Use of Photometry to Determine Tissue Density and Perfusion

Steven Asplund, Trevor Fowler, Victor Tseng

Introduction

Means of separating a subject from powered circuits for the patient's protection were discussed and examined. One of the simplest ways to separate a patient from a powered detector is through the use of light emitters and photodetectors, either visible or in the IR spectrum.

Photocells are P-N type semiconductors characterized by decreasing resistance when under illumination. They are made from several materials, ranging from cheap Cadmium Sulfide (in cameras) to Gallium Arsenide, which has a small bandgap (1.424 eV at 300K), allowing even low energy photons, such as in IR radiation, to excite electrons into the conduction band. Generally, the resistance of these devices varies as an inverse power function with light intensity:

$$R(I) = \frac{k}{I^m}$$

where R is the resistance, I is the intensity, and constants k and m are determined by the nature of the conductive material, and the geometry of the electrode. Following the general form for resistance of a wire:

$$R(I) = \rho(I)\frac{w}{l}$$

where ρ is the resistivity of the material as a function of intensity, w is the spacing between the electrode tracks, and l is the length of the electrode track.

Photocells have maximum conductance at certain wavelengths. Thus, there are specialized cells for visible light (photoconductors) and IR (phototransistors). In the first part of this paper, we will compare the transient and steady state behaviors of visible light conductors and infrared transistors. We use a Voltage-Controlled Current Source (VCCS) circuit to supply current to the LEDs, and a voltage follower to relay the signal from the photoconductor or phototransistor without voltage division due to loading.

In designing a sensory system based on photometry there are several factors which must be taken into account. First, a decision must be made as to the desired type of measurement to take. Then there is the type of light emitting device to use, the circuits and any filters built into the device, placement of the emitter and receiver and any mechanical design issues that need to be addressed.

In this paper, two different types of measurements were assessed: trans-illumination or epi-illumination. In the first option, trans-illumination, the material to be measured, in this case human skin and tissue, separates the detector and the emitter so that the light waves must pass through the material. Any changes in the material can then be measured as the intensity of the light changes due to the changing absorptive properties of the material. Of course absorption is not the only effect that causes the degradation of the signal, scattering due to interactions at the surface also play an effect, but to a lesser degree for trans-illumination. A clinical application of this is found in the concept of pulse-oximetry which is used in measuring blood oxygen levels.

The second type of measurement is epi-illumination which demands that no light be transmitted directly from the emitter to the detector. Instead, epi-illumination relies on scattered light from the transmitter reaching the detector through diffraction and reflection of the light source off of the material. This arrangement is useful for determining surface maps of tissue such as the hand and finger where there is a wide variation in the skin, tissue and bone structures.

The next major component of any photometry system is the type of emitter used in the system. In this laboratory both the effectiveness of the LED and IR sources are compared. Along with the type of light source to be used the decision to use filters, other noise-reducing, or signal amplifying circuit components must be made. Much of this report will detail the technical challenges behind designing an effective photometry system, their solutions or work-a-rounds and the final measurements taken with the system.

Methods

Comparison of Phototransistor to Photoconductor

The main purpose of Section A was to determine the effectiveness of the phototransistor and the photoconductor as detectors for IR and LED emitters, respectively. The emitter was powered by a voltage controlled current source (VCCS) and the detector by a voltage following op-amp circuit.

In both cases the emitter was placed so that maximum transmission would occur when the VCCS was driven by a periodic square wave function. Starting at low frequencies and then moving up to frequencies where the output of the detector did not reach a steady-state condition, the response time of the transient was observed and recorded. For both cases initial results indicated that the effect of the ambient lighting was detrimental to the response of the system. Only by covering the entire circuit with a large plastic ice bucket could we “shield” the system and observe a clear signal on the oscilloscope.

The VCCS circuit is shown in Figure 1. The green LED was used in trans illumination with a VT935G photoconductor, and the IR LED was used in trans illumination with a QSC112QT phototransistor. We used R1= 120kΩ , R2=100k, RE=100Ω. Please see the derivation for the current our of the VCCS in Appendix A.

