Title
Design Analysis and Performance Characterization of a Novel Bone Conduction Hearing Aid

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Publication Date
2018-04-01

DESIGN ANALYSIS AND PERFORMANCE CHARACTERIZATION
OF A NOVEL BONE CONDUCTION HEARING AID

By

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A capstone project submitted for
Graduation with University Honors

June 7, 2018

University Honors
University of California, Riverside

APPROVED

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Abstract

Microtia is an innate condition in which the individual is born with an under development in one or both of the ears. The level of underdevelopment varies from Grades 1-4 where Grades 3 and 4 are most commonly associated with no outer ear at all1. 90% of microtia cases are unilateral, meaning occurring only on one ear. Current treatments for this condition include either highly invasive surgical implants within the inner ear, or total reconstructive surgery of the ear. The cost of both of these options comes up to $50000-$65000 per ear2. A novel alternative is to utilize bone conduction technology as means for alternate treatment. Bone conduction technology converts sound waves into vibrations that are sent directly to the cochlea which will then be processed via the auditory nerve3. This is possible due to the nature of microtia where all of the internal components of the ear such as the inner ear canal and cochlea are intact and simply need stimulation which can be accomplished by placing the bone conduction transducer against a bone near the ear. A bone conduction hearing aid has been developed that picks up and transmits external sound via the help of signal processing and signal filtering. In addition, the device functionality and characterization were examined, and the results indicated that the device was up to quality standards and operates effectively.

Acknowledgments

I would like to thank my advisor Dr. Hyle Park for guiding me throughout this project and always helping me think of new and innovative approaches to accomplish the goal of completing this capstone. In addition I would like to thank my fellow group members in bioengineering senior design as this was a group project and without them the project would not have been completed and for always supporting me in terms of helping my own individual work. These people helped make this capstone a success and I cannot thank them all enough.

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Introduction

The anatomy of the human ear comprises of an external ear which contains the pinna (outside part of ear) and the external auditory canal (connects outer ear to inner ear), the tympanic membrane (ear drum), the middle ear which consists of ossicles (small bones that transmit soundwaves to the inner ear) and the eustachian tube (canal that links the middle ear with the back of the nose), and the inner ear which consists of the cochlea (contains nerves for hearing) and receptors for balance. The important aspects of the ear's anatomy that are crucial in hearing are mainly the external ear, the ossicles, and the cochlea.

To fully understand the impact of hearing loss, one must consider the process in which humans hear. The general process of hearing begins with the soundwaves travelling through the external ear into the external auditory canal and strikes the ear drum. Then, the ear drum vibrates converting the soundwaves into vibrations and these vibrations are amplified and sent into the cochlea for the beginning process of signal processing via the ossicles. In the cochlea the vibrations are converted into electrical impulses which can travel along the auditory nerve into the brain[4]. When one of these components is damaged or defective, then we arrive at hearing loss

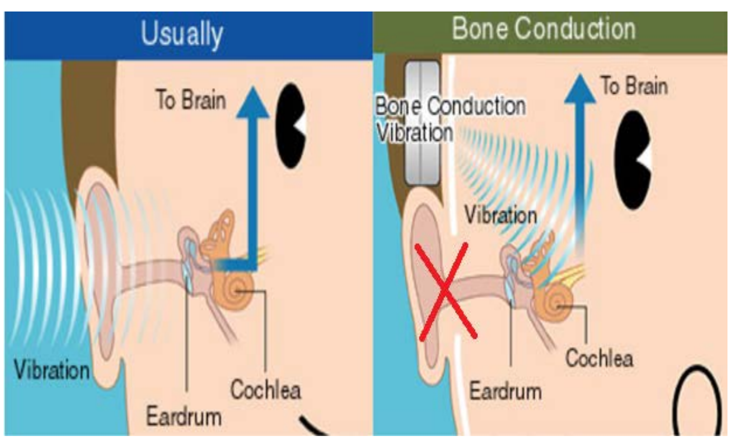

Figure 1: Depicts how a bone conduction transducer bypasses certain parts of hearing process and can be used as means for hearing

