Design and Fabrication of a Pulse Oximeter

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Design and Fabrication of a Pulse Oximeter.

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It is important to monitor the blood Oxygen Saturation for patients at risk of respiratory failure, to ensure proper perfusion of blood in their system. Preferably this information should be received periodically. These needs can be met via the non–invasive method of pulse oximetry. This is currently used in hospitals and other clinical settings.

The oxygen carrying molecule of blood is hemoglobin, which can be either oxygenated or deoxygenated depending on the location in circulatory system. By using the principle of differential light absorption and the assumption that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and deoxygenated hemoglobin and the knowledge of absorption coefficients at the two wavelengths, light intensity will decrease logarithmically according to Beer–Lambert's law. Using light emitting diodes and photo-detectors at two separate wavelengths (one at Infrared, another at red) and electronic circuitry (current-to-voltage converter, filters and amplifiers) I was able to obtain a pulsatile signal which can be processed to obtain an oxygen saturation reading.

Key words: Pulse oximetry, hemoglobin, light emitting diodes, photo detectors, oxygen saturation, reduced hemoglobin, oxygenated hemoglobin, Beer-Lambert's law.

1. Introduction

A pulse oximeter is a medical electronic device used to detect oxygen saturation in blood by transmission of light through a tissue. The light is absorbed and reflected by multiple tissue components including the skin, muscle and blood vessels.

Though the amount of absorption and transmission of different tissues may vary over a long time period, all absorption except that due to arterial blood flow are fairly constant. Light absorption due to arterial blood flow varies on a short time scale for two reasons. When the heart beats, blood is pushed into the arteries causing them to expand. The total amount of tissue between the oximeter's light source and detector increases because of the influx of blood; and so light absorption also increases. This principle can be used to measure a patient's pulse.

Additionally, oxygen is transported in the blood by hemoglobin and depending on whether hemoglobin is bound to oxygen; it absorbs light at different wavelengths. The graphs of hemoglobin light absorption when it is saturated with oxygen and when it is not are shown in Figure 1.

This effect can be seen with the unaided eye because hemoglobin in arterial blood is mostly saturated and appears red while venous blood, where it is mostly unsaturated, appears darker because it absorbs more red lights. This effect is taken advantage of in oximetry by passing two LEDs with different wavelengths (typically 660 and 910 nm) through the tissue. The ratio of absorption at the two wavelengths is used to determine the fraction of saturated hemoglobin. Reference tables based on experimental data exist.

Pulse oximeters are useful in any setting where a patient's oxygenation is unstable, including intensive care, operating, recovery, emergency and hospital ward setting.

Also pilots in unpressurized aircraft needs it,

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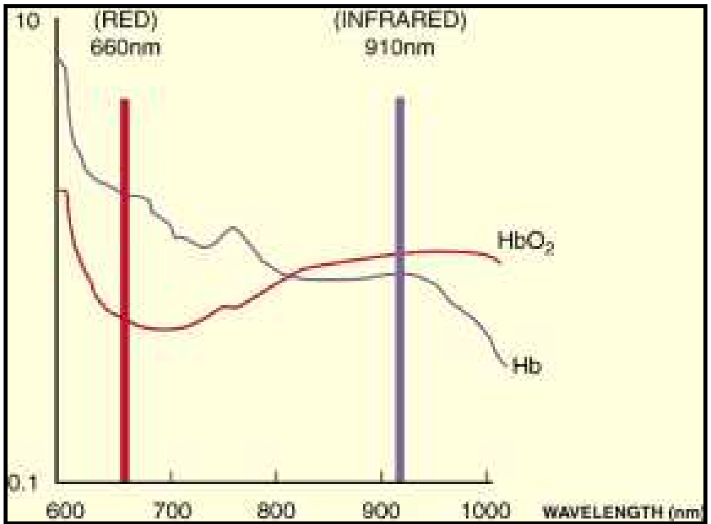

Figure 1: Absorption of oxygenated and non-oxygenated hemoglobin at different wavelengths

for measurement of oxygenation and to determining the effectiveness of the gaseous exchange in the blood or need for supplementary oxygen. Although a pulse oximeter is used to monitor oxygenation, it cannot determine the metabolism of oxygen, or the amount of oxygen being used by an individual. For this purpose, it is necessary to also measure carbon dioxide levels.

