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Miniature Wireless Reflectance Pulse Oximeter Connected to Mobile Application

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Photoplethysmography is a non-invasive physical method used for measurement and monitoring of arterial blood flow in the subject's body with application of light. Pulse oximetry is the modification of photoplethysmography enriched with monitoring blood oxygen saturation. Acquisition of pulse oximetry data can be achieved using two types of pulse oximeters: transmission or reflectance. Both methods require the use of physical light sources and a receiver, set in specific positions. This results in different construction of devices and may lead to diverse ways of calculating the blood saturation values. One of these ways uses second-degree polynomial made from three constants and a variable calculated with ratio of red- to infrared-based variables. We used this method to develop the wireless pulse oximeter paired with the dedicated mobile application. The device acquired 400 samples per second and calculated oxygen saturation level and heart rate, as well as provided data for photoplethysmography curve. In this system data are transferred in real time to the application, which displays the saturation values and presents photoplethysmography curve for last several heartbeats. Calculation of the values was checked with a commercial pulse oximeter and the results were mostly similar, with the difference in SpO_2 not greater than one percentage point and the difference in heart rate not greater than five beats per minute. The design of the pulse oximeter allows further miniaturization. Mobile application is intuitive for user and does not need any training.

topics: pulse oximetry, blood oxygen saturation, mobile devices, bluetooth

1. Introduction

One of the factors necessary for the functioning of developed living organisms is access to oxygen. It makes it possible to release energy that allows the entire body to function. Oxygen molecules are transported in the body using hemoglobin — a protein that is a part of red blood cells, which binds with oxygen and delivers it to cells. However, this process does not always meet the needs of the body. Due to an insufficient amount of oxygen in the environment or the occurrence of a certain pathological condition, the level of oxygenation (saturation) of the blood may drop below the level ensuring normal functioning. It is assumed that a healthy person should have the percentage of oxygenated blood, determined as SpO_2, at an approximate level of 98% [1], while a persistent drop below 95% may mean a potential threat to life [2]. With such a decrease in saturation, hypoxemia is still not visible. The inability to visually evaluate saturation has led to the development of new techniques for measuring this parameter, including pulse oximetry.

Pulse oximetry applications are not new to the market. It is possible to find both mobile applications that connect themselves with a dedicated pulse oximeter, as well as applications that allow to perform pulse oximetry measurements using a phone camera. The latter solution, which does not require the presence of pulse oximeter, is still being tested, however, does not always provide correct results [3, 4].

In clinical practice, the pulse oximetry device uses a sampling frequency of around 10–25 Hz. This value is sufficient for presenting the oxygen saturation values [5]. However, it is necessary to achieve sampling of at least 200 Hz or higher to allow more accurate determination of *heart rate* (HR) and other time-dependent parameters characterizing *photoplethysmography* (PPG) curve [5]. Since we have not found any reflectance pulse oximeter with the dedicated mobile application using a sampling rate of 400 Hz (or more), we decided to develop a system that provides more precise determination of time intervals, shorter than the cardiac cycle, to allow the detection of some cardiac arrhythmias (e.g. atrial fibrillation).

2. Material and methods

2.1. Physical background of pulse oximetry

Pulse oximetry is a non-invasive method of measuring arterial oxygen saturation, which is based on the phenomenon of selective light absorption [6]. Research has shown that light of different lengths is absorbed differently by oxy- and deoxyhemoglobin-hemoglobin, which, respectively, is and is not currently carrying oxygen particles. The absorption of light of a specific wavelength is expressed by the formula represented in the notation of Lambert–Beer's law [7]

$$A = \epsilon_\lambda \, c \, d, \tag{1}$$

where A is the absorption coefficient, ϵ_λ is the molar light absorption coefficient, c is the concentration of the absorbing substance, and d is the thickness of the absorbing layer.

