Low Cost Pulse Oximeter Probe

In Conjunction with Engineering World Health and the MEDCAL Project

Matthew Brian Parlato, Jonathan Meyer, Bogdan Dzyubak, Joseph Helfenberger

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Abstract

Hospitals in the developing world many times lack necessary medical equipment. Even some pieces of equipment that are considered cheap and disposable in developed nations are hard to obtain in hospitals of the developing world. The goal of this project is to design a cheap, accurate, durable, and easy to use pulse oximetry probe that is able to interface with a low-cost medical computer (the MEDCAL). To meet this goal, we have chosen to construct an ear transmittance probe. We plan to finalize and test this design to ensure its durability and accuracy.

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Introduction

Engineering World Health (EWH), an organization based out of Duke University, is dedicated to improving healthcare and living conditions throughout the developing world. Their website explains many of the difficulties that hospitals in the developing world face (such as unreliable electric power, inability to replace worn out devices, etc.). Of the listed devices that are needed in these hospitals, one is a low-cost pulse oximeter. The EWH project description states that:

It is now possible to purchase a pulse oximeter for about $100. Yet, this is one of the most requested pieces of medical equipment in developing world hospitals. The problem is that donated, low-cost, pulse oximeters quickly break in the continuous use environment of the hospital, and the batteries can be difficult to replace. The objective of this project is to take the elements of an off-the-shelf, low-cost, pulse oximeter and adapt them for long-term continuous use in the developing world.
(Engineering World Health)

Our clients, Amit Nimunkar and Jonathan Baran, are working in conjunction with EWH to create a low-cost medical computer, the MEDCAL. This device will interface with several pieces of electronic medical equipment, and it will be able to not only display and process their outputs but provide power for them and contain most of their delicate circuitry. Equipment that will interface with the MEDCAL besides the pulse oximeter includes but is not necessarily limited to: low-cost digital thermometers, electrocardiograms (ECGs), and digital spirometers.

The clients would like us to develop the probe portion of a pulse oximeter. This probe will house only the necessary electronic components (LEDs and photodiodes), and all other circuitry (i.e. digital logic, etc.) will be housed within the MEDCAL device or associated components, which is being built by our clients. Constraints on this probe will be very similar to the EWH constraints on the pulse oximeter as a whole. This probe must be:

1. **Durable enough to withstand the heavy use that it may encounter in hospitals of the developing world**
2. **Cheap enough to be mass produced for very little money (ideally under $8.00)**
3. **Accurate to within ± 5% (ideally to within ±3%)** (Fortney, 2009)
4. **Suitable for use with a variety of patients; it must be able to be used on everyone from infants to the elderly**

Background

In 2007, the amount of money spent on healthcare in the United States was $6,096 per capita (United Nations, 2007/2008). 28 developing countries in the world spend less than $100 per capita. These countries are primarily in Africa, including Haiti and Yemen. The average life expectancy from these countries range from 26 to 49 years while countries with leading life expectancies range from 62 to 74 years, with the US at 70 years (Murray, 2000). Though this is alarming, it is important to note that some of these developing countries spend as much as 5% of their GDP on healthcare, where some developed countries spend as little as 3.5% of their GDP on healthcare (World Health Organization, 2009). This demonstrates the stark contrast in the abilities of these developing countries to provide necessities to their people.

Pulse oximeters can directly detect hypoxemia, a lack of oxygen saturation in the arterial blood. Early detection of hypoxemia can prevent many complications such as systemic CO_2 buildup and oxygenation deprivation in tissues, which directly leads to tissue damage.

Many causes can lead to hypoxemia. If a patient takes an overdose of barbiturates, his/her medullary respiratory center can become depressed and cause his/her pulmonary alveoli to become inadequately ventilated. This results in a buildup of CO_2 and depression of O_2 in the bloodstream. A physiological shunt, when cardiac output goes through the regular pulmonary vasculature without coming into any contact with alveolar air, can also lead to hypoxemia. This is often seen in conditions such as pulmonary edema, pneumonia, and collapse of a portion of the lung (pneumothorax) (Mayo Clinic Staff, 2008). All of these conditions put the patient at great risk to develop hypoxemia.

