UNIVERSITY OF WISCONSIN – MADISON: DEPARTMENT OF BIOMEDICAL ENGINEERING

Electronic Stethoscope

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ABSTRACT

The traditional acoustic stethoscope has been in use for nearly 200 years, changing very little over that time. As one of the most important diagnostic tools in a doctor's repertoire, and comparatively low-tech by today's standards, many recent attempts have been made to upgrade the design of the stethoscope. However, as they are at least twice the cost of traditional stethoscopes and produce a sound different from a traditional stethoscope, these electronic stethoscopes have had a hard time catching on. As such, our client requests a redesigned electronic stethoscope consisting of a main receiver box, with both speakers and a headphone jack for listening, along with two wireless microphones that attach to the patient and detect the heart and lung sounds. The final prototype utilizes two microphones whose signals are sent through a quad amp which implements an initial gain of three and filters the input via a five pole Sallen-Key low pass filter. The two filtered signals are then sent to a mixer, which allows the user to select which input microphone they would like to use and adjust the bass and treble characteristics of the signal. Following the mixer, the signal is sent to another switch, which allows the user to choose between headphone or speaker output. Future work includes continued work to refine our circuit, and implementing wireless technology for transmission of the microphone signal. After implementing these two improvements, the circuitry would be wire wrapped, or printed on a circuit board, in order to fit it into the existing speaker case.

BACKGROUND

PROBLEM STATEMENT

Anesthesiologists need to listen to patients' heart and breath sounds during anesthesia care. Manual stethoscopes are commonly used but only allow for one listener and are uncomfortable for extended wear. An electronic stethoscope was developed which utilizes a speaker and microphone system, but it is too large for practical purposes. In order to improve upon the existing device, a more suitable power supply must be found. Ideally, changes should also be made to allow for a dual microphone system with wireless capabilities, as well as a main receiver with a speaker and a headphone jack for private listening.

STETHOSCOPE BACKGROUND

Although it is a very simple device, the stethoscope is one of the most important diagnostic tools in the medical world. Over almost two centuries, the stethoscope has been changed and refined often, but it has never strayed too far from the original design. Rene Theophile, a French physician, is attributed with the invention of the first stethoscope in 1816 when he was examining an obese patient [1]. His first model of the stethoscope was simply a wooden tube resembling a candlestick [2]. Over the years, this model has evolved into the device that we now recognize as the stethoscope through many small changes, such as adding earpieces for each ear and developing the combined bell and diaphragm chest piece [2]. Very few changes have been made to the model of the stethoscope since 1961, when Dr. David Littman patented a new, lighter model with a single binaural tube that drastically improved the acoustic technology. The stethoscopes that are now commonly used are called "Littman stethoscopes" for this reason.

A stethoscope is a very straightforward device. The chest piece consists of a shallow, bell-shaped piece and a clear, stiff diaphragm, which is then connected to the metal earpieces by a flexible tube. The bell is used to pick up lower frequency sounds, and the diaphragm is used for higher frequency sounds. When the chest piece is placed on the skin, vibrations within in the body are amplified by either the bell or diaphragm. These acoustic pressure waves then travel up through the tubing, resonating to the earpieces and into the listener's ears [3].

Very few changes have been made to the overall design of the stethoscope over the years because it does its job so well. However, there are a few problems with current models. For example, with the standard acoustic stethoscope, the listener is not able to amplify the sounds. This is sometimes a problem if he or she is only getting very quiet sounds through the stethoscope. Also, the earpieces of stethoscopes can be quite uncomfortable [4]. Although these are not enormous problems, current technology has introduced alternatives to the acoustic stethoscope.

CURRENT METHODS

In 1961, right around the same time that Littman patented his new model, a company named Amplivox produced the first electronic stethoscope. It was only meant to be an academic tool due to its large size and weight, and it also produced distinctly different sounds than what doctors were used to hearing [5]. Because of this, the idea was largely abandoned, and users returned to the conventional stethoscope [2]. However, some companies have returned to this idea and have introduced new devices to the market. Some enhancements that modern electronic stethoscopes have are sound transducers, adjustable gain amplifiers, and frequency filters [4].

Although these improvements have been made, the electronic stethoscope still has not been embraced by the medical community. This is because the sounds that the listener receives through the earpieces are mixed with electronic noise, causing the sounds to be different than the non-electronic, acoustic stethoscope [4]. Also, electronic stethoscopes are very sensitive to surrounding noises, and these will overpower the sound of the heart and lungs [4]. Many electronic stethoscopes on the market do not have the original bell and diaphragm or tubing, which help filter background noise and produce a sound that the listener is more familiar with [4]. Electronic stethoscopes, like standard acoustic stethoscopes, only allow one listener, which is not preferable for a teaching environment. They also are about $400 MSRP, which is much more expensive than an acoustic model. Current models on the market only have one input microphone, so the head of the stethoscope must be moved to listen to other areas of the body. This project will fix many of the problems of currently marketed electronic stethoscopes tailor the stethoscope to our client's specific needs.

PREVIOUS PROTOTYPE

The current prototype follows the general block setup featured in Figure 1. The target sounds originate from the vibrations of the stethoscope's thin diaphragm, and the sound waves reverberate through the rubber tube. This tubing acts as a mechanical low pass filter, assisting in imitating the original sound of a non-electronic stethoscope. Located at the end of the tube is a condenser microphone housed in a plastic coupling device designed in SolidWorks and printed on a 3D printer.

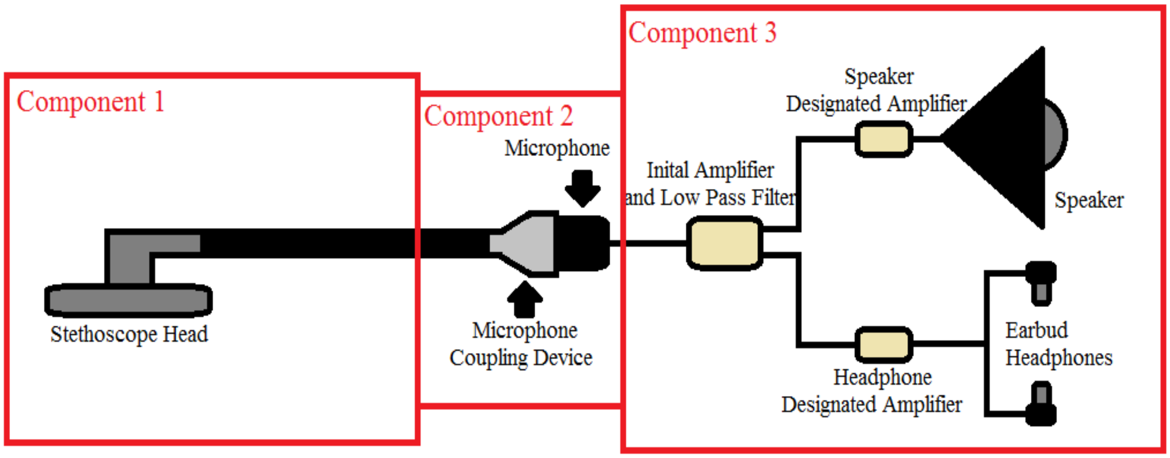

Figure 1: General block setup for current design showing three major design components: initial sound pick-up, conversion of acoustic sound to electrical signal, and amplification, filtration, and audio sound of the signal
Image Courtesy of: Spring 2011 Stethoscope Team

