Pulse oximetry optical sensor using oxygen-bound haemoglobin

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Abstract: In this paper we report a unique approach to measuring oxygen saturation levels by utilising the wavelength of the haemoglobin instead of the conventional absorption difference. Two experiments are set up to measure the wavelength of the haemoglobin bound to oxygen at different oxygen saturation levels with the help of a spectrometer. We report a unique low cost and robust wavelength monitoring SpO_2 sensor that measures the SpO_2 by using the colour of the blood and not the absorption difference of oxyhaemoglobin and deoxyhaemoglobin. With use of a spectrometer, we show that the wavelength of the oxygen-bound haemoglobin has a relation to the oxygen saturation level. The proposed device is designed and experimentally implemented with a colour sensor to measure the SpO_2 level of the blood.

OCIS codes: (280.0280) Remote sensing and sensors; (280.4788) Optical sensing and sensors (130.0130) Integrated optics; (130.7405) Wavelength conversion devices.

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1. Introduction

In 1945, most deaths occurred in the home. By the 1980s, it was reduced to just 17% [1]. This statistic shows how far medicine has come on in just 60 years. People are living longer and have a better quality of life than at any other time in history. As we have better technology, we can detect health problems earlier than ever before and thus, we can take precautionary measures. Given that one of medicine's key aim is to pick up evidence of illnesses before symptoms occur [2], we can measure the key body symptom parameters of a human whose clinical condition is deteriorating within the home with help of wearable sensors [3–7]. The oxygen saturation level within the blood is very important, known as one of the 'vitals', it is one of the standard measurements for health professionals. SaO_2 is defined as the percentage of haemoglobin with bound oxygen and is termed as SpO_2 when measured by a pulse oximeter. The average level is 95-100% [8]. An oxygen level below 90% is considered low, resulting in hypoxemia [8]. In this paper, we will discuss the measurement and monitoring of the SpO_2 as one of the 'vitals' of the human body. We will also discuss another unconventional way of measuring SpO_2 by utilising the wavelength of the oxygen-bound haemoglobin, to decipher the oxygen level. This technique is different from the methods used today. The proposed device is wireless, robust and will be implemented in the form of a ring to be worn on the finger, so the user may use the device at home without being disturbed by wires.

There are two types of haemoglobin; functional and non-functional. Functional haemoglobin binds and transports oxygen through the body and non-functional haemoglobin cannot bind or transport oxygen and is present as carboxyhaemoglobin (bound to carbon monoxide) and methaemoglobin which contains ferric iron (Fe3 +) [9]. There are two types of functional haemoglobin; oxyhaemoglobin (HbO_2) and deoxyhaemoglobin (Hb) [9]. Body tissues absorb light differently which can be used to calculate the oxygen saturation of oxyhaemoglobin and deoxyhaemoglobin by using the formula; $SpO2 = \frac{[HbO2]}{[HbO2]+[Hb]}$ [10]. Using a pulse oximeter, a volumetric measurement can be obtained with aid of differences of light absorption within the blood, this method is known as photoplethysmography (PPG). As a SpO_2 monitor needs to measure the percentage of haemoglobin with bound oxygen just within the arterial blood, a manipulation of taking the pulsatile flow and non-pulsatile flow can be used. The pulsatile flow is a measurement of the arterial blood, background tissue and venous blood. The non-pulsatile flow is the combination of the background tissue and the venous blood. Therefore, taking the non-pulsatile from the pulsatile flow will leave just the arterial blood value. The apparatus needed are two LEDs and a photo detector. The two LEDs are of different wavelength; 660nm, red light and 940nm, Infrared light (IR). Oxyhaemoglobin partially absorbs the IR light and deoxyhaemoglobin absorbs red light. The processor can then calculate the concentration of deoxyhaemoglobin and oxyhaemoglobin.

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The stated formula can be used to determine the overall percentage of the oxyhaemoglobin within the arterial blood. The most common places for a SpO_2 monitor to be attached to are finger, toe, or ear. These measurements give an accurate reading although can be misread if the user is wearing red finger nail varnish or if the monitor is moved and the processor calculates absorbed light wrongly.

Should oxygen saturation level fall below 90%, hypoxemia occurs. Causes can be (inter alia) sleep apnoea, asthma crisis or pulmonary infection [8]. A. Nobuyuki *et al* [11] perform an experiment which monitors a patient with sleep apnoea and measures their snoring with sound measurement and SpO_2 values. The measurements were obtained at their home to aid a restful night's sleep as it was deemed unnecessary for the patient to be in the hospital for the trial measurement. The patient had a pocket sized SpO_2 monitor on their finger. Although the WEC-7 SpO_2 monitor was small and unobtrusive, the patient still had to sleep with it on the finger. This could have led to a disturbed sleep for the patient and so the results would not show a typical night's sleep. The experiment would have also been disrupted if the measurements of the levels were erroneous if, for example, the patient rolled over or let some external light through the monitor during REM sleep. If the patient had been wearing a different or less intrusive SpO_2 monitor, they might have had a better night's sleep and the researcher may have obtained more reliable and consistent results without the threat of the SpO_2 monitor potentially falling off. Some SpO2 monitors may be able to read the SpO_2 over a period of a day but it would be much harder to gain the results over a longer period of time with a SpO_2 monitor on an extremity [12].

Wearable sensors can be placed on many places of the body in contemporary wearable sensors including; stick-on electronic tattoos or directly printed onto human skin to enable long-term health monitoring [13]. As the sensor technology is improving so vastly, it seems appropriate to produce a sensor that is comfortable and convenient for the user. Many individuals wear rings as jewelry and do not remove them at night and so are conditioned to wearing them.

As the traditional SpO_2 monitor needs to be attached to a bodily extremity to work, it would be difficult to monitor the oxygen saturation during the whole day. In this research paper, we explain a unique way of measuring SpO_2 by using the colour of the blood and not the absorption difference of oxyhaemoglobin and deoxyhaemoglobin. This method is produced as a ring and not an extremity device for easier use within the home mainly due to the purpose of a user being able to use their fingers if the device was as a ring and not on the end of the finger.