The implementation of a pulse oximeter for spot checks is particularly important in cases where patient feedback is limited. This includes cases where a patient is under anesthesia or unconscious. If the patient suffers from debilitating conditions or is under critical care, a pulse oximeter can provide important feedback during crucial moments. Detection of oxygen saturation is also important in newborn infants, where oxygen saturation can be low, especially during premature birth. A spot-check pulse oximeter could provide relevant information so that necessary steps to prevent infant death are taken (Askie LM, 2003).

Operational Principles

A pulse oximeter detects oxygen saturation by shining light through a tissue. The light is absorbed and reflected by multiple components including skin, muscle, and blood vessels. Though the amount of absorption due to tissues may vary over a long time period, all absorption except that due to arterial blood flow is 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. Because of the influx of blood, the total amount of tissue between the oximeter's light source and detector increases, and therefore, so does light absorption. 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 shown in Figure 1.

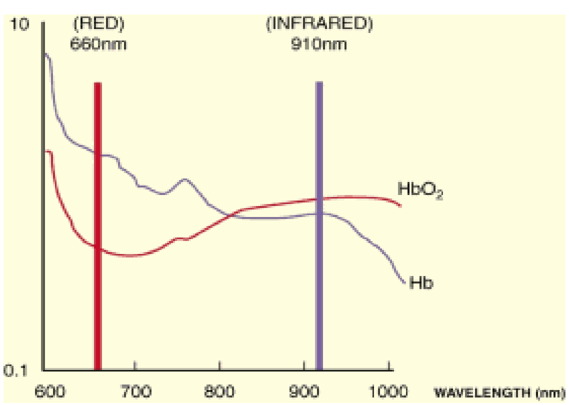

Figure 1. **Absorption of oxygenated and non-oxygenated hemoglobin at different wavelengths. (Google)**

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 light. This effect is taken advantage of in oximetry by using two LEDs with different wavelengths (typically 660 and 940 nm) and shining them 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 but the calculation is beyond this text.

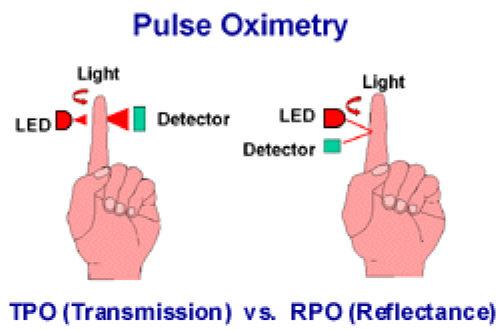

Figure 2. Transmittance vs. reflectance pulse oximetry setups. (AG&R Distributors, Inc.)

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 2). 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.

Basic Probe Electronics

For ease of replacement, the circuit is split into three components: the probe, the adapter, and the low cost processing device, the MEDCAL, which the adapter plugs into. The probe itself contains minimal circuitry (Figure 3). The LEDs used are 660 and 940 nm. However, their values are not exact and may vary by ±5%. Thus, a resistor with a certain value is used to show the deviation of each LED from the expected value and introduce the correction when MEDCAL calculates the ratio of absorbed red to IR light. Thirdly, the probe contains the photodiode which detects the light. The photodiode requires up to 5 V to run. In total, the probe will connect to a bundle of nine wires. The wires are – the resistor connections (two connections per resistor), the input for each LED, the power for the photodiode, its output, and a ground reference.

