Wireless Stethoscope for Anesthesiologists

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Abstract

Anesthesia providers need to listen to patients' heart & breathing sounds during anesthesia care. Manual stethoscopes are the standard method but only allow one provider to listen at a time and can be uncomfortable over an extended period of time. The manual method is hard to position and secure on the patient's skin. There already exists a rather expensive Bluetooth system, and some old do-it yourself FM wireless systems, but it would be more simple and far less expensive to have a fully prepackaged commercial system. We have proposed a system with multiple wireless chest pieces that can all be heard from a central transceiver box. This box can connect to a speaker for more than one person to listen, or a headphone jack for private listening. Pediatric anesthesiologists commonly want to be able to compare breath sounds from the right and left chest, so a two microphone capable system is preferred. Resistance to high-frequency electrical signals in hospital environments is required.

Background

The Stethoscope

The stethoscope has been a crucial medical tool for the past 200 years, allowing doctors to listen to sounds of the heart, lungs, and abdomen. Its invention is attributed to a French physician, Rene Laennec, in 1816, who originally used a rolled up piece of paper to listen to a patient’s heart [1]. Since then, the stethoscope has been greatly refined, but the basic acoustic principles have remained the same. Currently, two different types of stethoscopes are available on the market: acoustic and electronic.

The modern acoustic stethoscope uses a bell and diaphragm chest piece with rubber tubing leading to the two earpieces. The bell captures lower frequency sounds, while the diaphragm, a small plastic disc, captures higher frequencies [2]. The acoustic pressure captured by the chest piece is then transmitted to the earpieces through the flexible rubber tubing. Although acoustic stethoscopes are still the most common type they have several drawbacks. For example, they attenuate certain frequencies due to tubular resonance effects [3], and do not allow for amplification or filtering of the sound.

Electronic Stethoscope

The first electronic stethoscope was developed in 1961, but was extremely bulky and cumbersome. Originally, these models sounded very different than traditional acoustic models due to electrical interference and sensitivity to surrounding noise. Over time the sound quality has been greatly improved through the use of sound transducers, adjustable gain amplifiers, and frequency filters [4]. However, current devices are still not ideal, and generally have not been accepted by the medical community. They are very expensive, are usually wired, and only allow for one listener.

Frequencies in Operating Rooms

The device must not emit frequencies in the operating room that could cause other equipment to malfunction. The signals that the design is sending from both the microphone and the transmitter are all under the usual signals used in most operating room machines. The wireless transmission from the chest pieces to the transceiver is broadcasted at very high frequency (VHF). VHF spans from 30 MHz to 300 MHz. Most operating equipment deals with signals 600 Hz or greater [6]. It can be noted that “equipment operating in the WMTS bands (608

MHz to 614 MHz, 1395 MHz to 1400 MHz, and 1427 MHz to 1432 MHz) has primary status and is protected from interference by other devices." [6]. Therefore, this eliminates the possibility of the transmitter reaching a signal that would disrupt the other equipment. Hospitals are typically worried about cell phone and other types of ultra-high frequencies (UHF) which pose a threat to the functionality of operating room signals. As our system uses VHF, instead of UHF, it poses no complications.

Previous Designs

The previous design, completed in the Fall of 2011, utilized a homemade chest piece with a built in microphone. The electric signal was then passed through a series of filters and amplifiers to produce a cleaner signal. A mixer was also added to adjust bass and treble. Finally, the signal was passed to an audio speaker with a headphone jack.

This semester, our team plans to simplify the whole process by utilizing a traditional acoustic chest piece instead of the makeshift one used before. Additionally, our microphone will be located in the tubing, allowing it to capture the sound as it is traditionally heard. This should eliminate the need for complex filters and amplifiers.

Design Requirements

The design of the wireless microphone system must be able to clearly identify and transmit the signals from the patients breathing. The sound quality doesn't need to be perfect because the main function of the design is to detect whether the patients breathing is being interrupted; not for diagnostic purposes. However, better sound quality will result in a more effective overall product. The receiver should detect signals as low as 50 Hz and the wireless transceiver should not interfere with other medical equipment. Radio frequency interference

(RFI) can be a problem with ultra high frequencies from devices like cell phones and Wi-Fi devices. The transceiver transmits signals from 30 MHz to 300 MHz, which should avoid RFI in the operating room. The design should be audible to an entire room through a small speaker system. It should also have the capability for headset listening, which requires a headset plug-in on the speaker system to allow for private listening. The size of the design should be no bigger than the size of a hand. Bulkiness can cause an issue for doctors, so a smaller system would be ideal. Another aspect of the design that requires attention is the battery life. The battery life should ideally last for 20 straight hours and have a rechargeable battery. View the Product Design Specification in the Appendix for the complete requirements.