Using (1), it is possible to create a formula containing the molar light absorption coefficients for two different wavelengths implemented, i.e.,

$$\frac{A_{\lambda 1}}{A_{\lambda 2}} = \frac{\left(\frac{\mathrm{SpO_2}}{100\%}\epsilon_{oxy\lambda 1} + \frac{100\%-\mathrm{SpO_2}}{100\%}\epsilon_{deoxy\lambda 1}\right) c\, d}{\left(\frac{\mathrm{SpO_2}}{100\%}\epsilon_{oxy\lambda 2} + \frac{100\%-\mathrm{SpO_2}}{100\%}\epsilon_{deoxy\lambda 2}\right) c\, d}. \tag{2}$$

The $\mathrm{SpO_2}$ parameter is expressed as a percentage, therefore the molar absorption coefficients of the specific wavelengths should be multiplied by the corresponding percentage of the appropriate type of hemoglobin in the blood.

This solution reduces the formula by disposing of the concentration of the substance and the thickness of the absorbing layer, so they do not have to be known to calculate the oxygen saturation. Knowing the light power before absorption by the tissue, the absorption values for both wavelengths can be calculated, which makes the number of unknown variables reduced to only one — $\mathrm{SpO_2}$, the blood oxygen saturation. The formula after transformation is shown by

$$\mathrm{SpO_2} = \left(A_{\lambda 2}\epsilon_{deoxy\lambda 1} - A_{\lambda 1}\epsilon_{deoxy\lambda 2}\right) \times \left[A_{\lambda 1}\left(\epsilon_{oxy\lambda 2} - \epsilon_{deoxy\lambda 2}\right) - A_{\lambda 2}\left(\epsilon_{oxy\lambda 1} - \epsilon_{deoxy\lambda 1}\right)\right]^{-1}. \tag{3}$$

Pulse oximetry typically uses infrared and red light. In recent years, the usefulness of green light has also been noticed, working better in patients with dark skin providing increased universality [8]. The selection of the light wavelength is based on the differences in the absorption of the beam by oxygenated and non-oxygenated blood [2].

One of the data sets often cited for this purpose is the research results of Dr. Scott Prahl, who measured the molar light absorption coefficient for wavelengths from 250 to 1000 nm. Part of the results of his research is presented in Fig. 1 [9].

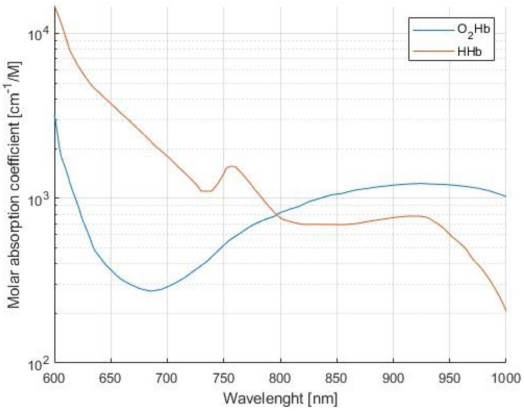

Fig. 1. Molar absorption coefficient for wavelengths in the range 600–1000 nm (based on data collected by Scott Prahl) [9]. O_2Hb denotes oxyhemoglobin, and HHb — hemoglobin.

It is possible to find two beams of light such that one will be absorbed much more strongly by oxyhemoglobin and the other by deoxyhemoglobin. Due to this, the previously mentioned equation can be used.

In pulse oximetry, there are currently two types of pulse oximeters, i.e., transmission and reflection. Both types consist of a set of at least two diodes, emitting lights with different wavelengths, and an optical receiver to measure the amount of absorbed light. The difference in their construction is the location of the detector in relation to the transmitter; in the first type, the light must pass through the entire thickness of the tissue because the detector is placed behind the object being illuminated, while the second type has a detector placed next to the transmitter. With this structure, the pulse oximeter measures the dose of light reflected in the body. This type is more susceptible to interference, but it is also more universal. Transmission pulse oximeters can collect information from parts of the body such as the ear or finger, while reflective pulse oximeters can be used in places with a much thicker absorbing layer that the light beam cannot penetrate.