The signal is then sent through a DC blocking capacitor followed by a non-inverting voltage follower, a second-order low pass filter, and finally an active gain stage providing a gain of 10. The corner frequency for the filter is 800 Hz. Before the signal is routed to the desired audio outputs, it is subjected to voltage dampening by a potentiometer that acts as a volume control. The speakers currently being utilized are rated for 5 watts at 4 ohms. For headphone amplification, the LM386 was chosen and offers a nominal gain of 20. In order to drive the speakers, a high-powered TDA2003 was chosen to provide a gain of 100, which can be altered by varying the resistors and capacitor values within the circuit. Currently the device draws 12V DC and pulls approximately 100mA at peak speaker output from a variable power supply. The collection of single supply operational amplifiers utilizes a virtual ground of 6 volts, created by a series of buffered voltage dividers (Figure 2).

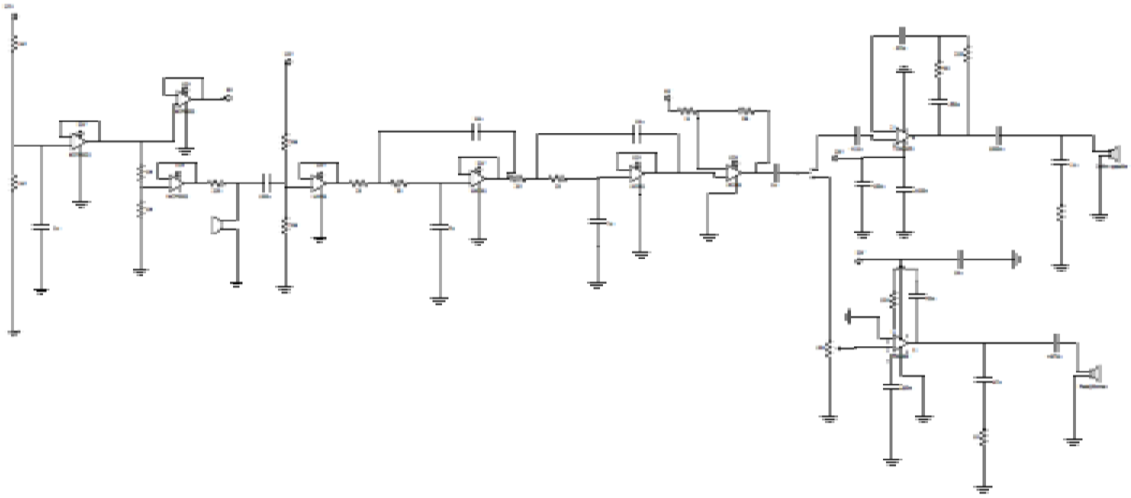

Figure 2: Current electronic stethoscope circuit diagram with microphone input located on the left and audio outputs on the right
Image Courtesy of: Spring 2011 Stethoscope Team

The housing for the main receiver box is a clear polycarbonate box, which contains the speakers and all the user controls including power switches and volume controls for both headphones and speakers. On the side of the box is a small hole for the input wires from the condenser microphone, with the lid to the housing being secured by six screws [6].

Considerations for improvement this semester include shrinking the overall dimensions of the housing to make the device more practical for clinical use. The target size is no greater than a 5” cube. The loose wires will also need to be secured and protected in accordance with improving aesthetics and safety. An additional input microphone will be added to allow for the user to compare and contrast two separate lung sounds, which will be especially useful in determining which bronchi the endotracheal tube enters during pediatric procedures. A final consideration would be to ideally make both input microphones wireless.

DESIGN CRITERIA AND CONSIDERATIONS

Despite having a general schematic (see Figure 3) for how the final prototype will look, there are three main components of the design that need to be evaluated. Therefore, the design options are broken up into three different categories: microphone type, wireless technology, and amplifiers. As can be seen in Figure 3, the final prototype will consist of a main receiver box holding the speaker and headphone jack, all the internal circuitry components, and the wireless receivers for the two microphones. Attached to each stethoscope head will be a microphone, a lithium coin battery for power supply, and a wireless transmitter.

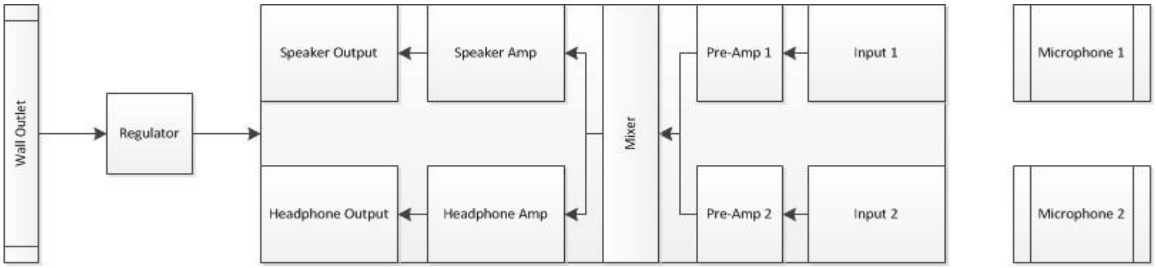

Figure 3: A preliminary schematic of the main components of the design. Inputs from microphones are located on the right, with power from a standard AC wall outlet on the left. Arrows inside main receiver box designate the direction of signal processing.

FUNDING

Funding for the prototype will be supplied by the client, Dr. Scott Springman. Dr. Springman suggested a budget of $200-$300, with the team contacting Dr. Springman when the money is needed. If the team expects to go over this budget, Dr. Springman must be notified in order to work out an alternative funding source or request a larger budget.

MICROPHONES

In order to determine the best microphone to use in our final design, three different types were analyzed and compared. The three types of microphones that were considered for use were a condenser microphone, a fiber optic microphone, and a MicroElectrical-Mechanical System (MEMS) microphone.

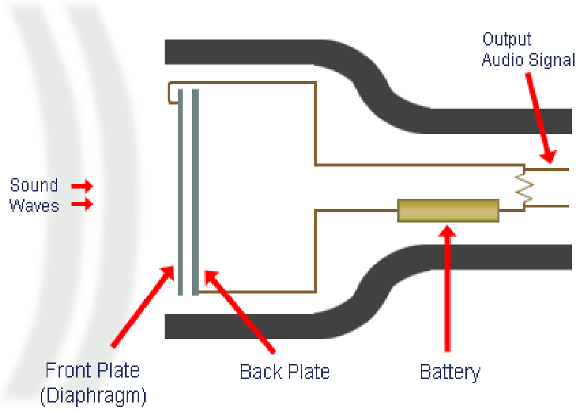

Figure 4: A cross-section look at a condenser microphone.
Image Courtesy of: http://www.mediacollege.com/audio/microphones/condenser.html

The first option, a condenser microphone, works by means of a capacitor, which converts acoustical energy into electrical energy (Figure 4).The front plate, diaphragm, is made of lightweight material and vibrates when hit by sound waves. This causes the distance between the diaphragm and the back plate to change; resulting in a change of capacitance as given by the formula $C = \frac{\varepsilon A}{d}$. In order for the change in capacitance to take place, a voltage must be supplied across the two capacitor plates. This voltage is supplied by some type of external power source, usually a small battery within the microphone. The external power source also allows for the condenser microphone to have a higher output when compared to types of self-powered microphones, such as the dynamic microphone. Due to their sensitivity to sound and good frequency response, condenser microphones are a popular choice in laboratory and sound recording studios [7].