The main purpose of Section A was to determine the effectiveness of the phototransistor and the photoconductor as detectors for IR and LED emitters, respectively. The emitter was powered by a voltage controlled current source (VCCS) and the detector by a voltage following op-amp circuit.

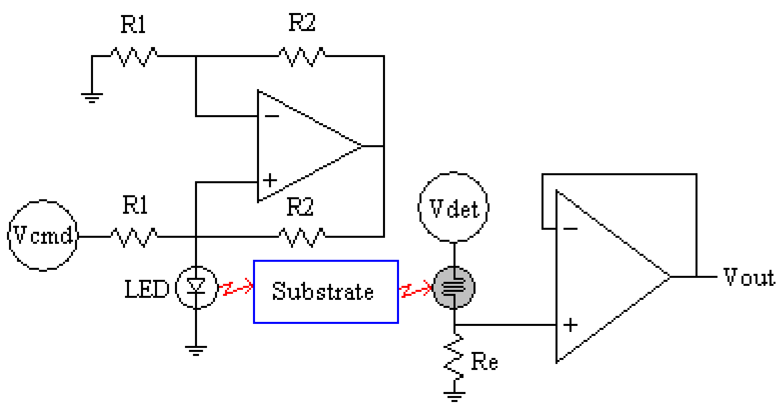
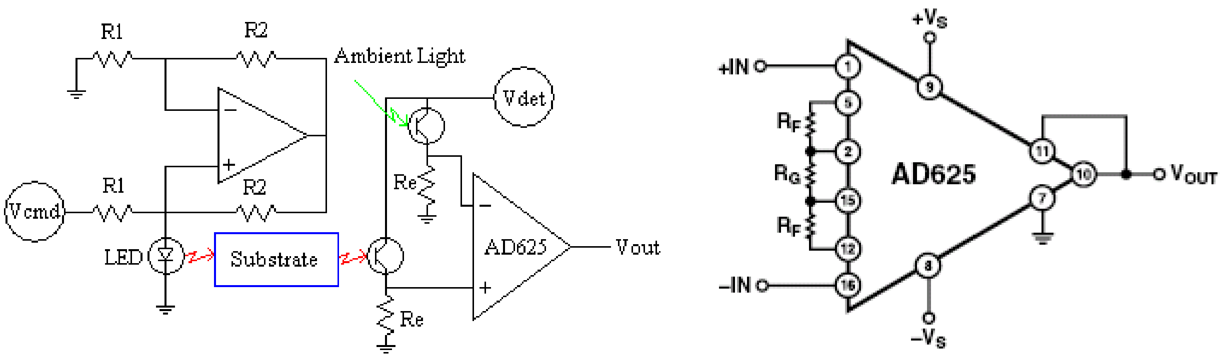


Figure 1 Schematic of voltage controlled current source (left) which powers the emitter (LED) and a simple detector circuit composed of a detector device (photoresistor in above schematic) and a voltage follower amplifier.

Absorbance/ Scattering and Photometry System Design and Testing

Initially, we elected to pursue a more technically challenging photometry system then the one suggested in the Lab 6b handout.



(a) **(b)**

Figure 2(a) modification of circuit shown in Figure 1 consisting of an alternative detector circuit which uses a instrumentation amplifier to cancel ambient light.

(b) Wiring diagram for the AD625 instrumentation amplifier modified from the AD625 spec. sheet

Unfortunately, the designed system did not perform as expected for either the epi-illumination or trans-illumination. For more detail on the problems and sources of error, please see the Discussion and Results section of this lab report.

With the failure of the first system, we constructed a second system based on the design of the emitter/ detector circuits in Section A. This schematic for the revised circuit is shown in Figure 1. After constructing the circuits and testing that the behavior of the photometry system was as expected, we calibrated the system. In our initial design, we choose to use an IR emitter and a phototransistor detector; for the second design we chose to use a green LED and photoconductor as our emitter and detector. Furthermore, we elected not to follow the standard single-channel photometry procedure given in the lab handout, instead choosing a more intuitive protocol. First we placed the emitter and detector facing each other so that maximum transmission would occur.

