# Skin Color Monitor

Jack Ho, Team Leader
Brian Ginter, BSAC
Joseph Yuen, BWIG
Patrick Kurkiewicz, Communications

BME 300/200
Department of Biomedical Engineering
University of Wisconsin-Madison
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**Client**
**John G. Webster, Ph. D.**
*Department of Biomedical Engineering*

**Advisor**
**William L. Murphy, Ph. D.**
*Department of Biomedical Engineering*

## Abstract

Many menopausal women suffer from hot flashes, the symptoms include momentary sensation of heat, sweating, flushed face, and increased heart rates. In drug and other treatment development, developers use devices to record the accounts of hot flashes in women. Devices that accurately study hot flashes in women are especially useful in developing new drugs to help relieve the symptoms of hot flashes. Currently, the devices used to monitor hot flashes are big, bulky, and simply inconvenient to wearers. We hope to develop a device that will accurately monitor hot flashes by detecting the change in skin color during a hot flash. This device aimed to be small, comfortable, cheap, and effective. A LED will shine light onto the skin to be reflected and detected by a phototransistor which will produce leakage current proportional to the amount of light detected. This current will alter the output voltage of the device, allowing us to record changes in skin color. Our team has created a functional prototype consisting of a polycarbonate casing and a thin acrylic shield that keeps the skin immobilized during testing. A set of tests have been preformed to in which the device has shown its ability to detect color change.

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## Problem Statement

Our client, Professor John Webster has presented us with the task of creating a device that uses changes in skin color to monitor and record hot flashes in women. The device is to be used in research and testing of experimental menopausal drugs. Traditionally, hot flashes have been monitored by use of a journal and or electrodes attached to the chest. However, our client indicated that the journal is extremely inaccurate and the use of current electrode devices is uncomfortable, inefficient, and expensive. Our device will detect when the skin becomes flushed using changes in skin color as an indicator. Our client has expressed interest in us creating a device that is capable of performing the said task using a small, comfortable, and relatively cheap design.

## Background Information

The most common symptom of menopause in women is hot flashes. Hot flashes are sensations of heat a woman experiences that are marked by excessive sweating and flushed appearance of the skin. During a hot flash, the capillaries near the surface of a woman's skin dilate in an attempt to cool the body (WedMD, 2007). This will give the skin a reddish appearance, similar to the flushed appearance one gets after exercise. Hot flashes often occur at night and can be very debilitating to sleep patterns (Stöppler, 2007). The length of a hot flash can fluctuate from several seconds to as long as an hour. Hot flashes occur in eighty five percent of women as they approach menopause and twenty to fifty percent have hot flashes that persist for years.

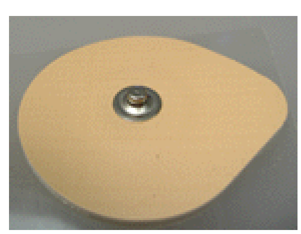
Currently there are many treatments for the onset of hot flashes. Hormone replacement therapy is a common form of treatment for hot flashes. Also some antidepressants and other drugs have been found to help curb the symptoms (Wikipedia, 2007). Given these current options, there is still a great need for the development of drugs. For years, studies were performed with subjects using journals to record hot flashes (Webster, 2007). As stated before, this method is ineffective given their ambiguous and subjective nature.

According to Dr. Jim Bindon from the University of Alabama:

"Originally, in the early 20th century, skin color was measured on a 34 tone scale. This was common practice until the 1950's, when the spectrometer was created. Currently, one of the most commonly used devices to measure skin color is a reflectance spectrometer. A reflectance spectrometer shines a specific wavelength of light onto the skin and then measures how much light is reflected back to the skin. Based on these results, the machine is then capable of producing a quantitative report on the skin's color" (Bindon, 2004).

## Current Devices

Presently, research studies are often conducted with monitors that involve electrodes attached to the chest. These electrodes then run wires down the chest to a device kept on the belt. The electrodes measure differences in voltages across the wearer's skin indicating a hot flash. A hot flash causes the skins sweat ducts to adjust which alters the difference in voltage across the skin (Webster, 2006).



An example of a current device on the market is the BIOLOG device, manufactured by UFI (UFI, 2007). While the device does well to monitor hot flashes, it presents several problems we plan to address with our device. First of all, it is too heavy (200 g) to be worn comfortably as well as too bulky (3.3 x 7 x 13 cm). The device also requires wires be run from electrodes to the device which also reduces comfort levels. Moreover the device only has a 24-hour battery life, which greatly restricts how well drug tests can be performed and also the length of those procedures. The BIOLOG system also is expensive; about $2,200 USD and the software needed for it is about $2,000 USD (UFI, 2007).

**http://www.ufiservingscience.com/HFMon1.html**

To the best of our client's and our knowledge, we will be the first to create a hot flash monitor based on changes in skin color (Webster, 2007).

## Design Constraints

Our design must follow a specific set of constraints detailed by our client, Professor Webster. First, the device must provide detailed readings of skin color change every 10 seconds to indicate a hot flash. The device must be FDA approved for humans with low voltage and no issues with heating the skin. The attachment of the device to the skin must also be non-irritant. It must demonstrate accurate readings of voltages that demonstrate an ability to detect a hot flash. The device must have sufficient power to last for an overnight reading, and must also have an on/off switch to preserve battery life. The device may be disposed once battery is dead due to targeted low cost (discussed later). It must also have a stored shelf life of at least 1 year in original packaging. The device is to be attached to the skin while the wearer is resting and may be removed for necessary daily activities. The maximum size of the monitor should be less than 1 x 6 x 6 cm (or 36 $cm^3$) and have only smooth edges to prevent skin irritation. The weight of the device must be less than 50 g. Specifications for size and weight were discussed by our team and client in order to have a device small enough to not affect the wearer's physical and aesthetic lifestyle. The device must be made of materials that are safe for human use and have a smooth, sleek appearance that is "user-friendly", and should be aesthetically pleasing. Finally, our target budget should be less than seven dollars per device, making it a viable disposable device. (A full product design specification is available **Appendix A**.)