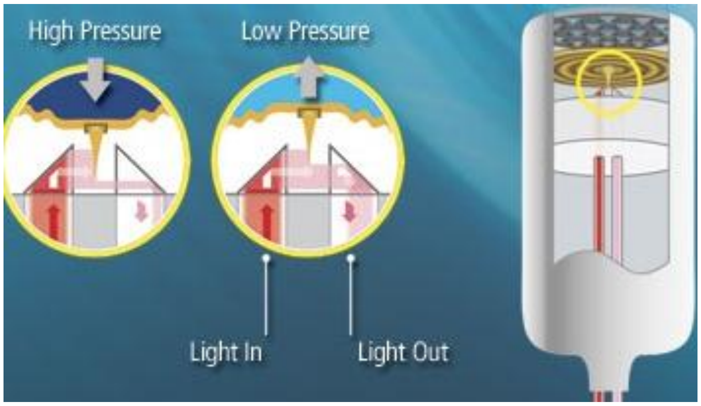

Figure 5: The inner workings of a fiber optic microphone.
Image Courtesy of:
http://www.optoacoustics.com/technology/core-sensor-platform

The second microphone option was a fiber optic microphone (Figure 5). Fiber optic microphones work by sensing changes in light intensity, rather than changes in capacitance or magnetic fields like traditional microphones. Light from a laser source travels through an optical fiber, where it illuminates the surface of a reflective diaphragm at the tip of the microphone. When the diaphragm vibrates due to sound waves, the light intensity being reflected off the diaphragm is changed. This change of light intensity, transmitted by a second optical fiber, is detected by a photo detector. The photo detector then transforms the light intensity into an analog or digital audio signal for transmission. Because fiber optic microphones do not react to electrical or magnetic fields (EMI/RFI immunity), and because they possess a large frequency response range, fiber optic microphones are ideal for use inside industrial turbines or in MRI suites, places where traditional microphones are ineffective [8].

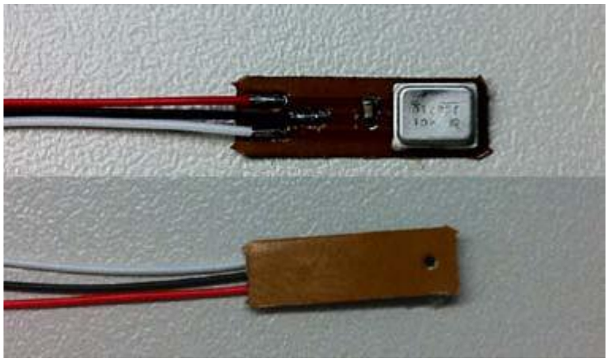

Figure 6: An MEMS microphone attached to the evaluation board.
Image Courtesy of:
http://www.analog.com/en/audiovideoproducts/imems-microphone/admp401/products/product.html

The final microphone considered was a MEMS microphone (Figure 6). MEMS, or MicroElectrical-Mechanical System, is the name given to very small mechanical devices driven by electricity. The microphone's mechanics are similar to a condenser microphone, the main difference being that the MEMS microphone is mounted on a circuit board of approximately 15 mm^2. The microphone element consists of an impedance converter and an output amplifier, transmitting a digital audio output signal recorded from the microphone head. The microphone head faces through a hole in the bottom of the circuit board, while the body of the microphone element is located on the top. Due to their extremely small size, MEMS microphones are used in smartphones and Bluetooth headsets, as well as other similar applications [9].

WIRELESS

For audio transfer, three wireless signals were considered: Bluetooth chipsets, an FM transmitter, and PurePath wireless. Bluetooth chipsets utilize low-power radio frequency transmission [10]. They are extremely small and relatively inexpensive. However, they are more difficult to integrate into a circuit, as they are inflexible in their implementation. A circuit must be built around the Bluetooth chip, increasing its complexity.

The second wireless option analyzed was an FM transmitter. This method would be similar to sending the audio from an iPod to the radio of a car. An FM transmitter system would be easy to implement, but would use significantly more power. The transmitter is larger than desired, and the high power necessary to run it would require additional bulky batteries attached to the stethoscope. The problem of ensuring the FM signal was not in use would also have to be considered.

The final wireless option was TI's PurePath Wireless system. PurePath Wireless sends an uncompressed digital audio signal over a strong radio frequency link [11]. PurePath was designed solely for audio transmissions, so the sound quality is excellent. This system is available in development kits, making it easy to implement. The kits also come with rechargeable batteries with a 22-hour battery life.

AMPLIFIERS

Two main classes of amplifiers were considered for signal amplification, AB and D. Both act in similar fashions, taking power from a source and using it to increase the amplitude of a signal while maintaining the input signal's shape. The main advantage of a class-D amplifier is power efficiency. Usually metal–oxide–semiconductor field-effect transistors are used and operate with extremely low resistance and thus have minimal power dissipation and can reach peak efficiencies of over 90% [12]. However, using a class-D amplifier which converts the analog input signal into a digital value introduces distortion called quantization error [13]. This error can be hard to compensate for, especially if implemented incorrectly.

For this reason, class-AB will be used in our design in order to greatly improve feasibility. Class-AB amplifiers sacrifice some efficiency in favor of linearity. Peak efficiencies will be lower than 78.5%, and thus would require a heat sink [14]. Since our design calls for a relatively large speaker, the receiver box housing will be spacious enough to accommodate several of these heat sinks. Utilizing class-AB amplifiers will also allow for the circuit to remain analog, simplifying the detailed schematic and allowing for easier alterations to be made after testing.

DESIGN EVALUATION

MICROPHONE

The condenser, fiber optic, and MEMS microphones were evaluated on a weighted scale ranging from zero to ten over a variety of design criteria (Table 1). The most important design criteria were given the highest weight and include size and sensitivity/frequency response. These two aspects were determined to be the most important design aspects since they are critical if the microphones were to fit on the back of a stethoscope head and give a quality sound back to the user.

