# Infant Monitoring Device: Heart Rate Detection

## BME 462L: Design for the Developing World

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**Abstract**

Infants whose cardiac systems are compromised are at risk of irregular heart rhythms that can go unnoticed by untrained parents for extended periods of time. Infants are incapable of clearly communicating needs and pathologies -- as such, it is up to parents and healthcare professionals to recognize and address dangerous physiological conditions. This puts them at risk of further complications, so a non-invasive, wearable device can alert parents to arrhythmia before more severe, visible symptoms present. The need for a cost-effective, easy-to-use, and accurate infant monitoring device has not yet been met in the developing world. One vital sign that can be used to estimate an infant's overall cardiac functionality is heart rate, as abnormal rates are often indications of pathologies such as infection and hypovolemia.

A preliminary wearable infant heart rate monitor was developed using optical plethysmography to measure changes in volume along the infant's index finger attached with velcro. This device is easy to use and can be placed by individuals trained with a infographic sheet that contains no words for generalizability. This device is designed for use by parents of at-risk infants who required postpartum medical care and will ring an alarm the parents if it detects an abnormal heart rate outside the normal range for infants found in literature. The sensor itself is connected to an offsite processor and display, that will measure the number of beats tracked within a user-designated time frame, or during continuous monitoring. Statistical testing on the prototype indicates that all specifications are met except for safety, which is difficult to ascertain due to variability in how much an individual is inclined to tighten the velcro. Other important specifications from accuracy of the device's estimated heart rate and ease of use for untrained populations in developing worlds were both met, according to z-tests for pass/fail conditions and a one-tailed t-test for accuracy. This easy to use device will empower parents and caregivers by reducing their response time in seeking medical attention. A focal point of this design is to allow for modifications by future teams, in adding different types of sensors all contained within one external compartment. This way, infant monitoring can extend from heart rate to respiratory function, blood volume, and other measures that can alert parents to difficult to observe ailments.

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**Clinical Need**

Congenital heart defects historically have been difficult to diagnose and treat, and most infants diagnosed had little to no chance of survival past the first year. However, with the advent of improved technology, diagnostic measures, and care away from the hospital setting, these infants now live into adulthood. This is not the case in developing worlds where resources are unavailable and access to medical care is limited. Infants are particularly susceptible to death from undiagnosed conditions, in part because of their inability to communicate and also b\due to the inability of parents to recognize symptoms of CHD. Within the United States, approximately 1% of babies born per year (roughly 40,000 infants) are diagnosed with some form of CHD -- a relatively high proportion, which is unforttunatley comparable to all other countries. It is important to note, however, that while the proportion of infants diagnosed may be lower in developing worlds due to older technology and less access to medical training, this does not necessarily indicate a lower percentage of the population that is afflicted (Data and Statistics, 2016). It is estimated that approximately 880 infants are missed diagnosed, which shows the higher plausibility of missed diagnoses in developing worlds (Key Findings, 2016). Furthermore, infant populations affected by any other condition, such as infection and/or malnutrition, are susceptible to less severe forms of cardiac compromise.

Compared with children, adolescents, and adults, infants typically have unique physical characteristics, including, but not limited to, a more pliable trachea, heavy use of intercostal muscles during accessory breathing, and a comparatively large surface area with respect to body volume. These physical differences manifest themselves in specific vulnerabilities for infants, whose cardiovascular systems are at risk, which is why it is imperative that medical professionals in the developing world be able to recognize these conditions before life-threatening conditions develop. In developing worlds, sophisticated technology is typically not available or too expensive to be used for every infant. Thus, using heart rate monitoring at home as a proxy for overall cardiovascular health is much more feasible and will be used to warn caregivers at home about the possibility of heart failure. Accurately diagnosing the type or severity of CHD is not as important in this case, as the primary goal is to make parents more aware of the possibility of a life-threatening condition and to get infants hospital care as soon as high risk symptoms occur.

Congenital heart defects and other forms of cardiovascular compromise are especially dangerous since they can contribute to a host of comorbidities including pulmonary edema, inadequate perfusion, and hypothermia. With each of these conditions, infants will undergo what is referred to as compensation, where the body will exert extreme amounts of effort to maintain normal physiological conditions and vital signs until a sudden, unexpected collapse of organ systems. (Mistovich, 2014) Coupled with the infant's inability to communicate,

parents and caregivers away from the infant will have no idea that the infant is exerting severe physical effort until it is already too late. Thus, this device is intended to warn parents with an audible alarm system based on swelling of the abdomen/appendages and irregular heart rates that typically present with a decline in cardiac function. In this compensatory phase, the infant's heart rate will be relatively constant, but sudden fluctuations and drastic differences per minute are also indicative of compensatory mechanisms -- this will be measured with the wrist device in conjunction with swelling. Furthermore, pulmonary edema and swelling will negatively impact the infant's respirations, as the pliable trachea will be compressed by the expanding cardiopulmonary system and fluids in the alveoli inhibit adequate gas exchange, contributing even more to inadequate peripheral perfusion.

There are other at-home infant monitoring devices available to parents in developed countries -- however, the majority are too expensive and face other barriers to use in the developing world. This is reasonable as most infants will already have been diagnosed in countries with access to more advanced technology, and the focus will be not on recognizing CHD but in alleviating symptoms. The current market is filled with devices that focus on respiratory rate, since not breathing is much more immediate than poor heart function. An extensive patent search was conducted to ensure that any past literature and designs were not emulated by the new medical device. This portion is included in the Intellectual Property Analysis in the appendix. In contrast to the current market, the infant monitoring device centered around cardiac function will be more of a alerting tool for caregivers, not to accurately distinguish between different pathologies but to alert parents to the possibility of rapidly declining health in infants. This gives parents the power to better influence the health outcomes of their children, given that they typically will not have the luxury of hospital visits unless severe symptoms are expressed. The device will also be significantly cheaper and easier to use than competitors' devices, as the target demographic is less financially and technologically equipped. The devices will not be given to all families, but only those that healthcare professionals believe to already be at high risk for pathologies based on their neonatal condition. Ultimately, since the symptoms of cardiovascular compromise can manifest in a variety of ways, it is less important to recognize the specific abnormality than to get the infant to a medical facility.

**Specifications**

**Table I:** Specifications listed with minimum, typical, and maximum allowable measurements, green indicates the device passed, red indicates a failure, yellow indicates not tested.

| Specification | Minimum | Typical | Maximum |
|---|---|---|---|
| **Safety -** Pressure (kPa) experienced by subject's finger due to device's attachment mechanism | 0 | 15 | 60 (Tang et al., 2014) |
| **Cost -** Total production cost for complete unit | $0 | $30 | $75 |
| **Ease of Use -** X percent of users must be able to place sensor as directed when consulting provided directions | 80% | 90% | 95% |
| **Ease of Use -** X percent of 20 tested users must be able to recognize an irregular heartbeat indicated by the alarm without any instruction | 80% | 90% | 95% |
| **Accuracy** - X percent of one-minute measuring windows return within 6 beats of measuring pulse with two fingers on the opposite wrist | 85% | 90% | 95% |
| **Performance –** Device will alarm _ of the time if measured pulse is at critical infant heart rates (below 80 or above 140 bpm) | 90% | 95% | 99% |

## Final Design Descriptions

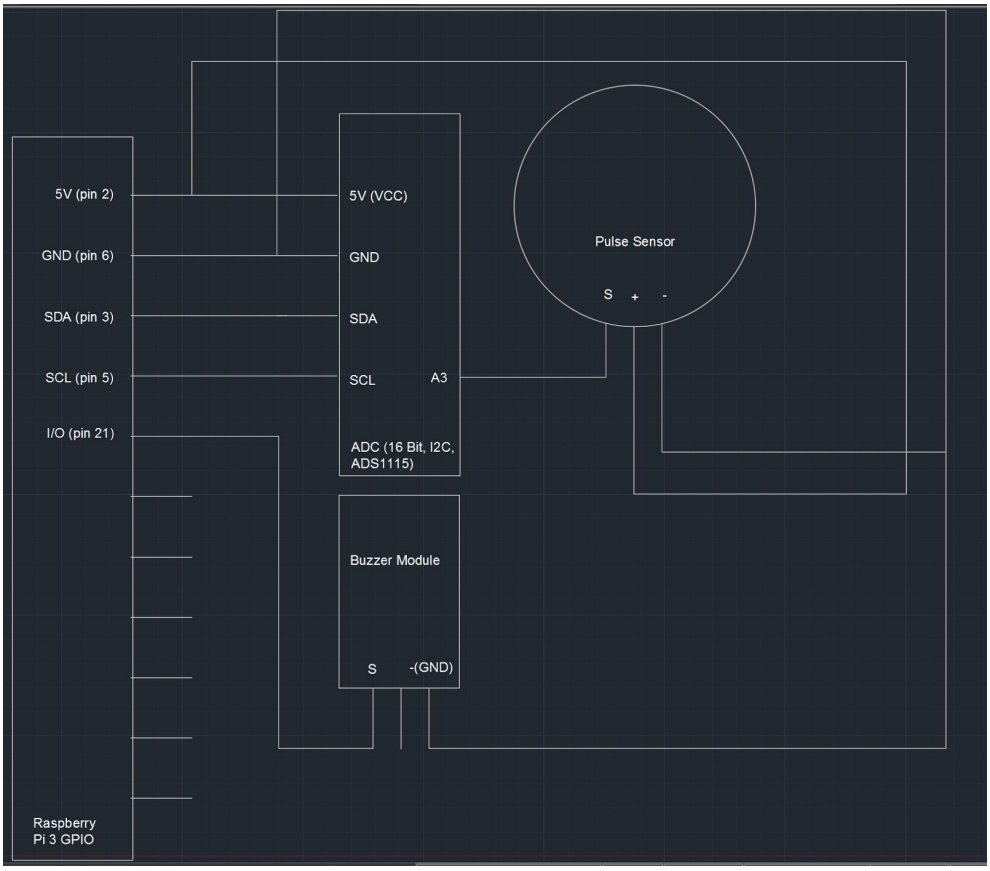



**Figure 1**: Final Basic Design CAD electronic connections. Shown are the GPIO connections between the Raspberry Pi 3, ADC, buzzer module, and Pulse Sensor, the minimum design components for pulse measurement and a sound-based alarm.

Our final design iteration of the infant heart rate monitor focuses on the proof-of-concept of the potential future design of a unified, multiple sensor infant health monitor that is both accurate and low cost.

With this in mind and looking into hardware, we elected to use the Raspberry Pi 3 for its ability to be rapidly prototyped via a maker-friendly operating system (Raspbian) and ability to be interfaced through many input devices (keyboard, mouse, monitor, GPIO pins). This means that though we have submitted our most recent (final) design iteration, it is still highly modifiable and capable of adding additional functionality. With this in mind, our final design involves this Raspberry Pi 3, an ADC (ADS1115 sourced from Adafruit), the Pulse Sensor (available from Amazon, but the same part is reproduced by several companies, but is a simple plethysmograph that relies on reflectance measurements, but has interesting and very robust adaptive-gain characteristics that we'll talk about later), a buzzer module, and wires connecting the components together. The ADC module uses I2C to communicate with the Raspberry Pi,

which allows for less connections and expandability on the I2C bus for other components (such as the RGB LCD 16x2 display that we employed in one other iteration to show ease of display and as a cheap alternative to using a monitor). The ADC itself allows for 3 analog inputs. The Pulse Sensor is powered by simple 5V and ground pins, and has an analog output that scales between 0 and 5. The ADC converts this analog output to digital that is transferred to the Pi via I2C. The Pi then processes this signal and determines whether or not to sound the Buzzer module, which emits a high decibel tone when powered with a static 5V input in the S pin, output by pin 21 of the Raspberry Pi. In a different final iteration of the Heart Rate monitor, we focused on displaying the plethysmograph waveform on a monitor, for debugging and calibration. This way, we could determine proper thresholding for beat detection, which varied between pulse sensors.


