Estimation of SpO_2 and Heart Rate based on Photoplethysmographic Measurements at the Sternum

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***Abstract*— Continuous observation of a patient's health parameters in the hospital is very important. Oxygen saturation and heart rate are two important health parameters to determine the early warning score** [1], [2]. **These 2 health parameters can be determined by using photoplethysmography (PPG). The PPG uses light of different wavelengths and a photodetector to capture the reflected light.**

Raw data was obtained from 2 different devices. On the first device, 2 PPG sensors are present in a different location. This makes it possible to determine at which location the PPG sensor measures the best data. The data transfer is accomplished via a USB connection. In the second device, there is only 1 PPG sensor present and the data transfer is transferred via MQTT over Wi-Fi.

For the data analysis, little difference in data quality was observed between the raw data coming from both the devices. The raw data was filtered in MATLAB using a lowpass filter with a cutoff frequency of 1 Hz and an infinite impulse response (IIR). Then the data is processed in MATLAB to determine the heart rate and oxygen saturation values.

Tests were conducted on 4 healthy volunteers, and the extracted data has indicated that both the phi value and the heart rate are fairly stable. The next step is to determine the SpO_2 level based on the phi value. Furthermore, the heart rate variability (HRV) and the respiration rate (RR) can be calculated.

Finally, when the case is correctly positioned with the correct settings for the LED intensity, a very nice signal is measured that ensures that we are able to obtain a good and stable result.

I. Introduction

DUE to the COVID-19 pandemic, it is very important to be able to continuously monitor the health of patients in hospitals. Important factors to determine the early warning score of the patient are the heart rate, the blood pressure, the respiration rate, the oxygen saturation and the temperature [1]. To determine these, different sensors are needed. The following sensors are used to determine the health parameters: photoplethysmography (PPG), an electrocardiogram (ECG), an optical thermometer and an accelerometer. [3], [4]

In this paper, the focus lies on the determination of oxygen saturation and heart rate. For these determinations, the PPG sensor will be used.

The light-emitting diodes of the PPG are used to send out light with different wavelengths. Depending on the wavelength, the amount of energy transferred into the skin varies. The light travelling through the skin and tissues gets absorbed and reflected, this reflected light is detected by a photodetector and gives us the PPG signal. [5]

The absorption of light in human blood mainly depends on hemoglobin. Green light is best absorbed and therefore used to determine the heart rate. The heart rate can be determined from the peaks of the PPG signal.

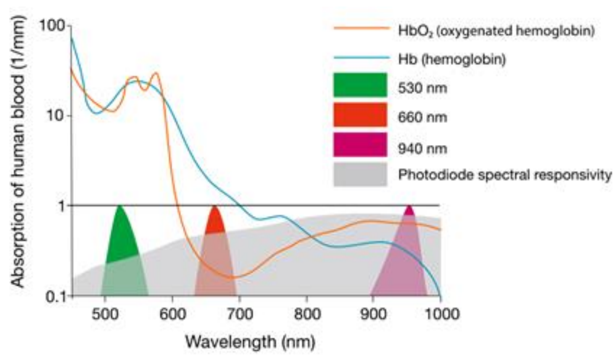

Fig. 1. The absorption of human blood versus wavelength of light [6]

For the determination of the oxygen saturation, it is better to use red light (660nm) which is better absorbed by non-oxygenated hemoglobin (Hb) and infrared light (960nm) which is better absorbed by oxygenated hemoglobin (HbO_2). As a result of the different absorption levels (Hb vs. HbO_2) the SpO_2 level can be calculated by the following general formula:

$$SpO_2 = \frac{HbO_2}{Hb + HbO_2}$$

Eq. 1. The SpO2 value in function of non-oxygenated hemoglobin (Hb) and oxygenated hemoglobin (HbO2) [6]

Fig. 2 shows that the signal can be split into 2 parts, a DC component "steady part" and an AC component "pulsatile part".