Table 1: The design matrix for the three microphone options

Weight	Desgin Aspects	**MEMS**	Fiber Optic	Condenser
0.3	Size	**10**	9	7
0.3	Sensitivity/Frequency Response	**9**	10	10
0.15	Cost	**8**	3	7
0.1	Power	**9**	7	6
0.1	Feasibility	**8**	5	7
0.05	Interference from Medical Devices	**7**	10	7
	Total	**8.95**	7.85	7.8

Since a priority in this design was to use two wireless microphones, the size of the microphones was very important and therefore given a weight of 0.3. The microphone must be small enough to attach to the back of an existing stethoscope, so as not to be overly large and uncomfortable for the patient. The microphone’s sensitivity and frequency response were equally important, also receiving a weight of 0.3. The frequency response of the microphone must allow for the user to hear the heart and lung sounds as much as possible; the microphone must be able to detect sounds as low as 100 Hz. All three microphone choices scored well in these two categories, with the exception of condenser microphone size. Condenser microphones, while small and able to fit on the back of a stethoscope head, were not available as small as MEMS microphones. All three microphone choices could detect sounds as low as 100 Hz, with the fiber optic and condenser microphones able to detect sounds as low as 20 Hz.

Cost was the next most important aspect, given a weight of 0.15 due to the budget set forth by our client. Both the MEMS and condenser microphones are relatively inexpensive, while the fiber optic microphones cost upwards of $400.00, resulting in a low score in the cost category.

Power and design feasibility were the next two aspects, both receiving a weight of 0.1. The microphones must be able to be powered using a small power source, such as a lithium coin battery, and the circuitry for the microphones must be straightforward enough to allow us to build the prototype. MEMS scored high in this category as it takes the lowest power of the three at 1.5 Volts. MEMS also received the highest score in feasibility, with many companies offering MEMS microphones on prebuilt "evaluation boards", ready to be incorporated directly into a prototype.

Finally, interference from medical devices was the sixth design aspect rated. At a weight of 0.05, it was the least important of the six. The fiber optic microphone scored the highest in this category due to its EMI/RFI immunity, while the other two types scored lower due to their components being susceptible to magnetic interference

Overall, the MEMS microphone received the highest total score of 8.95, followed by the fiber optic microphone at 7.85 and the condenser microphone at 7.8. Because of this, the MEMS microphone is the microphone of choice for the final design. However, if the MEMS microphone proves unsatisfactory, a small condenser microphone will be used instead.

WIRELESS

The Bluetooth chipset, FM transmitter, and PurePath wireless system were also evaluated on a weighted scale ranging from zero to ten over five design criteria (Table 2). Transmission quality was given the highest weight because accurate transmission of heart and lung sounds is imperative in an emergency room setting. PurePath, with its lossless CD-quality, was rated the highest in this category. Bluetooth and an FM transmitter had lower quality than desired. Feasibility was given the next highest weight. A workable circuit design is necessary in order for the semester deadline to be met. In this respect, an FM transmitter would be the easiest, with PurePath having similar feasibility. A Bluetooth chipset, on the other hand, would be extremely difficult to integrate into the stethoscope system. Because the budget is specified as $300, cost was rated third most important. While the chipset and transmitter were both fairly inexpensive, the PurePath option is significantly more expensive. However, this does not remove PurePath from consideration.

Table 2: The design matrix for the three wireless options

Weight	Design Aspects	Bluetooth Chipset	**Purepath**	FM Transmitter
0.3	Transmission Quality	8	**10**	7
0.25	Feasibility	4	**7**	8
0.2	Cost	8	**6**	9
0.15	Power	8	**9**	7
0.1	Size	10	**6**	5
	Total	7.2	**7.9**	7.45

Power needed to run the wireless was the fourth design aspect rated. An FM transmitter takes up the most power and would need AAA batteries that would be replaced often. A Bluetooth chip takes up very little power and could run on a lithium coin cell for long periods of time. The PurePath system was rated the best because it has a rechargeable battery that can simply be plugged in to a USB port or wall outlet. Size was considered the least important because the different wireless options are all fairly close in size, and any difference would be minor. Because the stethoscope bell will be attached to the patient, the wireless system must be small enough that it is not bulky, even on a child. The Bluetooth chip is only about the size of a fingernail, so it was given the best size rating. PurePath and an FM transmitter are similar in size, with the PurePath being slightly smaller. With all factors considered, it was determined that PurePath wireless is the best wireless option for the electronic stethoscope design.

FINAL PROTOTYPE

STETHOSCOPE HEAD

Throughout the semester, various possibilities for a stethoscope head were considered. Ultimately, the team decided not to go with an acoustic stethoscope head as the Spring 2011 team had done. Instead, the team decided to mimic the stethoscope head with a custom made design. The client provided the team with a metal head that was much smaller than a traditional head, with a thirty millimeter diameter and an eight millimeter height. This type of head is not seen as often as a traditional head, but is still used by some doctors. Duplicates of the metal head were produced in SolidWorks and manufactured out of Acrylonitrile butadiene styrene (ABS) plastic using the FDM Dimension Elite printer (see Figure 7). This duplicate also included a hole of six millimeter diameter in the back designed to fit the microphone. The microphone was then kept in place by a layer of silicone gel.

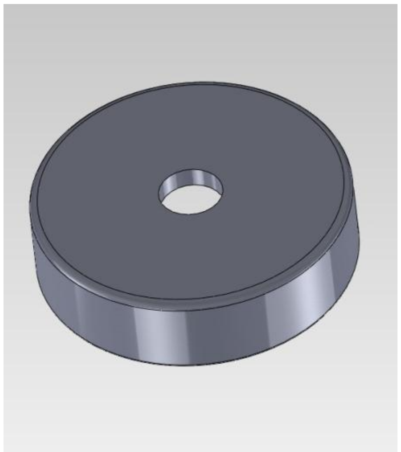

Figure 7: The SolidWorks design for the head.

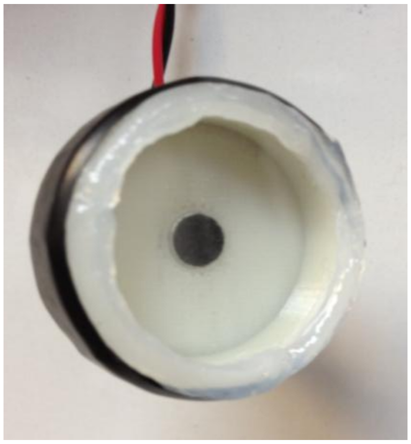

Figure 8: The completed plastic stethoscope head with shrink wrap diaphragm and silicon ring.

Upon first testing of the circuit, it was found that the signal of the heart and breath sounds being produced was not at an acceptable level of clarity. The team decided that one way to get a better quality of signal was to implement a mechanical filter based off of the design of the acoustic stethoscope. As mentioned previously, there are two parts to the head of an acoustic stethoscope: the bell and the diaphragm. The diaphragm is particularly good at amplifying heart and breath sounds, which is why the team mimicked this model in the final design. A piece of Duck Crystal Clear Shrink Film was placed over the open side of the plastic head and shrunk until it was taut, duplicating the effects of the diaphragm on an acoustic stethoscope. In order to further increase the amplification and filtering through the head, a layer of silicone gel was placed on the rim of the plastic head on top of the new diaphragm. The purpose of this ring of silicon was to create a type of seal against the patient's skin so that less sound would escape, and it is very similar to the ring of rubber on the bell side of an acoustic stethoscope. This was the last addition to the completed head (see Figure 8). Testing with the improved head produced a much clearer signal (see Figure 9) than with the initial bare plastic head or the traditional acoustic stethoscope head.