**Figure 2**: Integration with RGB LCD display

In terms of software, we used Python with several imported libraries such that we could interface with the ADC and RGB LCD, and used several libraries that allowed for cool animations of the plethysmograph waveforms. They are listed in our tutorial.

Additionally, we designed a wordless, visual diagram for users to consult when placing the device. This diagram was provided to users during the testing phase and is designed for use by untrained parents in correctly positioning the device on the infant (Figure 3).

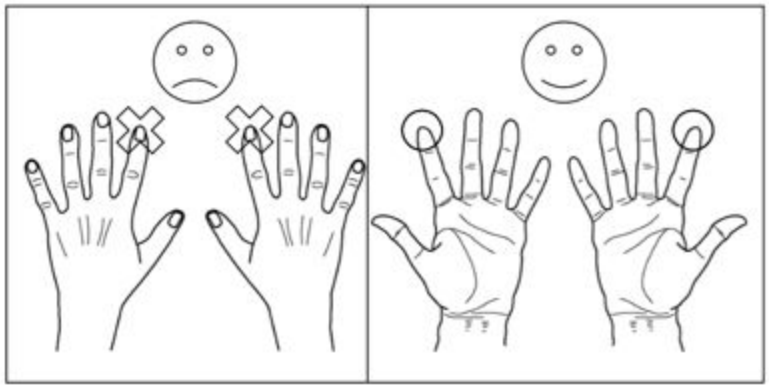


**Figure 3:** Visual Instructions

**Parts Inventory, Cost, and Assembly Instructions**

**Table II**: The cost of the base unit as CAD drawn above in **Figure 3**.

| *Component* | *Price* |
|---|---|
| Raspberry Pi 3 | $ 35.00 |
| micro-SD card | $ 6.20 |
| ADC (I2C 3-channel) | $ 9.99 |
| Pulse Sensor | $ 6.99 |
| Alarm | $ 1.99 |
| Power Supply | $ 8.79 |
| Wires, velcro, etc | $ 5.00 |
| **Total base cost:** | $ 73.96 |

**Table III**: The costs including the peripherals used for prototyping and further development.

| | |
|---|---|
| Monitor (HDMI) | $ 110.60 |
| HDMI cable | $ 9.99 |
| keyboard/mouse | $ 15.00 |
| 1 hrs labor (7.25/hr) | $ 7.25 |
| Breadboard | $ 19.95 |
| **Total peripherals cost** | $ 162.79 |
| | |
| **Current iteration cost** | $ 236.75 |

With the shown tables, we show the cost of the base unit, which just includes a usable pulse sensor, raspberry pi to process this data, and an alarm to indicate that something is wrong. This unit relies on a normal wall-outlet power source. This cost can be reduced by using a lower grade Raspberry Pi (likely a Raspberry Pi Zero would do the job for only 5 dollars a unit), or using a cheaper microcontroller like an Arduino or Particle Photon. There are many alternatives, but building on the most powerful and economical microcomputer, the Pi, shows that possibility for growth and development for this project.

**Instructions for Assembly**

Plug all peripherals into the Raspberry pi- -keyboard, mouse, hdmi, and finally the Micro-USB

Setup raspberry pi with SD card with Raspian already on the card

Go to command line and type in the following commands:

*sudo raspi-config*
Then navigate to advanced options, then enable I2C. Then exit the configurations window.
Then type in and execute the following commands in this order:
*sudo apt-get update*
*sudo apt-get install build-essential python-dev python-smbus git*
*cd ~*
*git clone https://github.com/adafruit/Adafruit_Python_ADS1x15.git*
*cd Adafruit_Python_ADS1x15*
*sudo python setup.py install*
*sudo pip install adafruit-ads1x15*
*sudo apt-get install libblas-dev*
*sudo apt-get install liblapack-dev*
*sudo apt-get install python-dev*
*sudo apt-get install python-smbus*
*sudo apt-get install i2c-tools*
*sudo apt-get install libatlas-base-dev*
*sudo apt-get install gfortran*
*sudo apt-get install python-setuptools*
*sudo easy_install scipy*
*sudo apt-get install python-matplotlib*
*sudo apt-get python-pip git*
*sudo pip install RPi.GPIO*
*git clone https://github.com/adafruit/Adafruit_Python_CharLCD.git*
*cd Adafruit_Python_CharLCD sudo*
*python setup.py install*

Once the software libraries are installed, download the base code from gitlab, or copy and paste the code from the appendix. The Python IDE should compile and run from that script.

## Testing Methods

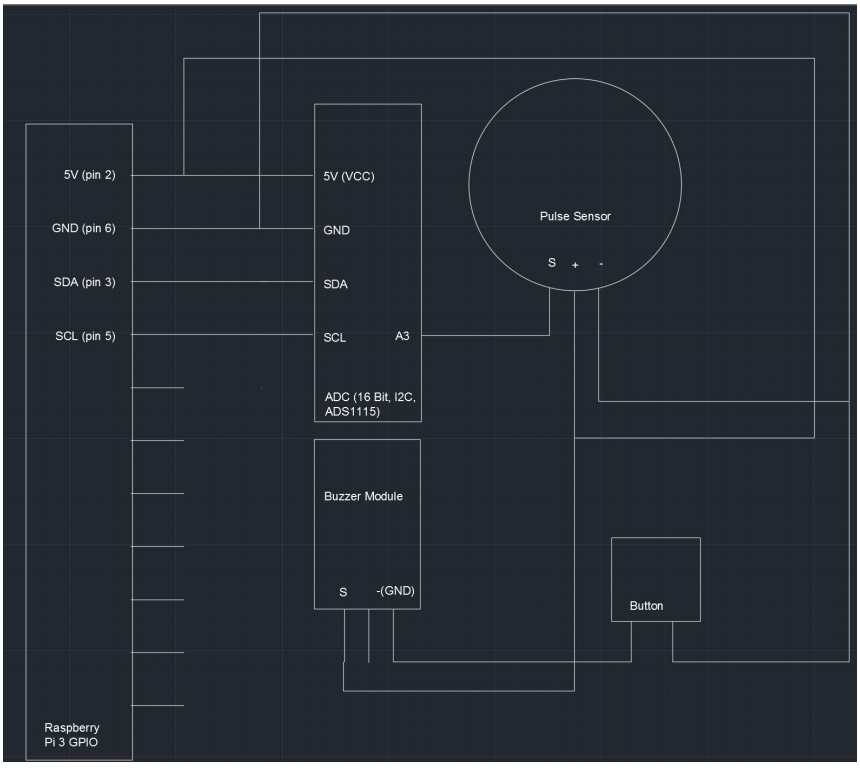



**Figure 4:** Circuit Diagram for the Infant Heart Rate Monitor

During testing, the accuracy and ease of use specifications were tested using a sample size of twenty Duke University students. All three specifications were tested on each person in one trial. First, the general concept of the sensor, that it was an infant monitoring device for measuring heart rate in the developing world, was explained to the subject. A sheet of paper with the grayscale wordless instructions was handed to the person and the amount of time needed for them to place the sensor on their own person was measured. Then, team member Delta Ghoshal ran the program uploaded to the device to see if a heartbeat was registered. If it was registered, the person was recorded to correctly place the device. If not, notes were made about how the device was placed incorrectly, to see whether the wordless instructions should be updated, and Ghoshal placed the device correctly on the person. This test is for evaluating the first ease of use specification: at least 90% of users must be able to place sensor as directed after being trained.

Then, for one minute, group member Jake Son measured the subject's radial pulse while the program measured and counted the heartbeats, and the measured and actual number of counted beats was recorded. This test is the same as was completed for the initial testing phase and is for evaluating the accuracy specification: 95%  of one-minute measuring windows should return within 6 beats of measuring pulse with two fingers on the opposite wrist.

Finally, Delta Ghoshal activated the piezospeaker alarm with a handheld buzzer and asked the subject what they thought the sound meant and what actions they might take after hearing it if the device was attached to their infant. The ease of use specification, that 90% percent of 20 tested users must be able to recognize an irregular heartbeat indicated by the alarm without any instruction, was recorded as met if the person answered, in some way, that the alarm represented an irregularity in the infant's heart rate or an impetus for the parent to seek medical instruction.

After the results of the testing, the difference between measured and actual heartbeat was compared to the allowed discrepancy of 6 beats using a one-tailed (right-tail), one-sample t-test. The null hypothesis is that the population mean of the absolute difference between actual and measured values is equal to 6. The alternate hypothesis is that the discrepancy between actual and measured values is greater than 6, meaning it did not meet the specification. A a-test for comparing proportions was used for the two ease of use specifications, where the null hypothesis is that the percentage of "passed" subjects is comparable to the specified percentage, and the alternative hypothesis is that the measured percentage is lower than what is specified (left-tailed).

**Testing Results**

The following table contains the total results from the twenty people (anonymized) whose data were collected in the manner described in the "Testing Methods" section.

**Table 6:** Tabulated results of the device during specifications testing.

| Trial | Placed device correctly on first try? | Number of beats counted by device | Number of beats counted by radial pulse | Correctly identified alarm? |
|---|---|---|---|---|
| 1 | Yes | 59 | 59 | yes |
| 2 | Yes | 75 | 74 | yes |
| 3 | Yes | 88 | 88 | yes |
| 4 | No | 70 | 70 | yes |
| 5 | No | 68 | 68 | yes |
| 6 | Yes | 58 | 60 | yes |
| 7 | Yes | 71 | 70 | yes |
| 8 | Yes | 71 | 72 | yes |
| 9 | Yes | 96 | 79 | yes |
| 10 | Yes | 63 | 63 | yes |
| 11 | Yes | 74 | 74 | yes |
| 12 | Yes | 75 | 73 | yes |
| 13 | Yes | 90 | 88 | yes |
| 14 | Yes | 81 | 78 | yes |
| 15 | Yes | 80 | 80 | yes |
| 16 | Yes | 67 | 67 | yes |
| 17 | Yes | 86 | 86 | yes |
| 18 | Yes | 74 | 74 | yes |
| 19 | Yes | 64 | 63 | yes |
| 20 | Yes | 59 | 57 | yes |

As seen in **Table IV**, the device met all the specifications; 90% of people were able to place the device correctly, all 20 trials met the accuracy specification (the difference between true and measured heartbeats was not more than 6), and 95% of people correctly interpreted the alarm sound.

The difference between measured and actual heartbeat was compared to the allowed discrepancy of 6 beats using a one-tailed (right-tailed), one-sample t-test. The null hypothesis is that the population mean of the absolute difference between actual and measured values is equal to 6. The alternate hypothesis is that the discrepancy between actual and measured values is greater than 6, meaning it did not meet the specification. With 18 degrees of freedom, a t-statistic of -5.01, and a p-value of 1.000 (calculated with MATLAB), we fail to reject the null hypothesis and can conclude with statistical significance that this design met the specification.

For the statistical testing of the ease of use specifications, a z-test was used for the analysis of the first ease of use specification: at least 90% of users must be able to place sensor as directed after being trained. The null hypothesis is that the difference between the specified proportion and the true proportion is zero. The alternate hypothesis is that the difference between the specified and true proportions is positive, meaning that the true proportion was not high enough to meet the specification. Again, MATLAB was used. With a z-score of 0 and a p-value of 0.5, we fail to reject the null hypothesis and conclude with statistical significance that the design met the placement specification.

For the statistical testing of the second ease of use specifications, that 90% percent of 20 tested users must be able to recognize an irregular heartbeat indicated by the alarm without any instruction, a second z-test was used for the comparison of proportions. The null hypothesis is that the difference between the specified proportion and the true proportion is zero. The alternate hypothesis is that the difference between the specified and true proportions is positive, meaning that the true proportion was not high enough to meet the specification. Again, MATLAB was used. With a z-score of 0.134 and a p-value of 0.53, we fail to reject the null hypothesis and conclude with statistical significance that the design met the placement specification. Additionally, **Figure 5** is a box and whisker plot of the amount of time needed among the test subjects to correctly place the device.