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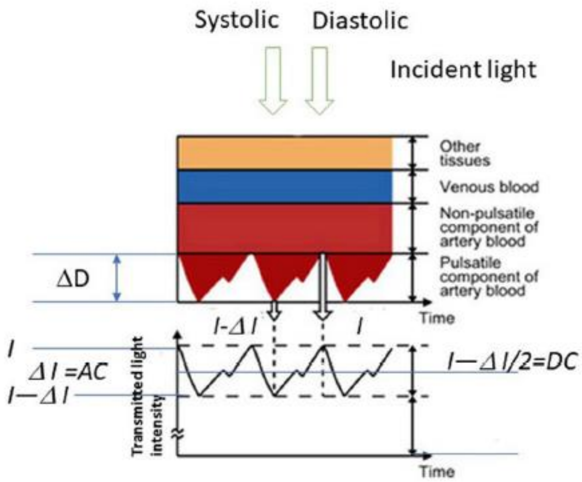

Fig 2. Variation in light attenuation by tissue [7]

The AC component is calculated by taking the difference between the peaks and valleys of the signal. The DC component is then calculated by taking the difference between 1 and half of the AC component's value. Also called the average between the peaks and troughs. These calculations will be done for at least 2 light sources with different wavelengths.

$$\Phi \equiv \frac{\Delta A_{660}}{\Delta A_{940}} \cong \frac{\frac{AC_{660}}{DC_{660}}}{\frac{AC_{940}}{DC_{940}}} = \frac{Eo_{660} * S + Er_{660} * (1 - S)}{Eo_{940} * S + Er_{940} * (1 - S)}$$

Eq 2. The phi value in function of the AC and DC components and the phi value in function of the SpO2 value and some constant values [5]

In eq. 2, the AC component at a certain wavelength is divided by the DC component with the same wavelength, this is done for the different wavelengths. Then the ratio of these results will be taken to obtain phi. The obtained phi value must still be calibrated for each person. The phi value can also be seen as an initial result, as it should remain stable. Eo_{660},Er_{660},Eo_{940},and Er_{940} are constant and predetermined values. Now the SpO_2 value can be calculated.
The test subject's heart rate can also be determined using the PPG sensor. The heart rate is determined by the number of peaks detected per minute.

II. Methods and Materials

A. Data acquisition

To determine the heart rate and oxygen saturation we made use of a device built within the WearIt4Health Interreg project. The device contains amongst other things, a PPG sensor, namely the BIOFY® SFH 7072 from Osram. Which contains two photodiodes, three green LEDs (530 nm), a red LED (655 nm) and an infrared LED (940 nm). This sensor is connected to an analog front-end (AFE4900 from Texas Instruments) to generate the excitation currents and convert the signal to the digital domain.

1. For the first measurements, a case was 3D printed in which a PPG sensor was installed in 2 different places (one on the side and one in the middle), whereby the AFE was connected to an evaluation module so that the values could be measured via cable. Because the AFE can only drive 4 LEDs and 2 PPG sensors were connected, only green and infrared light could be measured for each sensor. The signals are measured with a sample rate of 500 samples / second. After stopping the measurement, the data is stored in an Excel file.

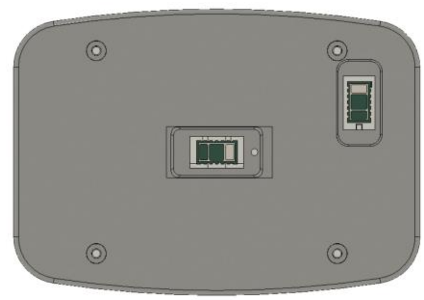

Fig. 3. Top view of the case with 2 PPG sensors

2. A wireless version of the device was used, in which only one PPG sensor is installed. This sensor is coupled with an AFE4900, therefore allowed measuring the red LED as well. The data is transmitted via the MQTT over a Wi-Fi network created by on a Raspberry Pi.[8] Hereby longer measurements and on different parts of the body were measured. The signals are measured with a sample rate of 200 samples / second, in order to conserve energy. The recorded values are converted to an Excel file by means of MATLAB code.

