sensor design. For LED sensors, current, light intensity, or decay time can be measured depending on the application required. The system is adaptable to a range of sensors outputs while still producing the required PPG signal waveform.

Increasing and decreasing the pressure caused the tube to dilate and contract evenly and consistently across the entire sensor. The PPG waveform was consistent across all tests for each wavelength validated and creates a 30 bpm pulse, confirmed by the oximeter. The compliance of the silicone tube was calculated as 2.5 mL/mmHg, aligning with typical vascular compliance of humans (~2.1 mL/mmHg) [13].

Adjusting the start position of the leadscrew slider allowed control of peak waveform amplitudes. Larger amplitudes corresponded to increased dilation and more pressure throughout the tube. Changes in amplitudes had no effect on the results while maintaining adaptability.

PPG waveforms have been extensively used and validated for pulse oximetry and pressure monitoring. However, systems for LED sensors that use PPG signals for detection have not. System validation enables development and testing of LED sensors, specifically to measure blood analyte concentrations. The adaptability of the system allows for any sensor that detects through PPG signals to also be tested.

B. *Limitations*

During validation tests, bubbles in the tube arose from air in the syringe mixing with the working fluid while the system was operating. Bubbles may have reduced the consistency of results. To prevent bubbles, the water can be degassed, and with the system set up vertically, a thin layer of paraffin oil on top of the water creates a barrier at the air-liquid boundary.

V. CONCLUSION

PPG signals are used extensively in biomedical sensors for monitoring and diagnosis. A physical PPG system was created to aid in development of an optical glucose sensor. The key requirements for the system were: 1) the waveform created mimics that through an artery, is adaptable, and repeatable; and 2) the working fluid can be interchanged. The designed physical system met all specifications and requirements. The pulse wave shape can be manipulated by driving the motor, via an Arduino, in different configurations.

The system was experimentally validated in four ways. Optical transparency was confirmed for 660 nm to 1550 nm wavelengths through a mean sensor output change of 1.1 - 9.5 % for ink water compared to water and 10.5 - 32.4 % change for air compared to water (NIR only). The signal visually aligns with a typical PPG signal shape with a pulse of 30 bpm detected. The pressure change within the tube was ~120 mmHg per cycle with a total tube compliance of 2.5 mL/mmHg.

Overall, the adaptable physical PPG system developed meets all design specifications and requirements. The PPG waveform produced is consistent and adaptable to research needs. The system can be adapted to different sensors through adapting mounts. Performing validation tests with different PPG sensors or wavelengths of light would be beneficial to examine the complete adaptability and robustness of the system. This tool is low-cost, easy to implement, and can aid in the development of a range of PPG signal medical devices.

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