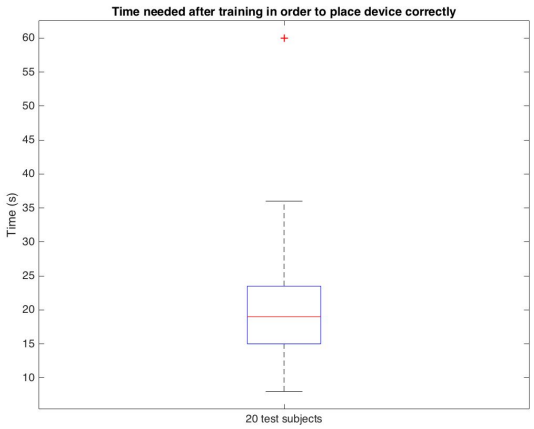



**Figure 5:** Box and Whisker Plot of Training Time

The safety specification, the performance specification, and the cost specification were not tested. The safety specification was failed because the Velcro strap around the sensor could be cinched extremely tightly around the finger, especially since the subject placed the device instead of a trained professional. The performance specification was not tested because it was programmed to be sensitive to infant heart rate healthy ranges, and it was not possible or desired to induce aberrant high heart rates in the subjects. Furthermore, the lower alarming threshold of 80 bpm would likely cause many of the subjects to trigger the alarm, as 80 bpm falls within the healthy range for a grown adult. Finally, the cost specification was not tested, but the itemized cost of the device as is is greater than the specification, meaning that the device failed the specification.

In summary, it can be concluded with statistical significance that the device met the accuracy and ease of use specifications. However, it failed the safety and cost specifications and needs further optimization to meet those goals.

**Design Iterations**

***Barebones Prototyping: From Initial Testing Document***

*Prototype 1: Heart rate detection using a photoplethysmograph (chosen)*

This device consists of a green LED and photodetector pair on a preconstructed integrated circuit that outputs voltage of transduced, reflected LED light received by a photodiode. By placing the device on the index finger and using the Arduino code provided with the sensor, which employs digital peak detection, the prototype measures the volume change within the index finger, converts that to a pulse, and met the specification in Table II. We selected this prototype as the main sensor moving forward with our design. The two following prototypes were discontinued after testing, for reasons listed below in the Testing section.

*Prototype 2: Heart rate detection using a piezo-membrane*

This device consists of a thin piezoelectric film connected to a detachable buffer circuit chip. Theoretically, the pulsatile changes in blood volume should result in a measurable deflection. This deflection is what is sensed when reading a pulse by a patient's neck or wrist. We sought to use a piezoelectric membrane, which transduces mechanical deformation of the film into voltage. Initial testing showed no discernable signal, but after some modification to the placement and secure placement of the membrane, a signal was found with a direct connection to an oscilloscope. This design currently requires athletic tape to bind the piezo-membrane directly on a pulsatile portion of the body. The generated images below were generated with the membrane placed on the wrist.

*Prototype 3: Heart rate detection using bioimpedance*

The final prototype consisted of a 50 kHz, 4 mV sinusoidal pulse connected via an input resistance, currently a potentiometer set to 20 kΩ, to an LF353 operational amplifier. The diagram for the circuit is shown here:

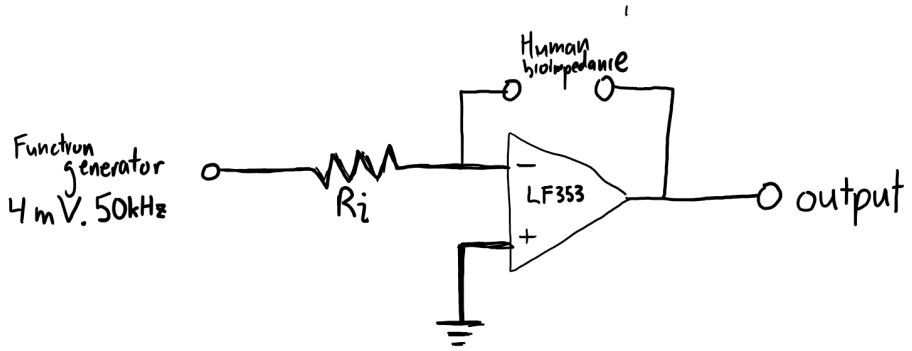



**Figure 6**: The basic bioimpedance amplification circuit, with a variable Ri resistor to modify gain, and human bioimpedance, which should vary as a function of respiration rate and heart rate. The input from the function generator gives a driving current that should be amplified by this inverting amplifying circuit, and the output should show this output.

The infant's thoracic impedance serves as the feedback resistor in the inverting amplifying circuit, which changes the circuit gain, affecting the output. Effectively, the circuit transduces thoracic impedance to a voltage output. Then, by measuring how the output changes with time (and pulse), peak detection can be used to infer heart rate data from the changing bioimpedance of the infant's body. This op-amp circuit was not sensitive to heart rate or respiration, as the output signal had a very low SNR. An experiment was done to compare circuits made with different R*i* values and its effect on the output signal-- there was no relation between the two.

***Practical and Final Prototyping***

The photoplethysmograph was selected as our sensor of choice for the heart rate sensing device as a result of our testing. The chest-strap respiratory sensing device was selected by our sister group, so we plan for our future combined design to be attached to the infant's chest. This means our practical prototype must account for chest-mounting conditions. Our next steps are two-fold. First is to design the physical mechanisms for the sensor. We plan to design a chest-strap-based "housing" for the sensor. This housing will include a vinyl covering for the exposed electronics, a reconstruction and reinforcement of the wire connections to prevent pin-pullout. Second is to further design our circuitry to make the sensor compatible with the Raspberry Pi (to be compatible with the respiratory group). Although the device comes with Arduino-based code, there are superfluous functions and the threshold is hardcoded and is therefore less sensitive on regions of interest on the body (such as the wrist and chest). Therefore, we are currently writing our own code to fit our needs and also adapt it for the Raspberry Pi because our collaborators in the infant respiratory rate measuring group plan to use the Raspberry Pi for their final design. We also plan to add an alarming mechanism to the overall circuitry, such as a speaker or LED. In final integration and refinement, we plan to finalize our specifications testing, and begin to move towards integrating our sensor circuit with respiratory impedance sensors from our collaborators. Once this is complete, all specifications from both groups may be tested on the final prototype.

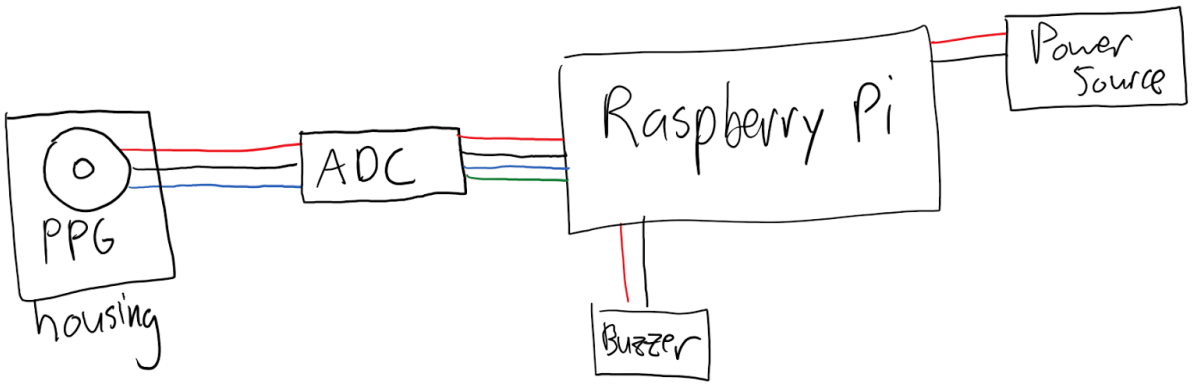


**Figure 7**: The basic circuit diagram of the overall final circuit. This includes the final housing for the PPG, an ADC to convert the signal from the PPG, a buzzer that can be activated by the Pi, and a power source that can either be a wall-outlet or a USB charging battery.

***Testing Methods from Initial Testing Document:***

During this initial testing period, only the accuracy specification listed in **Table I** was tested, as it was the most important specification in our decision matrix. Ten separate people were attached to the device. For one minute, group member Jake Son measured their radial pulse while group member Delta Ghoshal counted the number of discernible beats as defined by the automated pulse-reading system. After a minute of data was acquired for ten people, a paired two-sample t-test was used to decide whether the sensor met the specification. This was completed on both the piezo-membrane sensor and the PPG.

The bioimpedance sensor was constructed, and the first objective was to create an automated pulse counting algorithm to work with the sensor output. The circuit was tuned with different Ri values to amplify the output, and various data captures were taken to more clearly evaluate the output signal to apply a pseudo-reliable pulse counting algorithm.

**Testing Results**

*Prototype 1: Heart rate detection using a photoplethysmograph*

The following are the results from the ten people (anonymized) whose heart rate data was collected in the manner described in the "Testing Methods" section. The data was taken when the sensor was placed on the subject's right index finger because the provided Arduino code, which we are currently in the process of rewriting, was optimized for this placement.

**Table V:** Tabulated results of the PPG when compared to the golden standard of measuring heart rate from the wrist. Each trial was conducted on a different subject, and heart rate was determined simultaneously via device and the golden standard for 1 minute. The sum of the pulses for the minute are compared. Note that there is very little error, and statistical testing show that there is no statistical difference between these two measurement methods.

| Number of beats counted by device | Number of beats counted by radial pulse |
|---|---|
| 67 | 67 |
| 48 | 48 |
| 55 | 54 |
| 66 | 64 |

| | |
|---|---|
| 79 | 74 |
| 75 | 73 |
| 82 | 78 |
| 66 | 65 |
| 79 | 79 |
| 51 | 51 |

Although these data were collected using the provided Arduino code on the index finger of the subject, the device was shown to output useful data when connected to other regions of the body by observing the oscilloscope trace of the device and noting that the peaks corresponded to heartbeats and customized code could be written to detect the heartbeat from other locations on the body.

The difference between measured and actual heartbeat was compared to the allowed discrepancy of 6 beats using a one-tailed (right-tailed), one-sample t-test. The null hypothesis is that the population mean of the absolute difference between actual and measured values is equal to 6. The alternate hypothesis is that the discrepancy between actual and measured values is greater than 6, meaning it did not meet the specification. With nine degrees of freedom, a t-statistic of -7.997, and a p-value of 1.000 (calculated with MATLAB), we fail to reject the null hypothesis and can conclude with statistical significance that this prototype met the specification.

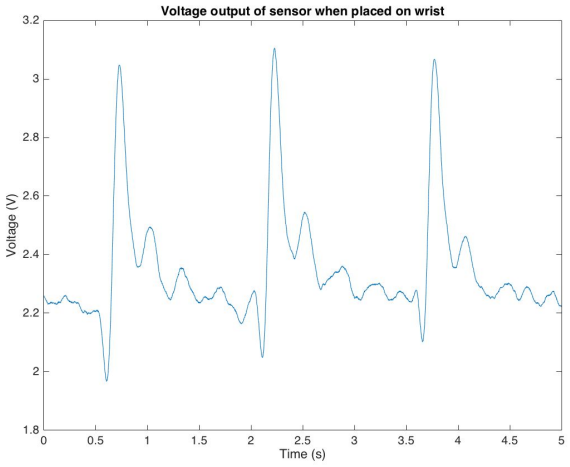



**Figure 8**: The voltage output as a function of time, with the PPG placed on the pulse point of the wrist. Note the very high rise to a local peak, with a second-order response following each of the maximum peaks. Each initial peak is considered a "measured pulse." A peak detection algorithm can be used to determine repeated pulses.

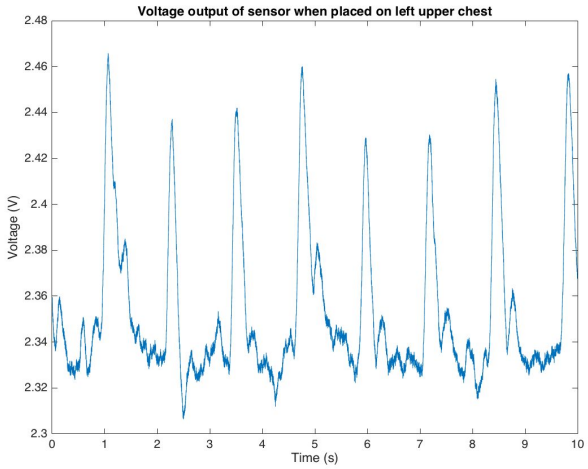



**Figure 9**: The voltage output as a function of time, with the PPG placed on the left upper chest, a likely location with the respiratory rate chest strap's design, the same peaks can be found and a peak detection algorithm can be used.