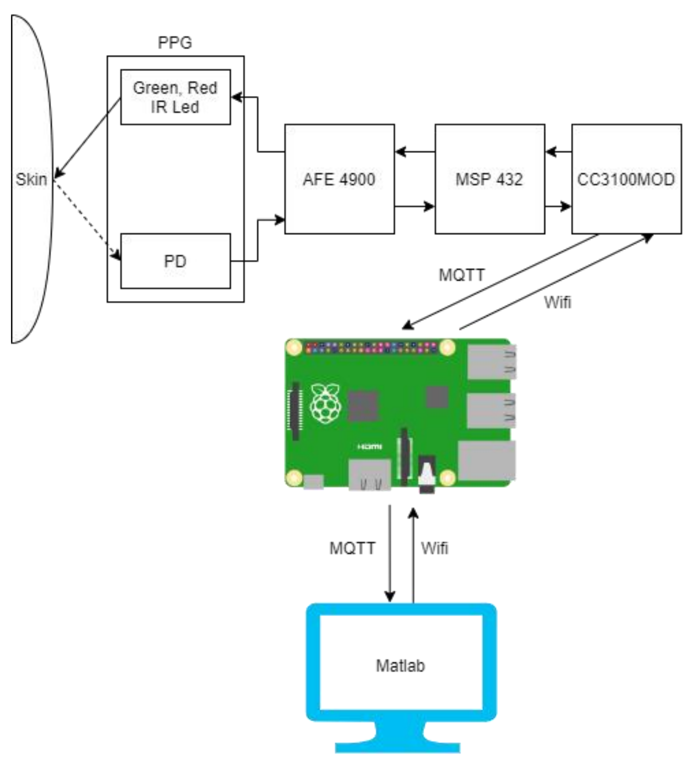

Fig. 4. Block diagram of the data flow between sensor and computer

3. As a validation method, measurements were also recorded from the index finger. This was done by exerting light pressure with the finger to the PPG sensor.

During all measurements, subjects assumed a calm posture and no unnecessary movements were made. To determine the optimal position of the sensor, measurements are taken while moving the sensor across the sternal bone. When the expected pulsating heart rate is visible on the monitor, the sensor is secured to the chest with medical tape.

B. Data analysis

1. By using the evaluation module, data can be read directly from the AFE4900 EVM software and can be viewed live. The program removes the DC component from the signal and filters the signal. This filtering consists of a Notch Filter of 50 Hz and a 6th order low pass filter with a cutoff frequency of 20 Hz.
2. The data from the wireless version is filtered in MATLAB by the 'lowpass' function; this is a lowpass filter with a cutoff frequency of 1 Hz and an infinite impulse response (IIR).

a) Calculating the phi value for determining the SpO_2 content:

Next, the AC and DC components are calculated for all signals (green, red and infrared). This is done by calculating the peaks and valleys of the signal using the ‘findpeaks’ function. The AC signal is the peaks minus the valleys and the DC signal is the valleys plus half of the AC signal.
With these components, the phi value can be determined with following equation:

$$\Phi_{IR-GREEN} = \frac{\frac{AC_{GREEN}}{DC_{GREEN}}}{\frac{AC_{IR}}{DC_{IR}}} \quad and \quad \Phi_{IR-RED} = \frac{\frac{AC_{RED}}{DC_{RED}}}{\frac{AC_{IR}}{DC_{IR}}}$$

Equation 3. Phi value with ratio of AC and DC of IR/Green and IR/Red

b) Calculating the heart rate:

To determine the heart rate, the average time between the peaks of the filtered signal is taken. The times of the peaks were already obtained by the ‘findpeaks’ function. By averaging the differences between the peaks we obtain the seconds/beat. Dividing 60 by this factor gives the heart rate. This method can only be used when the patient is sitting still, because any movement can affect the signal causing unwanted peaks. [9]

III. RESULTS

A. The first measured data, as shown in fig. 5, was measured with the case without Wi-Fi using the PPG sensor at the edge of the case. The algorithm used 15 seconds of data at a sampling rate of 500 data points per second. As previously mentioned, the data is already filtered with a lowpass filter and a notch filter. Furthermore the DC component has been removed, which results in a signal that can dip below 0 mV.

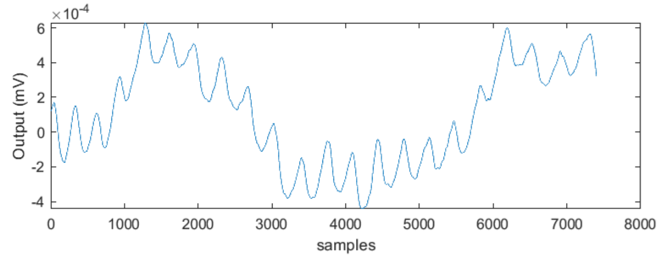

Fig. 5. Signal from infrared which is containing the number of samples on the x-axis and the measured voltage values on the y-axis

By filtering out the DC component, it is impossible to calculate a correct phi value and subsequently determine the SpO_2 level. The incoming data that will be used in this paper will therefore be unfiltered data. The incoming data will be provided with an algorithm containing the necessary filters. As a result, filtered data will be created in which the DC component is still present.