There are few sensor artefacts that have been the subject of publication (but which are not yet commercially available) regarding ringed devices though use the traditional absorption method to calculate the oxygen levels. J. Sola *et al* [14] show the ring attached to the left index finger. The ring sensor is worn on the left hand and the calibration SpO_2 monitors are worn on the right. The SpO_2 around the whole body varies as there are more/less capillaries and different blood flows depending on parts of the body that need more oxygen than others. It is difficult to say even that the SpO_2 level is the same for both hands at any one time if they are any great distance apart. Another known prototype of a ringed SpO_2 monitor is produced by F. Adochiei *et al.* [15], the device transmits the SpO_2 and heart rate value via RF to a patient monitoring device which logs the data received. The monitor, like J. Sola's monitor also uses the absorption method. Choosing the correct material for the sensor is also very important as it must not interfere with the monitoring readings. There are technologies available now that allow sensors to be woven into materials ready for detection. Plastic optical fibres (POF) can be used to measure SpO_2 with help from 690nm and 830nm lasers [16]. These fibres can be very expensive for the final product which needs to be robust and sustainable to be worn over long periods of time and in case of medical institutions, used on different patients.

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There are also few health monitoring sensors that measure other vitals via the use of a ring [17]. Considering most health problems within the home occur in elderly patients, it is important to keep the technology simple and easy to use; the less interaction the users have with the monitoring devices, the better. There are technologies around that permit the user to view their health vitals in real time via use of a smart phone [18]. As there is currently no available technology that will allow a continuous SpO_2 monitoring within the home, a system needs to be implemented which can measure SpO_2 and send it on to a medical examiner to view the patients history of oxygen saturation during the day and night.

In this research paper we intend to demonstrate a correlation between the wavelength of the oxygen bound haemoglobin and the percentage of oxygen bound with haemoglobin. The higher the wavelength: the higher the SpO_2 value. We show that the proposed optical sensor is able to detect a change in oxygen saturation via the colour of the blood. The more oxygen within the blood, the brighter the red; the brighter the red, the lower the red value of our proposed colour sensor will be. We report a unique SpO_2 monitoring optical sensor device which is affordable as the sensor used is quite basic and already pre-embedded making it compact and robust. The user will be able to comfortably use it all day/night, performing real-time measurements, without any uncomfortable irritants.

2 Measuring SpO_2 with wavelength

The unconventional method proposal statement is as follows: Blood is red because of the protein 'haemoglobin'. Haemoglobin has a molecule called a "heme" which has the metal iron in it. When the iron is oxygenated, it becomes red. When the iron is deoxygenated, it becomes a darker red [19]. Using this statement, the prediction can be made that the more oxygen the blood has, the brighter the red will be, therefore, a longer wavelength should be produced. Likewise, the less oxygen there is within the blood, the shorter the wavelength should be.

An experiment was set up to see the correlation between the wavelength of the haemoglobin within the blood and the SpO_2 value. A high intensity white LED was placed on the nail side of the index finger and a spectrometer (on the opposite side) was recording the wavelength in the blood. At the same time, an SpO_2 monitor was placed on the middle finger. When the output of the spectrometer was saved, the SpO_2 reading was recorded. Figure 1 shows the schematic of the spectrometer set up of the index finger's system. An ultra-bright LED is used to ensure maximum penetration through the finger. It must be white light so that all of the wavelengths are emitted, this is crucial in discovering the SpO_2 as the wavelength absorbed by the blood can be found. The index finger is used as the SpO_2 monitor is more comfortable on the middle finger to help the experiment run smoother and obtain quicker and accurate results. After the LED is shone on the nail side of the finger, the spectrometer can be used to find the wavelength of the oxygenated blood. The spectrometer's sensor is attached to a fibre optic cable to gain the fastest result to be read. Once the spectrometer has saved the wavelength, the SpO_2 value is noted for use later.

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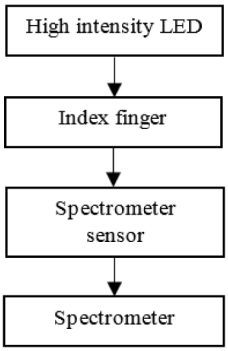

Fig. 1. Schematic of the spectrometer set up.

Figure 2 shows the measurement being taken with the spectrometer's sensor with the index finger and the SpO_2 monitor on the middle finger. There were two people participating in obtaining the results. During the experiment, the room's lights were turned off and the spectrometer's sensing cable was placed firmly on the finger to reduce the ambient light reach the sensor.

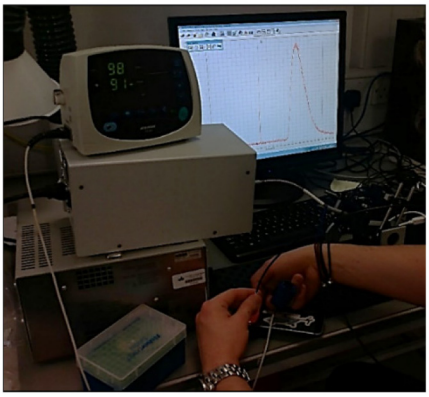

Fig. 2. Photograph of the spectrometer measurement attached to the index finger with a phone's bright LED on the nail side and the SpO_2 monitor attached to the middle finger.