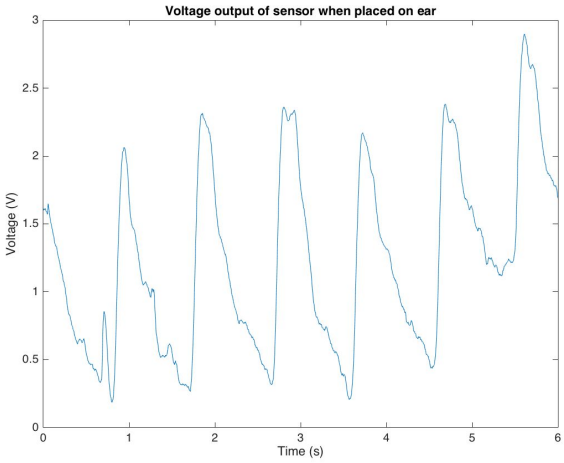



**Figure 10**: Voltage output as a function of time, with the PPG placed on the earlobe. A very strong signal results. This data informs that the PPG acts as expected, as the earlobe is a common PPG placement location.

*Prototype 2: Heart rate detection using a piezoelectric film*

Data for the piezoelectric film was difficult to collect, as it required the subject to be motionless to eliminate background noise. Initially, the system was tested by bending the film manually until peaks were identified -- however, the film could produce voltages up to 55V, which would permanently damage the film. Thus, the system was tested with two 1Mohm resistors in parallel to reduce but retain an observable signal. The figure below illustrates peaks that correspond directly with the bending of the film.

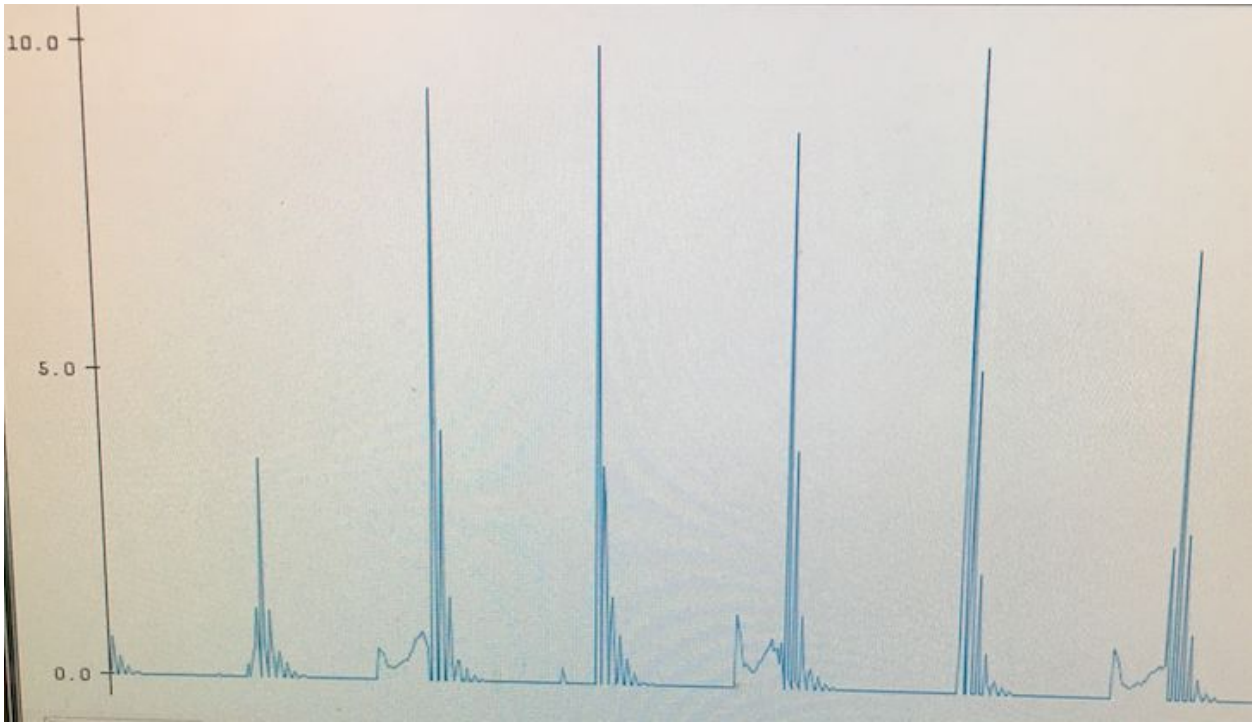
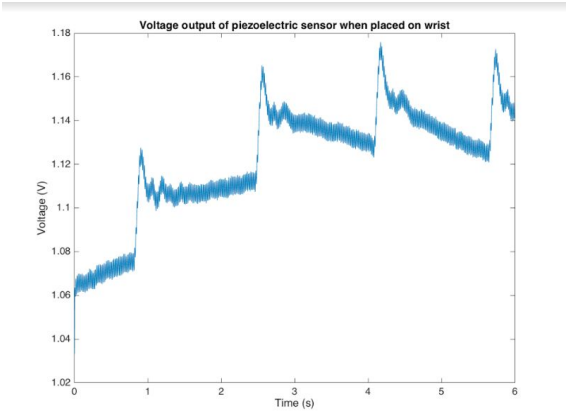



**Figure 11**: The voltage output as a function of time, with each peak corresponding to a flick of the piezo-electric membrane, with an Arduino reading the voltage output of the membrane.

However, when the piezoelectric film was attached to the wrist at the wrist with athletic tape, there seemed to be no discernible signal. Upon closer inspection, a smaller variation in voltage was identified (~2mV deflection of signal from the baseline), which was two orders of magnitude smaller than that of the manual adjustment of the film. Testing with the piezoelectric sensor proved to be difficult, as any larger movement of the wrist would induce major fluctuations in the piezoelectric film that renders the signal unreadable.



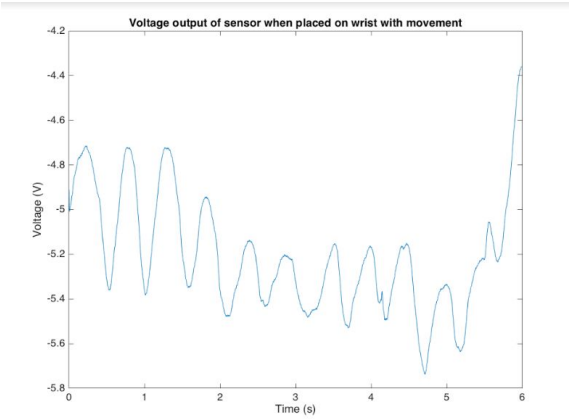



**Figure 12**: Left: the voltage output of the piezo-electric membrane when placed on the wrist and wrapped with athletic tape, with the whole arm held very still. Right: voltage output of the membrane when arm is slightly moving.

**Table VI**: The data gathered when comparing oscilloscope-found pulses versus pulses found by wrist. The differences were calculated on the right.

| Number of beats counted by eye on Oscilloscope | Number of beats counted by radial pulse | Difference |
|---|---|---|
| 54 | 68 | -14 |
| 65 | 77 | -12 |
| 59 | 64 | -5 |
| 50 | 62 | -12 |
| 73 | 65 | 8 |
| 68 | 66 | 2 |
| 69 | 73 | -4 |
| 40 | 56 | -16 |
| 48 | 61 | -13 |
| 53 | 67 | -14 |

Using this data, a simple one sample t-test was conducted. The difference in the number of beat counted, based on the selected specification, was within 6 of the beats counted by the radial pulse.

**P value and statistical significance:**
The two-tailed P value equals 0.0004
By conventional criteria, this difference is considered to be extremely statistically significant.

**Confidence interval:**
The hypothetical mean is 6.00
The actual mean is -8.00
The difference between these two values is -14.00
The 95% confidence interval of this difference:
From -19.71 to -8.29

**Intermediate values used in calculations:**
t = 5.5436
df = 9
standard error of difference = 2.525

*Prototype 3: Heart rate detection using a bioimpedance amplifier*

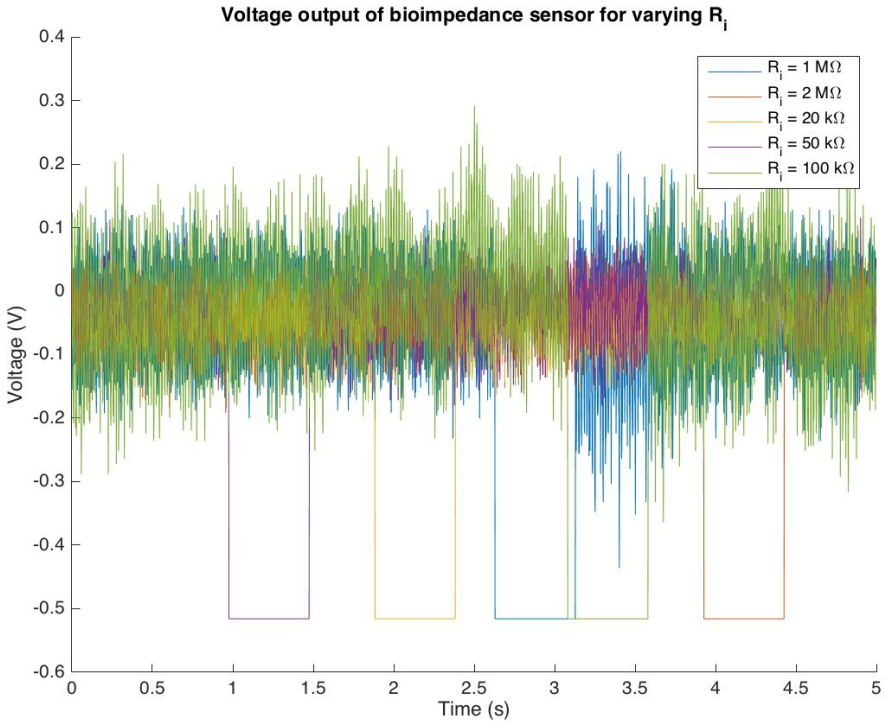



**Figure 13**: *The voltage output of the bioimpedance amplifier as a function of time, with different Ri resistor values. The -0.5 volt artifacts are a result of the analog reading software. Note no significant difference between the Ri resistor values.*

The data captures from the bioimpedance amplifier show that the bioimpedance sensor does not generate a recognizable, physiologically-relevant signal. Because the bioimpedance sensor

produced no discernible heart rate signal, it was determined that no automated system could be used to discern heart rate, and thus fails the accuracy specification by definition.

The selected final design we have chosen to pursue is the photoplethysmograph, which was the only device to pass the accuracy specification of determining pulse reliably within a 1 minute window when compared to the current standard of measurement. A PPG signal can be acquired on the center of the chest, the side of the chest, the wrist, the finger, and the earlobe, which affords high versatility that the other two alternatives cannot reach. The PPG circuit has a high SNR when compared to the other alternatives, and the circuitry on the chip allows for adaptive-to-patient readings. This allows the PPG to be used on a wider population. For these reasons, the PPG was our selected sensor of choice.