We then wrapped both in black electrical tape to control for ambient light sources. Increasing the driving voltage from zero to 5.5 V peak-to-peak and taking calibration readings with every 0.5 V increase we derived a calibration cure to use in the data analysis.
After calibration, we tested the photometry system on human tissue to determine if our design was capable of performing as expected. To keep the emitter and detector in the same spatial relationship a special sensory-holding device was constructed. Please see Sensor Arrangement Design, this section for more details.

For the final testing, we choose to use epi-illumination. Please see results and discussion for more details on this design choice. Two scattering maps were made using the photometric system. The first was a scattering map constructed of a subject's right index finger at three different points. The other scattering map showed differentiations on a subject's right palm.

Results and Discussion

Discussion of Emitter/Detector Characteristics

When the circuit was unshielded, the output signal to noise ratio was very low. We shielded the circuit by covering in dark. When we drove visible LED circuit with a 1 Hz square wave at 4V P-P, the voltage at the output jumped up instantaneously and at the same time as the "on" step of the input. However, at the "off" step of the input, the output resembled the discharging of a capacitor. We measured a $t_{1/2} = 60\,\text{ms}$, which was the time required for the output voltage to decay to half of the maximum value. When we increased the frequency of the square wave to 5 Hz, we observed the same behavior. This was the case until we increased the frequency far above 10 Hz. For high frequencies, the photoconductor became saturated. In other words, the resistance of the photoconductor was not allowed to increase again, thereby causing a nearly DC stream voltage to flow through. Based on our $t_{1/2}$, the "off" phase of the photoconductor can be modeled as:

$$V = V_{\max}\left(\frac{1}{2}\right)^{\frac{t}{0.06}}$$

Therefore at a period T, the voltage after the input "kicks back in" (at $T/2$) is:

$$V(T) = V_{\max}\left(\frac{1}{2}\right)^{\frac{T/2}{0.06}}$$

As the period becomes smaller and smaller, the voltage at the end of the period becomes closer to the maximum voltage.

The current supplying our LED is:

$$\frac{V_{cmd}}{\sqrt{2}R_1} = 0.024mA$$

Green LEDs emit light at 3.2×10^{-2} candela at 10 mA. Assuming linearity, our LED is emitting light at 7.68×10^{-5} candela. This is most likely a poor assumption. A more appropriate assumption would be to assume a relationship of the form $L = L_0 + k\left(1 - e^{-i}\right)$, but we have no idea what the baseline luminosity value is. Since the lights goes out spherically, it goes through 4π steradians. Thus the luminosity of the light is $4\pi \times 7.68 \times 10^{-5} = 9.65 \times 10^{-4}$ lumens. The radius of the sphere that the light passes through is 1 cm. Thus the intensity of the light is

$$\frac{9.65 \times 10^{-4}}{4\pi(0.01)^2} = 0.77\, lux$$

To convert between lux and fc, we note that 1 fc = 10.76 lux. Thus the intensity is

$$\frac{0.77}{10.76} = 0.07\ fc$$

In the standard curves provided by [1], the response time is the time required to change from 10% to 90%, or from 90% to 10% of the full "on" value. This change corresponds to a factor of 9, which is close to 2^3, which would correspond to 0.18 s to decay, using our measured constant. However, the decay response time at the level of illumination we approximated above is approximately 0.07 s and the activation time is 0.4 s. Our decay computation is close to the value from the curve, but instead of seeing a 0.4 s activation time, we saw an instantaneous jump. Since we do not know how the curves were procured, we cannot make a conclusion based on this inconsistency in activation behavior.

The response time of the phototransistor is determined by the capacitance of the collector-base junction, and the value of the load resistance [2]. In general, phototransistors with higher gain have a slower response time. We drove the IR LED with a 4V P-P square wave. For frequencies between 1 Hz and 500 Hz, the output was very digital, meaning that it followed the input sharply. When we increased the frequency to 1 kHz, we began to see a tail with a very small time constant. Although we did not measure this constant, the curve from [3] indicates that the time for the voltage to change from 90% to 10% of the maximum value should be approximately 6 μs. However, the response of these devices should be even with respect to the changes in input. In other words, we expect the rise time to be equal to the decay time [3]. We observed a virtually non-differentiable jump at activation, which is similar to the behavior observed for the photoconductor, and disparate with the standard curve.