3. Spectrometer measurements, results and discussions

The results were obtained after the spectrometer completed the readings of intensity of transmission at different wavelengths. Each reading number was noted next to the respective SpO_2 value. The results suggested a correlation between the higher the oxygen levels, the higher the peak wavelength. Figure 3 shows the spectrometer reading when the blood oxygen was at 97% for person 1, the peak wavelength is at 632 nm. The x-axis represents the wavelength measured in nm and the y-axis is the intensity level that can be changed by the colour of the skin, thickness of the finger and the amount of light received by the spectrometer. The intensity's units are watts per square meter, so a slight change in position of the spectrometer's placement on the finger could result in a large change in intensity. A peak can be seen between 430nm and 450nm within many of figures. This peak is within the ultraviolet spectrum. Although its intensity reaches up to ~40% of the peak wavelength at 632nm, it can still be seen as insignificant as it is only the red wavelengths of values 620nm to 750nm which are being monitored as W. Nahm *et al.* [20] shows the changes in tissue absorbance caused by blood pulsation. The non-invasive experiment showed a different relation between absorption at 600 and 940nm. As this is within the red spectrum, we can look specifically within this range.

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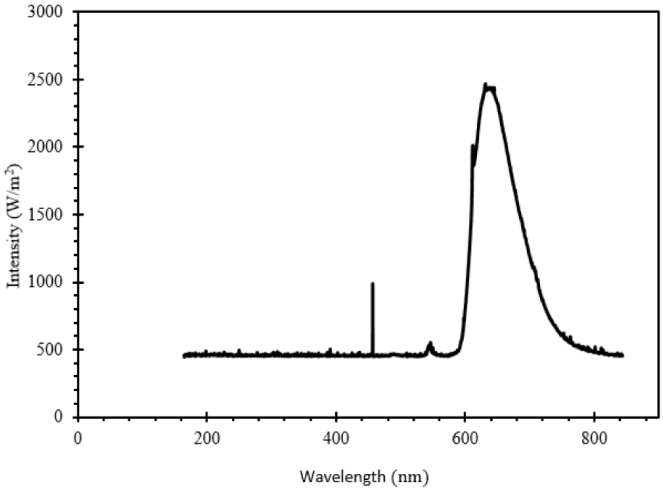

Fig. 3. Graph of the first participants' wavelength when the SpO_2 level was at 97% with the peak wavelength at 632nm. Values below 600nm can be ignored as only the red light wavelengths are relevant for measuring pulsative blood need detection.

Figure 4 shows the spectrometer's reading when the SpO_2 value was at 96% for person 2. The peak wavelength is 624 nm. Figure 5(a) illustrates both participants' results together in one graph. The oxygen levels were both at 97% and the peak wavelength of each person's result was 632 nm.

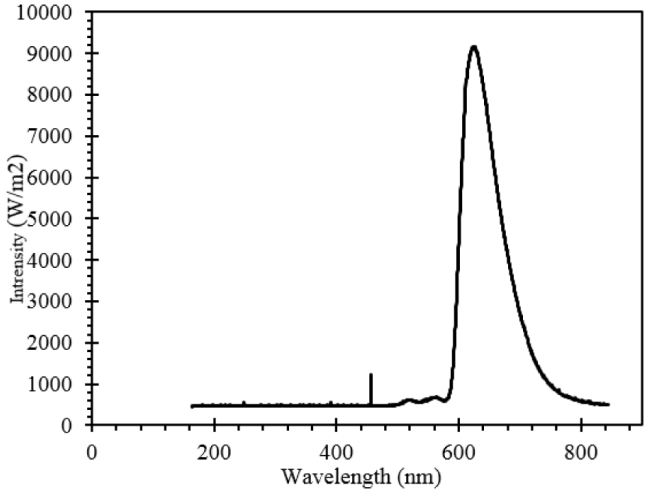

Fig. 4. Graph of the second participant's wavelength when their SpO_2 level is at 96%. Sharp peak at 624nm. This suggests a lower SpO_2.

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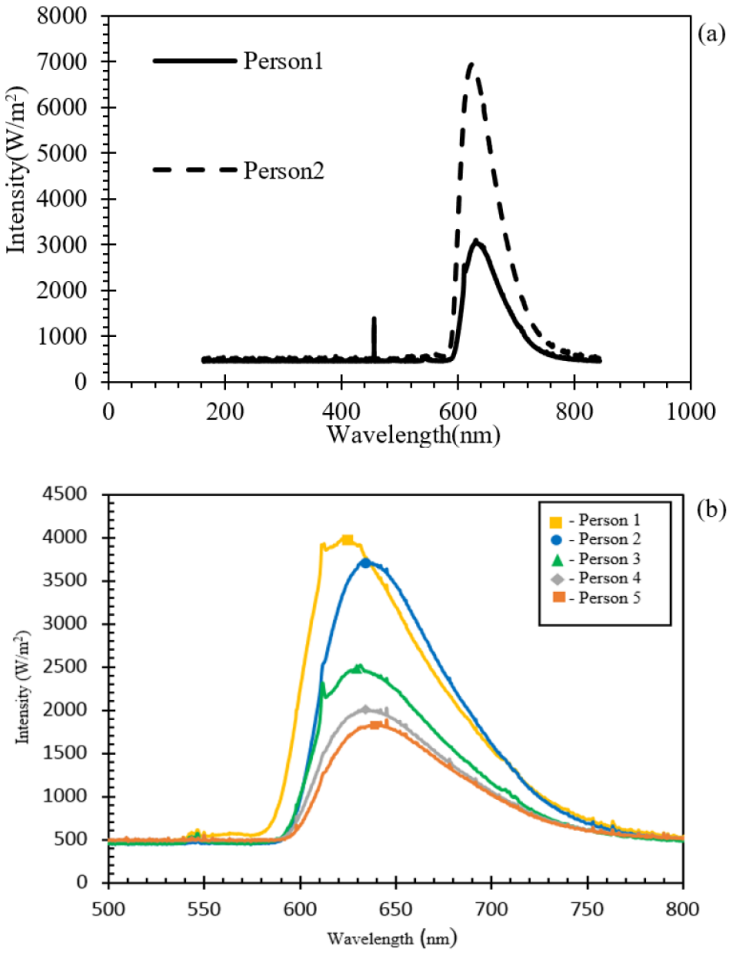

Fig. 5. (a) Graph showing the first and second participant's wavelength when both participant's SpO_2 levels were at 97%. They both have the same wavelength peak but a different intensity level. Figure 5(b) Graph showing five different spectrometer readings with different participants. Each participant has a difference in intensity and wavelength.