Funding

The total cost of the project must be under $200. The funding is provided through our client, Dr. Scott Springman, an anesthesiologist at the UW Hospital. The total cost of the design can easily meet the $200 budget. The main cost will be the speaker system, which will increase in price depending how clear of quality the client requires to hear breathing sounds. The tubing, microphone, headset, and wireless transmitter/receiver are all under $100 dollars, leaving room for late changes that may improve the design.

Final Design

For the final design, it was decided that all design requirements could be met without presenting any problems. Therefore this design is wireless, has multiple stethoscope heads, and should accurately replicate the frequency of sounds our client wishes to hear. A visualization of the appearance of the final design can be seen below:

This design will make use of readily available stethoscope heads that are intended to be hooked up to a traditional stethoscope headset. These stethoscope heads can be adhered to a patient's body using disposable adhesive strips cut into the shape of a two dimensional torus. Stethoscope heads can be easily interchanged between plastic and metal, as during some surgeries nonmagnetic materials must be employed. These adhesives are readily available from medical equipment suppliers and are currently used to attach acoustic stethoscopes to patients.

To convert this to a wireless system, while maintaining accurate sound reproduction, these tubes are cut shortly after they leave the stethoscope head. A microphone is then placed into the tube, along with any physical dampening or filtering material deemed necessary by future testing. This microphone will receive the sound waves and convert them to an analog electronic signal. The microphone will be selected so that it picks up all signals within the desired frequency. The current client, an anesthesiologist, needs only to hear the sound frequencies that correspond to breathing, so the signals must pick up signals from the breathing airway (low of 50 Hz). However, the device can also pick up signals from the heart so the doctor can listen to the patient's heartbeat.

The microphone will be a component of a repurposed wireless stage microphone setup. These setups are commercially available at a reasonable cost. Each stethoscope head will be connected to its own wireless transmitter via an electrical wire connection. This allows the transmitter, a small box the size of a deck of cards, to be placed anywhere on the patient or the operating table. This flexibility of placement ensures that it will not interfere with any surgical procedures. As wireless stage setups are commonly employed with varying combinations of multiple microphones and transmitters combinations, our system will be extremely flexible in accommodating the placement of multiple stethoscope heads. Our current client is only requesting two stethoscope locations at this time, the design reflects that by implementing two separate stethoscope units each with its own stethoscope head, microphone, and transmitter.

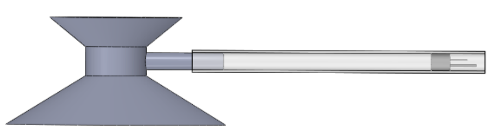
Once the analog electrical signal produced by the microphone is received by the transmitter it will be converted to a digital signal and broadcasted wirelessly. Commercially available transmitters use FM broadcasting at frequencies between 150 and 250 MHz to transmit the signal, allowing them to be safely used within an operating room. These transmitters will be powered by a removable battery allowing a user to replace it immediately if it runs out of charge. To conserve cost this design will employ simple alkaline batteries; however, rechargeable batteries could be substituted for future higher priced models.

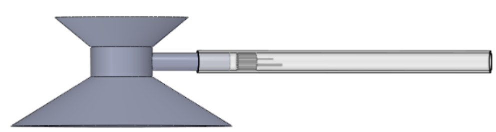
The broadcasted signals will be received by a transceiver, again repurposed from a wireless stage setup, which will have to be plugged into a wall outlet. This transceiver will be capable of receiving signals from multiple transmitters. This is accomplished by setting each transmitter to a unique FM frequency. Users can then cycle through each stethoscopes audio signal by changing the transceivers receiving frequency. The transceiver converts the digital FM signal and outputs an analog audio signal through a universal 3.5 mm audio cable jack. Using a standard 3.5 mm audio cable the users can easily connect this system to a speaker or a headset.