When looking at the DC component of fig. 5, a superimposed sinusoidal waveform is observed. This sinusoidal shape is present due to the breathing of the subject. When the subject holds his breath, this additional component will become almost non-existent.

In the lowpass filter, a cutoff frequency of 1 Hz and an infinite impulse response were used.

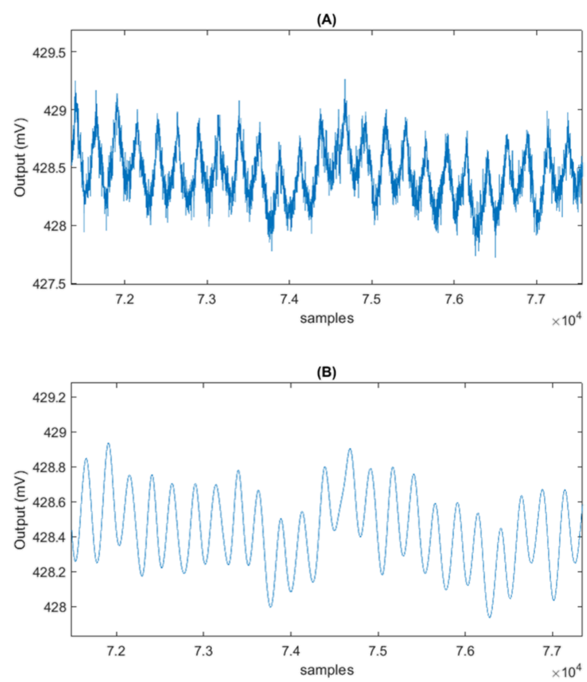

Fig. 6. (A): unfiltered data with DC component present, (B): filtered data with lowpass filter and with DC component present.

The case without Wi-Fi is replaced by a case with Wi-Fi for the following results. The unfiltered data has a sampling rate of 200 data points per second.
One hour of data is collected with the Wi-Fi-case. The case was placed at the top of the sternal bone as described in methods and materials.

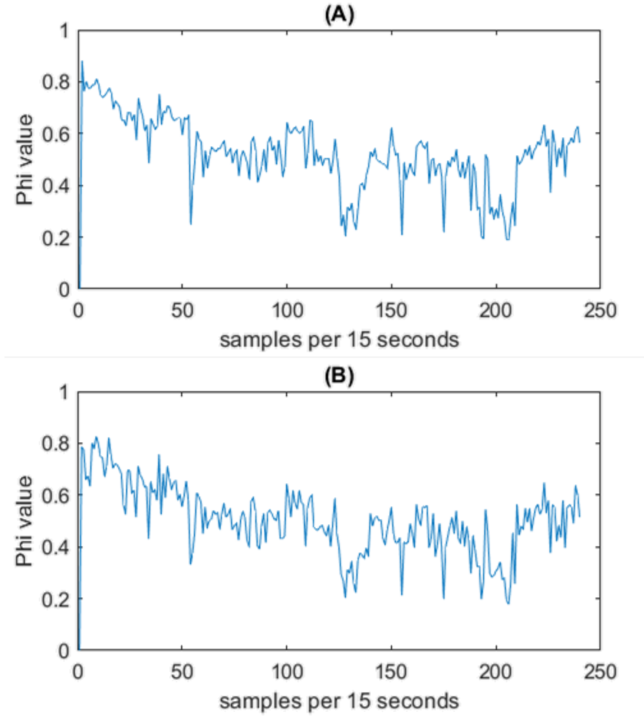

Fig. 7. (A): The median of the phi value (the ratio of red to infrared) every 15 seconds at the top of the sternum. (B): The mean of the phi value (the ratio of red to infrared) every 15 seconds at the top of the sternum

As shown in fig. 7 there is no stable phi value during the test period. It is obviously visible that there are still some problems with the algorithm and/or the case.