It is clear to see that the second participant's y-axis value of intensity is much higher than the value of the first participant. This could be caused by the difference in fingers of the participants. Skin colour, thickness, light received to the spectrometer and other variables will change the intensity. This is not a problem as it does not affect the wavelength of the result. Therefore a person's skin tone or difference in thickness of fingers for said person does not affect the overall result.

Figure 5(b) shows five different SpO_2 readings from the spectrometer. It is clear to see the shift in wavelengths shows that the red colour of the blood is a different shade of red. This clearly shows that as there are different colours of red within the blood, the oxygen binding is different in each reading. The yellow line (person 1) has a wavelength of six hundred and twenty six nanometres, the blue line (person 2, with the highest wavelength) shows six hundred and forty two nanometres, the green line (person 3) has a wavelength of six hundred and thirty three nanometres, the grey (person 4) at six hundred and thirty seven nanometres and the orange (person 5) is at six hundred and forty nanometres.

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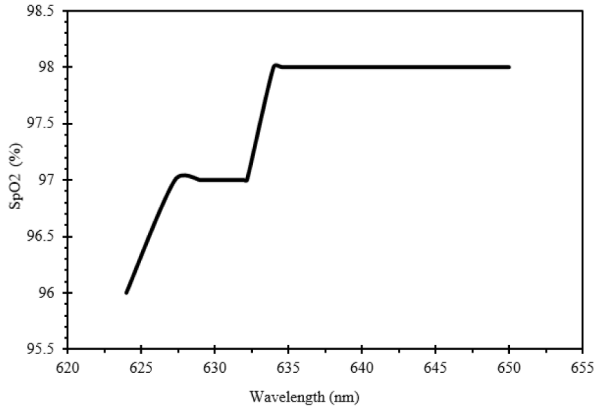

Fig. 6. Graph showing the change in wavelength over level of SpO_2. The higher the peak wavelength, the higher the SpO_2 value.

Figure 6 shows the overall results from the peak wavelengths and their corresponding SpO_2 Values. It shows that the higher the wavelength, the higher the SpO_2 value. The spectrometer used within the experiment was a Hamamatsu mini spectrometer, a highly sophisticated and accurate device. When the SpO_2 is at 98%, the highest recorded value was 650nm and the lowest at 634nm. The range of SpO_2 at 98% is 16nm. When the SpO_2 value is at 97%, the highest value given is 632.2nm and the lowest 627.3nm, giving a range of only 5nm. As only one 96% value was recorded and the spectrometer saves the value over a duration of about 10 seconds, the real value may have been just a low 97% and thus the range could be at least 10nm, which is more likely. Never the less, it is clear to see that the higher the wavelength, the greater the value of SpO_2.

As this experiment indicated some evidence of correlation with respect to the prediction, it can now be taken to the next stage of creating the sensor at a much lower price without affecting the accuracy. We developed a home-made spectrometer using black card. A slit can be inserted into the bottom to let the light in and then a sheet from a DVD-R can be used for the diffraction grating to reflect the incoming light from the slit onto the bottom of the card [21]. The card spectrometer was made into a strengthened black plastic model by using the same dimensions within the 3D printer shown in Fig. 7. The model is extremely affordable to make as it is made up of a small amount of plastic and a DVD. This can then be placed onto a digital camera to take a photo of the given spectrum shown in Fig. 8.

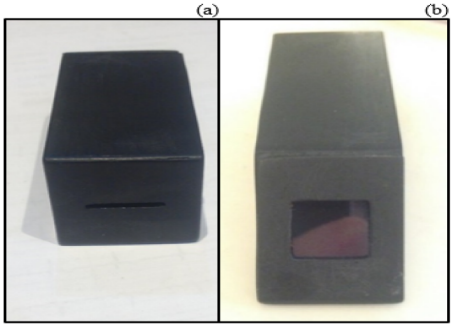

Fig. 7. (a) Back view of 3D printed spectrograph with slit (15mm x 2.5mm). (b) Front view of spectrograph with diffracting grating (15mm x 15mm).

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Fig. 8. Image of 10.1 MP camera attached to the spectrograph. The diffracted light entering the slit can be captured.

The 10.1 MP camera captured white light via the 3D printed spectrometer, with the output shown in Fig. 9(a), displaying the whole visible spectrum. Once the 3D printed spectrometer was attached to the camera lens, a finger can block the slit with a high intensity LED behind the finger to allow the camera to view the absorption of the finger. The red light is passed through and the colour of the blood can be captured as seen in Fig. 9(b). The next step is to deduce the peak wavelength of the new red image.

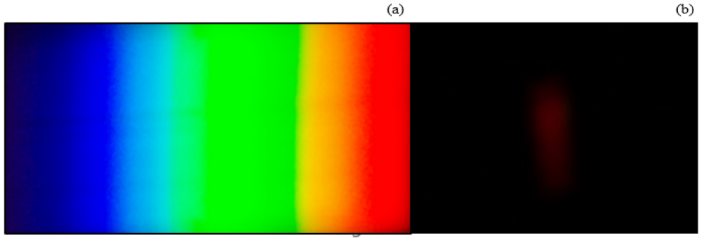

Fig. 9. (a) An image captured by the camera of white light through the slit. It shows the visible spectrum. 9 (b) An image of the index finger's blood colour. The image's colour can be analysed to work out its corresponding wavelength and thus SpO_2 value at that moment in time.