Thus, it seems that in the interest of meeting the defined specifications, the photoplethysmograph is the best candidate for infant heart rate monitoring, modularity, and compatibility with the respiratory group. It is versatile in placement, and has an accurate peak detection mechanism that will be useful in informing the alarm of non-traditional heart rate conditions, including tachycardia, bradycardia, and arrhythmias. The device is also cost-effective, and is useful in a monitoring device that is simple enough for variability and modularity in function.

d. KT Analysis from class assignment

**Table VII:** KT Analysis for What the Medical Device Can and Cannot be Used For

| | Is | Is not | Distinction | Possible cause |
|---|---|---|---|---|
| **What** | There is a need for at home infant monitoring devices for infants at risk of cardiovascular compromise | Diagnostic tools for CHD and other cardiovascular compromise | Since the target demographic is untrained adults, it important not to design the device as a diagnostic tool. | There are not currently available medical devices that meet this need (especially lacking in cost effectiveness) |
| **When** | This device is intended for at home use, after discharge from the hospital. | The infant has pressing issues in other bodily systems (i.e. respiratory) | Focusing only on heart rate when there is a more severe body system at risk limits the ability of parents to recognize potential harm. | Infant health can deteriorate slowly over time with no visible symptoms until it's too late. |

| | | | | |
|---|---|---|---|---|
| **Where** | The device is intended for use at home by untrained adults, when the parent has to be away from the child for short durations of time (hours). Must be in audible range of a capable caretaker | Meant to be used without any oversight, leaving the baby alone for extended periods of time. | Since the device only passively catches instances of high risk heart ailments (bradycardia/tachycardia), a caretaker must be near to hear the alarm in order to provide appropriate interventions in time | If the device is within audible range of a capable adult, proper interventions can be undertaken in order to address cardiovascular problems quickly. This is likely a problem that would be encountered if the buzzer is not loud enough. |
| **Extent** | Must be able to accurately measure heart rate and alarm parents to dangerous ranges of cardiovascular activity | Not intended for use at the hospital, as there should be more sophisticated technology available. Furthermore, it is not intended as a diagnostic tool, merely an alarm. | The device must only be used to reduce the response time of parents in getting their infants medical attention, not in identifying and distinguishing between different conditions | A vital sign as simple and untelling as heart rate should not be used for anything more than as a holistic measure of heart rate. |

**Decision Matrix**

First, the specifications are ranked versus one another to identify the most important ones (Table VIII).

**Table VIII**: Decision Matrix to Determine Specification Rankings

| **Specification** | **Safety** | **Cost** | **Ease of Use** | **Accuracy** | **Performance** | **Durability** | **Total** |
|---|---|---|---|---|---|---|---|
| **Safety** | - | 1 | 0 | 0.5 | 1 | 0 | 1.5 |
| **Cost** | 0 | - | 0 | 0.5 | 1 | 0.5 | 1 |
| **Ease of Use** | 1 | 1 | - | 0.5 | 1 | 1 | 4.5 |
| **Accuracy** | 0.5 | 0.5 | 0.5 | - | 1 | 1 | 3.5 |
| **Performance** | 0 | 0 | 0 | 0 | - | 0 | 0 |
| **Durability** | 1 | 0.5 | 0 | 0 | 1 | - | 2.5 |

From this, a rank-ordered list is generated listing the specifications in order of how important they are (Table IX).

**Table IX: Rank ordered list of specifications and their importance**

| **Specification** | **Weighting Factor** | **Classification** |
|---|---|---|
| **Ease of Use (E)** | 90 | Critical |
| **Accuracy (A)** | 75 | Critical |
| **Durability (D)** | 65 | Important |
| **Safety (S)** | 50 | Important |
| **Cost (C)** | 40 | Important |
| **Performance (P)** | 20 | Optional |

Next, scores are assigned each of the prototypes based on their performance on each specification (Table X).

**Table X:** unweighted scores for each prototype

| **Weighting Factors:** | **90** | **75** | **65** | **50** | **40** | **20** | **-** |
|---|---|---|---|---|---|---|---|
| **Designs** | **E** | **A** | **D** | **S** | **C** | **P** | **Total** |
| Chest electrodes | 4 | 7 | 3 | 9 | 9 | 10 | 42 |
| Commercial Plethysmograph on Wrist | 9 | 8 | 7 | 9 | 8 | 10 | 51 |
| Self-Constructed Plethysmograph on Wrist | 8 | 7 | 6 | 7 | 7 | 10 | 45 |
| Commercial Plethysmograph on Chest | 3 | 8 | 8 | 9 | 8 | 10 | 46 |
| Self-Constructed Plethysmograph on Chest | 2 | 7 | 6 | 7 | 2 | 10 | 34 |

Finally, the scores are weighted according to Table IX and the highest-scoring choice was selected (Commercial plethysmograph on wrist), as seen in Table XI.

**Table XI:** Weighted Scores Comparing Different Potential Prototypes for Monitoring

| **Weighting Factors:** | **90** | **75** | **65** | **50** | **40** | **20** | **-** |
|---|---|---|---|---|---|---|---|
| **Designs** | **E** | **A** | **D** | **S** | **C** | **P** | **Total** |
| Chest electrodes | 360 | 525 | 195 | 450 | 360 | 200 | 2090 |
| Commercial Plethysmograph on Wrist | 810 | 600 | 455 | 450 | 320 | 200 | 2835 |
| Self-Constructed Plethysmograph on Wrist | 720 | 525 | 390 | 350 | 280 | 200 | 2465 |
| Commercial Plethysmograph on Chest | 270 | 600 | 520 | 450 | 320 | 200 | 2360 |
| Self-Constructed Plethysmograph on Chest | 180 | 525 | 390 | 350 | 80 | 200 | 1725 |

**Morph Chart**

Table XII contains the morph chart of decisions made in order to best meet each specification.

**Table XII**: Morph Chart Analysis for Specification Requirements

| **Desired functions** | **Partial Concepts to achieve each goal** | | |
|---|---|---|---|
| **Safety** | Hollow Shell Case Band Design | **Box case + straps** | Box case + adhesives |
| **Cost** | Preowned Parts | **Mass produced parts** | Parts Assembled From Scratch |
| **Ease of Use** | **Video Instructions (no language)** | Pictogram | Verbal instructions |
| **Accuracy** | **Calibration Step** | Window Size | Multiple Sensors |
| **Placement** | **On Wrist** | On Ear | On Chest |
| **Performance** | Loud Alarm | **Accelerating Sound** | Lights and Sounds Together |

| | | | |
|---|---|---|---|
| **Durability** | Waterproof Materials | Tight internal packing | **Sealed (epoxy, silicone fillers)** |

**Regulatory and Standards Analysis**

The device is classified based on its level of invasiveness following a global regulatory model for medical devices. The wearable infant monitoring device is designed to be non-invasive, and as such is classified as a Class A low hazard device based on guidelines set by the Global Harmonization Task Force (GHTF). This device is intended for short term use, typically for several hours while the parent is away from the infant on a day to day basis.

A Premarket Notification (PMN or 510(k)) must be sent at least 90 days prior to the production of a medical device intended to be distributed. This is important as this device would be introduced for the first time, and the USFDA must be able to identify the type of device before it is released into the market. These notifications are analyzed by three different organizations within the FDA, by a combination of biomedical engineers, physicians, and other scientific professionals. This particular device will require both laboratory and clinical testing to ensure the safety of the device, and to test whether specific standards applicable to the device are met. Additional testing includes comparing the effectiveness of the device to another comparable model in the current market, to demonstrate substantial equivalence.

Formal design control documentation will be required to keep track of the process used to develop the product, as iterations of medical devices are important for understanding why certain design choices have been made. A Medical Device User Cover Fee Sheet (Form FDA 3601), a CDRH Premarket Review Submission Cover Sheet, Certification of Compliance, Indications for Use, a 510(k) Summary, and a Truthful and Accuracy Statement. The device may be subject to audits, for a variety of aspects of the device. This Quality Audit gives the USFDA confidence in both the safety and efficacy of the newly introduce medical device. The process will take approximately 90 days, as per the requirement stated by the USFDA. However, this is the minimum requirement set by the USFDA, and can be a much longer process.

**Standards**: EN 60601-2-27:2006 -- Medical electrical equipment - Part 2-27: Particular requirements for the safety, including essential performance, of electrocardiographic monitoring equipment

**Table XIII:** EN 60601-2-27:2006 Analysis

| Standard | Explanation |
|---|---|
| Object | Our materials fall within the criterion required by this particular standard |
| Normative | N/A |
| Terms and Definitions | This standard is not met, as it was ultimately decided not to use lead wires (instead using components that are pre-soldered and pre-cased) |
| General Requirements | Our materials fall within the criterion required by this particular standard, as it is a device that utilizes electrocardiographic monitoring equipment |
| Protection Against Electrical Hazards from ME Equipment | Our material does not fall within the criterion required by this particular standard, as it does not require direct exposure to ME equipment -- this is handled by a safer interface in the selected sensor (photoplethysmograph) that does not involve hazards from ME equipment |
| Protection Against Mechanical Hazards from ME Equipment and ME Systems | There is not enough information available to determine the status of the standard. However, it is necessary that the attachment of the photoplethysmography device is not a source of physical displacement or harm. |
| Accuracy of Controls and Instruments and Protection Against Hazardous Outputs | N/A |

**Ethical Concerns for Project**

This device design is primarily a proof of concept, so it consists of a bare circuit with insulated wires leading to each component: the sensor, the ADC, the Raspberry Pi, and the buzzer. Because it was unknown how future semesters might expand and modify the functionality of the device, and because of the results of this primary and secondary cost study, no enclosure was constructed for the device. As a result, there is a risk of the user injuring themselves on the exposed aspects of the device. The ethics of choosing not to place the device inside a box are discussed below.

There are several assumptions:

- It is possible to produce this box locally where the device is being constructed.
- Without the box, people are prone to injuring themselves on the device.
- The device functions equally well with or without the box.
- The total amount of available aid in the sector is M, the device without the box costs B, and the box costs N.
- The device serves X = 1 individual over its useful life (a very conservative estimate, as the device may theoretically be used for a variety of infants).

*Primary Cost*

First, the primary cost, or the harm done by including the enclosure, is calculated. There is a cost associated with this feature because the increased cost of the device results in fewer people being able to access it. This metric is reported in disability adjusted life years (DALYs).

From the WHO's data on DALYs due to several conditions worldwide [REF], cardiovascular diseases and other neonatal conditions cost 18,787,103 DALYs for people aged 0 to 59 months. In 2012, there were 653,155 people in this age category, meaning there were 28.8 DALYs/person lost due to cardiovascular disease in 2012. It should be noted that, although the WHO itemizes the DALYs into subcategories of cardiovascular diseases, this device is intended to protect against a wide array of arrhythmias, so the general metric is considered. Neonatal conditions are any that are not associated with birth-related trauma or sepsis.

When the safety feature is absent, the number of people served by the device is:

$$P = \frac{XM}{B}$$

When the safety feature is present, the number of people served by the device is:

$$P = \frac{XM}{B+N}$$

Therefore, the difference in people served is:

$$\Delta P = XM\left(\frac{1}{B} - \frac{1}{B+N}\right) = M\left(\frac{1}{B} - \frac{1}{B+N}\right)$$

By multiplying this by the DALY cost per capita of cardiovascular disease, we find that the primary cost of adding the device is

$$PC = 28.8M\left(\frac{1}{B} - \frac{1}{B+N}\right)$$

*Secondary Cost*

Next, the secondary cost, or the harm done by excluding the enclosure, is calculated in DALYs. Because the primary users of the device are infants who tend to touch everything near

them, it was assumed that 5% of infants will suffer some sort of injury if the box is not included. This injured population is calculated as such:

$$I = \frac{0.05XM}{B} = \frac{0.05M}{B}$$

To calculate this secondary cost in DALYs, it is multiplied by the WHO's DALY estimate of the proportion of DALYs due to unintentional injuries in people aged 0 to 59 months, which was 10,583,659 DALYs or 16.2 DALYs per capita:

$$SC = \frac{0.05M}{B} \cdot 16.2 = \frac{0.81M}{B}$$

To compare primary and secondary costs, it can be seen that the total available aid M cancels out and is not important. The cost B is taken to be $73.96 because it is assumed that the device will not be employed with the external monitor and other peripherals. The cost N is taken to be $6 because that was the cost of the 3D-printed box employed by the respiratory infant monitoring group. Therefore, the primary cost of including the box normalized to M was 0.03 DALYs, while the secondary cost of not including the box normalized to M was 0.02 DALYs.

$$28.8\left(\frac{1}{B} - \frac{1}{B+N}\right) = 0.03 \sim \frac{0.81}{B} = 0.02$$

As a result, to include the box costs more DALYs than to exclude the feature, so it is ethically correct to not include the enclosure, as the number of DALYs resulting from those who can no longer access the device exceeds the number of DALYs arising from the injuries that the box would have prevented.