The first encountered problem during the obtainment of the data is movement. Every movement results in sub-optimal or even unusable data. Second, the functioning of the PPG sensor was verified to ensure it is still working correctly. To validate the PPG sensor, the monitor was placed on the finger instead of the chest.

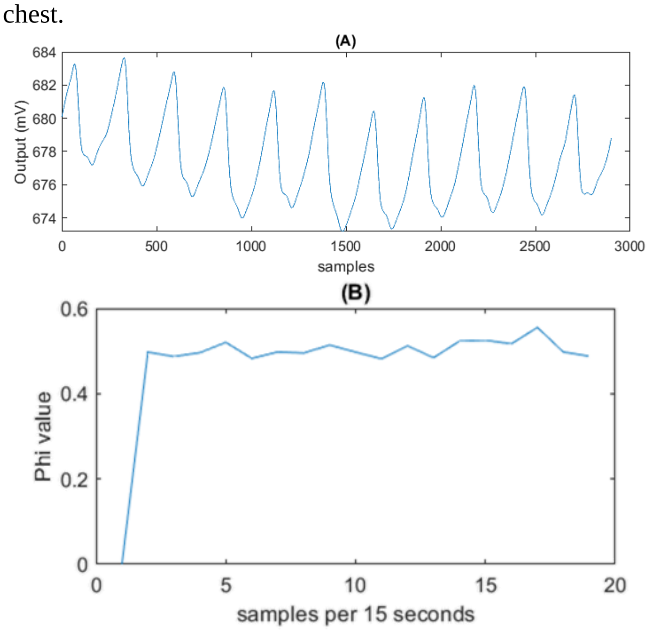

Fig. 8. (A): Data signal on the finger over 15 seconds from the red led. (B): The median of the phi value (the ratio of red to infrared) every 15 seconds

Fig. 8 clearly indicates that both the PPG sensor and the algorithm work well after testing on the finger. In addition there is a nice signal during 15 seconds and the phi value remains fairly stable during the data set. On the other hand are the small peaks and valleys the result of less good or bad data.

Testing on the finger revealed poor contact between the skin and the PPG sensor when attached to the chest. Bad and incorrect data is measured by the PPG sensor. This problem is solved by making a small adjustment to the case.

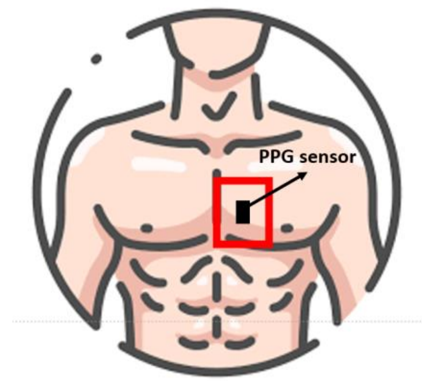

Fig. 9. Location of the case on the chest [11]

In the position shown in fig 9, the sensor provides the best data possible for the three different LEDs. When the case is placed higher or more on the right of the chest, especially the red and infrared sensors give poor data. The green sensor still provides a nice and good signal at all of these locations.

In addition to finding a good location on the chest for the device, the correct setting of the LED intensity is important. These settings are changed in the WearIt4Health graphic display shown in Appendix A. The table below gives a short summary of the data in function of the LED intensity.

Table 1. Intensity of the LEDs

Red	Infrared	Green
Intensity: 0-16 a.u. Bad data	Intensity: 0-16 a.u. Bad data	Intensity: 0- 2 a.u. No data
Intensity: 16-32 a.u. Ok data - Preferably better	Intensity: 16-32 a.u. Ok data - Preferably better	Intensity: 2-4 a.u. Good data
Intensity: 40+ a.u. Good data	Intensity: 40+ a.u. Good data	Intensity: 4+ a.u. Good data - no more changes

Fig. 10 clearly shows a good obtained signal. Also, the phi value is now fairly constant. The small peaks and troughs are the result of less good or bad data again.