For both the visible light and IR system, there was no delay in the output signal. In other words, the input and output were in phase, disregarding the decay behavior. With just one LED and detector pair, it is impossible to tell whether the decay is caused by the LED or the detector. However, given two LEDs and a detector, we can tell. First, the two LEDs must be identical. We put the LEDs at equal distances from the detector. We arrange the LEDs so that one will light up when the positive part of the square wave runs through, and the other will light up when the negative part runs through. If the decay is not a property of the LED, but the detector, we should see a constant output voltage. If the decay is a property of the LED, we would see an output voltage with spikes where the decaying tail of the previous pulse overlaps with the light from the next pulse. This would not happen if the LED was perfect (meaning that it is either on or off).

Sensor Arrangement Design

The specialized device for securing the emitter and sensors underwent several revisions during the process of the lab. The first concept was to have two individual black-foam tubes into which the subject would place their finger. The first tube contained the actual emitter/ transmitter arrangement and would take the measurement. The second tube was to act as an ambient light/ other effects control with only a detector. The signal from the control tube was to be removed from the measured signal by the integrated op-amp circuit.

The wiring for the emitter/ detector and control detector was connected to the breadboard with provided wire and heat-shrink wrap. Each tube had the ends flattened by heating on a flat surface, which allowed for one end to be effectively blocked using a combination of scrap foam and electrical tape. Because we were not sure at first if we were going to use epi-illumination or trans-illumination, holes were bored into the foam of the sensory tube at three positions allowing for the detector to be placed adjacent to the transmitter with electrical tape separating them (epi-illumination) or directly opposite the tube (trans-illumination). The holes were then either covered with electrical tape or filled with clay. Finally, the open ends of both sensory and control tubes were fitted with zip-ties and adjusted so that the subject's finger would fit snugly and minimize further the entrance of ambient light.

When it became obvious that the initial circuit design with the integrated op-amp was not a viable option and the circuit used in Section B was decided on as a fall-back, the securing device was modified. The circuitry was replaced and instead of simple heat-shrink, the connections were soldered then wrapped in electrical tape. Furthermore, the concept of the second, "control" tube was deemed unnecessary and removed. Thus, a one tube, epi-illumination set-up was used for the finger mapping. To accomplish the palm mapping, more modifications were needed. The upper half of the tube was removed, forming a half-moon. Both ends were capped. The overall arrangement of the emitter/ detector remained the same. This design was not nearly as effective at limiting ambient light, thus for the palm mapping the ambient lights were turned off as an extra precaution.

LED Control Circuit Design

This segment of the device was designed simply as a light source (in this case a light emitting diode) controlled by a voltage controlled current source. The circuit is shown in Figure 2.a. The current through the LED (light emitting diode) can be found using the following relationship:

$$i = \frac{V_{Cmd}}{R_1}$$

where V_{Cmd} is the command voltage applied to the circuit using a function generator, and R_1 is the value of the resistors labeled as such in Figure 2.a (Derived in appendix 1). Using an independent current source is wise in this case because LED's respond more predictably to current and not voltage, and the voltage-current relationship cannot be modeled accurately using passive electronic components such as resistors.

Since the maximum current that may be applied to the LED is 150mA (value found in bioengineering 302 lab manual, lab 6a), we decided to use a 100Ω resistor so that we would get illumination in a useful range when applying a 3-7 V command signal. Since the function generator has a maximum output of 10 V (amplitude), there was no risk of burning out the LED's used in the experiment (a V_{Cmd} greater than 15 V would be necessary to burn out the LED).

Detector Circuit 1: Ambient Light Canceling Using an Instrumentation Amplifier (Figure 2.a)

The first decision to be made was whether to use the Infrared LED (Ir LED) with the phototransistor or to use a visible light LED with the photoresistor. Using the knowledge gained in experiment 6a, we decided to use the Ir LED/phototransistor pair due to their high bandwidth and hemoglobin's high absorbance within the infrared range.