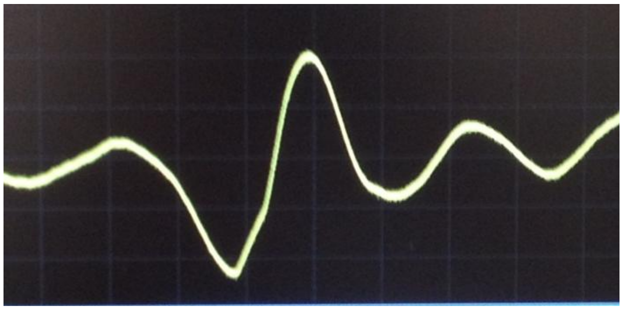

Figure 9: A screenshot of the signal of a heartbeat produced by the final prototype.

MICROPHONE

The microphone used in the final project was a Panasonic WM-61A electret condenser microphone. These microphones work by using a capacitor to convert acoustical energy into electrical energy. Condenser microphones require an external power source, which the design of the circuit was able to provide. This allowed the microphone to have a higher output. Due to their relatively small size, a diameter of six millimeters, the team decided that this microphone would work very well in the stethoscope head. The microphone is situated in the plastic stethoscope head, and wires reach from the microphone to the circuit. The frequency response of this microphone detects down to 20 Hz and up to 10 kHz. The condenser microphones were not out of budget, and quite easy to implement into the final design.

While an MEMS microphone was deemed the most viable option at the time of midsemester presentations (see Design Evaluation: Microphone on page 10), it was determined through further research and consultation with Tim Balgeman, Ikaria, and Mark Allie, Electrical and Computer Engineering Department, that in fact a small condenser microphone would be better suited for our needs. It is because of this input that the Panasonic WM-61A electret condenser was chosen as the microphone for the final prototype, rather than a microphone of the MEMS variety.

SPEAKER

Choosing a speaker for the final design was very important, because the rest of the design could work perfectly, but if the speaker being used didn't have the frequency range needed, there would be no working product. The team decided on the Pyle Home PCB4BK 4-Inch 200-Watt Mini Cube Bookshelf Speaker for the final design. This speaker boasted a frequency response curve of 20 Hz to 18 kHz, which encompassed the frequency range that design required. The box size was relatively small, at 4.8 inches in height, 4.8 inches in width, and 5.2 inches in depth, and the speaker itself had an eight ohm impedance. This speaker was connected to the circuit at the output and produced the heart and lung sounds that came from the circuit.

CIRCUITRY

Two microphones feed into two quadruple operational amplifiers that amplify and filter the signals. From the two op amps, the signal goes into a single mixer. There, the sound is further filtered and volume, treble, bass, and balance between the two signals can be altered. A switch then sends the output to an amplifying circuit for the speaker or headphones, from which sound can be heard. The system is powered by 12 VDC.

Per the client's request, there are two separate microphone inputs. Since the microphone can only handle 2 V, a voltage divider was used to reduce the power entering the microphone. A voltage divider consists of two resistors: one from ground and one from the 12 V source. Their point of intersection has the formulated 2 V, which is the voltage source for the microphone. The equation and circuit diagram for a voltage divider can be seen in Appendix A.

A capacitor separates the microphone circuit from the LM324 quadruple operational amplifier. This way, the LM324 can function at the full 12 V without affecting the voltage of the microphone circuit. The LM317A voltage regulator is also used. This voltage regulator keeps a floating input voltage of 6 V with rails at 0 V and 12 V. Voltage is floated in order to allow the frequency to oscillate with higher amplitude. A ground-referenced voltage would cause the signal to "rail out", hitting these voltage rails and losing some of the signal.

The LM324 contains four independent op amps connected in series. The first two are inverting amplifiers used for amplitude gain. The initial amplifier has a gain of one, while the second has a gain of three. The gain is determined by the resistors connected to the inverting input. The other two op amps within the LM324 are used as a five-pole Sallen-key low-pass filter with a corner frequency of 1000 Hz (Figure 10). Noise frequencies above 1000 Hz will be significantly reduced, until frequencies above approximately 1200 Hz will not be heard at all. The equation and circuit diagram for an inverting Op Amp of $gain = x$ can be found in Appendix B. The equation and circuit diagram for a Sallen-key low-pass filter can be found in Appendix C.

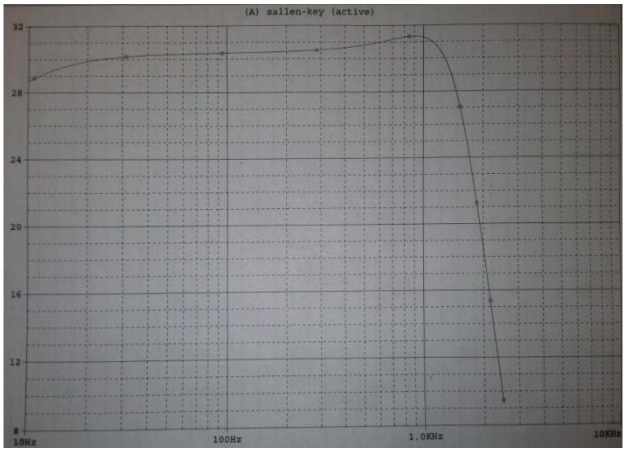

Figure 10: Five pole Sallen-Key low pass filter readout in Pspice with cutoff frequency set at 1500 Hz.

The signals coming from the two LM324 quadruple op amps both feed into the LM1036 mixer. The LM1036 includes potentiometers to control bass, treble, balance, and volume. To eliminate background noises in the stethoscope, treble sound is reduced while bass is increased. This allows for low heart sounds to be heard more prevalently.

Since the mixer has two inputs and two outputs, a switch is placed after the mixer to determine which microphone output is heard. A second switch then sends the signal to an amplifying circuit for either the speaker or the headphones. The TDA2003 is placed before the speaker to amplify the signal. This op amp has a gain of 100, which is sufficient to be heard on a speaker over the ambient noise of an operating room. Because the speaker amplifier requires a significant amount of power, a heat sink is attached as a precaution to prevent overheating. The TDA2003 output feeds into the speaker to allow for multiple listeners in an operating room setting.

If the switch after the mixer is flipped, the signal will instead be sent into the LM386 amplifier and into the headphones. This amplifier has a gain of 20. A headphone jack is attached to the amplifier output, so that the listener may connect headphones of his or her choosing.

The completed circuitry diagram can be found in Appendix D.

TESTING

Various forms of testing were implemented to ensure our design was performing to the desired specifications. During the design processes, specific tests were conducted to ensure our team was on the correct path to finish the design correctly and on time.