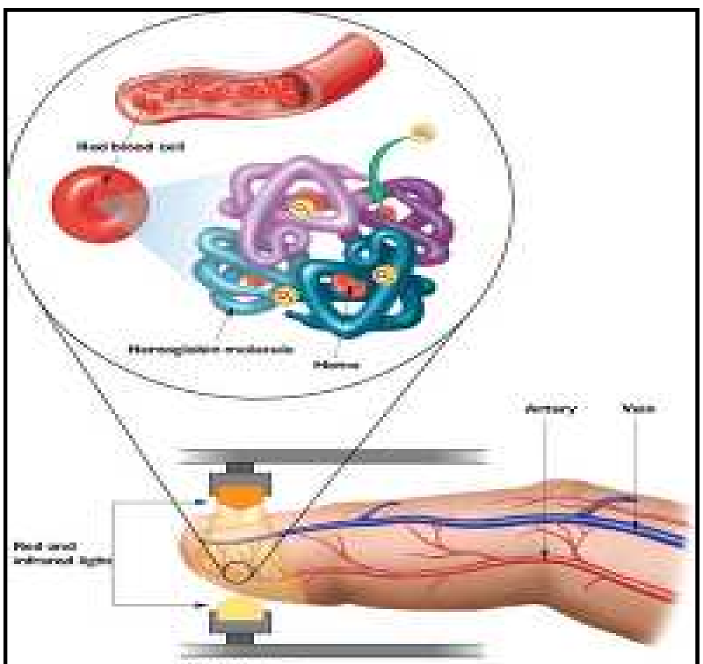

Figure 2: How pulse oximeter works to measures oxygen

It can also be used to detect abnormalities in ventilation. Because of their simplicity and speed, pulse oximeters are important in emergency medicine and are also very useful for patient with respiratory or cardiac problems for diagnosis of some sleep disorder such as apnea and hypopnea. Portable, DC powered pulse oximeter's are useful for pilots operating in a non pressurized aircraft above 10,000 feet where supplemental oxygen is required. Portable pulse oximeters are also useful for mountain climbers and athletics whose oxygen level may decrease at high altitude or with exercise. Some that are portable employ software that charts a patient's blood oxygen and pulse serving as a reminder to check blood oxygen level (Wikipedia, 2012). Figure 2 shows how pulse oximeter works to measures oxygen saturation

2. Design Methodology

There are two approaches to developing an oximeter probe. The first is called transmittance, the second is called reflectance. The difference is in the way the elements within the probe are positioned (see Figure 4). A transmittance probe has two LEDs on one side and a photodiode (light detector) on the other. The tissue to be imaged (commonly a finger or an ear) is inserted between the two. A reflectance probe has the LEDs and the photodiode on the same side. It must be placed over a point with underlying bone. Light is emitted by the LEDs, passes through tissue and blood vessels, reflects off bone, passes through the tissues again, and is then detected. It is good to note, that a significant amount of light will reflect off the skin in the reflectance setup, and, unlike in the transmittance setup, this light will be detected. Thus, reflectance probes have a high offset and a lower signal-to-noise ratio than the transmittance probes. Reflectance setups also require a significantly greater amount of light. Thus, either more LEDs or more photodiodes need to be used.

Transmittance probes are commonly placed on a finger or ear and are very convenient to attach and remove. Reflectance probes can be placed on the forehead or the sternum. Their advantage is that, regardless of the patient's size (infants to very large adults); the attachment site is always similar. Both, the transmittance and the reflectance probes are used clinically, though the transmittance probe is more common due to the simplicity of signal analysis and convenience of attachment. (Low cost pulse oximeter probe, 2009).