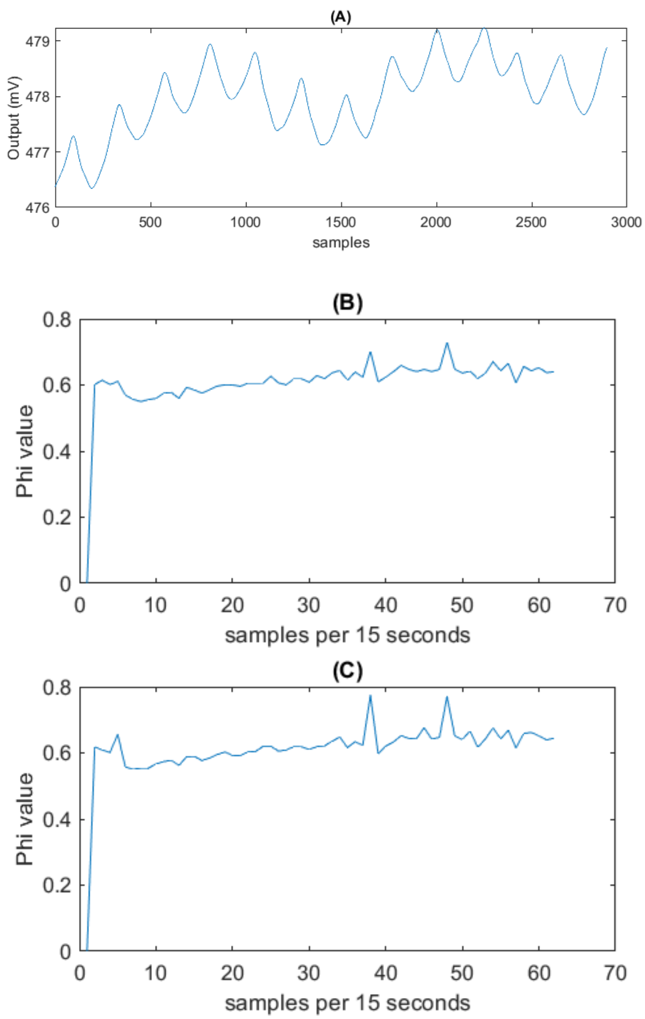

Fig. 10. (A): Data signal on the chest over 15 seconds from the red led. (B): The median of the phi value on the chest (the ratio of red to infrared) every 15 seconds

When comparing the results on the finger with the results on the chest, it can be concluded that both phi values are fairly stable. The average phi value of the chest is slightly higher than the phi value of the finger, this is because of the size of the DC component. Fig. 8A shows that the value of the DC component is around 680mV while the value of the DC component for the chest is around 478mV. Therefore, it can be concluded that the calibration for determining the SpO_2 value also depends on the location where the signal is measured.
The next step is to compare which LED-colors will give the best phi value and heart rate. This is calculated as explained in 'Methods and Materials'.

By the comparison of the different ratios in fig 11, which are "Red/Infrared" versus "Green/Infrared" versus "Red/Green", it can be concluded that "Red/Infrared" gives the best results in SpO_2 calculation. For the heart rate, it can be concluded that the best and most constant results are obtained through the green LED.

IV. Outlook

To determine the constants in Eq 2, tests must be performed with a medically validated device. With these constants and the phi value obtained earlier, the SpO_2 level can be calculated. [5] The setup of the test will be as follows: the case with Wi-Fi is placed in the right place on the chest to measure the best values. Then official medical sensors are placed on the finger and ear to measure oxygen saturation and heart rate. The test takes place in a hypobaric chamber, so that the effect of reduced oxygen saturation can be simulated and measured. The following devices will start measuring at the same time so that the data can be linked.
Then the data obtained will be processed. Processing will be done by plotting the calculated phi value with the agreed SpO_2 value measured by the medical device. A line can then be drawn through these points, showing the relationship between the phi value and the SpO_2 value.

Other things that can be determined from the data coming from the PPG sensor are respiration rate (RR) and heart rate variability (HRV):

- To determine the respiration rate, one can look at the DC-component of the PPG signal. The time between peaks is 1 breath. Here the RR can be determined in the same way as the heart rate.