## Design Alternatives

In generating different design possibilities, it is important to consider design requirements. After some preliminary research and brainstorming, the design process was initiated. Ideas were evaluated according to the customer specifications and the top three designs were selected: box & barrier, cave, and laser design. We will now discuss the three designs

### Design 1: Box & Barrier

*Overview*

The box design is the first and most basic design of our skin color monitor designs. Its purpose is to successfully monitor the change in skin color during hot flashes. Since our client, Professor John Webster, has some specific demands on the way the monitor should work, he provided us the basis of the design.  Perhaps the most important of his specifications is that the device should detect differences in the tone of a wearer's skin using light.  He also requested that the design weigh no more than 50 g and the light be as close to the skin as possible.  The design functions by shining light onto the skin and monitoring the differences in reflected wavelengths and intensities.  This more basic design is what our other more sophisticated designs were based on.

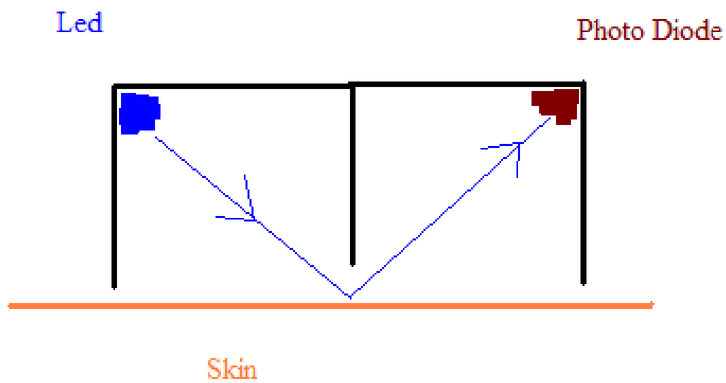



**FIGURE I: THE BOX DESIGN**

While picture is a poor indicator of the complexity of the design, it shows clearly how the design will function.  It detects the difference in skin color by shining a light from the led on the skin and absorbing the reflected light with a photodiode.  The resistance of the PD is dependent on the absorbed intensity.  This means that the color of the skin can be quantified in terms of voltage across the photodiode.  The above design may be the simplest of our designs, but it is the calibration and wiring that is required may be harder to implement compared to our other design ideas.

According to Kevin Elicieri of the University of Wisconsin—Madison blue light is the best color to use because it is the wavelength that is absorbed the least by the skin

(Elicieri, 2007). A report written by Elli Angelopoulou from the University of Pennsylvania, however, suggests otherwise. In that article, the studies suggest that red light spectrum reflects the best off skin (Angelopoulou, 1999). We plan to collect experimental data with differently colored LEDs in our prototypes which will provide the determining factor in deciding on which wavelength to use. Also, the more important property is the *change* in reflected intensity during hot flashes, not the intensity of one wavelength of light at one time.

Because of this importance, the distance and angle of light must be set carefully and kept constant at all times to produce accurate results. To make this easier, the design will be constructed of hard plastic. We will have to perform tests with the various conditions that a woman will experience to determine a way to keep the distance of the LED and PD (photodiode) from the skin from fluctuating. In the box design, the LED and PD are to be 2 mm away from the skin. We want the system to be as close to the skin as possible, allowing the PD to receive as intense readings as possible while also ensuring the system will not be in contact with the surface of the skin. 2 mm was chosen as a starting point because it allows ample room for skin deformation into the device; however, we plan to collect experimental data from future testing in order to get the optimal distance. The angle will also be such that the light is able to reflect off the skin and hit the PD with the greatest intensity, however experimental data will determine how precise the calibrations will need to be. The purpose of the barrier in this design and the opaque walls in all designs are to minimize the amount of light reflected off the walls of the device and other ambient light that may hit the PD, since extra light picked up, not reflected from the skin, would reduce the accuracy of the device.

The exact dimensions and power source of the design are still somewhat in speculation, but we currently estimate that the monitor will be 5 by 5 by 2.5 centimeters. Ideally, we would like to use the smallest battery possible to keep the weight of the monitor under 50 g.

*Advantages:*

The first benefit of our first device is its simplicity. Another advantage is its firm, sturdy shape. Depending on when the device is to be worn, it is important that the monitor stays intact and produces accurate results despite the wearer's movements. This could mean sustaining a bump from a co-worker or withstanding a significant amount of pressure if the woman should roll over on it in her sleep. The size and weight of the monitor are also advantageous aspects of the box design. It is important that the woman be able to function normally throughout the day and that she not be hindered by a bulky piece of equipment.

*Disadvantages:*

One of the advantages of the box design is also a disadvantage. While the rigid plastic will be durable, it will also be uncomfortable. For example, when pushed on, the barrier and edge of the device, even if designed smooth, may press into the wearer's skin and cause discomfort. Also, if users decide that the device will be more useful in detecting hot flashes during the day instead of only while the woman is sleeping, it is important that the device go unnoticed. Wearers will most likely be deterred from using a product that does not appear to be natural or that is not easy to conceal. Alternatives to harder plastic may also be easier to work with.

The source of light for this design may not be the most efficient option. In one of our later designs, a laser, for example, would be capable of focusing light in ways an LED could not. Because of the relationship between the dispersion of an LED's light and its distance from the skin, a small change in distance could cause a large change in the intensity of light picked up by the PD.

**Design 2: The Dome**

*Overview*

The dome design is similar to the box design. It is simply an improvement on the same principles on which the box design is based. While the outside design is not firmly set, once we build a working prototype, we will be able to modify the structure to make it more comfortable, less noticeable, and perhaps more appealing to the eye. After all, in today's world, customers and patients demand more than just results.

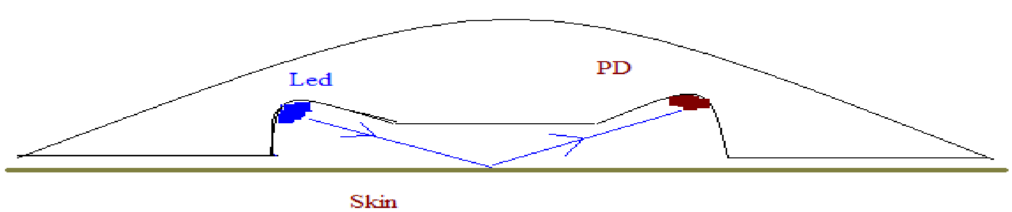



FIGURE 2: THE DOME DESIGN

The only differences between the above cave design and box design are the shape of the casing, the material from which it is constructed, and the way the barrier works. The dome design will be made of a softer material like rubber or some soft plastic. It will be just firm enough to avoid significant deformation while being subjected to realistic pressures.  Currently, we are thinking of using something simple like a large eraser for the prototype of this design.