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## Appendices

a. Schedule

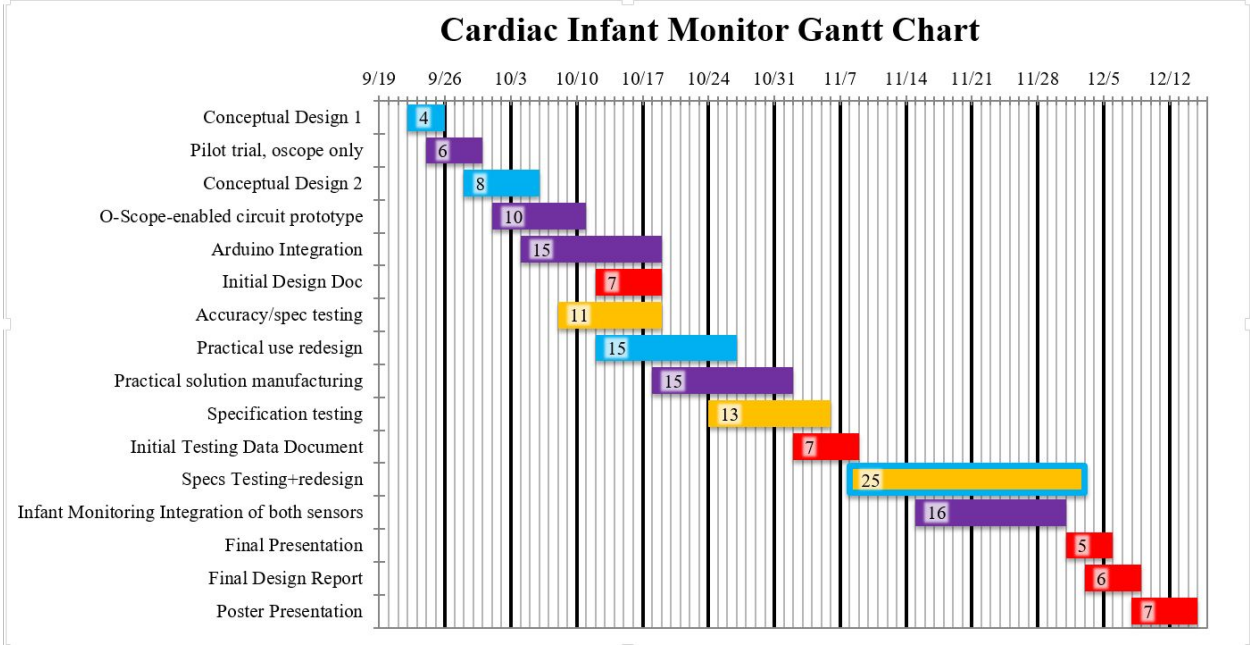


**Figure 14:** The Gantt chart outlining the tasks to be completed over the course of this semester. There are 3 planned design periods, 4 manufacturing periods, and 3 testing periods. Red bars designate time devoted to the major deliverables required for the project. The combined orange and blue region designates flexibility between design and testing at that point in the schedule. We have largely derailed from our schedule due to restrictions imposed on us early in the cycle in requiring us to test three different prototypes, delaying our final iteration with a pulse sensor, which was already well-established as a strong sensor for heart rate. We believe future teams can jump-start their project with this in mind.

b. Budget

| *Component* | *Price* |
|---|---|
| Raspberry Pi 3 | $ 35.00 |
| micro-SD card | $ 6.20 |
| ADC (I2C 3-channel) | $ 9.99 |
| Pulse Sensor | $ 6.99 |
| Alarm | $ 1.99 |
| Power Supply | $ 8.79 |
| Wires, velcro, etc | $ 5.00 |
| **Total base cost:** | $ 73.96 |
| | |
| Monitor (HDMI) | $ 110.60 |
| HDMI cable | $ 9.99 |
| keyboard/mouse | $ 15.00 |
| 1 hrs labor (7.25/hr) | $ 7.25 |
| Breadboard | $ 19.95 |
| **Total peripherals cost** | $ 162.79 |
| | |
| **Current iteration cost** | $ 236.75 |

Part costs were evaluated using Amazon, Adafruit, and Sparkfun online store catalogs.

c. Facilities and Personnel

This project will require specialized facilities and equipment in order to integrate the hardware and software into the monitoring device. The outer shell of the device prototype may be constructed using either 3D-printing or laser-cutting, and both machines will need to be reserved through the student shop resources on campus. The software and circuitry must be built and tested using sensors and basic electrical parts, such as passive elements like resistors, wires, and capacitors. Equipment necessary to build and test the device, especially in the barebones prototyping stage, includes an oscilloscope and multimeter in order to verify that the voltage and current readouts behave as expected. Additionally, a computer running Arduino software will be needed to upload and test code used by the device.

The personnel involved in this project are well-equipped to use the facilities described above to construct this device. Their curriculum vitae are attached at the end of this document,

but essentially all three members of this team have had experience with the computing platform proposed for this project, Arduino. Additionally, all members of the team have been trained on 3D rendering software and have used the laser cutter before.

d. Intellectual Property Analysis

**Table XIV: Description of Relevant Patents**

| Patent | Patent Relevance |
|---|---|
| 9,462,974 | Electrodes that are still functional with noise introduced from ambulatory movement is essential, especially for patient populations that cannot stay still (infants cannot be asked to remain still). With the infant monitoring device, having a sensor that can ignore or analyze the noise will help to increase the clinical value of the readings, and result in less false alarms for bradycardia and tachycardia. |
| 9,456,763 | This method of measuring bio-impedance signals will be used across the patient's two wrists, allowing for the measurement of heart rate with changes in impedance. Although this invention is for an implantable medical device while the infant device is non-invasive and external, it helps to synchronize the input signal so that it can be analyzed. |
| 9,433,380 | This wearable device remains on the chest and is an electrode patch that comes in direct contact with the skin for electric signals generated by the atrium. The wearable component of this invention could be implemented in prototypes with electrodes across the chest. A removable skin adhesive is useful as it eliminates the need to clean the device, which may not be feasible (especially if there isn't clean water). |
| 9,427,165 | This invention would allow for physicians to observe incidences of arrhythmia, or for the infant monitoring device, bradycardia and tachycardia, during health checkups. Although the goal of the device is to alert individuals to critical conditions in the moment, it may be useful for physicians to look at the conditions that caused the alarm to go off (specifically if there are trends in low or high bpm). |
| 8,140,143 | This washable, wearable biosensor is a counterpart to the previously mentioned patent about disposable adhesives – it may be more economical to have reusable sensors that do not need to be replaced. The ability to wirelessly transmit information is not only useful in the home setting to alert parents, but can also be used to alert hospitals or nearby physicians so that they can be prepared if patients are moving to the healthcare facility. |
| 8,655,441 | This device can be comfortably worn, and is designed to not only alert the user in real-time about dangerous physiological conditions, but also administer some sort of minor treatment to address the situation. This is ideal for further development of the infant monitoring device, as its |

| | |
|---|---|
| | inclusion in further prototypes would empower the user by providing more response time. The therapeutic effects of this device would be automated and not require additional training, which is important as it alleviates conditions until the patient can be seen at the hospital. |
| 14/018,262 | This system uses a peak detection algorithm that is capable of minimizing the noise component of movement. This device is intended for fitness monitoring, and addresses the need to monitor regular heart rate conditions, and account for those that are physiologically irregular. |
| 9,326,711 | This device measures blood volume in patients across a specified region, operating as a plethysmograph. The pulsation of the arteries/veins caused by ventricular contraction is reflected in peaks collected via light reflectance and absorbance. This sensor can be used to measure changes in blood volume across several parts of the body to locate the region with the most accurate results, compared to a measurement taken by a trained individual at the radial pulse. |
| 13/444,856 | This wearable device includes an accelerometer and optical sensors that allow for long-term, comfortable infant monitoring. This wearable device eliminates the need for disposable component, and does not have be positioned at a specific location by a trained physician, since the device will monitor vital signs once fitted onto the patient. |
| 13/526,055 | The electrostatic discharge protection layer for wristbands or any strap that may be attached to the patient provides an additional level of protection, addressing the safety spec. The signal electrode that would receive signals from electrical conduction across the skin can often rub against clothing worn over the device, causing a buildup of charge that can affect the measurements of the sensor. This removes the need to address the additional noise that may be introduced. |

**Table XV**: Journal articles that are potentially of interest

| **First Author** | **Title** | **Journal** | **Year** | **Impact on Design** |
|---|---|---|---|---|
| Sahni | "Noninvasive Monitoring by Photoplethysmography" | Clinical Perinatology | 2012 | Gives information on the waveform of the PPG that may be useful for edema detection or further data analysis. |

| | | | | |
|---|---|---|---|---|
| Fletcher | "iCalm: Wearable Sensor and Network Architecture for Wirelessly Communicating and Logging Autonomic Activity" | IEEE Transactions on Information Technology in Biomedicine | 2010 | Contains several design ideas for implementing different form factors, including the wristband that is currently proposed. |
| Johansson | "Monitoring of heart and respiratory rates in newborn infants using a new photoplethysmographic technique" | "Journal of Clinical Monitoring and Computing" | 2000 | This group found a good sampling rate and was able to measure both heart rate and respiration rate, then deconvolute the signals (which may be useful if this group integrates with the respiratory infant monitoring group) |
| Neuman | "Cardiopulmonary monitoring at home: the CHIME monitor" | Institute of Physics Publishing | 2001 | This paper is an overview of a commercial device with goals similar to this device, and it provides thresholds they found for infant bradycardia that might be implemented in this device. Additionally, the paper contains information concerning software-mediated, automated threshold calibration for different heart rate alarms. |
| Corwin | " Agreement among Raters in Assessment of Physiologic Waveforms Recorded by a Cardiorespiratory Monitor for Home Use" | Pediatric Research | 1998 | These authors are the same as the authors in Neuman et al., and this paper is about the same device. This paper contains helpful information about how it might be possible to train the software to recognize and characterize different pathological ECG waveforms, based on initial and ongoing input from trained professionals. |
| Patel | A Review of Wearable Sensors and Systems with Application in Rehabilitation | Journal of Neuroengineering and Rehabilitatio | 2012 | These authors overview the development of wearable sensors that track vital signs, particularly for those in rehab. |

| | | | | |
|---|---|---|---|---|
| | | n | | Novel sensor placement is helpful in guiding the development of prototypes and in what types of sensors will be most effective at which locations. |
| Borowski | Medical Device Alarms | Biomed Tech | 2011 | Investigates causes and management of false positive alarms in vital sign monitoring systems. This is applicable to minimizing unnecessary parent concern, with alarms for irregular heart rates based not on the actual signal but on noise or external factors. |
| Grajales | Wearable Multisensor Heart Rate Monitor | Wearable and Implantable Body Sensor Networks | 2006 | Multiple sensor placement with variability in locations allows for continuous heart rate monitoring, with built in abilities to recognize conditions when there are large differences in measurements. Large differences across the chest and wrist for example, may indicate slight embolism or poor peripheral perfusion. |
| Tapia | Real-time Recognition of Physical Activities and Their Intensities Using Wireless Accelerometers and a Heart Rate Monitor | Wearable Computers | 2007 | Allowing the device to measure not only the heart rate, but also relative motion and activity levels that may explain an abnormally heart rate, would help with infant monitoring in reducing the number of alarms that are non-pathological. |
| Fletcher | Clip-on Wireless Wearable Microwave Sensor for Ambulatory Cardiac Monitoring | Engineering in Medicine and Biology Society | 2010 | This method measures actual heart movement when clipped onto clothing over the chest, as opposed to other methods that measure electrical activity. The novelty of the clip-on idea is useful, as it requires less |

| | | | | |
|---|---|---|---|---|
| | | | | cleaning, is reusable, and does not have to be placed in a specific region. |

e. Pie Chart Analysis

Due to the fact that this proposed design involves a wristband-based heart rate sensor, the company chosen for the pie chart analysis was FitBit, Inc., which is a publicly-traded company traded under the symbol FIT. FitBit sells devices with a range of functionalities, including an array of wristband-based heart rate monitors. Table XVI contains the company's income statement for the year 2015 (January 1 - December 31). Figure 4 contains the pie chart with the designations of where the company's revenue was spent. The company's income statement is in the public record and was taken from the company's Yahoo Finance Profile.