In reflectance pulse oximetry, the $\mathrm{SpO_2}$ parameter can be calculated in a different way than that presented in (3). The modulation index R is taken as the basis for the calculations, based on the formula [1, 10, 11]

$$R = \frac{\mathrm{AC}_R/\mathrm{DC_R}}{\mathrm{AC_{IR}}/\mathrm{DC_{IR}}}, \tag{4}$$

where AC_R is the amplitude of the received red diode signal, $\mathrm{DC_R}$ is the constant component of the red diode signal, $\mathrm{AC_{IR}}$ is the amplitude of the received infrared diode signal, and $\mathrm{DC_{IR}}$ is the constant component of the infrared diode signal.

The R index calculated using (4) allows the calculation of the $\mathrm{SpO_2}$ parameter after constructing a second-degree polynomial based on it, in which

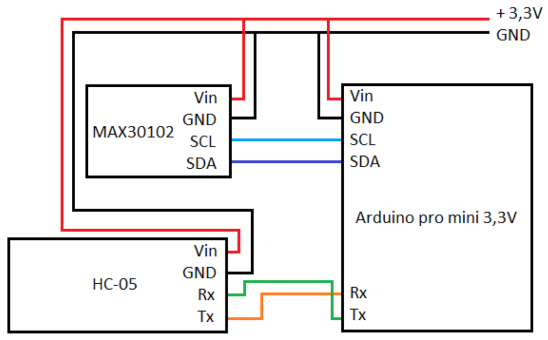

Fig. 2. Pulse oximeter connections diagram.

TABLE I

Experimentally gained coefficients used for calculations of SpO_2.

Polynomial degree (R)	Coefficient
2	1.60
1	−34.66
0	59.00

the coefficients at subsequent powers of the index R are determined empirically based on observations during device calibration [6]. The final form of the formula is

$$SpO_2 = \bar{A}\,R^2 + \bar{B}\,R + \bar{C}. \tag{5}$$

Here, R is calculated based on (4), and $\bar{A}, \bar{B}$, and $\bar{C}$ are the constants.

2.2. Oxygen saturation calculations

Calculations of the SpO_2 parameter are made based on (5). The polynomial coefficients in (5) were determined experimentally. The obtained values are presented in Table I.

Heart rate calculations were derived from division shown by

$$BPM = \frac{60}{t_{avg}}, \tag{6}$$

where t_{avg} is the average time between heartbeats expressed in seconds. Heartbeat was detected with a change of derivative from positive to negative above a set level.

2.3. Pulse oximeter

The pulse oximeter was based on the MAX30102 module connected to the Arduino Pro Mini 3,3V board. Data were transmitted to a mobile phone via the HC-05 module. The connection diagram is presented in Fig. 2.

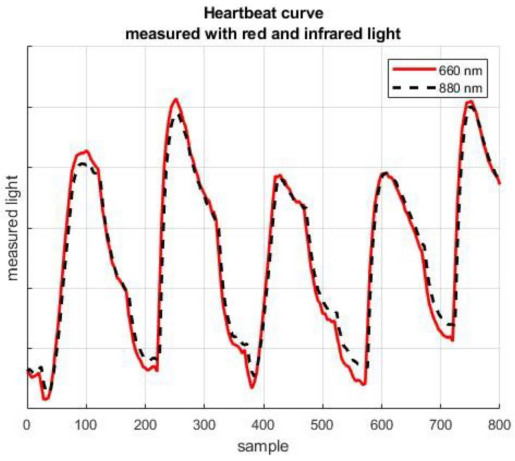

Fig. 3. Sample red (880 nm wavelength) and infrared (660 nm wavelength) curves. The measured HR of the patient was approximately 150 beats per minute.

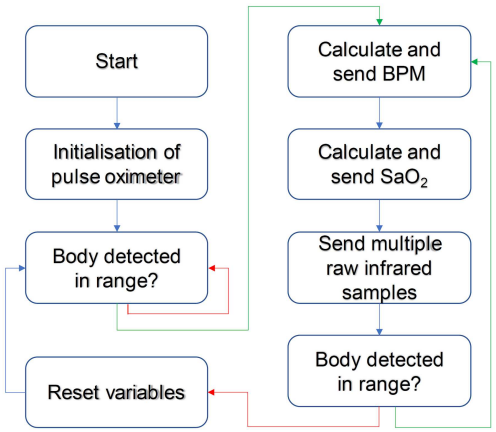

Fig. 4. Pulse oximeter code diagram.