Instead of having rigid edges in contact with the skin, the design will have a larger surface area to greatly reduce the pressure applied to the skin when the device is pushed on.  However, this means that the distance from the skin to the LED and PD may fluctuate.  To prevent light from going directly from the LED to the PD, we plan to carve "caves" for both into the case material instead of making a potentially uncomfortable barrier.

*Advantages:*

Like the box design, the dome design is cheap, lightweight, and small.  The difference is that, we believe, the dome could be designed to be less noticeable.  This makes it a much more appealing choice if the wearer is going to wear it in public. The most important difference that this device had over the box design is that it will be more comfortable, which is important in not causing additional stress to the wearer, especially if worn during sleep.

*Disadvantages:*

The only difference between the designs that is a disadvantage for the dome design is its softer material.  There is a possibility of the monitor flexing while being subjected to varying pressures and producing less accurate results.  The material from which the device is constructed, will determine how significant this flexing will be.

**Design 3: The Laser**

*Overview*

Both the box design and dome design involve some type of barrier between the light source and receiver to ensure the light detected is fully reflected from the skin. The barrier may cause discomfort to the patient, and it also takes extra time to fix the barrier into the case. To get rid of the barrier, a laser diode is used as the light source. Light emitted from laser diode is narrow and low-divergence, so light will be more focused and as a result, the signal received from the photodiode will mainly be the light reflected from the skin.

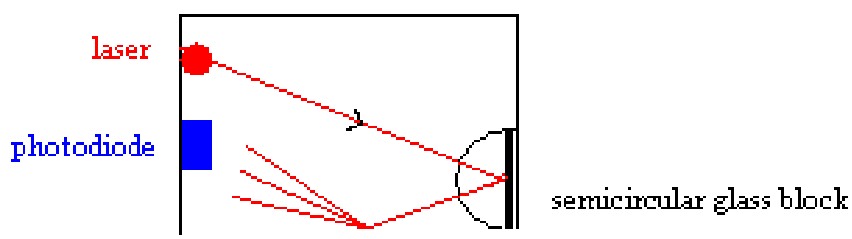



**FIGURE 3: THE LASER**

It may be easier to construct if all the electronic components are on the same side. To achieve this, a glass block is used to induce a total internal reflection of the laser emitted. The reflected light would then shine on the skin and back to the PD. A stiffer case would have to be used because if laser diode moves slightly out of place, it may affect the result.

*Advantages:*

The benefit of this design is that there is no barrier. This could decrease the manufacturing time and cost. Both the light source and receiver are on the same side. The firm, sturdy shape of the casing allows the device to take consistent measurements.

Since the light source is more focused, the intensity of light picked up by the photodiode will be higher.

*Disadvantages:*

Compared to regular LED's, the laser diode is more expensive (>USD 15) which exceeds our budget (DigiKey, 2007). Moreover, using a laser is potentially dangerous. Inappropriate use of the laser diode, such as accidentally shining into the eyes, could cause hazardous damage.

## Design Matrix

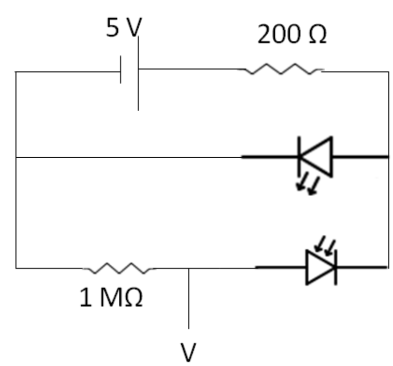
A design matrix was developed for the three unique designs to rate advantages and disadvantages based on several criteria: comfort, cost, light detection, safety, ease of construction, and durability. The criteria were weighted according to their importance. The ability of the pick up as much light as possible has the highest weight, as that is the main goal of our design. Cost comes next, as our budget is limited. Comfort and ease of construction are also put into high consideration.

| | Box | Dome | Laser |
|---|---|---|---|
| Comfort (0.15) | 6 | 9 | 6 |
| Cost (0.2) | 8 | 7 | 2 |
| Ease of construction (0.15) | 6 | 7 | 6 |
| Light Detection (0.25) | 5 | 7 | 6 |
| Safety (0.15) | 7 | 9 | 5 |
| Durability (0.1) | 8 | 7 | 6 |
| Total | 6.45 | 7.6 | 4.75 |

We believe the dome design will have better light detection ability than the box, since the light would be dispersed more broadly and give the greatest chance for detection in all possible conformations of the device. For the cost, the laser is the most expensive one while others can be made in a reasonable price. The laser is also potentially more dangerous compared to the LED's.  The dome design is the most comfort one as it will be made of soft rubber, in contrast to the harder, firmer cases of the other two designs. It is also the most feasible to construct as we used a large eraser as the soft case material early on.

## Circuitry

Our team decided to separate the design process of this part of the device since the circuitry can be applied to whichever device design we choose.  The circuitry used in our device is based on the properties of a photodiode.  When light is absent, the photodiode acts as a barrier, or an open circuit, preventing any current through it.  When light is present, photons will strike the diode creating a charged electron hole and producing a current across the device (Wikipedia, 2007).




Base design:  Light shined from the LED is absorbed by the PD, resulting in a change of output voltage, which is amplified by the op amp.

The goal of the device is to have the LED shine light onto the skin, which is then reflected back at the PD.  When the PD absorbs the light, current leakage will occur and a change in output voltage will be detected.  Possible use of op amps also provide a multitude of ways to fine-tune the circuitry such as changing linearity, offset, noise, and bandwidth, but most importantly amplify the change in output (Texas Instruments, 1995). The changes in output will then be recorded by the device for later analysis.