The simplest way to use phototransistors is to allow the current conducted through the transistor (which is a function of the light incident on the phototransistor's sensing region) to flow over a load to ground (such as the resistor R_e in Figure 2.a). The voltage can be measured at the junction of the resistor and phototransistor which is also proportional to the amount of light incident on the photosensor. Photoresistors act similarly, but are often described as a voltage divider described by the relationship below:

$$V_{sense} = V_{\det} \frac{R_e}{R_e + R_{photoresistor}}$$

This circuit is shown in Figure 1. Phototransistors can be described using the same relationship, but it is often not as intuitive to analyze semiconductor components in such a way. Re must be chosen, in the case of the phototransistor, so that the current through the transistor will not exceed its threshold current of 50mA. Therefore, if the detector voltage, V_{det} is to be 5V, then the resistor, Re must allow no more than 50mA of current at 5V. To meet this condition, Re must be 100Ω.

Since ambient light can be a significant problem for photo detection instruments such as the one being designed in this experiment (especially when measuring light scattered by epi-illumination technique), we decided it would be useful to use a circuit to reject the common mode signal from a second photo detector used as a reference. The logical choice for this application was to use a differential amplifier. We decided to use an instrumentation amplifier (AD625) for its ease of use and high common mode rejection ratio (CMRR = 90 dB at 60 Hz). The gain (G) of the operational amplifier is defined by the following expression:

$$G = \frac{2R_f}{R_g} + 1$$

where R_f is the feedback resistance of the instrumentation amp and R_g is the gain resistance of the instrumentation amp, both shown in Figure 2.b. To simplify the circuit we decided to keep the gain of the instrumentation amplifier as near 1 as possible, because we could then ensure that the amplifier would remain in its linear region by setting the detector voltage (V_{det}) and the source voltage (±Vs) equal. To accomplish this, the value of R_f would have to be much less than that of R_g. Values of 39Ω and 5.1MΩ were selected for R_f and R_g, respectively making the theoretical gain of the instrumentation amplifier negligibly greater than 1 which is within the operating range of the instrumentation amplifier (from AD625 spec. sheet).

Upon building the circuit and combining it with the sensor apparatus described in section 1 above, we were unable to illicit the expected response from the circuitry. Upon troubleshooting (after verifying that the circuit was built correctly) there were three possible sources of error in the circuit:

1. The instrumentation amplifier was not functional, however upon replacing the operational amplifier there was no change in the response of the circuit. The instrumentation amplifier was also tested with a known input signal and showed a response with gain less than 1.
2. The voltage controlled current source was defective and thus the Ir LED was not emitting light, however the Ir LED was replaced with a visible spectrum LED and was confirmed not to be the problem.
3. The Ir LED or phototransistor could have been destroyed when applying heat to the heat-shrink tubing as described earlier in this report. The phototransistors were replaced with photoresistors and the Ir LED was replaced with a red LED. We were still unable to elicit a response from the detector circuit.

In hindsight, it appears as if the problem may have been due to the non-ideal nature of the instrumentation amplifier. Since R_f was much lower than R_g, the assumptions normally valid for the instrumentation amplifier may have broken down, as shown by the response in described in item 1 of the list above.

Detector Circuit 2: Voltage Follower Circuit using an Operational Amplifier (Figure 1)