As seen in Table XVI, FitBit, Inc. had a total revenue of about $1.9 billion in 2015. It is assumed that this revenue came only from selling their products, so this number is also the total product price for the year. The ratio of this product price to the cost of the revenue, or cost of goods sold (COGS), is about 2:1, meaning that FitBit, Inc. sells their products for about twice as much as they cost to produce.

**Table XVI**: FitBit, Inc.'s 2015 income statement, where all dollar amounts were rounded to the nearest thousand. This data was used to create the pie chart in **Figure 3**.

| | |
|---|---|
| **Revenue** | |
| Total Revenue | $1,857,998,000 |
| Cost of Revenue | $956,935,000 |
| **Gross Profit (Total - Cost)** | **$901,063,000** |
| **Operating Expenses** | |
| Research Development | $150,053,000 |
| Selling General and Administrative | $402,830,000 |
| Non-recurring | - |
| Others | - |
| Total operating expenses | - |
| **Operating Income or Loss** | **$348,198,000** |
| **Income from Continuing Operations** | |
| Total Other Income/Expenses Net | -$59,230,000 |
| Earnings Before Interest and Taxes | $288,968,000 |
| Interest Expense | $1,019,000 |
| Income Before Tax | $287,949,000 |
| Income Tax Expense | $112,272,000 |
| Minority Interest | - |
| **Net Income from Continuing Operations** | **$175,677,000** |

| | |
|---|---|
| **Non-recurring Events** | |
| Discontinued Operations | - |
| Extraordinary Items | - |
| Effect of Accounting Changes | - |
| Other Items | - |
| **Net Income: $175,677,000** | |
| Preferred Stock and Other Adjustments | - |
| **Net Income Applicable to Common Shares** | **$114,018,000** |

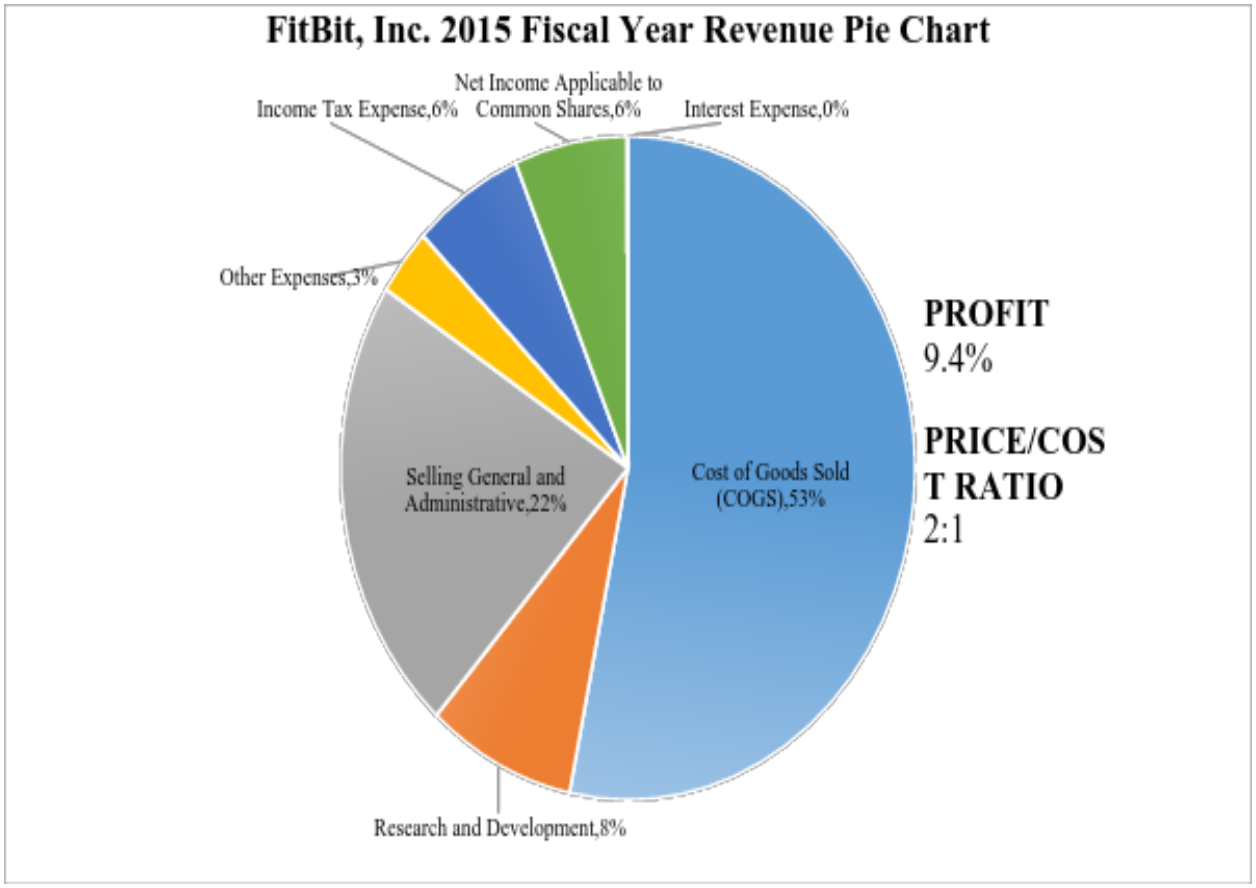


**Figure 15:** FitBit, Inc.'s 2015 expenditures, as parts of the company's total revenue for that first fiscal period. Note that the profit applicable to shareholders is 6.3%; 9.4% refers to the net income from continuing operations divided by the total revenue.

f. MAUDE Failure Mode Analysis

All failure data comes from the FDA's Manufacturer and User Facility Device Experience (MAUDE) database, in the "Monitor, Cardiac (Incl. Cardiotachometer & Rate Alarm)" product class.

**Table XVII:** 10 representative failure modes for the product class of this device.

| **Device** | **Outcome** | **Probable Mode of Failure** |
|---|---|---|
| Nihon Kohden Tomioka Corporation BSM-6700A Vital Sign Monitor | Patient was not harmed | Video display of heart rate information went out due to malfunctioning inverter board. |
| Nihon Kohden Tomioka Corporation ZM-530PA Transmitter | Patient was not harmed | The device was not properly attached to the patient, so the leads fell off and no signal could be measured. |
| Nihon Kohden Tomioka Corporation ZM-541PA Transmitter | Patient was not harmed | Device overheated and caused the battery contacts to melt. |
| GE Medical Systems Information Technologies Inc. Solar 800I Patient Cardio/Respiratory Monitor | Patient unharmed, but at higher risk for having heart failure going unnoticed | Device failed to alarm visibly or audibly when patient exhibited heart rate below the set bradycardia limit. |
| Nihon Kohden Tomioka Corporation ZM-530PA Transmitter | Patient was not harmed | Device displayed waveforms even when patient was unconnected, probably due to sticky residue on inside of case. |
| Philips Medical Systems V24/26 Component Monitoring System Bedside Monitor M1205A | Patient died | Ventricular tachycardia alarm failed to sound even though the patient had been in VT for 15 minutes. This failure is currently under investigation. |
| Philips North America Corporation Intellivue TRX+ | Patients burned | Approximately 35 units suffered heat damage to the |

| | | |
|---|---|---|
| Telemetry Transmitter M4841A | | casing and batteries, burning some patients and staff handling devices |
| Welch Allyn Inc. Propaq 242 Cardiac Monitor | Patient was not harmed | Device would not start due to self-extinguished fire from 4-year-old, corroded battery |
| Welch Allyn Inc Propaq Encore 206/EL | Patient was not harmed | Device would intermittently shut down without an alert (problem resolved after battery replacement) |
| Welch Allyn Inc Propaq 242CS | Patient unharmed, but at higher risk for having heart failure going unnoticed | Device failed to alarm visibly or audibly when patient exhibited low heart rate; however, problem could not be reproduced by service technicians. |

As seen in **Table XVII**, the most common failure modes were hardware failures (overheating, improper patient placement, or improper maintenance), the usage of old or poor-quality batteries, and likely software bugs that resulted in alarms failing to trigger.

G. Code

```
# Simple demo of reading each analog input from the ADS1115 from the PPG sensor
# Author: Jason Liu for BME462 with Dr. Malkin
# License: Public Domain


## import commands ------------------------------------------------

# import time library
import time

# Import the ADS1x15 module.
import Adafruit_ADS1x15

# importing CSV for data analysis of reading
import csv

# import pylot in general
import matplotlib.pyplot as plt

# import animations for pyplot
import matplotlib.animation as animation
#matplotlib.use('Agg')
```

```
# Create an ADS1115 ADC (16-bit) instance.
adc = Adafruit_ADS1x15.ADS1115()

## /import commands----------------------------------------------------

# Note you can change the I2C address-- in case you want to add more I2C-enabled things
from its default (0x48), and/or the I2C
# bus by passing in these optional parameters:
#adc = Adafruit_ADS1x15.ADS1015(address=0x49, busnum=1)


# The following is specifically for changing the gain on the ADC. Not changed (1) for
the PPG sensor
# Choose a gain of 1 for reading voltages from 0 to 4.09V-- for the ADC
# Or pick a different gain to change the range of voltages that are read:
#  - 2/3 = +/-6.144V
#  -   1 = +/-4.096V
#  -   2 = +/-2.048V
#  -   4 = +/-1.024V
#  -   8 = +/-0.512V
#  -  16 = +/-0.256V
# See table 3 in the ADS1015/ADS1115 datasheet for more info on gain.
GAIN = 1

# Main loop. # each loop needs to run faster than .375 seconds per loop to catch all
relevant beatdata
# for regular humans this value can be 0.75.
print("initializing...")

start_time=time.time()

five_iterator_bool=True
step_detected=True
beat_delaytimer=-0.5
five_index=0
five_data_list = []
beat_detected = []
instant_rate=60
sample_length = 15

five_data_list.append([])
five_data_list.append([])
five_data_list.append([])

for mainiter in range(0,5):
    print("new five loop initiating" + str(mainiter) +
"@#@#@#@#@#@#@#@#@#@#@#@#@#@#@#@#@#@#");
    plt.clf()
    while five_iterator_bool:
            # scales the PPG value to between 0 and 5 (originally from 0-26123)
            ppg_currentvalue_corrected5=5.0*(float(adc.read_adc(3,gain=GAIN)) /26123.0)
            five_loop_timeelapsed=time.time()-start_time
            five_data_list[0].append(ppg_currentvalue_corrected5)
            five_data_list[1].append(five_loop_timeelapsed)
            #print("iteration time:" + str(five_loop_timeelapsed));
            time.sleep(0.03)
```

```
            if five_index>4:

past_several_avg=sum(five_data_list[0][(five_index-5):five_index])/5
                    if past_several_avg > 3 and time.time()-beat_delaytimer>0.5:
                            beat_detected.append(True)
                            if sum(beat_detected) > 1:
                                    instant_period=time.time()-beat_delaytimer
                                    instant_rate=60/instant_period
                                    five_data_list[2].append(instant_rate)
                                    print("Heart Rate: " + str(instant_rate))
                            print("beat detected-------------------------------------")
                            beat_delaytimer=time.time()
                    else:
                            beat_detected.append(False)
            if len(five_data_list[0]) > len(five_data_list[2]):
                heart_rate_list = five_data_list[2]
                heart_rate = -1 if len(heart_rate_list) == 0 else
heart_rate_list[len(heart_rate_list) - 1]
                five_data_list[2].append(heart_rate)
            five_index+=1
            if five_loop_timeelapsed > sample_length:
                    five_iterator_bool=False
    print("five_loop successful! beats detected:")
    print(sum(beat_detected))

    fig=plt.figure()
    ax=plt.axes(xlim=(0,5),ylim=(0,5))
    line, = ax.plot([], [] , lw=2)

    plt.xlabel("Time (seconds)")
    plt.ylabel("Voltage (volts)")
    title = "Pulse Plethysmograph output window"
    plt.title(title)
    hr_box = ax.text(2.5, 2.5, '')

    def init():
            line.set_data([], [])
            return line,

    def animate(i):
            x=five_data_list[1]
            y=five_data_list[0]
            heart_rate_list = five_data_list[2]
            line.set_data(x[:i],y[:i])
            if x[i] > 4:
                ax.set_xlim(x[i] - 4, x[i] + 1)
            else:
                ax.set_xlim(0, 5)

            try:
                if heart_rate_list[i] >= 0:
                    hr_text = '%.1f' % heart_rate_list[i] + " BPM"
                    hr_box.set_text(hr_text)
                    hr_box.set_x(x[i])
                    hr_box.set_y(y[i])
            except (IndexError):
                    hr_box.set_text('')
```

```
            return line,
    frames = len(five_data_list[0])
    interval = float(sample_length) / len(five_data_list[0]) * 1000.0
    print(interval)
    anim = animation.FuncAnimation(fig, animate, init_func=init, frames=frames,
interval=interval, blit=False)
    plt.show()

#anim.save('first_success_5sec_JL.mp4',fps=30) video output doesn't quite work

print("plot successful")


print("program terminated successfully")
```