## Earlier Tests

*1st Prototype: Large Pink Eraser*

Our first prototype we designed was created out of a standard plastic eraser. We chose to make our prototype out of the soft material because it would offer greater comfort than a hard plastic design would. Using a razor blade, we hollowed out a reading area and two caves for the LED and phototransistor as detailed in our earlier cave design. We secured the components in place in the eraser using tape. Upon finishing the circuit and hooking up our device to a multimeter and power supply, we began to test the device. We realized very early on that this prototype would not be sufficient. The readings we got off the pink eraser were very scattershot. The readings were very unstable and fluctuated greatly even when it was not being touched. It was obvious this design would be inadequate to accomplish our task.

*2nd Prototype: Large Flexible Plastic*

Our second design was similar to the first but aimed to fix some of the issues with our first device. First of all, we colored the white plastic black so that all the light from the LED was either reflected back to the phototransistor or absorbed into the black color. Secondly, we attached the LED and phototransistor using hot glue in attempt to keep them better secured and stop the extreme fluctuations in readings. Lastly, we covered the top of the device where the wires exit with electrical tape to block out any ambient light that might leak in through the holes. Again we tested our device on various colors of construction paper. Upon testing, we discovered that second prototype could not only distinguish differences in color, but also remained relatively stable in its readings, unlike the somewhat random fluctuations that our previous attempt had been plagued with. Below are some of our results from our initial test of the second prototype.

| Surface | Large White Plastic Eraser |
|---|---|
| White Paper | 1.51 |
| Blue Plastic | 0.43 |
| Orange Plastic | 0.20 |
| Grey Counter | 0.41 |
| Black Pad | 0.11 |
| Skin | 0.17 |

After testing the device on construction paper, we decided it was time to attempt an actual human test to see if our prototype could detect a hot flash. Brian volunteered for the test, and we decided that the easiest place to detect flushed skin would be the face, so we placed the device on Brian's cheek and took a reading. The initial reading of Brian's face was around .22 V. Afterwards, we had Brian put a sweatshirt on and run for around 5-10 minutes up and down the stairs of the ECB building, in order to get flushed, thus simulating a hot flash. Upon returning, Brian's face was noticeably red and we quickly hooked up the prototype and found that the new reading was around .4 V, indicating some change in color. However, upon further investigation, we realized that the output from the multimeter varied greatly depending on how firmly the device was held to the skin. This problem did not present itself during our testing of construction paper because no pressure was needed to hold the device in place. While held against the skin, even miniscule variations in pressure would cause the readings to fluctuate. This ultimately rendered the design useless.

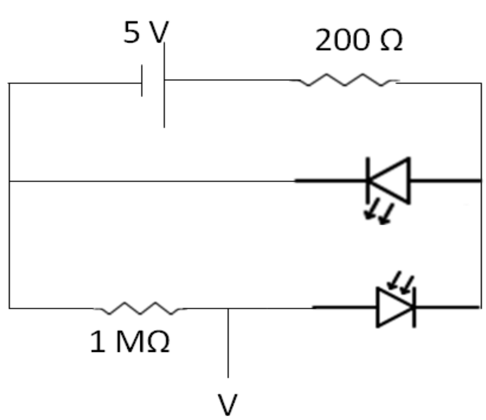
*3rd Prototype: Small Black Plastic*

Our third design was again very similar to our other prototypes. The internal structure of the device was identical to the rest, with several other noticeable improvements. First, the entire device was miniaturized. We did this in an attempt to keep the case from flexing too much during readings. By making the case as small as possible we hoped that it would stay semi-rigid against the skin. We also wanted to miniaturize the structure to make as concealable as possible for the wearer. Another improvement we made to this prototype was that we painted the entire casing black. We hoped that by doing this we would minimize interference and ensure that all the light reflected to the phototransistor came from the skin. Once again, we began testing our device on various colors of construction paper. Our results were very similar to those that we had obtained with the white plastic casing. However, when placed on the skin, the device also failed to gather a stable reading, much like the previous prototypes. This prototype was still too susceptible to differences in pressure. At this point, we decided we must reevaluate our choice of casing materials and sacrifice some comfort in order to try something more rigid.

## Final Design

After testing with the previous casing designs, it is safe to say that reliable results can be produced on hard, flat surfaces, but with soft, deformable surfaces like skin, improvement is much needed. The polycarbonate and acrylic materials provide superior casings for a number of reasons. It is rigid enough so that the LED and phototransistor can be immobilized; keeping the angle of emitted light and the distance from the surface constant. The materials are lightweight (acrylic = 1150 $kg/m^3$, polycarbonate = 1200 kg/m$^3$) and easy to work with. The device casing was easily fabricated using a drill press and various drill bits. Also, glue binds well to the surface so that the LED and the phototransistor can be held securely in place. The final design is composed of a blue LED and a phototransistor placed in a rigid black polycarbonate case, with a transparent acrylic shield glued at the bottom.

The circular polycarbonate had a diameter of 3.8 cm, with a height of 1.4 cm. The dimension for acrylic shield was 4.7 cm x 5.0 cm. Holes are drilled in the case as shown in the figure below, to place the LED and phototransistor, so no light is directly shined on the phototransistor.




*Clockwise from top left:*
interior cross-sectional view from side; device size comparison to quarter and computer mouse; device circuitry.

The above was the circuit used for the entire test. The 200Ω resistor was used to control the voltage across the LED not to exceed 4.0 V, which was the maximum forward voltage for the LED (Lumitex Inc., 2003). Initially, the phototransistor is reverse biased but when it detected light, there would be some leakage current which then passed through the 1 MΩ resistor. Since the current was small, a resistor with a large resistance was chosen to maximize the voltage measured across the resistor. This circuit could be improved by putting the 200 Ω resistor in series with the LED instead of the position as shown in the figure. This would allow the same voltage (4.0 V) applied across the LED, but now the initial voltage at the phototransistor is 5 V instead of 3.5 V. This would increase the leakage current and thus, a larger reading of the voltage measured.