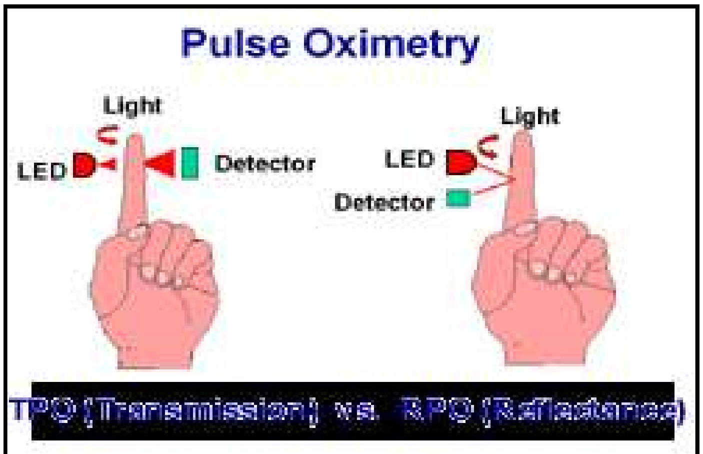

Figure 3: Transmittance vs. reflectance pulse oximetry setups. (AG&R Distributors, Inc.) AG&R Distributors, Inc. (n.d.). AG&R Distributors, Inc. Retrieved March 12, 2009, from AG&R Distributors, Inc. Website: http://agroximeters.com/tpo.gif

3.1 Materials Selection

The principles of light transmittance/absorbance through an arterial bed is used in this project, so I need a light source in order to transmit the light through a small area (such as the finger). I also need a detector that can convert the transmitted light into an electrical signal which would be my desired signal. Due to the fact that I am operating in a small area, I need small light sources and detectors. This can be accomplished via LED's and small photodetectors. These photodetectors can be either photodiodes or phototransistors, which are optoelectronic devices that work off the principle of detection of incident light which is then converted into an electrical signal. This electrical signal is a current. Since in electrical systems I wish to work with voltages (due to many factors, for example: ease of use, voltages is easier to manipulate etc) Therefore I need a system to convert this electrical signal into one I desire to work with. Therefore, both a hardware implementation (in order to acquire the signal) and software implementation (in order to post process it) are required.

3.2 Design Specification

The microcontroller: the microcontroller is the brain behind the operation of the main control panel. The microcontroller is responsible for the control of the seven segment display to enable appropriate readout of digits and characters. In operation, what the microcontroller does is this; first it accesses Digit 1, sends out data to Digit 1, then waits for some microseconds for the data sent to the display to light up well, then it moves on to Digit 2 does the same thing, next to Digit 3 and finally Digit 4.

The PIC (peripheral interface controller) microcontroller functions as a signal monitoring device. It coordinates and controls the signals that are used by other circuit components in the unit. The actions of the PIC is carried out based on the assemble language program that has been stored into its program memory. It has been designed to perform the following functions.

It receives analog signal from the phototransistor through its internal ADC module. The signals are then processed into decimal figures which are displayed on the seven segment display as a pulse value. It controls the action of the seven segment display by selecting the segments and passing out individual data one at a time using division multiplexing.

3.3 Design Analysis

In designing the pulse oximeter, first research was done in order to properly understand how one can use electronic principles in order to obtain a physiological signal such as blood oxygen content. The implementation for a pulse oximeter consists of both a hardware and software components. The hardware component consists of electronic circuitry in order to obtain the signal, while the software component consists of extracting the necessary information from this signal which will then be used to calculate the blood oxygen saturation.

There are many theoretical principles that are fundamental to understand how we can use pulse oximetry in order to obtain a signal relevant to physiologic function. However, due to the many different fields involved, this discussion will be limited to only the pertinent details that are necessary in order to understand pulse oximetry.

Hemoglobin is the oxygen carrying molecule of the blood and blood consists of millions of these molecules. It can also exist in two forms:

- Oxidized (or oxygenated) Hemoglobin denoted as HbO_2 and
- Reduced (or deoxygenated) Hemoglobin denoted as Hb.