If a speaker is employed, an active component system, in which a tweeter and a woofer handle the high and low frequencies, respectively, will be used to ensure accurate sound reproductions. The commercially available speakers that we will be using can reproduce frequencies from 20 Hz to 20 kHz. If a headset system is employed, the audio signal will be fed into a Bluetooth transmitter which will relay it to a wireless headset. Commercially available headset systems contain both the transmitter and a rechargeable headset. As this is a prototype design, speakers will be used to lower its cost.

Design Alternatives

Microphone at the end of tubing vs. microphone some distances away from chest piece

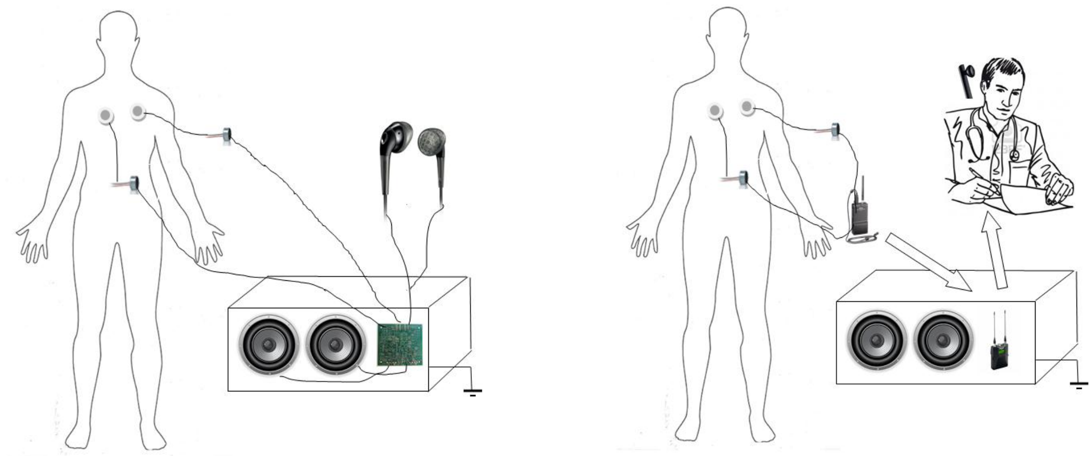




The microphone that picks up the signal from patient can potentially be placed at two different locations: close to the chest piece inside the tubing or some distance away from the chest piece inside the tubing. The signal intelligibility and patient comfort are two major factors in deciding the position of the microphone. Putting the microphone away from the chest piece prevents the potential contact between microphone and skin, which is likely favored by patients.

On the other hand, when placing the microphone certain distance from the diaphragm (roughly 5-8 cm away), there will be a significant increase of signal-to-noise ratio and reduction of signal amplitude. In order to achieve a signal of good quality, a better microphone needs to be purchased, which will increase the total cost of the project. A tube with larger diameter and thicker material has to be used in the design to fit the size of microphone as well as protect it. Incorporating the microphone near the stethoscope head, closer to the diaphragm, would have a better signal quality since the signal passes to the microphone with a shorter distance. However, the microphone needs to be adhered on the diaphragm with a certain stability to decrease the contact with skin.

Two different systems to transmit signals



In terms of transmitting and receiving the signal, two different systems could be used in the stethoscope: one with a connecting wire or one with a wireless signal. Previous groups have been working on designing the circuit that processes the signal and transfers it to the speakers and headphones wirelessly. The cost of making a printed circuit board would be low, except a sophisticated circuit design is essential for optimal sound quality. Further effort in testing and troubleshooting of the circuit would be required to assure the reliability of the system. The wire system also decreases the mobility of the stethoscope due to the long wire from the diaphragm to the receiver box. The wireless system significantly decreases the complexity of the circuit as the transmitter and receiver can be purchased. Moreover, it can provide noise reduction, signal enhancement, and both visual and audio output.