All calculations were handled by a pulse oximeter. After the device detected an object in its range, measurements started. Red and infrared samples were collected at a rate of 400 Hz. Next, the raw data was filtered by a low pass filter with a cut-off frequency of 3 Hz [12]. The filtered data was used for calculating oxygen saturation level and heart rate.

After every calculation, the acquired parameter was averaged and sent to the application. For the first 25 samples, averaging started after the third sample was collected and included every sample acquired to that time. Moreover, the averaging was performed using the last 25 samples. This approach reduced the impact of individual disturbances.

The heart rate graph was fed with data from the infrared light detector. Data is passed after filtering, but before averaging. Between the pairs of oxygen saturation level and heart rate, multiple infrared samples were sent. An example fragments of red- and infrared-based curve is presented in Fig. 3. Figure 4 shows the pulse oximeter code diagram.

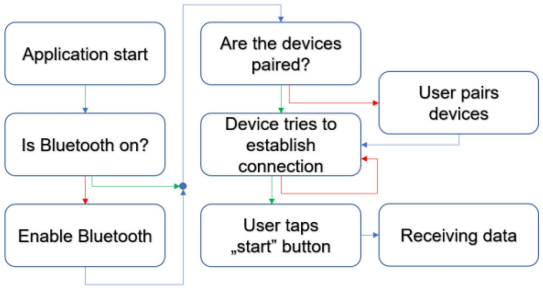

Fig. 5. Application diagram — from start to data reciving.

TABLE II
Data identifiers used in this project.

Data	Identifier
SpO_2	S
BPM	B
photoplethysmography sample	P

After initialization, the device emitted a red light and checked for the received red light signal to surpass the threshold of the emitted light intensity provided by the function from the MAX3010X Sensor Library programming library [13]. When the threshold was surpassed, the device calculated heart rate using (6). Next, with use of (5) and constants shown in Table I, the SpO_2 was calculated. For both variables, if they were the third or latter value calculated, the calculated averaged value was sent to the application. After the calculations, the red light values are sent to the application. Every 50 samples, the heart rate and the SpO_2 are recalculated. If the red light intensity drops below threshold value, the device resets.

2.4. Mobile application

The application was written in Java and designed for Android devices. It has a simple and intuitive interface, so it does not require instructions for use. The application's operation diagram is presented in Fig. 5. After connecting to the pulse oximeter, the application begins collecting data.

The data was sent with the appropriate identifier. The identifiers were presented in Table II.

A screenshot of the last stage of the application, used for data display, is presented in Fig. 6.

2.5. Tests and validation procedure

The results of the calculations made by the application were checked by a comparative method using the commercial pulse oximeter Microlife OXY 300

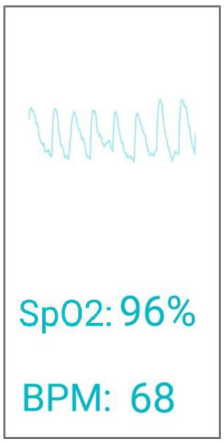

Fig. 6. Example application screenshot.

and the reflectance pulse oximeter MAX30102 connected to the application via the Arduino Pro Mini board. The tests were carried out under normal breathing and breath-holding conditions.

3. Results

3.1. Calculation tests

The range of tested SpO_2 values was considered sufficient for the range below 90%, as any drop below 95% may be alarming [2] and a drop below 90% for just a few minutes may have long-term effects [14] and qualifies for medical attention. Therefore, the tested range was dedicated to short-term examination.

The lowest result recorded was $SpO_2 = 85\%$, so the tested values include the range 85–99%. In the case of the lower range of tests performed, the blood oxygen saturation values did not deviate by more than one percentage point from the readings of the reference pulse oximeter. In contrast, at values of 94–99% the values coincided.