Approximately 99% of oxygen is bound to hemoglobin in red blood cells. Oxygen saturation denoted as SaO_2 refers to the ratio of oxygenated hemoglobin to the total concentration of hemoglobin, or simply:

$$SaO_2 = [HbO_2] / [\text{total concentration of hemoglobin}] \qquad \text{Eqn 1}$$

This SaO_2 is normally given as a percentage, and for a healthy individual is > 91% (on average however is around > 97%).

Due to the optical properties of both HbO_2 and Hb at 500nm-1000nm, it is possible to measure oxygen saturation. This is done by measuring transmitted light (through the tissue, normally finger or earlobe) at two different wavelengths. Making the assumption that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and reduced hemoglobin and their absorption coefficients at the two wavelengths, light intensity will decrease logarithmically according to Beer–Lambert's law. Using these principles an expression for the ratio of the intensity of light transmitted at two different wavelengths is given as:

$$R = \log10 (I_1) / \log10 (I_2) \qquad \text{Eqn 2}$$

where I_1 is the intensity of light at λ_1 (wavelength 1) and I_2 is the intensity of light at λ_2 (wavelength 2).

Once we know the absorbance coefficients of HbO_2 and Hb at the two wavelengths, we can find the oxygen saturation via the following formula:

$$SaO_2 = (\alpha r_2 R - \alpha r_1) / [(\alpha r_2 - \alpha o_2) R - (\alpha r_1 - \alpha o_1)] \qquad \text{Eqn 3}$$

where:

αr_1 is the absorption coefficient of Hb at wavelength 1
αr_2 is the absorption coefficient of Hb at wavelength 2
αo_1 is the absorption coefficient of HbO2 at wavelength 1
αo_2 is the absorption coefficient of HbO2 at wavelength 2
R is the ratio from equation 2

The wavelengths of transmitted light through the tissue, is chosen to be at 660nm (red light) and 940nm (Infrared light). These are the most practically used values, due to the fact that light at this wavelength is least attenuated by body tissues (tissue and pigmentation absorb blue, green and yellow light).

In pulse oximetry, only the part of the signal which is related to the inflow of Arterial blood at that segment is used for the calculation of oxygen saturation. When light at these wavelengths (IR and red) is transmitted through the tissue it gives a pulsatile signal as shown in figure 4. This signal varies with time in relation to the heart beat.

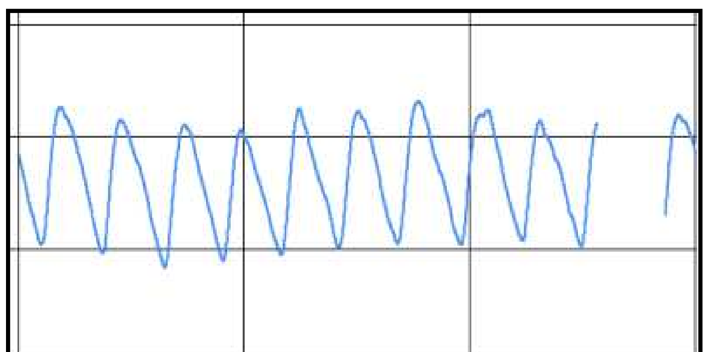

Fig 4 Pulsatile signal obtained when IR or red light is transmitted through the finger (Figure taken from Medical Electronics, Dr. Neil Townsend).

Therefore the heart rate of an individual can be extracted from this signal, (heart rate = frequency of signal).

From figure 4 the signal is a pulsating one, whose frequency is related to the individual's heart rate. From this I can extract the necessary information, which in my case will be the voltage measurements at any given time from this output signal. This voltage measurement relates to the intensity of the transmitted light and can be implemented into equation 2 and 3 in order to find our oxygen saturation reading. The signal in figure 4 however is just one example of a pulsating signal obtained. Different individuals produce small differences in the output signal (as will be seen in the results and discussion section of this report). (Hamzah Q, 2009)

3.4 General Safety Considerations

Sensors are sized according to the patient's weight; different manufacturers specify somewhat different ranges. It's important to use the correct size to avoid skin complications and ensure accurate readings. Even when the correct size is used, skin breakdown at the placement site, caused by pressure from the sensor, has been reported. Check that the right type of sensor is being used. The sensor site should be chosen based on which location has the best pulsatile vascular bed. Generally the finger is chosen first; however, forehead sensors are particularly useful in patients with poor peripheral circulation. Forehead sensors are also a good alternative in patients under general anesthesia whose extremities aren't readily accessible.