There are three main types of hearing loss that affect the individual in a myriad of ways. The first type of hearing loss is known as conductive hearing loss where basically it occurs when the outer or middle ear interfere with the successful journey of sound passing through. This type of hearing loss is the most common case and can be easily managed via the use of conventional hearing aids. The next type of hearing loss is known as sensorineural hearing loss and this occurs when components of the inner ear are damaged and not functioning properly and thus the transmitting of electrical signals is not feasible. Finally, mixed hearing loss is essentially a combination of both conductive and sensorineural hearing loss[5].

Congenital microtia is a genetic defect that falls under the category of conductive hearing loss as the problem arises with the external ear not being fully formed. The condition ranges from grades 1-4 where the state of development can range from an area of obstruction of the auditory canal to a point where the auditory canal is completely closed off and there is no external ear present[6]. Despite this defect of the outer ear, all the inner components are fully intact and the lack of stimulation for these components will result in the degeneration of a cochlea and as a result lead to an individual being completely deaf[7]. Although this a very severe condition, the target population that this affects is relatively small with around 40,000 cases and about 0.01% of babies born will have this condition[8].

Figure 2: Depicts different grades of microtia from Grade 1- Grade 4

Currently, for this condition there are only two major treatments, both of which include invasive and costly procedures. The two procedures are bone anchored hearing aid surgeries where a bone conduction transducer is surgically placed permanently on the skull, most commonly behind the ear[9]. This simplistic procedure can result in a cost of upwards of $20,000. The other option is total reconstructive surgery where an external ear is created and can cost around $65000. Thus, the implementation of a removable and convenient device such as a bone conduction hearing aid is desperately needed as it provides all the necessary functions of bone conduction technology such as converting soundwaves into vibrations and being transmitted to the cochlea as well as being easy to remove or operate. More importantly, the characterization and testing of this device in order to determine functionality was an integral part of any application of a hearing aid.

Materials and Methods

Development of Actual device prototype

The developed bone conduction hearing consisted of two microphones which function by picking up external sounds as well as noise cancelling due to the microphones picking up the sound wave and the opposite of the sound wave and combining them to essentially cancel out that noise. The sound then travels through an audio amplifier that increases the strength of the signal as well as a developed hardware bandpass filter whose function is to keep a range of sound frequencies and only transmit those to the bone transducer. The external case was created via a 3D-printed case with many cushions and mounted to a headband, allowing for a convenient and comfortable operational device. The entire device was powered via the implementation of a 1200 mAh battery and a power switch.

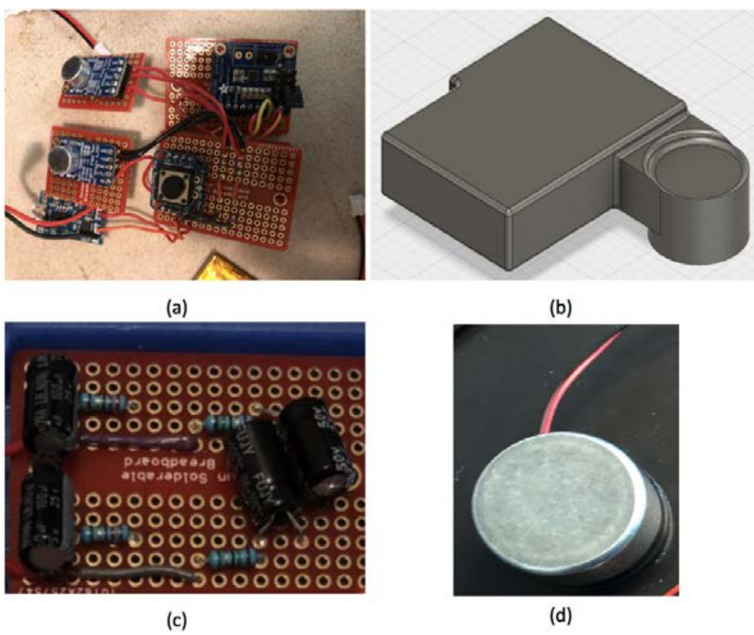

Figure 3: Depicts internal components of device itself with a) Complete circuit; microphones, breakout board for USB charging, power switch, stereo amplifier b) Auto-CAD of 3-D printed case, c) physical bandpass filter, d) bone conduction transducer