Design Matrix

Factor	Weight	Position of microphone	
		At the end of tubing	**Away from chestpiece**
Signal quality	0.3	9	7
Patient comfort	0.25	7	9
Cost	0.15	8	6
Ease of attachment	0.15	7	8
Safety	0.15	8	8
Total	1.00	**7.9**	7.65

The design matrix above is made to decide the position of microphone placement. Five factors are listed to compare the two different microphone positions: signal quality, patient comfort, cost, ease of attachment, and safety. Each specification is assigned with a different weight. Signal quality and patient comfort are the two most important factors, thus they have weight of 0.3 and 0.25, respectively. A score from 1 to 10 is assigned to each of design alternatives in each category. Placing the microphone close to the diaphragm has a good signal quality (9), low cost (8) while it is hard to attach (7) and may make patient less comfortable (7). Putting the microphone inside the tubing away from the diaphragm is more comfortable for patient (9) while it has poor signal quality (7) and costs more (6).

Factor	Weight	Signal transmit method	
		Wireless	**Wire**
Signal quality	0.2	9	7
Cost	0.2	7	8
Mobility	0.2	9	6
Accuracy	0.15	8	8
Reliability	0.15	9	8
Safety	0.1	8	8
Total	1.00	**8.35**	7.4

The design matrix above is made to decide the signal transmission method. Six factors are listed to compare the two different microphone positions: signal quality, cost, mobility, accuracy, reliability, and safety. Each specification is assigned with a different weight. The wireless system has better signal quality (9), high reliability (9), and high mobility (9) while the wire system is cheaper (8) to build. Overall, the wireless system scores higher (8.35) and is favored in final design of electronic stethoscope.

Testing

In order to make sure the wireless electronic stethoscope works properly in the clinical settings, different tests were conducted using the software, MATLAB. Microphones and speakers are the two most vital components in the system as they receive input and deliver output for the real signals. The first test ensures they work at low frequency, specifically when picking up the heart and breathing sounds. Then all the system parts were assembled and human testing was conducted to get sample signals and view the frequencies received by the system.

The speaker was tested by feeding a simple sinusoid signal from MATLAB. The code to generate the sinusoid signal with certain frequencies can be found in the Appendix section. Using this MATLAB test verifies that there are no major sources of distortion or corruption to the signal. The output is recorded using microphones from the speakers, as they are the end point of the audio signal processing. The microphones were then connected to the computer and using MATLAB, the signal from the speaker is recorded and plotted. Since the goal of this test is to discover whether the microphone and speaker are able to pick up and deliver the required low frequencies, fast fourier transforms are used to transform the sample signal from a time domain to a frequency domain. Figures 1, 2, and 3 (Appendix) show the results of the frequency response from the microphone and speaker. Three different signals (40 Hz, 50 Hz, and 1 kHz) are sent to the speaker, picked up by microphones, and finally sent back to MATLAB. After the fast fourier is transformed, the figures show peaks at 40 Hz, 50 Hz, and 1K Hz. This indicates that both the speaker and microphone are able to work at frequencies from 50 Hz to 1 kHz, where most of the tracheal breathing and heart beat frequencies are found.

After testing all the components of stethoscope system individually, sample signals were recorded and analyzed. The chest piece was placed on a test patient as the patient took several normal breaths. The microphones then picked up the signal and delivered it to the transmitter. The signal was detected wirelessly by the transceiver and then sent to the speaker output terminal. During the test, the trachea, lung, and heart signals were used as sources for signals. Figure 5 (Appendix) is a recording of the sample signal in the time domain. As it is shown, the signal is periodic and each peak represents a heart beat. By using the fast fourier transforms, signals in the time domian were transformed into frequency domain. Figures 5 and 6 (Appendix) show the frequency given by the heart beat and trachea, respectively. Both have similar frequency responses and the signals range from 50 Hz to 250 Hz.

Other tests were also conducted on battery and wireless transmitter. For the battery testing, the device was left on for an extended period of time to determine the battery life. It demonstrated that the current device can last 22 hours. Further improvements can be made by using Li-Ion batteries, which can be recharged by the device user. When testing the transmitter, the receiver was placed a certain distance away from transmitter in order to find the longest distance that a clear signal can be heard. The results indicated the transmitter can still operate properly approximately 15 meters away from the receiver, which is desirable for real world application.

Future Work

The following parts have already been ordered, received, and assembled. As the project progresses and more parts need to be ordered, they will be added to the parts invoice.