3.2. Heart rate

The calculated average heart rate typically varied no more than five beats per minute. Calculations were very sensitive to the movement of the device or a patient, which increased the calculated value.

4. Advantages and further development

The use of a smartphone or tablet connected to medical devices provides new opportunities for the development of pulse oximeters. It allows to connect to the Internet or even save data on the device

or in the cloud. Another potential advantage is the separability of the pulse oximeter and the screen on which the results are displayed. It allows measurements to be made remotely or by two people, and also makes it possible to reach hard-to-reach places while maintaining the comfort of reading the data. Although such capabilities have a rather narrow application, they can be useful in specific cases.

The advantage of the pulse oximeter presented in this article is small size and the ability to easily read results from the detached screen.

When it comes to the possibilities of further development of the project, the calculations can be moved from the pulse oximeter to the application. It would allow to use smartphones with much bigger computing power, further decreasing pulse oximeter size and energy usage. Also, a potential niche is veterinary medicine. By appropriately calibrating the coefficients of the polynomial of the R parameter, the device can be easily adapted to a specific animal species. The above-mentioned separability of the pulse oximeter and the screen may also be useful here, as it may make it easier to find the appropriate place to apply the sensor on the animal's body. Moreover, such use of the system with an application could be useful not only in medical clinics, but also, due to the simplicity of use, of interest to home users.

5. Conclusions

This article presents our own construction of a pulse oximeter wirelessly connected to a mobile device used to expand the capabilities of signal analysis including variations in systole/diastole time intervals. The pulse oximeter provides raw PPG data samples, as well as the calculated oxygen saturation level and heart rate. The application is dedicated to mobile devices and its task is to receive and display data sent by the pulse oximeter via Bluetooth.

The use of a pulse oximeter connected to a mobile device provides several new possibilities that seem to be unattainable with pulse oximeters used in their current form. Devices are constantly developing, and it is worth taking advantage of new technological possibilities, which is why we believe that our approach to the subject of pulse oximeters may help develop the hardware and software capabilities of these devices in the future, or at least become an inspiration for further innovations.

References

[1] E. Kaniusas, *Biomedical Signals and Sensors II. Biological and Medical Physics, Biomedical Engineering*, Springer, Berlin 2015.

[2] A. Cysewska-Sobusiak, *Modelowanie i Pomiary Sygnałów Biooptycznych*, Wydawnictwo Politechniki Poznańskiej, Poznań 2001 (in Polish).

[3] T.B. Jordan, C.L. Meyers, W.A. Schrading, J.P. Donnelly, *Am. J. Emerg. Med.* **38**, 925 (2020).

[4] S. Tomlinson, S. Behrmann, J. Cranford, M. Louie, A. Hashikawa, *Telemed. J. E Health* **24**, 527 (2018).

[5] T. Leppänen, S. Kainulainen, H. Korkalainen, S. Sillanmäki, A. Kulkas, J. Töyräs, S. Nikkonen, in: *Advances in the Diagnosis and Treatment of Sleep Apnea*, Vol. 1384, Eds. T. Penzel, R. Hornero, Springer, Cham 2022, p. 205.

[6] E.D. Chan, M.M. Chan, M.M. Chan, *Respir. Med.* **107**, 789 (2013).

[7] J.J. Patil, D.G. Maloney, *Anaesth. Intensive Care Med.* **15**, 522 (2014).

[8] N.P. Taylor, "*Green Light Shows Promise in Addressing Oximetry Racial Bias: Study*", MedTechDive, 2023.

[9] S. Prahl, "Tabulated Molar Extinction Coefficient for Hemoglobin in Water", Oregon Medical Laser Center, 1998.

[10] L. Hooseok, K. Hoon, L. Jinseok, *ICT Express* **2**, 195 (2016).

[11] M. Nitzan, A. Romem, R. Koppel, *Med. Devices* **7**, 231 (2014).

[12] N. Stuban, M. Niwayama, *Rev. Sci. Instrum.* **83**, 104708 (2012).

[13] D. Wiese, MAX3010x Sensor Library, 2021.

[14] A. Jubran, *Crit. Care* **19**, 272 (2015).