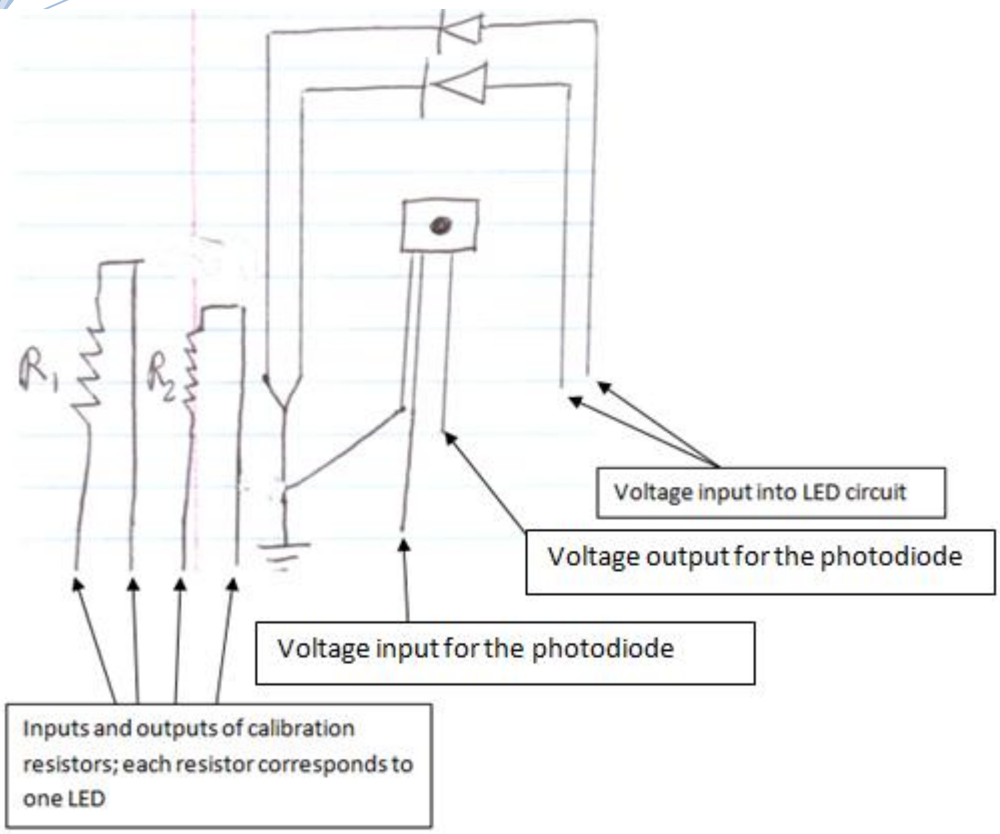

Figure 3. **Basic layout of electronic components housed in pulse oximeter probe.**

The adapter and the MEDCAL will be constructed by the client. The MEDCAL will perform all the processing, such as the pulse and oxygen saturation calculations. One adapter unique to a device type (oximeter, spirometer, thermometer, etc.) will be plugged into the MEDCAL at a time. The device being used will plug into the adapter. This allows a damaged probe to be replaced without replacing a significant amount of circuitry. The adapter contains the driving circuit that flashes the LEDs, as well as the pre-processing elements (see Figure 4).