Udita Delta Ghoshal
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## Education

**Duke University** Durham, NC, 2013-present
Declared Course of Study: Biomedical Engineering (Major), Genome Sciences and Policy (Certificate)
Relevant Coursework: Data Structures and Algorithms, Medical Instrumentation, Design for the Developing World (in progress)

## Research Experience

***Research Assistant: Cullen Lab*** January 2015-present

- Wrote a Perl script to parse through deep sequencing data and identify reads of interest
- Used cloning and luciferase-based assays to quantify the effects of m6A RNA methylation
- Data featured in May 11, 2016 edition of *Cell Host and Microbe*
- Currently also working on project to direct lentiviral integration using CRISPR-tethering
- Skills: Perl, cell culture, cloning, PCR, Western blots, transfection, transduction

***iGEM Research Project: Demonstrating Ultrasensitivity in the CRISPR/dCas9 System*** 2014

- Investigated cooperativity in *E. coli*, in the hopes of demonstrating cooperative repression and creating a bistable toggle switch
- Helped present work at an international conference and competition in Boston, where team won gold medal
- Designed and coded the website for the Duke team

## Work Experience:

**ECE 110L Lab Head Teaching Assistant** 2015- present

- Introductory electrical engineering course, labs are heavily Arduino-based
- Lead a section of 12 students
- Oversee weekly grading meetings

**Laboratory Assistant: Cullen Lab** January-August 2015

- Made buffers and helped with general laboratory tasks
- Cultured cells
- Cloned DNA constructs

**Front Desk and Journal Processing at Lilly Library** 2013- 2014

- Added incoming periodicals to the collection and processed interlibrary loans (ILLs)
- Maintained bound periodical volumes
- Assisted patrons at the front desk

## Skills

Java, Arduino, Python, Perl, MATLAB, LaTeX, Photoshop, HTML, CSS, Microsoft Office, AutoCAD, Google SketchUp

# Jake Son

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(858)-776-7553 | js545@duke.edu

## EDUCATION

**Duke University** — **Durham, NC**
*Bachelor of Science in Biomedical Engineering, Minor in Chemistry* — Expected 2017

- **GPA:** 3.5/4.0; **MCAT**: 98th percentile
- **Relevant Coursework:** Quantitative Physiology with Biostatistical Applications, Modeling Cellular and Molecular Systems, Signals and Systems, Fundamentals of Biomaterials/Biomechanics, Modern Diagnostic Imaging Systems, Introduction to Medical Instrumentation, Design for the Developing World, Metabolic Networks and Design, Medical Device Software Design, Organic Chemistry, General Chemistry, Biochemistry

## WORK EXPERIENCE

**Duke Medicine Department of Neurology** — **San Diego, CA**
*Research Assistant* — June 2016 to Present

- Tracked medication administration records for 150+ patients in a retrospective clinical study focused on NCSE and SE
- Presented 2nd author poster at the Annual Neurocritical Care Society Meeting

**Rady Children's Hospital** — **San Diego, CA**
*Summer Intern with Pediatric Cardiology* — May 2015 to August 2015

- Analyzed congenital heart defects, catheterization procedures, and associated biomedical equipment
- Worked with UCSD Engineers to integrate transfer of data from MRIs, CT Scans, and other medical imaging equipment from Rady Children's to research facilities

**EMT** — **Durham, NC**
*EMT – Basic, Teaching Assistant* — September 2014 to September 2015

- Incorporated core skills on multiple clinicals as a first responder
- Provided mentorship and aided junior members in clinical assessments and gaining practical skills

## COMMUNITY INVOLVEMENT & LEADERSHIP EXPERIENCE

**Compass-Deloitte Fellow** — **Durham, NC**
*Regional Council Director, Duke Captain, Compass Mentor, Compass Fellow* — September 2013 to Present

- Selected out of over 100 teams for Deloitte Consulting's advisory program to accelerate production and marketability of paintbrush grips ergonomically designed to alleviate pain from diseases, primarily arthritis
- Led team of twenty as Duke Captain to secure a $10,000 matching donation
- Invited to be a Duke Innovation & Entrepreneurship Initiative Student Liaison Committee

**GlobeMed** — **Durham, NC**
*Previously Finance Chair, Member* — January 2015 to Present

- Brought on new individual and corporate donors to sustain projects in Durham and with SHED in Tanzania

**Sexual Assault Prevention Team** — **Durham, NC**
*Co-Chairman* — May 2015 to Present

- Conducted research through a campus climate survey and consulted with various campus organizations to better understand the multifaceted nature of sexual assault and how it manifests itself in campus culture
- Presented research and recommendations to the Duke University Greek Alumni Council and IFC Presidents
- Recipient of the Order of Omega IFC President's Award for work with fraternities

**Duke Children's Hospital** — **Durham, NC**
*Child Life Program Volunteer* — June 2016 to Present

- Works directly with children to facilitate learning away from school and a safe playing environment isolated from hospital care

**Sigma Phi Epsilon NC Gamma** — **Durham, NC**
*Vice President of Finance* — May 2014 to May 2015

- Worked with a $100,000 budget, managed alumni outreach and helped organize philanthropy events
- Attended the Carlson Leadership Academy to train in strategic planning and chapter leadership
- Two-time recipient of the Duke IFC Merit-Based Scholarship

## SKILLS & INTERESTS

**Technical Skills:** Proficient in Matlab, Arduino, Microsoft Office, LaTeX, Python, Git, CAD
**Interests:** North Carolina Barbeque, watching basketball, violin concertos, chess, cooking, hiking

# JASON LIU

SENIOR BIOMEDICAL ENGINEERING STUDENT AT DUKE UNIVERSITY

**EMAIL:** jason.liu2@duke.edu **PHONE:** (302) 543-3966

## SUMMARY

Biomedical Engineering Student at Duke University, with interests in biomaterials, tissue engineering, additive manufacturing, hardware development in biosensors, and medicine.

## EDUCATION

**Pratt School of Engineering, Duke University Class of 2017**
BSE Biomedical Engineering 2017
2013-2016 All Semesters Deans List
GPA: 3.8

## EMPLOYMENT

**National Cancer Institute**, *Summer Intern in the Protein Engineering Section*, Frederick, Maryland — Jun 2012 - Aug 2012
Worked with: culturing and cloning Yeast (Strep. Griseus), DNA extraction, protein isolation, purification, crystallization. Gained proficiency in the use of BLAST sequence alignment tools and Vector mapping software.

**University of Maryland School of Dentistry**, *Summer Intern in Biomaterials and Tissue Engineering*, Baltimore, Maryland — Jun 2014 - Aug 2014
Worked with dental composite biomaterials, testing for biofilm formation and structural integrity. Worked with stem cell culture for osteogenic tissue engineering in rabbits. Studied current research in orthopedic solutions in regenerative medicine. 120 hours.
Publication co-author: Ping Wang, Liang Zhao, Jason Liu, et al., Bone tissue engineering via nanostructured calcium phosphate biomaterials and stem cells. Bone research (2014) 2,14017; doi:10.1038/bones.2014.17

**Duke University Pratt School of Engineering and Trinity College**, *Teaching Assistant*, Durham NC — Sep 2014 - Current
Teaching computational methods in engineering in MATLAB, teaching Calculus 2, teaching Multivariable Calculus, teaching Differential Equations
For the past year, I have worked as a lab assistant/instructor in BME354, a highly intensive teaching laboratory in biomedical instrumentation. 150 hours.

**Biomedical Research Department in the Nemours Alfred I. duPont Hospital for Children** — Jun 2015 - Aug 2015
, *Research Student*, Wilmington, Delaware
Worked with advanced hydrogel biomaterials and characterized their cellular response. I worked with cell types that typically populate the exterior layer of blood vessels including adventitial fibroblasts (AoAFs) and vascular endothelial cells (VECs). The goal of the research is to develop cost-effective, easy-to-use, injectable biomaterials that can be placed on the outer surface of at-risk blood vessels. 400 hours

**Pratt Fellowship under Dr. Ashutosh Chilkoti: Synthesizing an Antibody-Toxin Fusion Protein** — Jan 2016 - Current, Jan 2016 - Current
, *Undergraduate student researcher*, Durham, NC
I'm currently working to develop a novel antibody-toxin fusion protein drug, via protein engineering, that targets glioblastoma. Synthesizing the antibody and toxin requires skills in cloning, protein purification, chemical synthesis, and standard laboratory procedures. I expect to be able to publish, and present my work at the conclusion of my research, most likely when we validate the effectiveness and efficacy of the drug. 900 hours.

## SKILLS

**TECHNOLOGICAL PROFICIENCY:**: MATLAB, Javascript, HTML, LaTeX, Arduino, KNIME, Particle.io Photon integration, Biosensors, Analog Filter Design, 3D printing, Raspberry Pi, Laser Cutting/Engraving, CAD
**LABORATORY TECHNIQUES:** Cell and Tissue Culture (>2.5 years of experience), DNA Cloning and Vector Preparation, Handling model animals, Assay design (ELISA, Cell Titer, Translation), Immunostaining, Biomaterial Engineering (Calcium Phosphate, Alginate, Hydrogel, ELP), Flow Cytometry

## ACTIVITIES

**Duke Lion Dance Performing Group**, *Founder/President* — Sep 2014 - Current
Founder of the first Duke Lion Dance performing group. We perform at cultural events and around the community of Duke, sharing Chinese culture. Performed at the Duke Chinese Department Chinese New Year celebration 2/22/2015 and the Duke Asian Student Association Lunar New Year celebration 2/27/2015.

## VOLUNTEERING

**Duke Hospital Volunteering Program- Cancer Center and Emergency Department** — Sep 2014 - Current
, *Volunteer*
I assisted patients and provide hospitality to patients and family members in the inpatient cancer units, and currently volunteering in the Emergency department. Gained important insight as an observer of the patient, administrator, and healthcare provider environments. 120 hours.

**Duke University Alpha Phi Omega**, — Jan 2015 - Current
*Pledge Class Service Chair, Social Chair, Service I Chair, of the Lambda Nu chapter*
I am an executive member of the Alpha Phi Omega Service Fraternity, devoted to brotherhood, leadership, and service to the community and humanity. Gained logistics and planning skills as a past Service Chair, which included planning a service project for the local Hayti community. I have gained labor adaptability as a volunteer in many different environments. 300 hours.