To exclude motion artifact caused by shivering, patients should be kept warm. A study of trauma patients during pre-hospital transport found that those actively warmed with resistive heating blankets had significantly fewer oximeter alarms than those given wool blankets. To avoid potential interference from ambient light, the sensor can be covered with the patient's linens. Nail polish or artificial nails should be removed. Bedside equipment alarms can be frightening to patients and families, especially if they aren't attended to promptly. Quality assurance studies conducted by member hospitals of the Child Health Corporation of America's Pulse Oximetry Forum indicate that in pediatric populations, the false alarms that occur during continuous pulse oximetry cause needless anxiety for patients and families.

3.5 Sources of Errors

Motion artifact is a common cause of erroneously low readings and false alarms. Movement such as that caused by shivering or by conditions marked by seizures or tremors can hamper the sensor's ability to accurately detect the amounts of light absorbed. Improper fixing of the sensor (too loose or too tight), as well as venous pulsations associated with tricuspid regurgitation or an intraaortic balloon, can also cause motion artifact.

Higher than normal levels of carboxyhemoglobin (carbon monoxide-bound hemoglobin) or methemoglobin (created when the iron in hemoglobin oxidizes) also skew pulse oximetry readings. These substances absorb the oximeter's red and infrared wavelengths similarly to hemoglobin and oxyhemoglobin. Patients who have suffered smoke inhalation or carbon monoxide poisoning will have higher levels of carboxyhemoglobin. And higher levels of methemoglobin may occur with overexposure to various substances, such as nitrites and some topical anesthetics. Patients so exposed should be monitored by alternative methods.

Conditions that cause low blood flow or decreased perfusion will affect pulse oximetry readings. If the arterial pulse is weak, the oximeter will have difficulty isolating its signal from those of the surrounding venous blood, bone, and tissue. Causes of low perfusion include cardiac arrhythmias, heart failure, peripheral vascular disease, and hypotension. Vasoconstriction caused by hypothermia, smoking, or medication can also result in low perfusion. Altered pulse oximetry readings may be seen during acute vasoocclusive crises, such as those that occur in patients with sickle cell disease.

Early studies indicated that skin pigmentation has no significant effect on the accuracy of pulse oximetry. Whether nail polish adversely affects pulse oximetry readings taken on the finger also remains unclear. In one early study, researchers found that if the sensor was applied directly over the nail bed and the polish absorbed light differentially at the same wavelengths being transmitted and detected by the sensor-as happened when test subjects wore blue or green polish-the oximeter readings were inaccurate.

Sensor misplacement: If an oximeter fails to display data or a waveform and the patient has a pulse, check that the sensor is functional, adjust its position, or try taking a reading at another site. Keep in mind, though, that sensor designs vary somewhat depending on the intended site and that each device is calibrated accordingly. (For example, forehead sensors are usually adhesive, while finger sensors can be adhesive or clip-on.) Using a sensor at a site it wasn't designed for will result in an erroneous reading.

3. Results and Testing and Discussion

A prototype of the implemented design was verified to ensure that they are in good working condition according to the design. This was a vital stage in the development of the project since it involves ensuring that a given item, component or system meets the design specification or else how far it has deviated. The project testing encapsulated both hardware and software testing each carried out both in its pre-implementation stage and post implementation stage.

3.1 Hardware Testing

Testing the hardware for its conformability to the design specification entails testing the various hardware component parts or modules. This is of great concern since environmental conditions, wear, tear or extremely high current and voltage can easily affect hardware. The basic test equipments used in the design of this project are; digital multimeter and a microcomputer for the hardware interface test.