The case is in black as to absorb the light that shines on the case, so any signal that the phototransistor picked up is due to the reflection from the skin. A rigid case is used to prevent the movement of the LED and phototransistor due to external forces. As a slight change in position due to moving of the phototransistor will affect the amount of light it detected, a non-deformable case is desired. Previous tests with a soft eraser case had shown fluctuation in readings when small amount of pressure is applied to the case while the device is put on a rigid surface. This suggested that the fluctuation may not due to the deformation of the surface, but due to the deformation of the device itself and the reorientation of the LED and phototransistor. So a rigid polycarbonate case was used. Polycarbonate had a compressive strength of 12000 psi and a tensile strength of 10000 psi (polyweb.com, 2005).So it cannot be easily deformed or compressed. Testing showed that the reading is constant despite the varying pressures applied to the device –

supporting our previous hypothesis that the fluctuations in voltage is mainly due to the unstable position of the LED and phototransistor.

After getting a constant reading on a rigid surface, testing on different colored surfaces was done to observe the difference in readings between them. We faced a choice between using a red LED or a blue LED, as previous paper had shown that the wavelength of light which reflected the best off skin was in the region of red light (Angelopoulou, 1999), but the use of blue light was suggested by our client and another professional (Kevin Elicieri of the University of Wisconsin—Madison) As this will be discussed later in the testing section, we chose the blue LED because it showed a greater difference in the red color range, which is the most relevant to skin color during hot flash. Moreover, in theory, white paper reflects the most and should have the highest readings among each LED test, and black paper should have the lowest reading. From what we found in the readings for red LED, the highest reading is not at white but at the yellow paper. This uncertainty also had a factor in our choice of using the blue LED.

The phototransistor we used for entire test was a 900 nm clear lens phototransistor (Digikey serial: 425-1005-1-ND, 2007). It was chosen because compared to the other one we got, which was a 910 nm black lens phototransistor (Digikey serial: 425-1006-1-ND, 2007), it detected light closer to the visible region.

When testing was done with rigid case on the skin, the output voltage still varied when force was acting on the case. Since the case was obviously not deforming, this suggests the variance in curvature of the skin caused by the pressure results in different amounts of light reflected back to the phototransistor, consequently the reading is not constant. Our first solution to this problem was to increase the surface area of the case that would be touching the skin. An increase in surface area means less pressure with the same given external force, so the patient may feel less pressure at the attachment site. In addition, the greater contact area helps flatten and stabilize the skin; as a result the deformation will be greatly decreased. We chose to use the polycarbonate as the case for our prototype because it had a larger area.

Another modification to decrease skin movement was adding a flat thin transparent acrylic plate at the bottom of the device. The acrylic is rigid, with a compression strength of 11500 psi (polyweb.com, 2007). With this acrylic shield, the light is always reflected from the horizontal acrylic surface. When force is applied to this device while placed on the skin, the reading is constant because the skin is always pressed flat by that acrylic plate. Since the acrylic plate is transparent, the blue light from the LED can still reach the skin and reflect differently according to different color. Even though there is a lot of specular reflection which contributes to the final voltage reading, our tests showed that the amount of light that is reflected by the acrylic is more or less the same at different colors. So we can conclude that the final reading is composed of two reflections: reflection due to skin color and specular reflection off of the acrylic plate, in which the latter was determined to be constant. So when different voltage readings are observed, it can be said the difference is mainly due to the change of skin color.

*Cost:*

As our client would like the cost to be as low as possible (upper limit of $7), material chosen in our design were relatively cheap and popular. The one-foot black polycarbonate rod we got cost $18.39, so the cost for manufacturing one polycarbonate case is almost one dollar. The two resistors each cost 10 cents each, and the phototransistor was 30 cents. The most expensive part is the blue LED which priced $1.62. So the total cost for producing one prototype was $3.12, which was even lower than 50% of the cost upper limit.

| **Material** | **Cost** |
| --- | --- |
| **Polycarbonate** | $1.00 |
| **Blue LED** | $1.62 |
| **Resistor x 2, circuits** | $0.20 |
| **Phototransistor** | $0.30 |
| **Total** | $3.12 |

## Final Design Testing

*Final Prototype: Polycarbonate*

In order for the numbers produced in testing to be viable, a control is needed. Each time a test was conducted, a reading was taken on the grey countertop in the student lab. If it was .060V +/- .001V, the monitor was working properly. Testing with the black, polycarbonate casing was done on a number of different colors of paper and surfaces. The results ranged from .125V on white paper to .016V on black tape (Table 1; see **Appendix B** for full table of testing data). Since the numerical difference is not particularly large, it is necessary that the device be precise. Nearly all surfaces, when retested, produced numbers within .002V of the original value. This shows that the margin of error is close to +/- .001V, which was proved acceptable with the exercise test, which is discussed in further detail later (Graph 2).

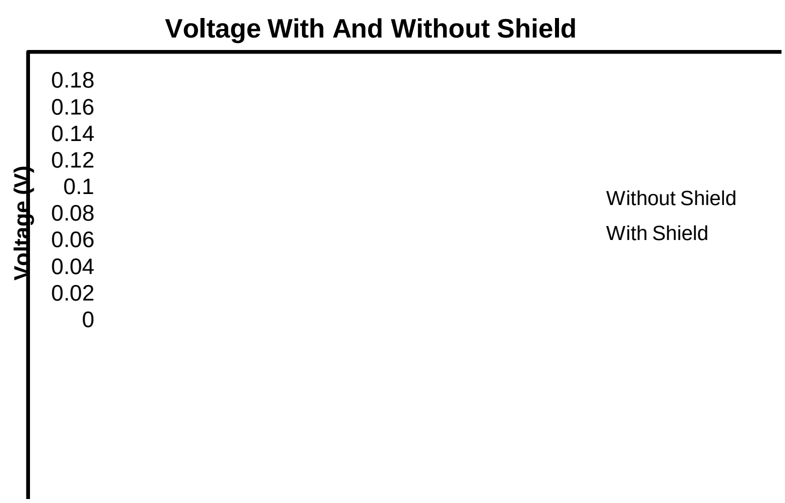
| **Table 1** Surface | Polycarbonate, Blue Led, no screen |
|---|---|
| White Paper | 0.125 |
| Teal Paper | 0.066 |
| Blue Paper | 0.103 |
| Lt. Blue Paper | 0.101 |
| Green Paper | 0.034 |
| Lt. Green Paper | 0.071 |
| Orange Paper | 0.074 |
| Orange/Yellow | 0.018 |
| Yellow Paper | 0.08 |
| Tan Paper | 0.058 |
| Red Paper | 0.026 |
| Hot Pink Paper | 0.107 |
| Lt. Pink Paper | 0.095 |
| Grey Counter | 0.06 |
| Black Tape | 0.016 |
| Patrick's Skin | 0.026 |
| Jack's Skin | 0.018 |