PARTS INVOICE

Part Description	Part #	Manufacturer	Amount	Cost
Stethoscope Chest Piece	00-390-A	AINCA	2	Donated
Tubing for Use with Chest Piece	P-151	AINCA	2	Donated
Microphone	GM-W62	Gem Sound	2	Free with Transceiver
FM Transmitter	GM-W62	Gem Sound	2	Free with Transceiver
FM Transceiver	GM-W62	Gem Sound	1	$90
Active Component Speaker	ET-AR504LR-BK	Eagle	1	$60

TOTAL COST: $150

Battery Life

The battery life of the transmitter is one aspect of the design that needs improvement. As of now, the transmitter operates on a standard 9 Volt battery. This battery matches the requirements of lasting more than 20 straight hours, however, it is not energy efficient or economically feasible for our client. In the future we hope to exchange the current battery with a lithium ion battery that can be easily recharged and used again. This would provide an effective way to

Adhesive Material

An adhesive material for the stethoscope head still needs to be created. The standard one used in hospitals would not fit the size of the new stethoscope head that we implemented for better sound quality midway through the design process. This material can easily be obtained and shouldn't provide too much investigation in order to find a quality and suitable way to adhere the stethoscope head.

Visual Frequencies

Another design improvement opportunity that the team has decided upon in the future is a visual representation of the signals being transmitted by the microphone. Our client did not specify for this, but we feel that this would greatly aid an anesthesiologist by not only being able to hear the breathing and heart sounds, but also being able to see them. The signal could easily be relayed through a computer program with signal processing technology, except actually designing a way to easily get this in operating rooms, while maintaining a lost product cost, would provide some challenges.