Processing the image's wavelength of the colour red produced and captured will help to measure the SpO_2. MATLAB could be utilised to turn the image into greyscale and calculate the amount of colour within each pixel. These values could then be plotted against the wavelength of known pixels of laser light to calibrate the MATLAB program. We deemed it unnecessary to produce said program as the spectrometers' main job was to produce the proof of concept. As there is a noticeable correlation between the wavelength and SpO_2, we can begin to investigate further. As the spectrometer is very expensive and difficult to fit into a ringed device, it seemed appropriate to implement a device that can view the change of wavelength.

4. Measuring SpO_2 with a TCS3200 colour sensor

Another experiment is set up where a TCS3200 colour sensor measured the amount of redness within the blood. The said sensor had a bright LED attached to it which is always on whilst the sensor is recording. The TCS3200 was deemed the best sensor to use as it already has an ultra-bright LED in a fixed position and brightness to which will eliminate any intensity problems we may face. The TCS3200 is considerably affordable and produces very accurate results. The microcontroller used was an Arduino Uno. The Arduino was programmed to take a reading of the colour sensor's red, blue and green values (Fig. 10). The experiment only took account of the red values from the colour sensor every second which was then stored onto a secure digital (SD) card to later be evaluated. The new device was placed on the index finger of the right hand and the SpO_2 monitor was placed on the right hand's middle finger to

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keep the variables constant for later correlation use with the first experiment. A counter was programmed to view which value corresponded to each measurement, when the SpO_2 value changed, the counter's number was noted (Fig. 11).

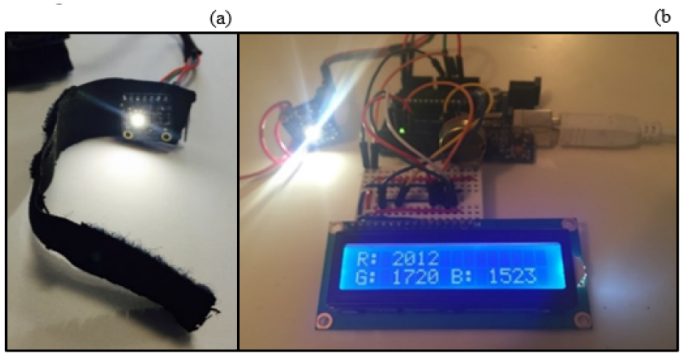

Fig. 10. (a) A photograph of the colour sensor attached to the elastic for the ring. (b) Shows the colour sensor attached to the Arduino Uno. After the red value has been found, it is printed onto an LCD screen and updated every second.

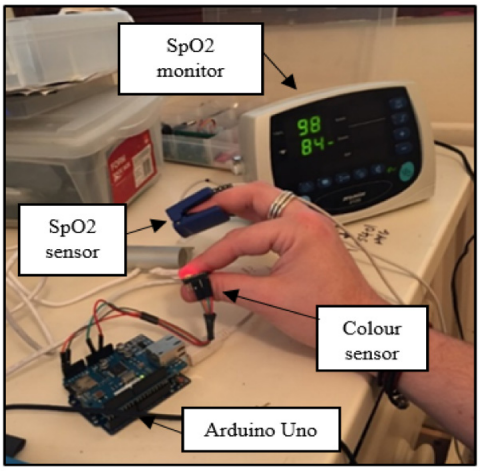

Fig. 11. Shows the index finger holding the colour sensor with the bright LED being fed to the Arduino micro controller to store the data and the SpO_2 sensor attached to the middle finger being read by the SpO_2 monitor.

4.1 Ring device results

The results obtained by the colour sensor showed that as SpO_2 increased, the red value decreased. As the sensor worked by using the intensity and the colour, the colour of the skin, thickness of the finger and finger placement affected the red's value, therefore the red value would be different for every user, although it did not change the fact that the redness of the blood was inversely proportional to the blood's oxygen saturation. The red value measures the saturation irradiance and gives a unit of $\mu W/cm^2$ [22]. As the intensity of transmitted light is low passing through the finger, the sensor will produce a high value. The higher the red value, the more red the entity in front of the sensor is.

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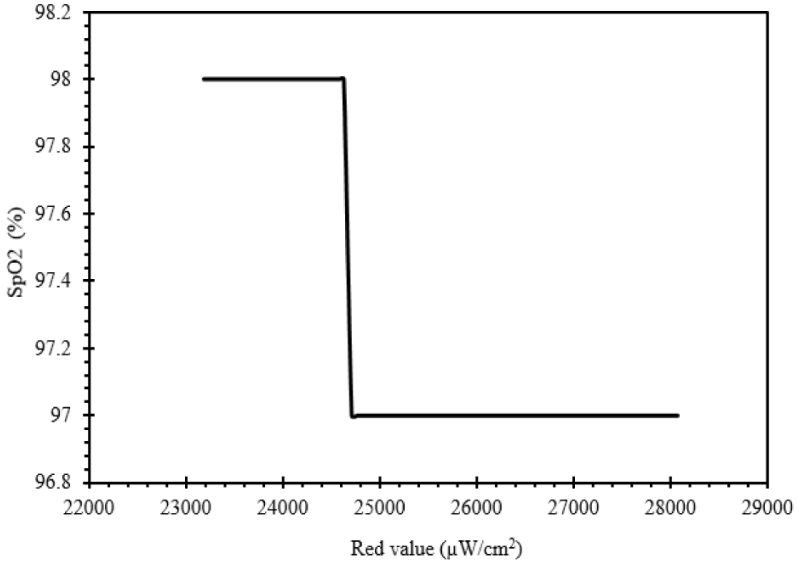

Fig. 12. A graph of the change in Red value as oxygen levels changed. It shows the higher the red value, the lower the SpO_2.