Testing is one of the important stages in the development of any new product or repair of existing ones. This is very important because many factors contribute to making a supposed good design to work after implementation. Since, it is very difficult to trace in a finished work, especially when work is somewhat involving in terms of complexity, testing was started early in critical stage in the development of the project.

The two stages of testing involved include;

- Pre-implementation testing
- Post-implementation testing

Pre –implementation testing

It is carried out on the components before they are soldered to the Vero-board. This is to ensure that each component is in good working condition before they are finally soldered to the board. The components used in this design can be grouped into

- Discrete components; e.g. resistors, transistors, capacitors, etc
- Integrated circuit components

Pre-implementation stage involves carrying out the appropriate verification test on the components to ensure that they match their specification prior to implementation on a project board and subsequently on a Vero board. At this stage the cable for the serial port interface was tested for continuity between its two ends for each of the lines used in the project to ensure reliable transfer of information bits.

The following tests were carried out on the discrete components.

Resistos: the two pins of the resistor were probed with multimeter switched to the ohm meter range and values obtained were compared with the value of the color code. Those within the specification tolerance were used. The procedure for testing the light dependent resistor and variable resistor is the same with the procedure for testing a conventional resistor.

Capacitors: the multimeter was switched to the voltage testing mode to a value slightly higher than the voltage setting for the capacitor. The positive of multimeter was placed on the positive terminal of the capacitor while the negative probe was placed on the negative terminal of the capacitor. The capacitor is good if a voltage reading is obtained which gradually decreases with time due to discharge of the capacitor.

Diodes: the multimeter was used to determine the positive (anode) and the negative (cathode) terminals of the diodes (including the LEDs used as indicators) used in this project work. The diodes were tested by for open/short circuit to ensure that currents flow through in it only in one direction.

Integrated Circuits: the integrated circuits were tested by first of all setting up the entire circuit on a project board. The circuit was then tested by applying different test input, to entire circuit will function properly when finally implemented on a Vero board.

Board Implementation: the implementation of this project was done in two stages. At first the circuit was realized on a project board by connecting up the various components as in the connection ascertained to conform to circuit design utilizing links where necessary. When the system was powered, it was observed that it worked effectively within design parameters and specifications.

Thereafter, the entire circuit arrangement was transferred to a Vero board for permanent connections using the soldering technique. Spot soldering was employed were necessary, dry joint where avoided and great care was taken not to damage the components by excessive application of heat from the soldering iron. Again, this unit was powered and observed to function satisfactorily and within design parameters and specification.

Post-implementation testing

Post implementation involves testing each module or unit of the hard ware after implementation to ensure that they perform their functions/operations intended in the design. This also includes subsequent tests on the complete system for precision.

3.2 Software testing

The primary purpose of software testing procedure is program validation. Validation refers to the degree to which software meets the specified requirement, while being closely related to program debugging. Testing is a process that simply proves the presence of errors. Debugging on the other hand involves localizing error, and determining its course.

Testing and debugging go hand in hand. The test process for the software involves two phases which are:

Sub-routine and module phase: These phases run concurrently with the software implementation. It involves testing the various subroutine and module as they were built interfacing the system hardware and the software. The hardware was calibrated with the software to ensure that they are synchronized.

4 Conclusion and Recommendation

Pulse oximeter is probably one of the most important devices in respiratory monitoring over the last few years; numerous studies have focused on the technical aspects of pulse oximeter and found that these instruments have a reasonable degree of accuracy, coupled with the ease of operation. Most instruments has led to the wide spread use of pulse oximeter for monitoring patient especially in the intensive care units.

4.1 Conclusion

Perhaps the major challenge facing pulse oximeter is whether this technology can be incorporated effectively into diagnostic and management algorithm that can improve the efficiency of clinical management in the intensive care units.

This report dealt with the implementation (specifically hardware implementation) of the blood oxygen monitor, which is better clinically known as the pulse oximeter. I first went about research into this field and why pulse oximetry is useful. After coming to a proper understanding behind the science of such a technology, I then went about a way to design a system that uses these principles to give me an electrical signal that I can use to find the oxygen saturation reading. Once this was accomplished I went about actually implementing and trying to receive meaningful results from the designs.