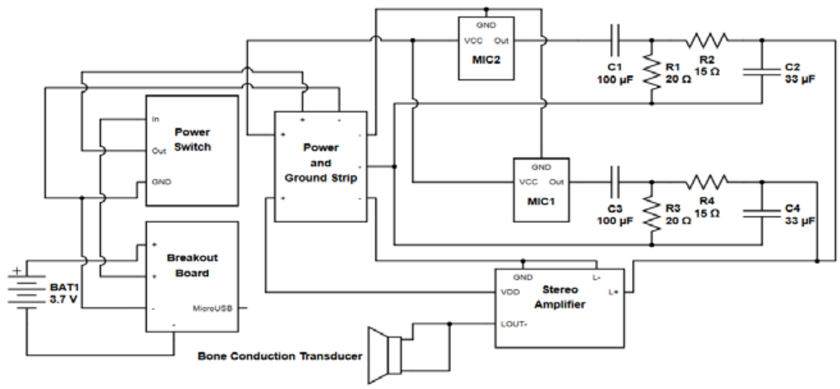

Figure 4: A circuit diagram depicting all of the components are connected on the breadboards

Development of Filtering

In order to determine the frequency range needed for the bandpass filter, fundamental frequencies of human speech were needed. MATLAB, a coding software, was utilized to implement a self-created code that functions by recording an audio sample for 5 seconds at a sampling rate of 32000 Hz. A time domain region was determined and used to show how the signal changed over time. The time domain region was converted to an FFT (Fast Fourier Transform) figure which displayed the range of frequencies detected vs the amplitude or strength of each frequency. For the audio samples a total of 4 subjects were recorded with two being female and two being male. Observing the FFT of each of the samples and taking the highest peak of each FFT, the fundamental frequency of that sample was determined. In order for an accurate bandpass filter to be designed, various sound samples in different environments were recorded to determine a frequency range for the bandpass filter

Using the frequency range determined via experimental testing, the bandpass filter components such as the resistors and capacitors needed were determined using the formula:

$$f_c = \frac{1}{2\pi RC}$$

Formula 1: cutoff frequency equation for determining filter specifications

These components helped build the physical bandpass filter employed within the device as well as used to create a simulation of the bandpass filter within MATLAB. The code itself first creates a time domain signal as mentioned before. Then the code takes the FFT of that signal in order to recreate that signal in frequency domain. Next, the impulse response of the filter is displayed. Finally, the last component that results from this code is the filtered frequency domain signal with the two regions cutoff. In order to test the performance of the filter, the window length (slope) of the impulse response was measured to ensure the roll-off rate was not too great.

Testing Functionality of Device

When testing the functionality of the device, the main component of testing was obviously whether or not sound was being conveyed to the subject, thus this was one of the main and easiest things to be tested. The way the testing was conducted was amongst the group members who essentially simulated microtia. This simulation was done by asking users to block their ear canals using ear plugs and noise cancelling headphones. A further comprehensive test of the filter's functionality was done using oscilloscope measurements where the input was placed prior to the filter and the output was placed directly after the filter. Simultaneous measurements were taken and uploaded to MATLAB where the analysis of the impulse response was taken. The key analysis that can be tested from these FFT spectrums within MATLAB is the Signal-to-Noise ratio. This comparison will determine the effectiveness of the filter as well as allow for quantitative evidence for measuring sound quality.