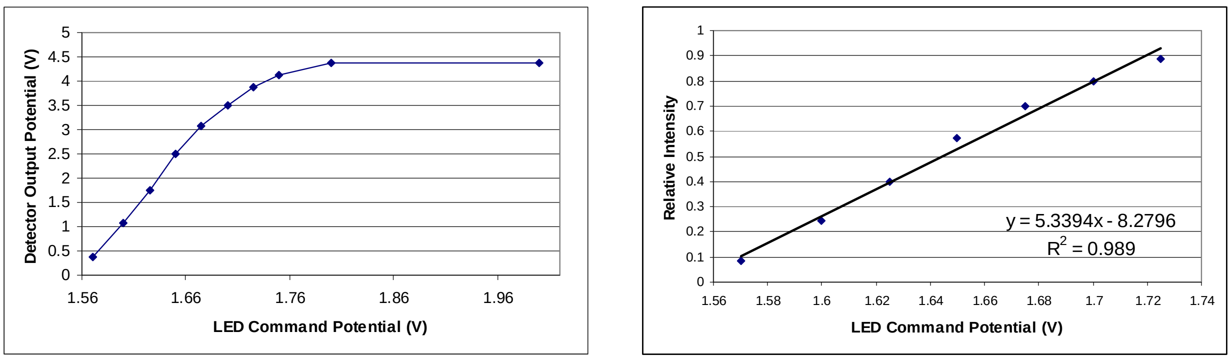
Due to the problems discussed in section 3 of the discussion and the time constraints imposed by other work, we decided to simplify the circuit significantly. Instead of using a differential amplifier to nullify any offset due to ambient light we decided to use the detector circuit from experiment 6a using a photoresistor/visible spectrum LED pair. We eliminated the problems caused by ambient light by conducting the experiments in the dark. This is a reasonable assumption to make because if this instrument were to be made, a housing would also be made to block most of any ambient light which could reach the photodetector. Ambient light compensation could also be conducted using a working version of the circuit proposed in section 3 or by using various signal processing techniques. We felt it was more important to examine the properties of the photodetectors and light transmission through tissue.

The circuit we used is shown in Figure 1. The values used for the voltage controlled current source are consistent with those discussed above. Re was set to 100kΩ because the operating range of the photoresistor is from about 1MΩ under very low light conditions to about 10kΩ. Therefore 100kΩ is about in the middle of the exponential response given by the photoresistor.

Calibration

Two different LED types were used, a red LED and a white LED. The red LED was used to measure levels of blood profusion in various places on a subject’s hand. The white LED was used to measure the density of the tissue in the same regions of the subject’s hand. Calibration of both LEDs was preformed by insulating the LED/detector pair from external light, and increasing the command voltage to the voltage controlled current source to increase the intensity of light emitted by the LED. The output values were recorded from the detection circuit. This way the raw signal from the LED may be recorded and thus scattering intensities may be compared to the raw intensity of the LED.

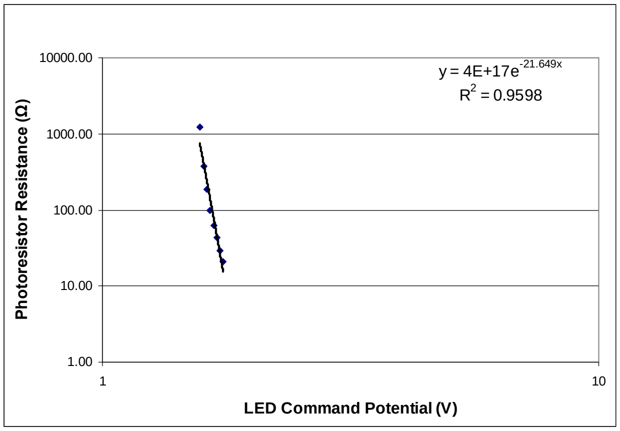
The calibration data and calibration fit (disregarding data points near the saturation threshold) are shown in Figure 3. We find in the range of 1.56 to 1.76 V the detector output and the LED command input vary linearly (Figure 4.b). Figure 3.b shows the linear fit in this region. At LED command potentials greater than about 1.8 the LED is near it light emission saturation point. Thus to calculate the relative intensities shown in Figure 3.b 2 V was used for the maximum intensity by assuming that at and command potential past 2V no more light would be emitted from the LED.

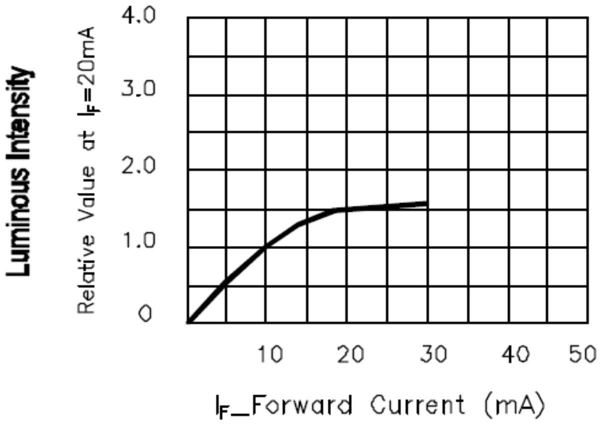


(a) **(b)**

Figure 3(a) Calibration response of red LED/photoresistor pair.
(b) Best fit line of calibration response disregarding saturated potentials.