The ability to keep the distance from the monitored surface constant is an improvement from the rubber monitor, but testing proved that the voltage across the phototransistor varied significantly when used on skin. For example: When a small amount of pressure was applied to the monitor during detection, the voltage was .026. Letting the monitor simply rest on the skin resulted in a reading of ~.020V and pressing hard on the monitor caused the voltage to drop to a near negligible value. This is because a small amount of pressure seals the parts on the monitor that make contact with the skin so that no ambient light can get in. Once this is done, increasing pressure causes the skin to bow up in the region within the monitor so that both the angle of reflection and the distance from the phototransistor change. It was concluded that while the design is accurate for hard, flat surfaces, it is useless for the monitoring of skin color. A method to keep the skin flat was needed to solve this problem.

A simple piece of clear, acrylic plastic was used as a shield in the monitor described above. This plastic greatly reduced the change in voltage across the phototransistor with respect to applied pressure. A small change (about .005V) occurred when an unrealistically large amount of pressure is applied (~80 lbs). This is likely due to the fact that skin temporarily changes color when pressed hard enough.

The shield solves all problems that the casing without the shield posed but created a potential new problem: specular reflection. Tests were needed to conclude that reflection of light directly off of the plastic instead of the skin would not affect the accuracy of the readings. A number of readings were taken on the same surfaces that the monitor without the shield was tested on (Graph 1, also see **Appendix B**).

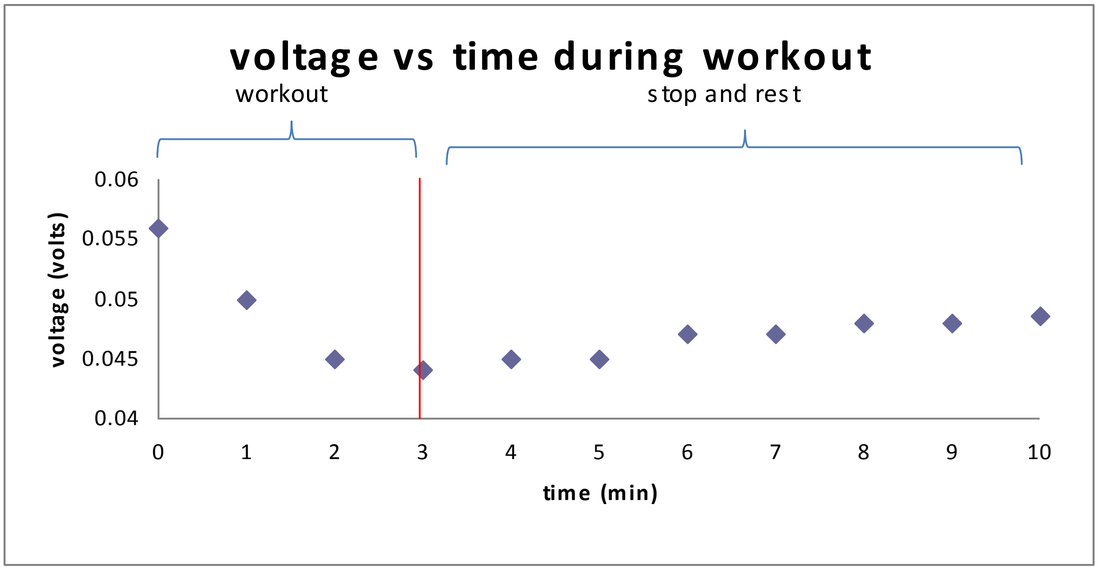
**Graph 1**




As depicted in the above graph, the addition of the shield caused a relatively constant change in the voltage output. This means that the changes in voltage from one shade to another should be the same with the shield as they are without the shield. The change in voltage was between .020 and .030 volts for all surfaces. The reason that the voltages are higher by about the same amount is because the amount of light reflecting off the plastic back into the photodiode is independent of the surface being tested. It can also be said that the higher reading for Patrick's skin when compared to Jack's skin is because Patrick's skin is lighter and not because there is a difference in pressure. The margin of error has been greatly reduced.

The final test was the most important. It doesn't matter how accurate the skin color monitor is if it can't detect the difference between flush skin and normal skin. Since having a hot flash is similar to the kind of reaction one gets when exercising, a test with Patrick on an exercise bike was used. The monitor was securely taped to his upper chest area, which is the probable region that will be monitored in potential patients. The test was done in real time with readings taken every minute for ten minutes (Graph 2). The main reason that the test was done in real time is that the progression of how the device behaves during the hot flash simulation can be easily seen.