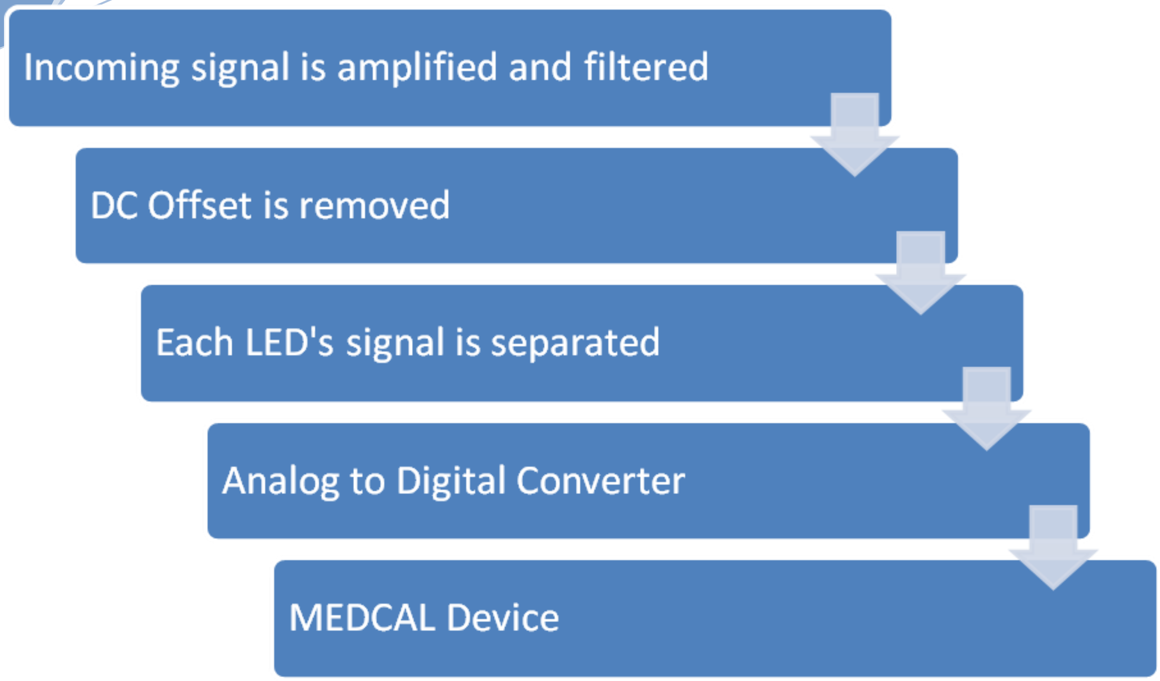

Figure 4. **Basic information flow from pulse oximeter probe to the adapter and then to the MEDCAL device.**

A microcontroller is used to time the LEDs, alternating between three states. In the first, only the red LED is turned on, in the second only the IR, and in the third, both LEDs are off. The switching between the states occurs at 480 Hz. The timing signal is also sent to the pre-processing circuit. First, the circuit verifies that the signal level is sufficient. If not, it sends feedback to the driver circuit to increase current, leading to an increase in LED brightness. Once the input from the photodiode is received, it is amplified, and the DC component and high frequency noise are removed using a bandpass filter. Then, the signal is separated into the red, IR, and ambient light components and the latter is ignored. Lastly, the signal is converted into digital form and sent to the MEDCAL.

In total, the MEDCAL receives several input signals including the offset resistances from the probe, the signal from the photodiode, and a device ID that identifies the oximeter adapter (also given by a resistor with two connections). The MEDCAL provides power for the circuits and will have an output pin for each of the LEDs, the photodiode, and two for the microcontrollers in the driver and pre-processing circuits. Other devices and their adapters will use separate ports, or, alternatively, different pins in one port may be used for each device.

Design Alternatives

We investigated three design options this semester: the finger transmittance probe, the forehead reflectance probe, and the ear transmittance probe. The primary issues analyzed with each design were their cost, durability, accuracy.

We also considered human factors and ergonomics of each of these designs. The probe designs need to be simple and intuitive to use, otherwise they may be misused or simply not used at all. Any given probe design must also fit a wide variety of patients without time consuming size adjustments between patients. The accuracy of the probe must not depend on the patient's physical characteristics (skin color, etc.) or on meticulous adjustments by the physician.

Option 1: The finger transmittance probe

The finger transmittance probe consists of a spring-loaded clip which attaches to the finger. One arm of the clip contains the probe's light source (two LEDs), and the other contains its photodiode, thus allowing the probe to measure the light transmitted through the finger.

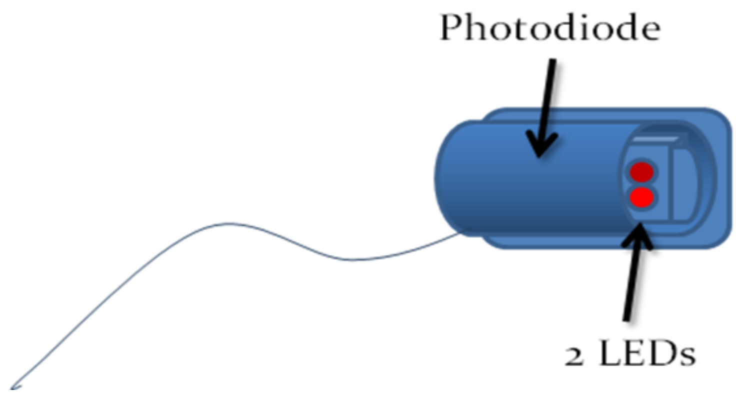

Figure 5. Finger transmittance pulse oximeter probe with the LEDs on one side and the photodiode on the other.

The primary advantage of the finger transmittance probe is its convenience for spot checks. It is easy to quickly apply it to a patient and quickly remove it. It is also relatively comfortable and unobtrusive. Unfortunately, it also involves some significant drawbacks, including:

- Mechanically, it is unlikely to be very durable because its hinge incorporates sharp angles and small holes, resulting in potentially significant stress concentrations.
- Its signal travels through the fingernail, and can thus be blocked by fingernail polish.
- The probe is difficult to use on small infants, as the probe is made for an adult finger.
- When a patient has extremely low blood pressure (i.e. after significant blood loss), the body reduces blood flow to the periphery to maintain adequate blood pressure for the vital organs and brain. Thus, signals from a probe on the finger can be difficult to accurately measure when patients are in critical condition.