- To determine heart rate variability, one must look at the time between the peaks. One way to determine the HRV is a method called RMSSD (The root mean square of successive differences between the heartbeats). The more variability there will be between heartbeats, the higher this value will be. [10]

V. Conclusion

The results obtained on the chest are a first indication of a properly functioning case and algorithm. A good signal is measured for both the red, the infrared, and the green LED. Furthermore, for a longer test set, a reasonably constant phi value was obtained, as well as the calculated heart rate. As mentioned earlier, the calculations of the SpO_2 level, the heart rate variability and the respiration still need to be added. Furthermore, the results of the measurements on different skin types can also be investigated.
Finally, the best position for the PPG sensor also needs to be determined. After the first results achieved with the case without Wi-Fi, the best results were obtained with the PPG sensor at the edge of the case. Tests were continued with the case with Wi-Fi. Because the case only has a PPG sensor in the middle, no further comparisons or conclusions can be made.

Acknowledgment

We would like to thank our promoter Thijs Vandenryt. He has helped and supported us during the entire period. We would also like to thank the University of Hasselt for giving us the opportunity to do this project. Finally, we would also like to thank the IMO-IMOMEC for allowing us to participate in this project.

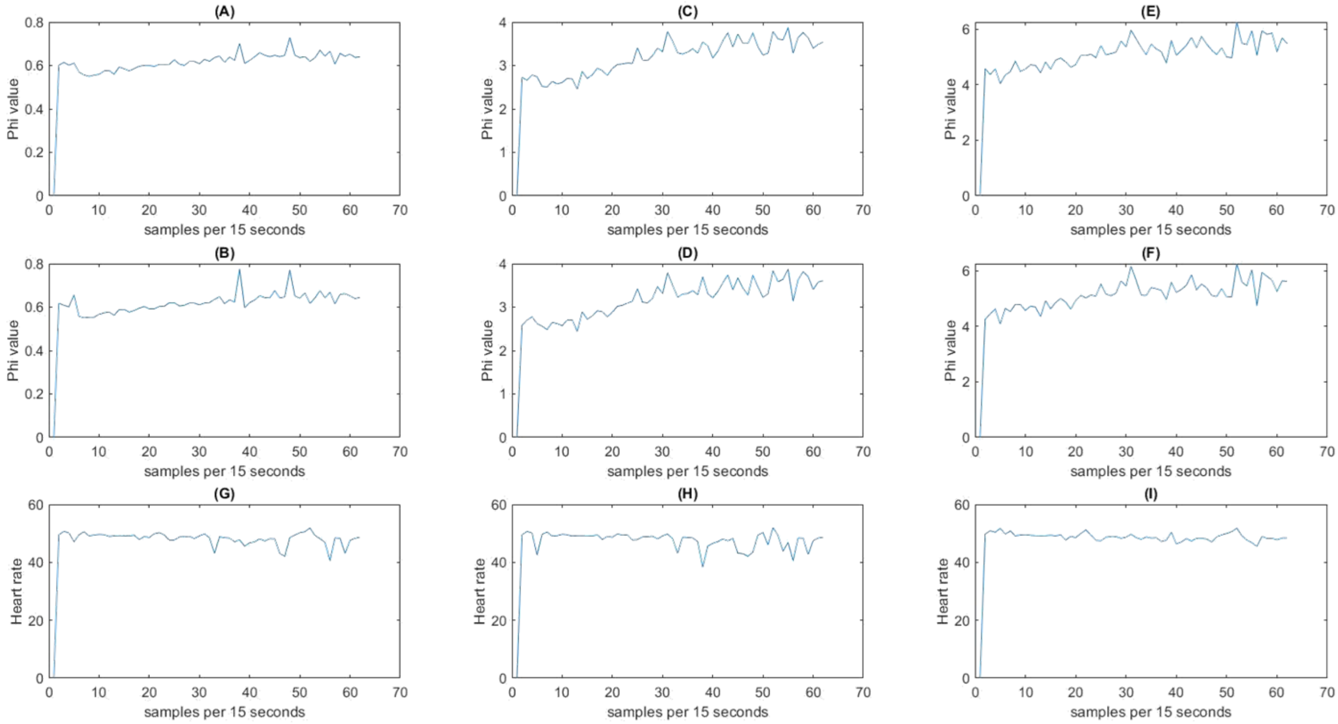

Fig. 11. (A): The median of the phi value on the chest (the ratio of red to infrared) every 15 seconds. (B): The mean of the phi value on the chest (the ratio of red to infrared) every 15 seconds. (C): The median of the phi value on the chest (the ratio of green to infrared) every 15 seconds. (D): The mean of the phi value on the chest (the ratio of green to infrared) every 15 seconds. (E): The median of the phi value on the chest (the ratio of red to green) every 15 seconds. (F): The mean of the phi value on the chest (the ratio of red to green) every 15 seconds. (G): The heart rate calculated from infrared every 15 seconds. (H): The heart rate calculated from red every 15 seconds. (I): The heart rate calculated from green every 15 seconds.