**Graph 2**

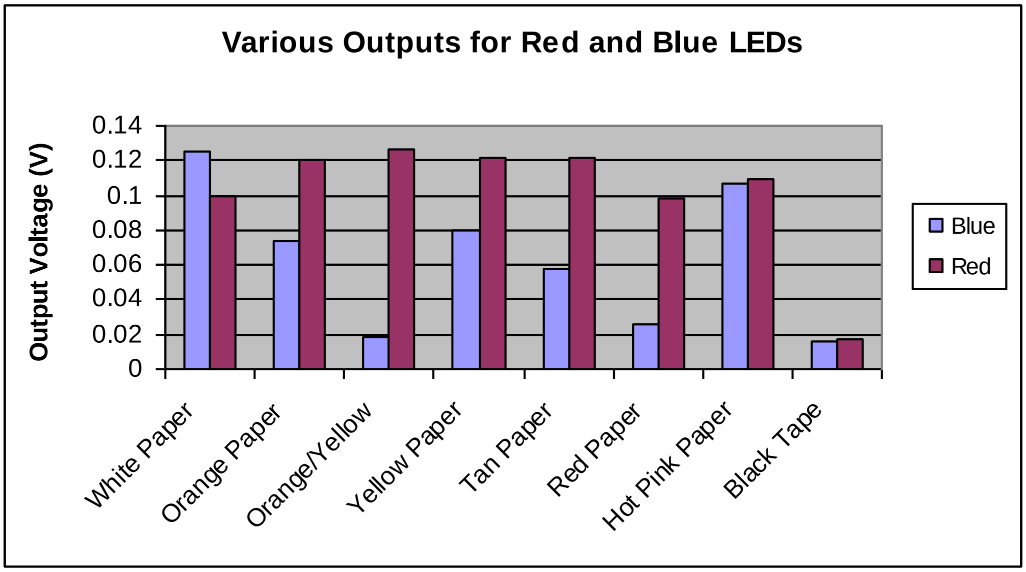



From the test it was concluded that the monitor can detect changes in skin tone due to flushing. The voltage dropped significantly during the workout period, which is expected because redder, darker skin absorbs more wavelengths of light than lighter skin does. If the test was carried out for longer, extrapolation of the graph's slope suggests that the voltage would return back to its original value. The reason that the increase of voltage during recovery happened at a slower rate than the voltage drop during workout is that Patrick's body was still trying to cool itself off some minutes after the workout phase (Gleeson, 2007). He even said he felt "uncomfortably warm" in the eighth minute of the test. His body kept blood near the surface of his skin for longer to reduce his core temperature back to a comfortable level. The monitor only needs to be accurate enough to show a difference between flush skin and normal skin. The experiment showed that the design is capable of doing just that.

Although Kevin Eliceiri suggested blue for the color of the monitor, testing was also done with a red LED without a shield

Angelopoulou's article on human skin reflectance had suggested that red light reflects better off skin (Angelopoulou, 1999). The monitor casing consisted of an acrylic cube painted black. Acrylic cube was used due to its size, which could house the larger red LED. Acrylic has very similar material properties to polycarbonate (polyweb.com, 2005), so this change in casing material would not have affected the device's capabilities nearly as much as change in LED color. For comparison, many of the same surfaces that were used for the polycarbonate monitor (blue LED) were used for the acrylic monitor. If the red LED is indeed a better choice, the voltage differences between colors would be greater than with the blue LED.  The results of the experiment suggested the opposite (Graph 3, also see **Appendix B**).

**Graph 3**




It was concluded that blue is the better choice for the LED color because small differences were found between the voltage outputs for different colors with the red LED. For example: As shown in Figure 3, little difference in the voltage output was found between any two colors that didn't include black.  The difference between the output for red and white surfaces was also smaller than with the blue LED.  This is not desirable for the monitor because when skin becomes flush, it is redder and less white than when it isn't flushed.  The purpose of the monitor is to produce noticeable results with change in skin tone and a monitor that features a red LED was proven to be less capable than one with a blue LED.

## Conclusions

From the earliest testing to the most recent, we found that the biggest concern in designing the color monitoring device was the ability to keep the orientation of the LED and phototransistor constant as well as keeping the testing area constant.  While the device shows accuracy in differentiating between colors, the range in output voltage is less than 200 mV, meaning that slight fluctuations in voltage, due to instability, can have an adverse effect on the devices accuracy. It was decided that a rigid casing is appropriate, despite having to sacrifice some of the wearer's comfort.

From what our team has observed during testing, our prototypes have been able to discern between a range of different colors, giving unique voltage ranges for different shades and colors.  For instance, darker colors, such as black, red, and general skin tones all fall between the range of 15-30 mV, while lighter colors such as white, pink, and yellow all fall between 80-125 mV, with white being extremely high due to its reflection of all wavelengths.  When the exercise test was performed in order to simulate a hot flash, we see an expected drop in voltage due to the rapid reddening of the skin during workout and this change in voltage is reversible upon recovery.  In fact, one can observe that the slower more gradual increase of voltage is due to the natural slower recovery time of the wearer, which was expected (Gleeson, 2007). Continued testing needs to be done to achieve standards of deviations in order to analyze the accuracy of the device and determine the allowable tolerances for error.

As mentioned earlier, the decision to use the blue over the red LED in our final prototype was decided after testing showed that the blue LED gave the best readings in showing color change.  While Angelopoulou's article states that the wavelength best reflected by skin is in the red spectrum (Angelopoulou, 1999), the reflection of blue light gives better discrimination between different colors.  The voltage levels attained with the red LED are in fact relatively higher, which supports Angelopoulou's findings that skin reflects red light the most, however because it reflects it so well, the differences between skin tones are harder to distinguish.

Along with having a rigid casing to ensure stability of the electronic elements, a method of stabilizing the skin was also devised. The use of the plastic shield to immobilize the skin, keeping it at a constant distance during testing, was shown to be essential. A slight concern that arises when using the clear shield is the specular reflection that occurs when the light reflects off the shield without ever being partially absorbed by the skin. However, the testing results show that the increase of output voltage is relatively constant at about 25 mV. This is expected, since the shield is secured onto the casing. The specular reflection will not change as long as the LED's properties and angle at which the light is shined does not change, meaning that the accuracy of our device will not change due to specular reflection.

## Future Work

Now that we have a working prototype, the method of attachment is something that will need to be decided. Current ideas for attachment include adhesive pads on the device or adhesive strips much like what one would see with bandages. We believe that the final size and shape of the device will have a lot to do with attachment; however, we believe that the device can be made small enough where it can be wore like a large bandage, while still keeping to the design size specifications of less than 3 cm x 4 cm x .5 cm.

Due to limited time, we were not able to do as many tests as we would have liked. More tests will need to be run to determine the standard deviations of the device. We would like to use programs such as LabVIEW in the future when performing our tests, to better record and analyze our data. Another thing we'd like to do is test the device on different ethnicities to ensure that the device will work over a range of different resting skin tones. While the device is targeted for menopausal women (age 45 – 55), we'd also like to test the device on different age groups to see if there is any discrepancy. In order to run these studies, subjects from outside the team will be needed and we may need to go through HIPAA rules and regulations on human subject testing.