The obtained results in Fig. 12 from one of the tests shows that as the red value increases, SpO_2 decreases. As only two values of the finger's oxygen saturation were taken, it is difficult to deduce the range of each value's average value of the SpO_2. Furthermore, we conducted another test where all of the corresponding red values to SpO_2 are averaged out to view how the values are affected (shown in Fig. 13(a)).The results concluded that the values obtained decreased proportionally. If more values for the 95% SpO_2 values were recorded made at a lower decimal, the red value would have been higher and thus produce a more inversely proportional graph. This makes sense as the more oxygen within the blood, the more orange the blood is thus the levels should be lower. If the blood has less oxygen, it is a darker red, therefore the red value will increase towards the IR spectrum.

Another participant's results were measured and showed that there was a range of about 700μW/cm^2 for every 1% change in SpO_2. These results could be coded to produce the specific ranges in oxygen saturation for this particular participant. Each participant's red values were different as their fingers may have has a different impact on the colour sensor. Once recorded, each participant's individual range could be added to their sensor to allow their specific SpO_2 value. Figure 13(b) shows the participant's change in red value as SpO_2 changed. The values ranged from 99% to 95% with a red value range from 20700 to 23450 μW/cm^2. This gave a 1% change in SpO_2 of ~540μW/cm^2 red value per known ranged values. Although the SpO_2 monitor has not reached levels lower than 95%, it is possible to predict that as there is less haemoglobin with bound oxygen within the blood, the red value will continue to increase and will be able to predict levels lower than that of the said graph.

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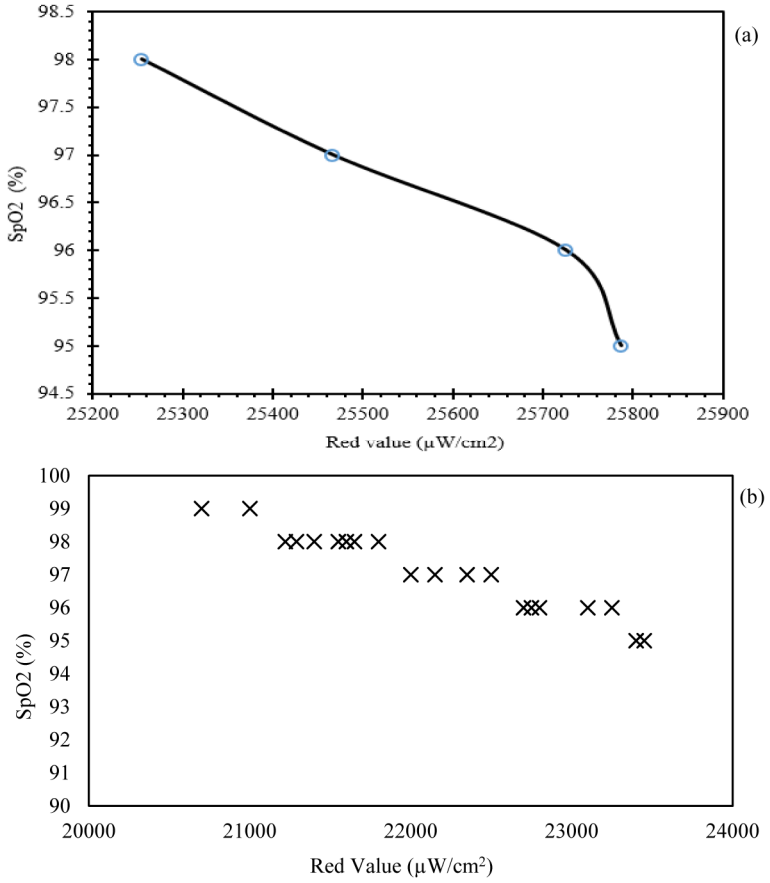

Fig. 13. (a). A graph representing the average SpO_2's corresponding red value. As the red value increases, the SpO_2 decreases proportionally. Figure 13(b). A graph of a participant's SpO_2 values ranging from 99% to 95% in SpO_2 and 20700 to 23450 in red value. The graph shows that each value of SpO_2 has a range of ~540μW/cm^2.

Taking the values from Figure 13(b), we can use Pearson's product moment correlation coefficient to view the negative linear correlation [23]. The resulting value *r* should produce a value between −1 to 1. The closer the value is to 1, the more linear the correlation and the closer the value *r* is to -, the more linear negative correlation. A resulting value of 0 shows no correlation between the data. By taking the Y values (SpO_2) and the X values (red value), we can insert them into the formula; $r = \frac{Sxy}{\sqrt{Sxx\,Syy}}$ by using the following equations:

$$S_{xy} = \Sigma xy - \frac{\Sigma x \Sigma y}{n},\ S_{xx} = \Sigma x^2 - \frac{(\Sigma x^2)}{n},\ S_{yy} = \Sigma y - \frac{(\Sigma y^2)}{n} \tag{1}$$

Hence the value *r* is;

$$r = \frac{\left(\Sigma xy - \frac{\Sigma x \Sigma y}{n}\right)}{\sqrt{\left(\Sigma x^2 - \frac{\left(\Sigma x^2\right)}{n}\right) \times \left(\Sigma y - \frac{\left(\Sigma y^2\right)}{n}\right)}} \tag{2}$$

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Where Σx is the sum of all of the red values, Σy is the sum of all of the SpO_2 values, Σx^2 is the sum of all of the red values squared, Σy^2 is the sum of all of the SpO_2 values squared, Σxy is the sum of all of the red values multiplied by the SpO_2 values and n is the total number of variables. Table 1 below shows the values of *X, Y, X2, Y2,* and *XY* values used for the formulas and Table 2 shows the sum products; Σx, Σy, Σx^2, Σy^2, Σxy and n.

Table 1. the X and Y values used to work out the product moment correlation coefficient.