The first tests conducted were in regards to the Sallen-key filter, in which the cutoff frequency must be confirmed to be reasonably close to the values calculated. A signal generator was utilized in the bioinstrumentation lab to send incrementing frequencies starting at 20 Hz and moving up to 2 kHz while the outputs were monitored via the oscilloscope. With both calculated cutoff frequencies of 1.5 kHz and 1 kHz this frequency response test was conducted with reasonable results. The initial gains were also checked using this method, where a sine wave was sent through and the resulting amplification was checked to match the set gain.

Our final design called for an initial gain of 3, which was decided upon after testing multiple gains with our floating input set at 6V and voltage rails at 0V and 12V. It was found by again utilizing the oscilloscope that the signal would substantially rail out, meaning a loss of signal due to the limitations of the 0 to 12 voltage range, with a gain greater than 5. However, with a gain of less than 3, the output volume would substantially decrease.

The next aspects that required testing were the voltage regulator and voltage divider. The regulator was checked with the use of the voltmeter to ensure the correct output of 6V was being generated by using the power generator set at an input voltage of 12V. The divider was also analyzed in a similar fashion to guarantee the microphones were only being supplied 2V.

MANAGEMENT AND PLANNING

At the beginning of the semester, the Gantt chart found in Appendix E was created as a time and project management tool. It was approximately followed throughout the semester to ensure that the project was on track and deliverables were completed on time. All expenses incurred throughout the semester were recorded in the budget that can be seen in Appendix F. As can be seen in Appendix F, the team finished the semester with expenses totaling $230.77, well within the budgeted range of $200-$300 provided by the client.

FUTURE WORK

While the team was able to develop a fully functional electronic stethoscope over the course of the semester, numerous improvements can be made in the future to fully satisfy our client's requirements and improve the final prototype. The future work can be divided into two broad categories: size reduction and functionality.

In order to decrease the size of the prototype, the circuitry must first be significantly condensed by one of two methods. First, instead of using a breadboard, the circuitry could be wire wrapped by using a 4" x 4" prototype board and wire wrapping tools. This would enable the circuit to fit into the back of the speaker enclosure, minimizing the size of the prototype and making it significantly more aesthetically pleasing. The second option would be to contact Texas Instruments, provide them with a copy of our final circuit schematic, and have them manufacture a custom made printed circuit board. This would further minimize the size of the circuitry, again allowing it to be placed in the back of the speaker casing.

The second area of improvement is in the prototypes functionality. A main goal at the beginning of the semester was to implement some form of wireless technology into the prototype in order to eliminate the need for wires stretching from the patient to the main receiver housing. Wireless technology, such as Bluetooth microphones attached to the stethoscope heads, would significantly improve the functionality of our prototype by eliminating the wires which currently connect the microphones to the main circuitry. Due to budget constraints, the team was unable to pursue wireless functionality during the semester. However, with a sufficient budget, a form of wireless technology could be implemented to further enhance the aesthetics and performance of the prototype. In addition to implementing wireless technology, the filtering and amplification stages of the circuit could be further modified. While the heartbeat is audible, some background noise still exists and the speaker volume is not sufficient to be heard in an operating room. Finally, class D amplifiers could be implemented to improve the overall efficiency of the prototype. Currently, class AB amplifiers are used which provide around 67% efficiency, whereas class D amplifiers have 97% efficiency. This added efficiency would cut down on the necessary power supply to the circuit and might allow the use of a battery pack for power, rather than the current source of a wall outlet.

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APPENDIX A: VOLTAGE DIVIDER EQUATION AND CIRCUIT DIAGRAM

Voltage Divider Equation:

$$V_{out} = \frac{R_2}{R_1 + R_2}(V_{in})$$

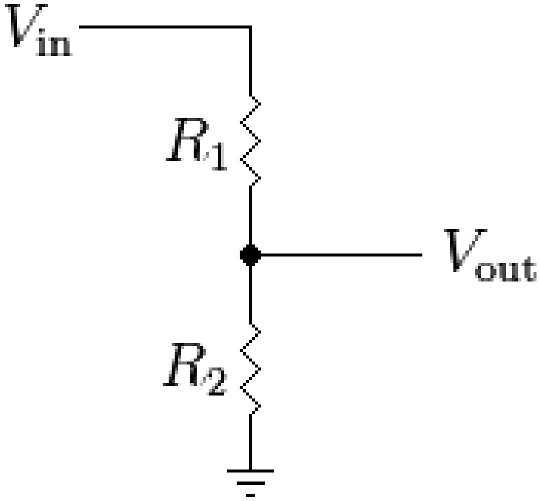

Figure 11: The circuit diagram for the voltage divider used in the prototypes circuit.

Image Courtesy of: http://upload.wikimedia.org/wikipedia/commons/d/db/Resistive_divider.png

APPENDIX B: INVERTING OP AMP EQUATION AND CIRCUIT DIAGRAM

Gain Equation:

$$Gain = \frac{R_2}{R_1} + 1$$

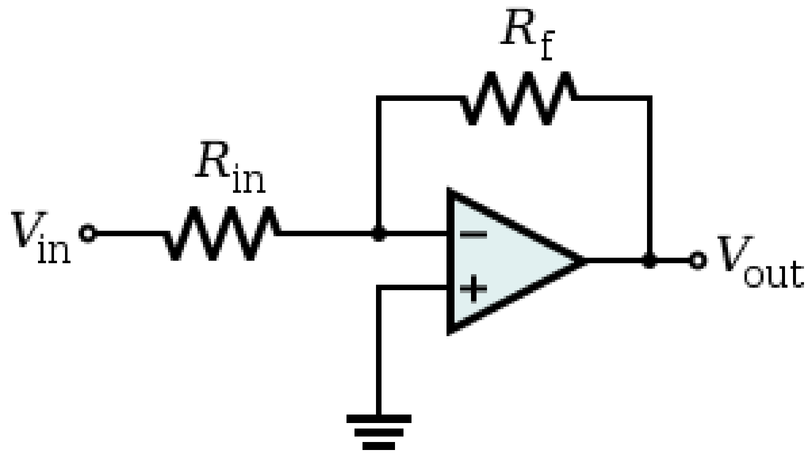

Figure 12: The circuit diagram for an inverting op amp of desired gain, as determined by above formula.
Image Courtesy of: http://upload.wikimedia.org/wikipedia/commons/thumb/4/41/Op-Amp_Inverting_Amplifier.svg/300px-Op-Amp_Inverting_Amplifier.svg.png