An initial and simple design was first implemented using an LED to transmit light through the finger, a photodetector to “sense” the transmitted light and a current to voltage convertor in order to convert this into a more useable electrical signal.
Implementation of this system was successful.

Finally, we have shown and proven with the implementation design, results, and discussion that a pulse oximeter signal can be obtained using transmission of light through the finger, which then can be processed by the necessary circuitry. We have seen that the result of my implementation is successful due to the fact they give us a 96.35 % oxygen saturation reading (knowing that a healthy individual has an oxygen saturation reading of > 91 %). We can conclude that our main goals and objectives for this project have been reached.

4.2 Recommendation

Based on my research, I recommend that:

- More funds should be channeled into the design and fabrication of biomedical equipments or devices here in our country, instead of patronizing ones designed in the western counties.
- People especially the youths should be challenged and motivated to embark on creative biomedical inventions and innovations using the principles and theories in science which will be based on proper analysis of the common biomedical problems.
- People should be educated on the need to regularly check their blood oxygenation and therefore advised to have a personal pulse oximeter.

References

[1] "Family Doctors" access June 14, 2012 @ http://www.cbc.ca/news/background/healthcare/familydoctors.html, [April 3, 2009].

[2] Tom Bailey. "Waiting for a family doctor" Internet: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1949098, March 2007 [April 3, 2009].

[3] College of Family Physicians of Canada, "Public opinion poll on physician wait time" [Decima Research poll conducted for the College] Mississauga, Ont: College of Family Physicians of Canada; 2006.

[4] Starfield B. "The importance of primary care to health", Internet: http://medicalreporter.health.org/tmr0699/importance_of_primary_care_to_he.htm, 1999 [April 3 2009].

[5] Neil Townsend. *Medical Electronics.*Michaelmas Term, 2001.

[6] Tremper K.K. "Pulse Oximetry", *CHEST,* 95, 713-715, 1989.

[7] Scharf J. and Athan S. "Digital Capture of Pulse Oximetry Waveforms", *IEEE,* 93, 230-232, 1993.

[8] Hoff Dave, Zhang Roy, Stalter Tad, Carlson Mike. "Pulse Oximetry", Undergraduate Thesis, University of North Carolina, U.S., 2003.

[9] Mendelson Y., R. J. Duckworth and G. Comtois, "A Wearable Reflectance Pulse Oximeter for Remote Physiological Monitoring", *28th IEEE Conference Proceedings*, p 912 - 915, September 2006

[10]Douglas A. Palmer, Ramesh Rao and Leslie A. Lenert. "An 802.11 Wireless Blood Pulse-Oximetry System for Medical Response to Disasters", AMIA *2005 Symposium Proceedings*, pg 1072, 2005

[11]Sweta Sneha and Upkar Varshney. "A wireless ECG monitoring system for pervasive healthcare", *International Journal of Electronic Healthcare*, 3, p. 32– 50, 200

[12]"Pulse Oximeter Laboratory" accessed June 17, 2012 @ http://www.ece.arizona.edu/~bme517/supporting%20documents/PulseOximeter/Pulse%20Oxi%20Meter%20Laboratory.htm, 2002 [Feb 2009].

[13]"Tabulated Molar Extinction Coefficient for Hemoglobin in Water" http://omlc.ogi.edu/spectra/hemoglobin/summary.html. March 1998, [Feb 2009].

[14]Ilana Bayer. Health Science 2LL3/2FF3, Class Lecture, Topic: "Blood", HTH SCI 2LL3 McMaster University Faculty of Health Sciences, Hamilton, Ontario, January 2008

[15]Inman. Health Science 2LL3/2FF3, Class Lecture, Topic: "Respiration: Gas Exchange", HTH SCI 2LL3 McMaster University Faculty of Health Sciences, Hamilton, Ontario, February 2008.