The only problem with using the calibration curve above (Figure 3.b) is that the response is actually sigmoidal, as shown in Figure 3.a. This is due to the response of the photoresistor to a linear increase in luminous intensity and the properties of the voltage divider described by the voltage divider equation. Figure 4.a shows the exponential decay response of the photoresistor's resistance varies with increasing input from the LED. When replacing Rdet in equation N for the exponential response shown in Figure 4.a, the response of the circuit is predicted to be sigmoidal as well. This validates the use of a linear fit for the calibration curve between 1.56 to 1.76 V.

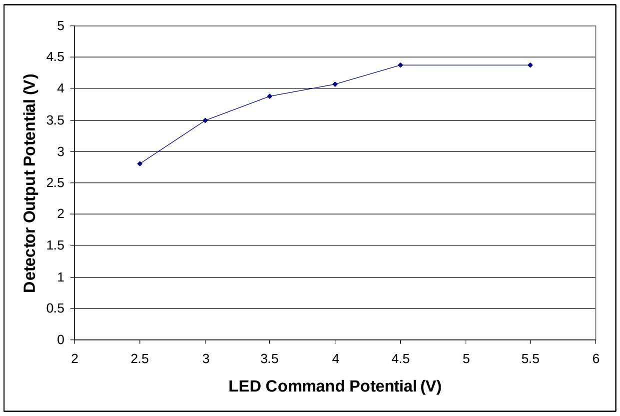


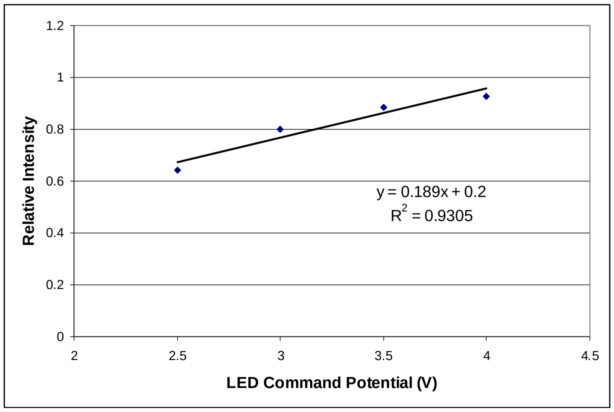


(a) **(b)**

Figure 4(a) Resistance response to calibration procedure shown in figure 3.a on a with an exponential fit line.
(b) LED intensity response curve as a function of current (courtesy of SPC technologies 92N5347 spec. sheet).

The response of the white LED is not as simple because of the absorbance spectrum of the photoresisitor. Since the photoresistor preferentially absorbs between 500 and 600 nm, a calibration curve doesn't nearly as much meaning for a polychromatic light source such as a white LED. Still, the white LED can be used to measure the relative absorbance of light by tissue and thereby the density of that tissue. A calibration curve was produced and is shown in Figure 5.b.





(a) **(b)**

Figure 5(a) Calibration response of white LED/photoresistor pair.
(b) Best fit line of calibration response disregarding saturated potentials.

Detection of Density and Blood Profusion in Skin Tissue

We conducted three experiments on the palm of a subject's hand, taking data at 5 defined points. These five points were defined as follows (also shown in Figure 6):

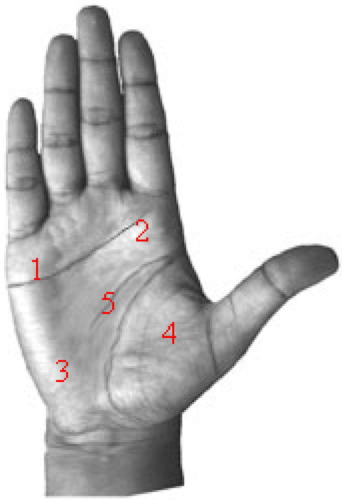


Figure 1 Diagrammatic representation of areas measured on palm of hand.