APPENDIX C: SALLEN-KEY LOW-PASS FILTER EQUATION AND CIRCUIT DIAGRAM

Equation for desired cut off frequency (f_c):

$$f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

Equation for desired quality factor (Q):

$$Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{C_2(R_1 + R_2)}$$

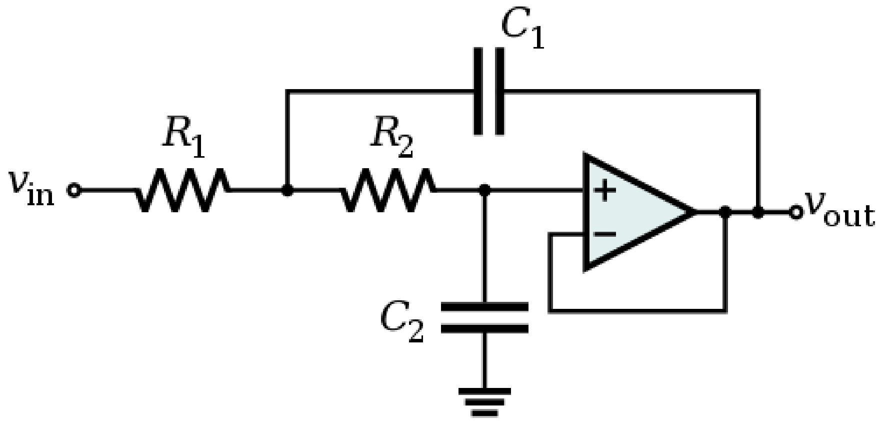

Figure 13: The circuit diagram for a Sallen-Key low-pass filter, as used in the final prototype.
Image Courtesy of: http://upload.wikimedia.org/wikipedia/commons/thumb/3/3f/Sallen-Key_Lowpass_General.svg/500px-Sallen-Key_Lowpass_General.svg.png

APPENDIX D: FINAL PROTOTYPE CIRCUITRY DIAGRAM

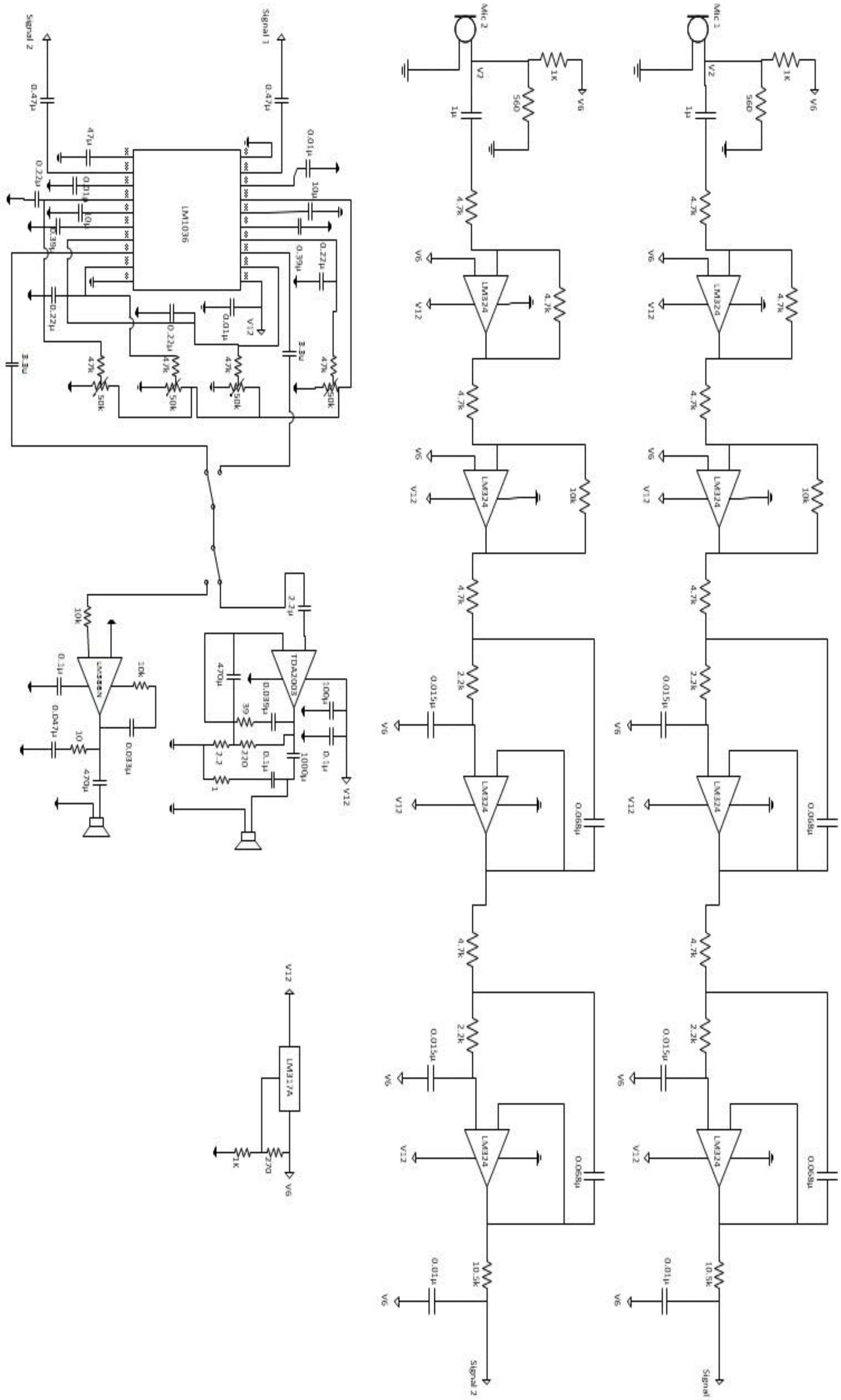

Figure 14: The complete circuit schematic for the prototype.

APPENDIX E: GANTT CHART

Team 3: Refinement of Electronic Stethoscope

Task	**September**					**October**				**November**				**December**	
	2	9	16	23	30	7	14	21	28	4	11	18	25	2	9
Project Research and Development															
Researching	X	X	X	X	X	X									
Brainstorming		X	X	X	X	X									
Design Matrix/Cost Estimation					▨	X	X								
Design Selection					▨	▨	X								
Ordering Materials							▨	X	X	X	X				
Prototyping								▨	▨	X	X	X	X		
Testing													X	X	
Final Prototype														X	X
Deliverables															
Progress Reports	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PDS			X												
Mid-semester Presentation							X	X							
Mid-semester paper							X	X	X						
Final Presentation														X	X
Final Paper															X
Meetings															
Client	X														
Advisor	X	X	X	X	X	X	X			X	X	X		X	X