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APPENDIX

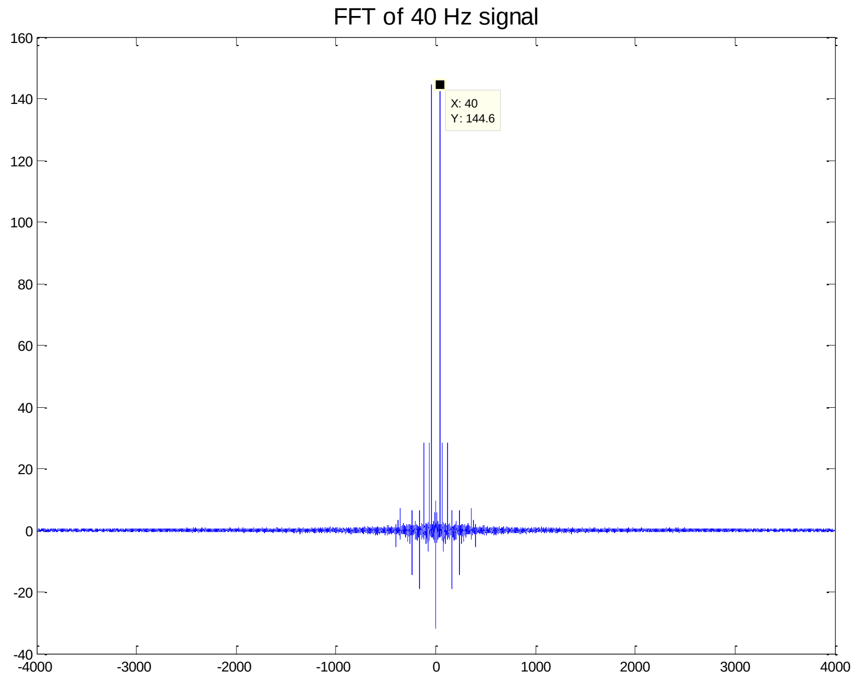

Figure 1. FFT of the 40 Hz signal from speaker

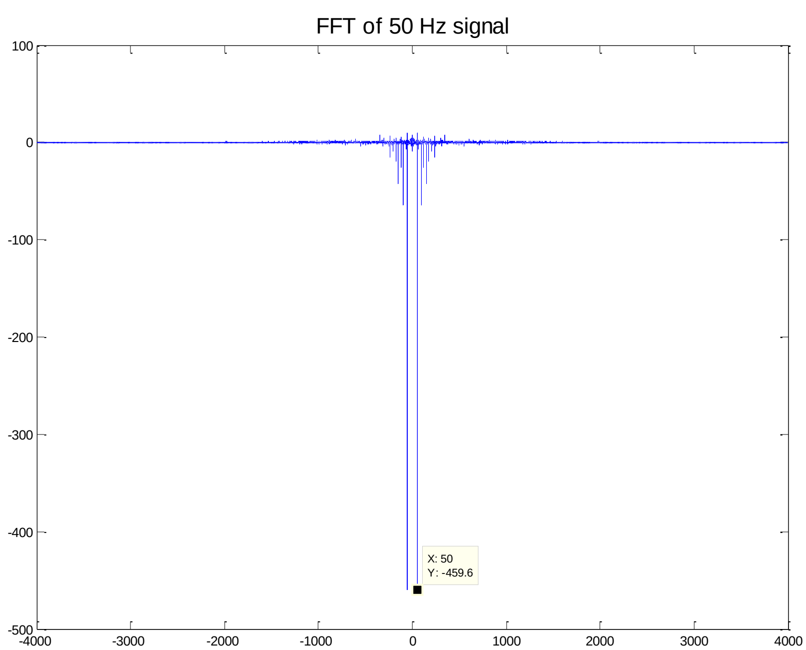

Figure 2. FFT of the 50 Hz signal from speaker

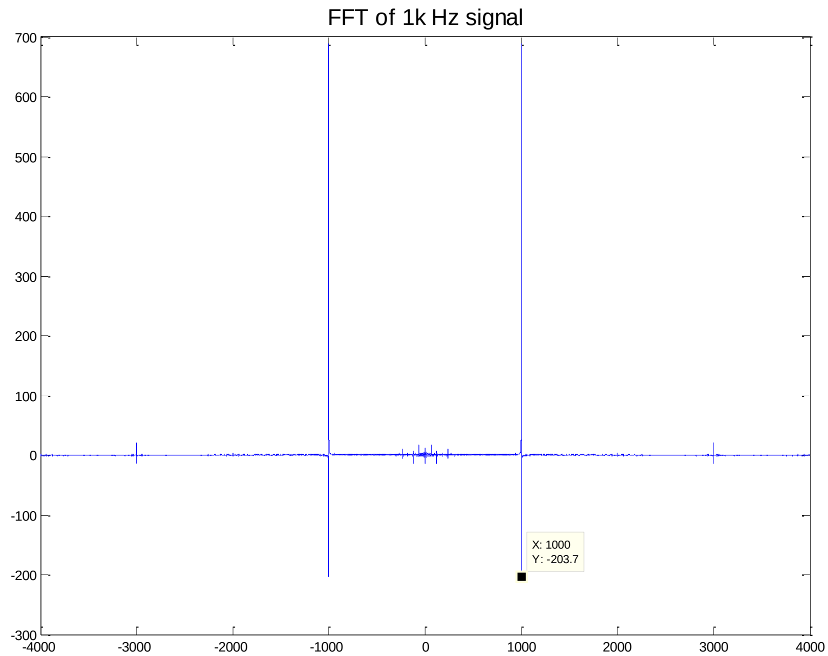

Figure 3. FFT of the 1 kHz signal from speaker

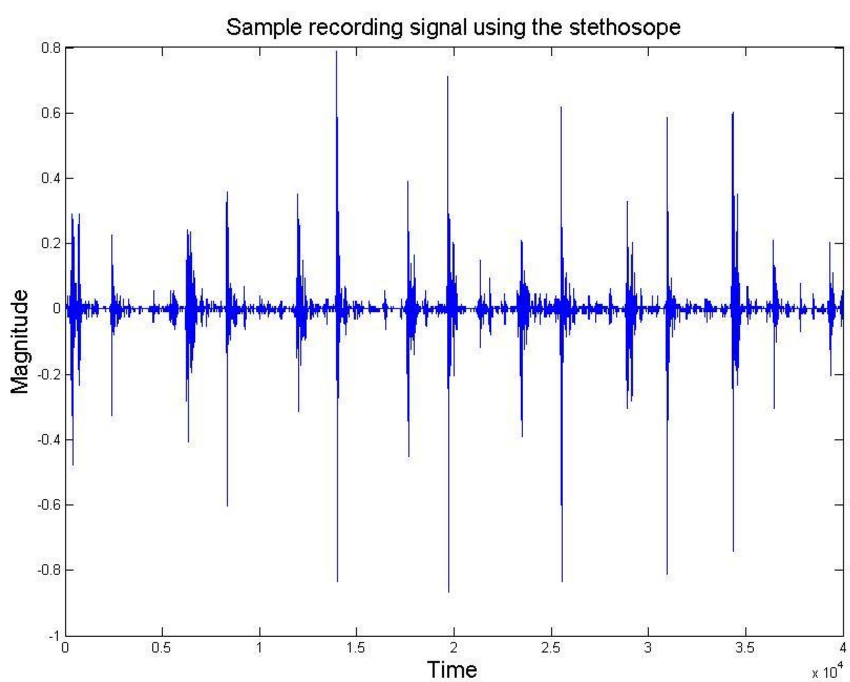

Figure 4. Sample recording signal using the stethoscope in time domain

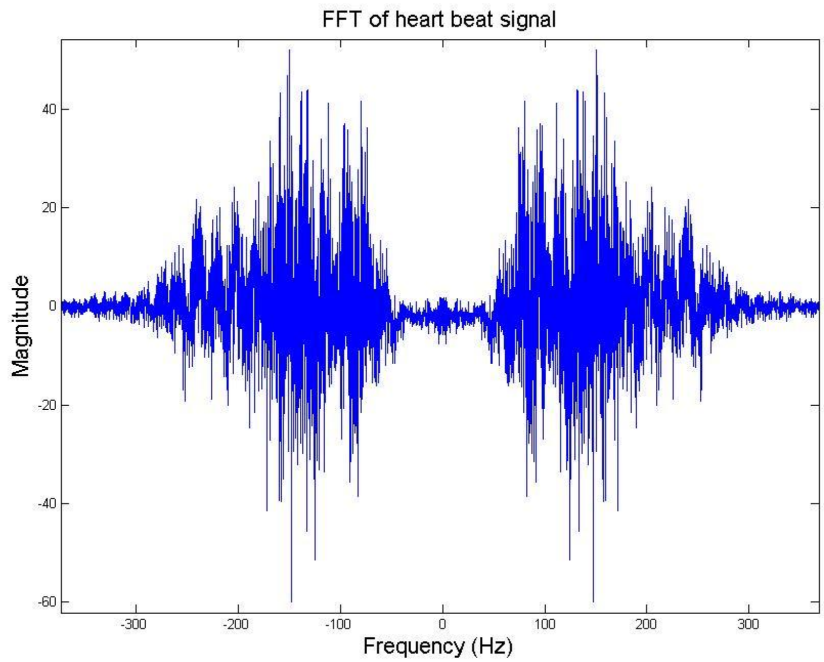

Figure 5. Fast Fourier Transform of the Device’s Heart Beat Response

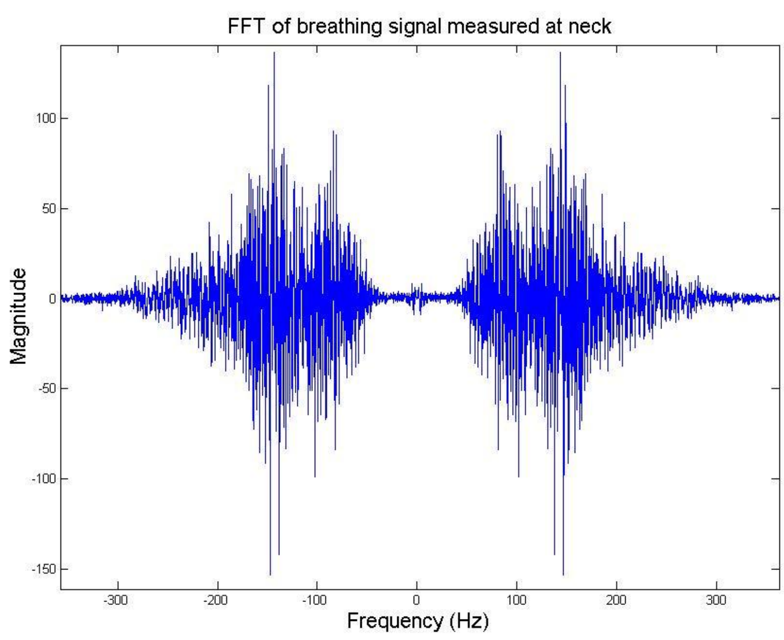

Figure 6. Fast Fourier Transform of the Device’s Trachea Response

Product Design Specifications

Problem Statement:
In every surgical procedure, anesthesiologists need to listen to the patient breathing sounds while they are asleep to ensure the safety of the patient. Manual stethoscopes, which have been used for years, are sufficient but cause discomfort to the listener and do not provide a wide range of activities to be done simultaneously. There are a few electronic stethoscopes in the market today, but it is too large and expensive for practical purposes. In order to improve upon the existing device, an efficient power system must be found that can maximize the life span of the device. Ideally, changes should be made for a small wireless system, as well as a main receiver with a speaker for multiple listeners and a wireless headset for private listening.