Option 2: The forehead reflectance probe

The forehead reflectance probe consists of a disc attached to the forehead with a headband. The face of the disc has two LEDs in its center, surrounded by a ring of three or four photodiodes, as shown in Figure 5.

The forehead probe presents several significant advantages, including the following:

- It has no moving parts and fewer stress concentrations than the finger transmittance probe, and thus it is probably more durable.
- Unlike most transmittance probes, reflectance probes can be used on both adults and infants, as they merely require a relatively flat perfused tissue backed by bone. It can also be used on multiple sites in the body (i.e. the forehead, temple, sternum, etc.)
- The head remains perfused even in cases of severe shock, in which the patient's peripheral circulation may be cut off.

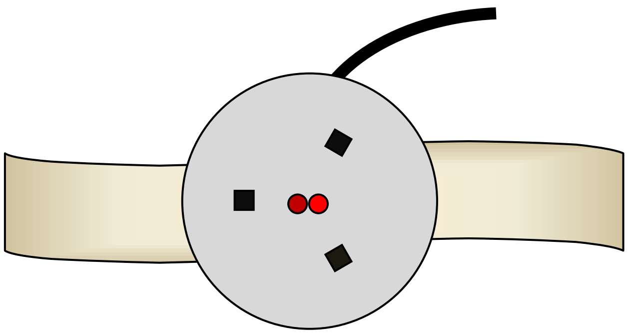

Figure 6. The forehead reflectance probe, with the LEDs located in the center of a disc, and radially surrounded by three photodiodes.

The forehead probe design also presents several significant drawbacks. The signal resolution offered by reflectance is lower, creating a higher possibility of an inaccurate reading. Also, the probe is not well suited for spot checks; the headband would need to be adjusted frequently between patients. Rushed physicians might entirely forego the use of the headband and manually apply the probe, which could potentially result in motion artifacts. Also, with constant readjustment, the headband would need to be periodically replaced.

Option 3: The ear transmittance probe

The third design option we considered would consist of two prongs which would be placed on opposite sides of the ear. One would house the LEDs, and the other would house the photodiode.

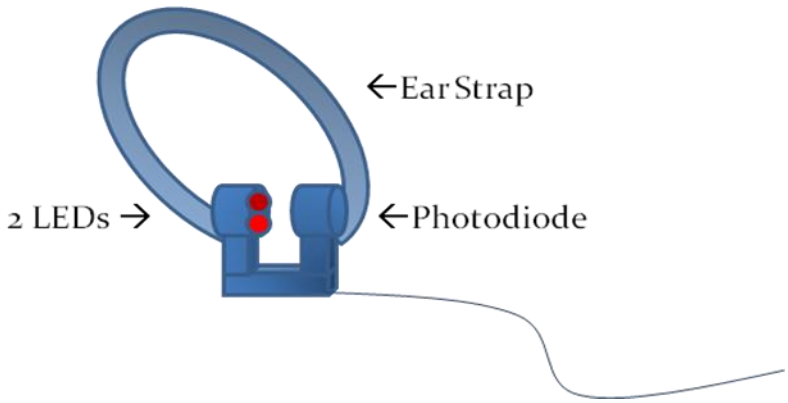

Figure 7. Ear transmittance probe with the LEDs on one side of the ear and the photodiode on the other.

The ear probe presents several significant advantages. Like the forehead probe, it uses the reliable perfusion of the head, and is thus more dependable on patients with severe blood loss. It has a higher signal resolution than the forehead probe, and thus less of a potential for error. It is also easier to use than the forehead probe, requiring little or no adjustment between patients, and is easier to use on patients who are lying down or are unconscious.

The primary disadvantage of the ear probe is that it may need to be adjustable to be used on both adults and small infants, and thus may be less durable than the forehead probe design.

Design Matrix

Our design matrix is shown in Table 1. As the matrix indicates, we decided to use an ear transmittance probe design, primarily because it uses a more dependable blood supply than the finger transmittance probe, yet is more convenient and has a higher signal resolution than the forehead reflectance probe.