APPENDIX F: BUDGET

Part Type	Part	Quantity	Unit Price	Total Price
	10000 pF 50V	15	$0.22	$3.24
	0.015 uF 50V	4	$0.46	$1.84
	0.033 uF 50V	3	$0.71	$2.13
	0.047 uF 50V	3	$0.32	$0.96
	0.047 uF 50V	3	$1.14	$3.42
	0.068 uF 50V	4	$0.53	$2.12
	0.1 uF 100V	6	$1.82	$10.92
	0.22 uF 16V	10	$0.24	$2.40
Capacitors	0.39 uF 50V	15	$0.36	$5.40
	0.47 uF 25V	10	$0.30	$3.00
	3.3 uF 25V	2	$0.86	$1.72
	10 uF 16V	10	$0.61	$6.09
	10 uF 16V	4	$0.83	$3.32
	47 uF 16V	4	$1.63	$6.52
	470 uF 16V	5	$0.33	$1.65
	1000 uF 16V	4	$0.46	$1.84
	1 ohm 1% tolerance	3	$0.22	$0.66
	2.2 ohm 5% tolerance	3	$0.34	$1.02
	39 ohm 1% tolerance	3	$0.97	$2.91
	220 ohm 1% tolerance	3	$0.97	$2.91
	2.4 Kohm 1% tolerance	3	$0.14	$0.42
	2.4 Kohm 1% tolerance	3	$0.14	$0.42
Resistors	4.7 Kohm 1% tolerance	6	$0.15	$0.90
	10 Kohm 1% tolerance	5	$0.15	$0.75
	10 Kohm 1% tolerance	3	$0.15	$0.45
	10.5 Kohm 1% tolerance	2	$0.15	$0.30
	47 Kohm 1% tolerance	5	$0.16	$0.80
	47 Kohm 1% tolerance	3	$0.15	$0.45
	50Kohm potentiometers	7	$1.50	$10.50
	Car Amp 497-11263-5-ND	3	$1.72	$5.16
	Dual Amp LM1458NNS-ND	3	$1.18	$3.54
Misc. Circuitry Components	Headphone Jack	1	$2.73	$2.73

	Mixer LM1036N-ND	3	$3.01	$9.03
	PC Board 4" x 4"	1	$7.33	$7.33
	Push Button Switch	3	$6.58	$19.74
Microphones	Microphone P9925 - ND	5	$3.09	$15.46
Speakers	4-Inch 200-Watt Mini Cube Speakers (Pair)	1	$28.99	$28.99
Miscellaneous	Silicone gel	1	$3.89	$3.89
	Sub Total			**$174.93**
	Shipping			**43.95**
	Tax			**11.89**
	Total			**$230.77**

APPENDIX G: PRODUCT DESIGN SPECIFICATIONS

Product Design Specifications—Refinement of Electronic Stethoscope

September 16, 2011

Team: Kyle Jamar, Michael Scherer, Meghan Anderson, Taylor Weis
Client: Dr. Scott Springman
Advisor: John Webster

Problem Statement:

Anesthesiologists need to listen to patients' heart and breath sounds during anesthesia care. Manual stethoscopes are commonly used but only allow for one listener and are uncomfortable for extended wear. An electronic stethoscope was developed which utilizes a speaker and microphone system, but it is too large for practical purposes. In order to improve upon the existing device, a more suitable power supply must be found. Ideally, changes should also be made to allow for a dual microphone system with Wi-Fi capabilities, as well as a main receiver with a speaker and a headphone jack for private listening.

Client Requirements:

- One high-quality microphone; ideally two wireless microphones
- Microphones should be attachable using standard medical adhesive
- Option for headphone or speaker listening
- Universal headphone jack
- Main receiver should fit in someone’s hand
- Cleanable with disinfectant wipes
- Cost efficient
    - ~ $300.00
- Must be able to withstand long term storage at room temperature

Design Requirements:

1) Design Requirements
    a. *Performance Requirements:* Must accurately convey heart and lung sounds at correct frequencies and appropriate amplification. Must be able to easily and quickly switch between headphone and speaker listening functions.
    b. *Safety:* The device must not endanger or contaminate the patient on which it is being used in any way or cause danger to the person who is operating it.
    c. *Accuracy and Reliability:* See Performance Requirements. The frequency and amplification must be accurate enough to detect problems in the patients’ cardiovascular system.

d. *Life in Service:* The device must not degrade or become unreliable for up to 10 years of usage, assuming correct precautions in cleaning and protection of electronics are taken by the owner. Battery life should be at least 12 hours.
e. *Shelf Life:* The prototype should not degrade over time in storage for at least 10 years.
f. *Operating Environment:* The device must be able to operate reliably in a hospital operating room. The device may be exposed to blood or other bodily fluids throughout the course of a procedure, but should not be exposed to large amounts of liquid for an extended period of time.
g. *Ergonomics:* The receiving station with speakers should not have rough edges or any loose components, and the volume adjustment for the speakers should be easy to use. Microphones should comfortably, yet securely, attach to the patients' chest. The device interface and its connection should not obstruct or obscure the use of the stethoscope.
h. *Size:* The receiver with the speaker should be no larger than the size of a hand and the microphones should be of comparable size to a stethoscope head.
i. *Weight:* No quantitative limit, but must be easily portable by one person.
j. *Materials:* The materials used should be safe for use around humans. They should meet standards for surgical use, such as being non-abrasive, non- toxic, non-radioactive, non-flammable, and non-corrosive. The materials should be easily disinfected by use of cleaning wipes.
k. *Aesthetics, Appearance, and Finish:* The device should be aesthetically pleasing, with a smooth, clean finish. All wires should be properly concealed within the receiver housing.

2) User Specifications
  a. *Intended Use*: The client will not be using the device for diagnostic purposes. It will be used to monitor a patient's heartbeat during surgical procedures and as a result only needs to be able to detect a heartbeat and not determine abnormalities.
  b. *Frequency Range*: Because the device will not be used to diagnose heart abnormalities, the prototype does not need to detect frequencies below 100 Hz. In order to limit interference from other devices in the operating room, the high frequency cut off should be close to 2,000 Hz.
  c. *Sound Quality*: The sound quality should be sufficient enough to determine that the heart is beating and the respiratory system is functioning normally. This means filtering out interference from other operating room machinery. The client would prefer if the sound reproduced is similar to what is heard from a traditional stethoscope but also commented that it would be interesting to hear new sounds generated by our device. The client also noted that since it was not being used for diagnostic purposes, sound quality as good as that found in a traditional stethoscope is not necessary.
  d. *Volume*: Since the device will be used in a standard operating room, the biggest concern with volume level is whether it can be heard over the ambient sounds of the other operating equipment present. As the operating room is not a very large

room, sound projection is not an issue; if the device can be heard over other operating room equipment, it will be loud enough for the room size.

  e. *Power*: The main receiver and speaker box portion of the prototype can be powered via a wall outlet. The individual microphones should be battery powered.
  f. *Additional*: The client requested that the main box of the prototype should have a way to be attached to the instrument cart currently used in the operating room. He suggested attaching brackets to the side of the device and securing it to the instrument cart.

3) Product Characteristics
  a. *Quantity:* One fully functional prototype is required at this time.
  b. *Target Product Cost:* The target manufacturing cost for the product is no more than $300.00, which includes microphones, receiver, speakers, and headphones.

4) Miscellaneous
  a. *Standards and Specifications:* The device as a whole will need FDA approval because it is a medical device that has the possibility to be used on humans. The device will adhere to client specifications.
  b. *Customer:* The product should follow the client's requirements for the headphone and speaker interface, while ideally having two wireless microphones.
  c. *Patient Related Concerns:* The device will come in direct contact with the patient. Therefore, the device must be sure not to: cause damage to the patient's skin, infect or poison the patient in any way, or leave debris after use. The device should not endanger the operator.
  d. *Competition:* There are currently a handful of similar devices on the market. However, none are optimal for our client's needs due to their excessive cost.