1. 1 cm proximal to beginning of 5th finger.
2. 1 cm proximal to beginning of 2nd finger.
3. 7 cm proximal to beginning of 5th finger, placed slightly lateral such that the distance from the edge of the palm and the detector was equal.
4. 7 cm proximal to beginning of 2nd finger, placed slightly lateral such that the distance from the edge of the palm and the detector was equal.
5. The estimated surface projection of the centroid of the hand onto the palm.

These measurements were taken under three different conditions. First the white LED was used to measure the density of the skin in each area. Then the blood in the palm was diffused out by keeping the palm above the patients head for a period of time before taking measurements. Finally a third round of measurements was taken with high blood perfusion through the palm by clapping the hands together, or by vigorously rubbing the hands together. The results of these experiments are summarized below in table 1.

Table 1 Output voltage and estimated % transmission from the epi-illumination experiment described above. The positions correspond to the positions on the hand in figure 6.

	White LED		**Red LED, Low perfusion**		**Red LED, High perfusion**	
Position	Output V	% transmitted	Output V	% transmitted	Output V	% transmitted
1	4.38	99.7	1.63	37.9	1.88	40.0
2	3.75	75.4	1.13	35.7	1.88	40.0
3	3.56	68.0	1.63	37.9	1.63	37.9
4	2.44	24.4	0.88	35.4	1.25	36.0
5	3.63	70.5	1.38	36.5	1.50	37.2

Interestingly, you can tell the density of the tissue imaged from the percent of the white light transmitted. If you feel your hand, you can approximate the density or "toughness" of the skin by touch or gentle pinching of the skin in the above places on your hands. You will see that the tougher areas (such as the thumb pad) correspond to lower transmission of white light. The output voltage for position one seems to have saturated the circuit. There was probably a break in the light insulation causing a leakage of light to the detector. The data from the red LED is much more subtle. It is interesting to note that the percent transmitted in the high perfusion case is greater than the low profusion case for all positions. This is true because hemoglobin (a major constituent of blood) reflects red. This is why your blood looks red when it is oxygenated but purple when deoxygenated. Thus, with a more sensitive instrument, the level of oxygenation could be measured by the amount of red light reflected at any point in time. This is the basis behind pulse oximetry.

Conclusion

Optical properties of photodetectors were observed. Photoresistors were found to have slow response times and were highly affected by ambient light, but were also easiest to use because photoresistors detect light in the visible range. Phototransistors were found to have faster response times and have a higher ambient light tolerance, but were difficult to troubleshoot because of their absorption outside the visible range.

Several photodetector circuits were built to use light as a modality for measuring physical parameters. A detector which corrected for ambient light was attempted, but was abandoned due to various problems which were unable to be eliminated by quick troubleshooting. A second, simpler circuit was built, by which we were able to make measurements. After completing multiple calibration curves, we were able to measure accurately skin density and blood profusion in the palm of a subject's hand.

References:

[1]http://optoelectronics.perkinelmer.com/content/RelatedLinks/photocell%20introduction.pdf

[2]http://optoelectronics.perkinelmer.com/content/RelatedLinks/PhototransistorCharacteristics.pdf

[3]http://optoelectronics.perkinelmer.com/content/RelatedLinks/PhototransistorTypicalCharacteristicCurves.pdf

Appendix 1: Derivation of Voltage Controlled Current Source Equation

Applying KCL at + gives:

$$\frac{V_+ - gnd}{R_1} = \frac{V_+ - V_o}{R_2}.$$

Applying KCL at – gives:

$$\frac{V_S - V_+}{R_1} = \frac{V_+ - V_o}{R_2} + \frac{V_+ - gnd}{R_{LED}} = \frac{V_+ - V_o}{R_2} + i_{out}$$

Thus

$$\frac{V_s - V_+}{R_1} = \frac{V_+ - gnd}{R_1} + i_{out} = \frac{V_+}{R_1} + i_{out}$$

Thus

$$i_{out} = \frac{V_s - V_+}{R_1} + \frac{V_+}{R_1} = \frac{V_s}{R_1}$$