Table 1. Design matrix comparing finger, forehead, and ear probes.

	Weight	Finger	Forehead	Ear
Cost	10%	7	7	8.5
Accuracy	25%	5.5	6.5	7.5
Ease of Use	20%	9	5.375	6.25
Range of Use	20%	8.5	7.625	6.25
Durability	25%	4.375	7.625	7.25
Total	100%	66.7	68.3	70.4

Future Work

Though we have decided upon a pulse oximeter probe design that satisfies the goals of this project, much work must still be done. The actual housing of the probe must be designed and tested to ensure its durability and ease of use. A way to mount all of the electronics of this probe (the two LEDs and the photodiode) to ensure solid attachment, and thereby the minimization of motion artifacts, must be found.

This semester, there are three clear goals that we hope to accomplish as a team:

1. **Testing of the probe design's accuracy and ease of use**
2. **Mechanical testing of the probe's durability**
3. **Development of a working prototype by the semester's end**

Testing of the probe design's accuracy and ease of use is essential, as it is undesirable to build a probe that either does not work or is too complicated to use. Secondly, building a durable probe is also essential as this probe will be used heavily and will most likely not be used under ideal conditions. Thirdly, a working prototype must be developed. This prototype will not only help our client understand our probe design, but will also allow us to have a product that may be fully tested. This prototype can then act as a working model for EWH doctors to evaluate and give us feedback on. It is hoped that this feedback can then be used to further improve the design of this probe.

Conclusion

The goals of the project were fourfold, in that the constructed probe must be:

1. **Accurate**
2. **Cheap**
3. **Durable**
4. **Suitable for a variety of patients**

We decided that the best pulse oximeter probe design to satisfy these goals was one which works on the principle of transmittance through the ear. This probe will have a robust mechanical design that will not only be easy for the doctor to use, but will also be extremely durable. The electrical components and mechanical design of the probe must be such that it can easily be interfaced with the MEDCAL device that the client is developing. This device will not only satisfy our client's needs, but will have the potential to significantly improve conditions in the hospitals of developing countries.

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Appendix A

Product Design Specifications

EWH Pulse Oximeter

Version: 3.1
Date: 2/25/09
Last Modified by: Jonathan Meyer

Team

Bogdan Dzyubak
Joe Helfenberger
Jonathan Meyer
Matt Parlato

Clients

Amit J. Nimunkar
Dept. of Biomedical Engineering
608.698.7413
ajnimunkar@wisc.edu

Jonathan M. Baran
Dept. of Biomedical Engineering
608.263.4660
baran@wisc.edu

Advisor

John G. Webster
Dept. of Biomedical Engineering
2148 Engineering Centers Building
1550 Engineering Drive
Madison, WI 53706
608.263.1574
webster@engr.wisc.edu

Function

The purpose of this project is to develop a low-cost pulse oximeter for use in developing countries. It will be integrated with the MEDCAL, which records and displays patient data. The oximeter must be rugged, durable, and inexpensive.

Design requirements

1. Physical and Operational Characteristics

c. *Accuracy and Reliability*:

- The probe must be precise to increments of 1% SpO_2.
- The pulse oximeter must be accurate to within 5% SpO_2 (Fourtney).
- Must contain one resistor per LED which specifies the LED's deviation from the specified wavelength

f. *Operating Environment*:

- The device must be operable in 100% humidity.
- The device must operate in a temperature range of 0°C to 38°C.
- The device must be rugged.
  - The device must be able to be dropped from 1.5 m onto concrete without breaking.

h. *Size and weight*:

- Size: the probe should be smaller than 4 cm × 4 cm × 4 cm.
- Weight: the probe should be lighter than 100 g

j. *Materials*:

- Must be mass-producible.

k. *Attachment:*

- Must attach to the ear, with LEDs on one side of the ear and a photodiode on the other.

2. Production Characteristics

a. *Quantity*: Mass produced.

b. *Target Product Cost*: under $8. Though this is our target cost, our prototype can be above this specification.

3. Power and Data Transfer

- The device must interface with a central processing unit for both power and data transmission.
- The device must run on ±5V.

3. Miscellaneous

- The device must withstand sterilization with isopropyl alcohol or a weak bleach solution (Fourtney).

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