Continued research and development will also lead to optimization the device. A more efficient circuit may be found by fine-tuning the circuitry with different resistors, LEDs, phototransistors, etc. which may perform better under our desired conditions. Currently our phototransistor's optimal range is 900 nm, while red light (highest visible wavelength) is between 620-750 nm. Different combinations of op amps could also increase the efficiency of the device via noise reduction and voltage amplification as stated in the circuitry section.

As the device is meant to be of miniature size and worn on the wearer's body, we plan to eliminate the breadboard by having a printed circuit chip made for our device so that it can also be housed in the casing. We'd also like to have a chip that will record the data and from which we can download data after each use and connect a small watch battery to the device as its power source. Once we've achieved those goals, we will no longer need to hook the device up to a power supply and voltmeter in order to run it. Ultimately we'd also like to employ an on/off switch so that power can be saved and extend service life.

We had chosen the polycarbonate as our final design; however, now that the plastic shield will be implemented, having a large contact area in order to reduce the deformation of skin will not be needed, since the shield will keep the skin flat. This means that we can make the device much smaller, since we only need to make it large enough to fit the LED and phototransistor. Furthermore, the outside of the device can be smoothed down to allow more comfort to the wearer. Future designs may be completely made out of acrylic as it is less dense than polycarbonate (1150 $kg/m^3$ vs. 1200 $kg/m^3$), while also having similar compressive strength (~11750 psi) (polymerweb.com, 2005).

We may also choose to redesign the device in order to eliminate the specular reflection given off by the acrylic shield. Our client suggested placing the phototransistor and LED both on one side of the device and have the LED shine light away from the two components, this way all the specular reflection would reflect off the shield and into the black walls of the casing where it would be absorbed. The light not specularly reflected will still reflect off of the skin in all directions. In this suggested design, the phototransistor will only pick up the light reflected off the skin. While this design may eliminate specular reflection, testing will be needed to determine the effectiveness of this design, as the intensity of light picked up by the phototransistor will be greatly reduced, since there will only be a small fraction of light that is reflected back to the phototransistor.

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## Appendix A

**Product Design Specification**

**Client Requirements:**

- Miniature size & weight.
- Record color changes at least every 10 s**.**
- Low cost.

**Design Requirements**

**1. Physical and Operational Characteristics**

a. *Performance requirements*: Must record changes in skin color every 10 s by displaying voltage changes proportional to the amount of light detected by photodiode.

b. *Safety*: Must be FDA approved for humans. Small voltage and low duty cycle that powers the LED and photodiode will be safe for continual use without overheating the skin. Method of attachment must not irritate skin.

c. *Accuracy and Reliability*: Must output varying voltage levels corresponding to amount of light reflected from the skin at least at an interval of 10 s. Changes will be measured to study skin color changes.

d. *Life in Service*: Must last for the minimum duration of an overnight recording and retrieval of data. There will be an On/off switch to preserve power when recording is not needed. Will be disposed of after multiple uses.

e. *Shelf Life*: Must have a shelf life of at least one year when stored in original packaging.

f. *Operating Environment*: Will be attached to wearer's chest while he/she is at home and/or asleep. May be taken off during daily activities such as during shower to prevent damage to device. When unattached, the device will be stored away from outside exposure.

g. *Ergonomics*: Will be fabricated with no sharp edges in order to prevent irritation or injury to the wearer. On/off button will be contoured with the smooth casing of the device.

h. *Size*: Maximum size of 6 cm x 6 cm x 1cm including device and all possible attachments. "Device only" size goal of 3 cm x 4 cm x .5 cm

i. *Weight*: Must be lighter than 50 g.

j. *Materials*: Fabricated with no materials that irritate or otherwise harm human skin. Must be soft and smooth to prevent discomfort while attached to wearer.

k. *Aesthetics, Appearance, and Finish*: The texture and finish should be small, sleek, comfortable, and smooth for optimal comfort and minimal notice. LED within the device will also act as an “on” signal.

**2. Production Characteristics**

a. *Quantity*: Working prototype. Likely to be mass produced, determined based on demand, in future if prototype meets all desired specifications.

b. *Target Product Cost*: < $7 USD

**3. Miscellaneous**

a. *Standards and Specifications*: FDA approved for normal human use.

b. *Customer*: Women aged 45 to 55 will be the primary wearers. The device will be small and concealable. It should be as unobtrusive and comfortable as possible, especially since it will be worn continuously. Women are more apt to wear tight fitting clothing as well so the device should not be noticeable given reasonable attire.

c. *Patient Related Concerns*: The device should have no issues with sterilization, as it will be external and disposed of as desired. The data collected must be stored confidentially, both for the patient’s rights and to preserve the objectivity of the study.

d. *Competition*: A device shown to us by our client Professor Webster used two electrodes to sense changes in skin resistance. The advantage to our device is the measure of color change is less obtrusive than attaching electrodes directly to the skin. All other monitoring devices found were large and obtrusive.

## Appendix B

### Complete table of final design's recorded data

| Surface | Blue Led, no screen, Polycarbonate* | w/Clear Shield* | Red Led, no screen, Acrylic Cube* |
|---|---|---|---|
| White Paper | 0.125 | 0.161 | 0.1 |
| Teal Paper | 0.066 | | 0.025 |
| Blue Paper | 0.103 | | |
| Lt. Blue Paper | 0.101 | | |
| Green Paper | 0.034 | | |
| Lt. Green Paper | 0.071 | | |
| Orange Paper | 0.074 | | 0.12 |
| Orange/Yellow | 0.018 | 0.043 | 0.126 |
| Yellow Paper | 0.08 | | 0.122 |
| Tan Paper | 0.058 | | 0.121 |
| Red Paper | 0.026 | | 0.098 |
| Hot Pink Paper | 0.107 | | 0.109 |
| Lt. Pink Paper | 0.095 | | |
| Grey Counter | 0.06 | | 0.042 |
| Black Tape | 0.016 | 0.045 | 0.017 |
| Patrick's Skin | 0.026 | 0.056 | |
| Jack's Skin | 0.018 | 0.044 | |

*Fluctuation < ~2 mV