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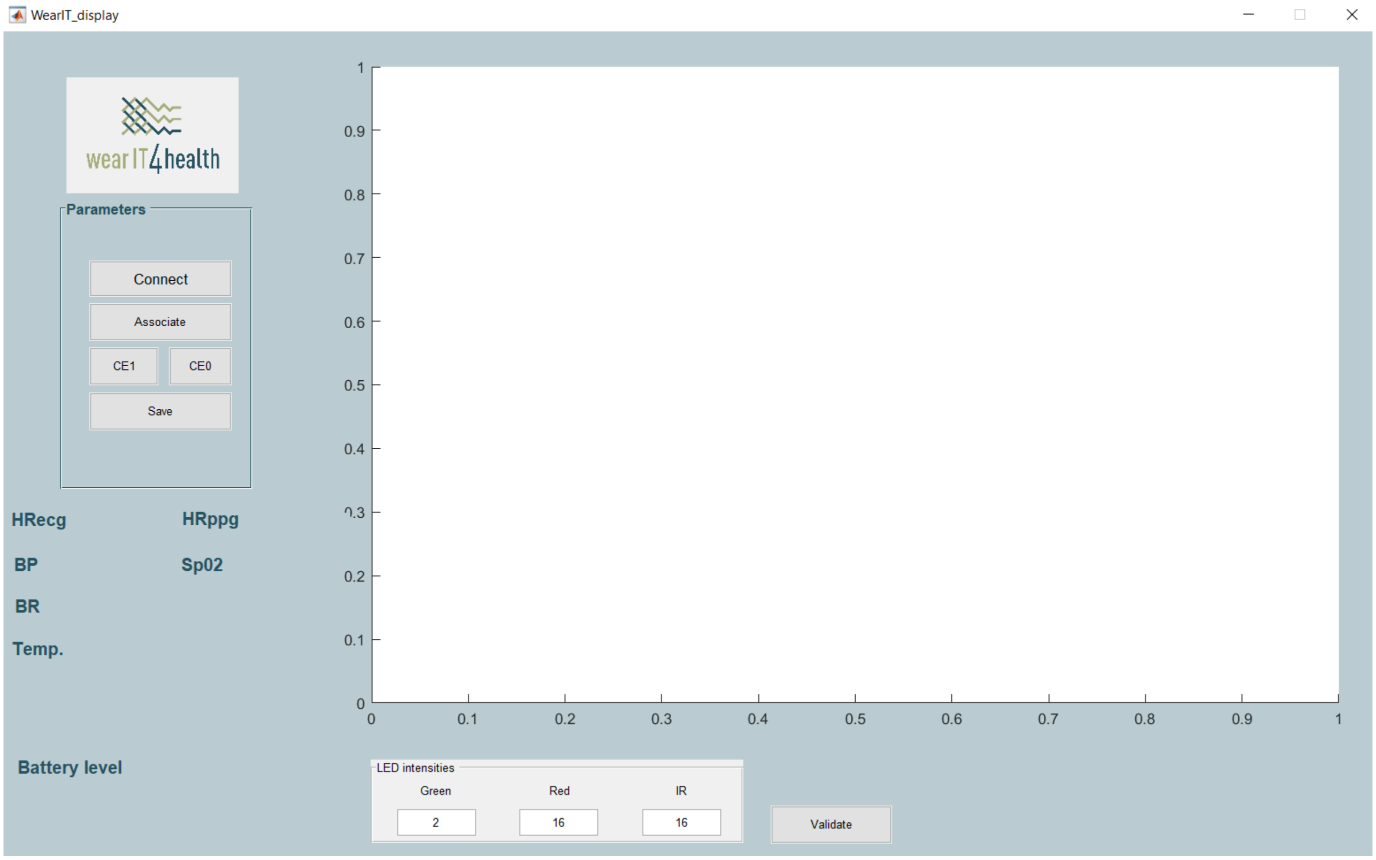
APPENDIX A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