X	Y	X^2	Y^2	XY
20700	99	428490000	9801	2049300
21000	99	441000000	9801	2079000
21220	98	450288400	9604	2079560
21290	98	453264100	9604	2086420
21650	98	468722500	9604	2121700
21550	98	464402500	9604	2111900
21600	98	466560000	9604	2116800
21400	98	457960000	9604	2097200
21800	98	475240000	9604	2136400
21800	98	475240000	9604	2136400
22000	97	484000000	9409	2134000
22150	97	490622500	9409	2148550
22350	97	499522500	9409	2167950
22500	97	506250000	9409	2182500
22700	96	515290000	9216	2179200
22800	96	519840000	9216	2188800
22750	96	517562500	9216	2184000
23100	96	533610000	9216	2217600
23250	96	540562500	9216	2232000
23450	95	549902500	9025	2227750
23400	95	547560000	9025	2223000

Table 2. the sum products and *n* used for the formulas.

ΣX	ΣY	ΣX^2	ΣY^2	ΣXY	n
464460	2040	10285890000	198200	45100030	21

The results showed Sxy to be −18940, Sxx to be 13361800 and Syy to be 28.57. Once placed into the formula, the coefficient's value is −0.97. This shows extreme linear negative correlation between the red value and the SpO_2.

Once the data values had been collected after many tests, the rate of change of SpO_2 with the red value can be predicted and the SpO_2 will be able to be worked out by using the red values with respect to themselves. Each user will have their own set of values that will need to be originally calibrated with the use of a SpO_2 monitor as the thickness of fingers and colour

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of the skin can have an effect on the red value. After the calibration is completed, the SpO_2 device is ready for use.

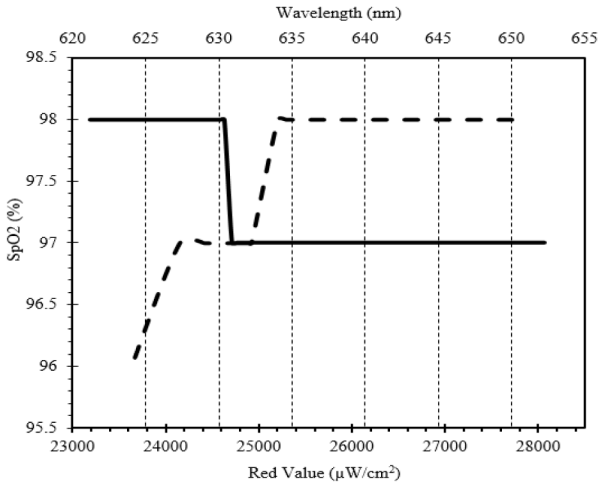

Fig. 14. A graph representing the correlation between the wavelength and red value as SpO_2 changed. As SpO_2 increases, the red value decreases and the wavelength increases. This shows that the higher the red value, the lower the wavelength.

The above graph (Fig. 14) shows the obtained results of the spectrometer experiment and the Arduino's colour sensor's experiment. It shows that the higher the wavelength of the oxygen bound haemoglobin, the higher the SpO_2. It also shows the lower the red value, the higher the SpO_2. Our experiments demonstrate that there is a strong correlation between the wavelength and the red value of the colour sensor and can measure the wavelength of the oxygen bound haemoglobin. From this experiment, we can suggest the data implies a correlation between the wavelength of the oxygen bound haemoglobin and the change in oxygen saturation.

4.2 Making the SpO_2 device wireless

The next step is to make the proposed SpO_2 device wireless. We use 433MHz RF chips to transmit the red value to another device base. This way we save the energy on the data logging. As the antennas are of quarter λ and are 433MHz, it is possible to work out the optimum length of the antenna. Given that; $c = \lambda f$, where c is the speed of light ($3x10^8$m/s), f is the frequency (433 x106Hz) and λ , the wavelength; we can calculate the optimum length of the antenna will be 0.693 meters. Due to the antenna being a quarter wave, the overall antenna length will be 0.173 meters (17.3cm). This can produce a radius range between the antennas at 30 meters. Though path loss is quite strong, at thirty meters, the power to receive the transmitted signal is still over the −105 dB limit. This shows that the signal can be received at the base device (which could be connected to the internet) in a large, thick walled house. Figure 15 shows the colour sensor, SD shield and transmitter device and another receiving device which can log the data.

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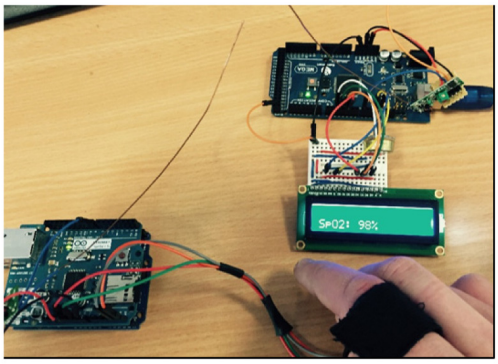

Fig. 15. Left: Ringed device reading the SpO_2 value and transmitting the value to the receiving device via a MX-FS-03V transmitter. Right: Receiving device displaying the SpO_2 value via a MX-05V receiver.

The system can now be attached to a mathematical model where each red value will be matched to a corresponding SpO_2 value. A ring is made from black elastic material and the sensor is placed inside. Choosing the material for the proof of concept experiment was difficult as a material was needed for the ring to be comfortable for the user to wear over a long period of time. The black elasticated material assured that no ambient light or external factors affected the red value and also made the sensor exert the same pressure and maintain a fixed placement on the finger. Using the Arduino's serial monitor, the program is able to send the red value and the corresponding SpO_2 (Fig. 16).

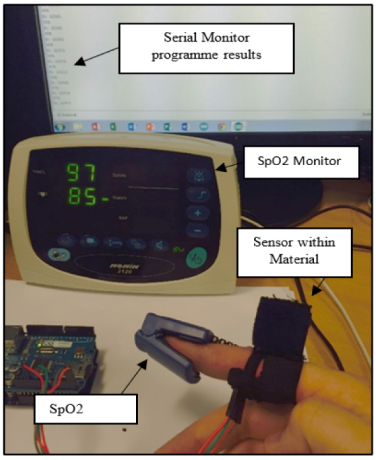

Fig. 16. Shows a photograph of the accuracy testing with the SpO_2 monitor and ringed device on the same finger. The serial monitor is reading the values from the program, ready to send to the server.