Client Requirements:
- One high-quality microphone
- Microphones should be attachable using standard medical adhesive
- The size of the stethoscope head should be no larger than the regular ones used
- Option for headphone or speaker listening
- Main receiver should be as small as possible without effecting sound quality
- Should be able to detect frequencies of the patient breathing
- Battery powered to last ideally 15 hours
- Cost efficient
- Must be able to withstand long term storage at room temperature
- Cleanable with disinfectant wipes

Design Requirements:
1. Performance Requirements: Must accurately convey breathing at correct frequencies and appropriate amplification. Must be able to easily and quickly switch between headphone and speaker listening functions. The device also should not cause the physician trouble due to its size.
2. 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. This includes not interfering with signals of other operating machines in the room.
3. Accuracy and Reliability: See Performance Requirements. The frequency and amplification must be accurate enough to detect problems in the patients' breathing pattern.
4. 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 15 hours.
5. Shelf Life: The prototype should not degrade over time in storage for at least 10 years.
6. Operating Environment: The device must be able to operate reliably in a hospital operating room. The device should not come into contact with blood or liquids during procedures, but if it does for a short period of time it must be ensured that the patient or physician will not be hurt.
7. Ergonomics: The receiving station with speakers and the transmitter should not have loose components or any physical components that could cause harm, and the volume adjustment for the speakers should be easy to use. The two microphones should comfortably, yet securely, attach to the

patients' neck. The device interface and its connection should not obstruct or obscure the use of the stethoscope.

8. 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. The transmitter should be able to attach directly to the physician or patient.
9. Weight: Must be easily to carry to different rooms by the physician.
10. 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.
11. Appearance: The device should be aesthetically pleasing, with a smooth, clean finish. All wires should be properly concealed within their respective devices.

User Specifications

1. Intended Use: The client will not be using the device for diagnostic purposes. It will be used to monitor a patient's breathing during surgical procedures and as a result, only needs to be able to detect a breathing frequencies.
2. 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 highest frequency reached should be 2000 Hz.
3. Sound Quality: The sound quality should be sufficient enough to determine that the respiratory system is functioning normally. This means filtering out interference from other operating room machinery. The client also noted that since it was not being used for diagnostic purposes, sound quality as clear as that found in a traditional stethoscope is not necessary.
4. 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 sounds of the other operating equipment present. The device should not be too loud to disrupt any conversation in the room, but also needs to be heard over other machinery.
5. 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.

Product Characteristics

1. Quantity: One fully functional prototype is required at this time.
2. Target Product Cost: The target manufacturing cost for the product is no more than $200.00, which includes microphones, receiver, speakers, tubing and headphones.

Miscellaneous

1. 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. Customer: The product should follow the client's requirements for the headphone and speaker interface, while ideally having two wireless microphones.
2. Patient Related Concerns: The device will come in direct contact with the patient. Therefore, the device must be safe for the patient's skin and not cause harm in any way to the patient's overall health. Regular adhesive used by the physician will ensure that the patient is not harmed.
3. 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 and bulkiness.

MATLAB CODE:

```
% Sample sinusoid signal.
n = 0:1/44108:10;
freq = 10000;
x = 100*cos(2*pi*freq*n);
soundsc(x,44108);

% Record your voice for 5 seconds.
recObj = audiorecorder;
disp('Start speaking.')
recordblocking(recObj, 5);
disp('End of Recording.');

% Play back the recording.
play(recObj);

% Store data in double-precision array.
myRecording = getaudiodata(recObj);

% Plot the waveform.
figure;
plot(myRecording);

fs=8000;
N=40000;
fHz=(-N/2:N/2-1)/N*fs;
X2=fft(myRecording);
figure;
plot(fHz, fftshift(X2));
```