In our test experiment, we have involved three participants where the SpO_2 monitor is placed on the middle finger and the ring is placed on the index finger in order to ensure an accurate reading (Fig. 17). Every thirty seconds, the SpO_2monitor's value was recorded as well as the ring's SpO_2 value. They were later placed onto graphs [Figs. 18(a) 18(b) 18(c)] to see how accurate the ring was with the new method to the real oxygen value of the finger. The dotted lines are the real SpO_2 values and the solid black lines are the device's calculation of the SpO_2 by use of the red value.

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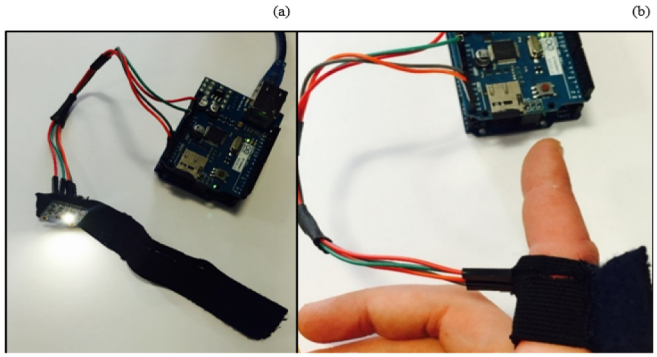

Fig. 17. Two images of the ring device, (a) with the ring off and (b) with the ring on the index finger.

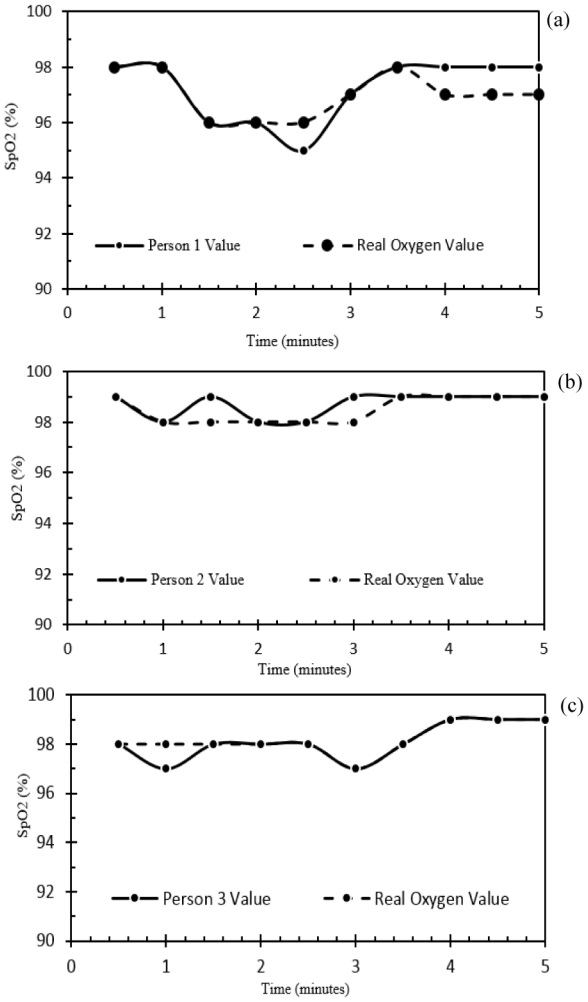

Fig. 18. (a). Person 1's accuracy testing. Absolute error no more than 1%. 60% matching with real value. Figure 18(b) Person 2's accuracy testing. Absolute error no more than 1%. 90% matching with real value. Figure 18(c) Person 3′s accuracy testing. Absolute error no more than 1%. 80% matching with real value.

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Our experiment results confirm that our proposed SpO_2 monitoring finger ring is very accurate, it was never more than 1% out in absolute value. Five minutes is a sufficient amount of time to constantly check the monitor, to see when it changes as the SpO_2 will fluctuate during said time. Though there was a slight lag in the device when the real value changed, after a couple of seconds, the device was able to stabilize to the correct value which shows a slight change in calibration is required. Person 1's results device value's highest SpO_2 reading was at 98% and lowest at 95% (shown in Fig. 18(a)). The real readings for person 1's oxygen saturation levels read from 98 to 96%. Person 2's results fluxed between 99 and 98% (shown in Fig. 18(b)).When the values were off with the ring device, they were higher than the actual results which suggests the change in calibration could be to lower the red value ranges slightly. Person 3′s device's results were only off once (shown in Fig. 18(c)). This was at the 1 minute stage where the real value was higher than the device's results by 1% at 98% and not 97%.

5. Conclusion

We have demonstrated a SpO_2 optical sensor monitoring device that would be able to be placed on the human body as a finger ring. We have developed the experiment and tested the proposed SpO_2 optical sensor ring on real patients, where it has been shown to be accurate. The proposed SpO_2 optical sensor ring is robust and easy to operate, which can be given to patients at the home for maximum restfulness for the professional's assessment and save the use of hospital bed spaces. Our proposed and developed SpO_2 optical sensor ring can be programmed to alert the user or health professional if the SpO_2 level has fallen too much. It can also be programmed to see if the ring is being worn by the user.

Our proposed SpO_2 optical sensor is a real-time device that can be worn on a daily basis at home or outside of the home. A transceiver could replace the RF chips so that when the user is not at home, data can be logged onto the device and then sent to a base station. When in range again, RTS/CTS (ready to send/clear to send) protocol can be utilised. The SpO_2 optical sensor will have a greater impact on users whose oxygen levels need to be monitored periodically or over a longer period of time. Costs will be low as the mathematical model within the microcontroller will enable just the one sensor to produce the SpO_2 from the red value detected. This device can be easily integrated to other health vital measurements such as heart rate or body temperature.

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