Besides analysis of the filtering itself, other forms of analysis of sound quality and performance were tested as well. The best way to test the quality of sound was determined using a very specific and detailed hearing test (audiogram) that helped determine adjustments to amplification or frequency range needed. Accompanying the test was a survey that determined addental quality checks such as comfort and ease of operation. A specific check that was included was determining whether or not the placement range of the transducer was the best quality. This was done by testing different regions around the ear and essentially asking which location range sounded the best. Some other questions in the survey included the comfort level, opinions on battery level, and overall usefulness. The results of this questionnaire would help determine which aspects of the device to adjust.

Results

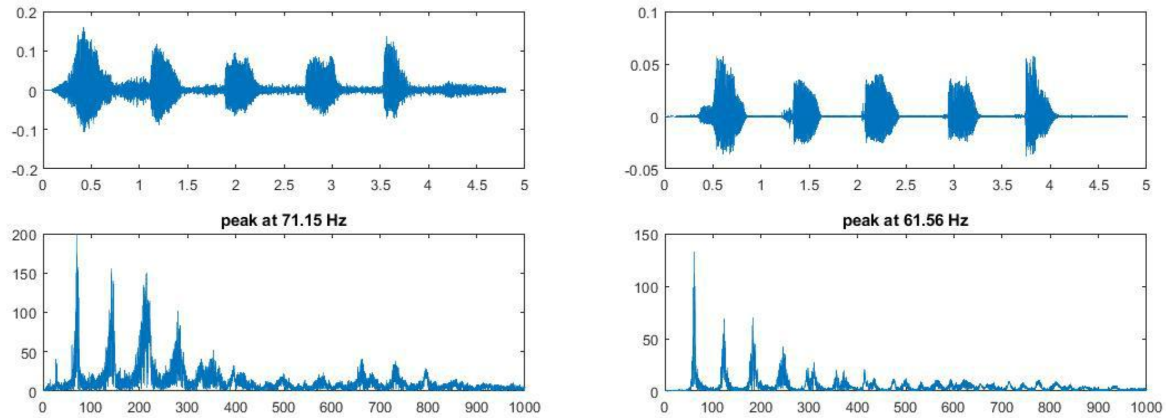

Figure 5: Shows an audio recording in a noisy environment and quiet environment in both the time domain and frequency domain. The fundamental frequency is observed at around 72 Hz with resonance frequencies at 146.4 Hz, 220.4 Hz, 291.3 Hz, and 353 Hz. Based on these observations the cutoff frequencies were determined to be 72 Hz and 322 Hz

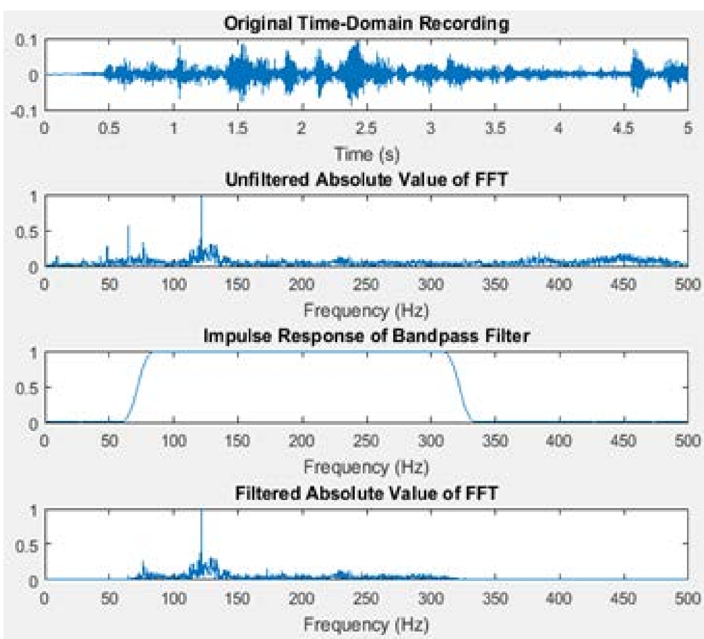

Figure 6: Shows the original time-domain recording, unfiltered absolute value of the FFT, impulse response of the bandpass filter, and filtered absolute value of the FFT

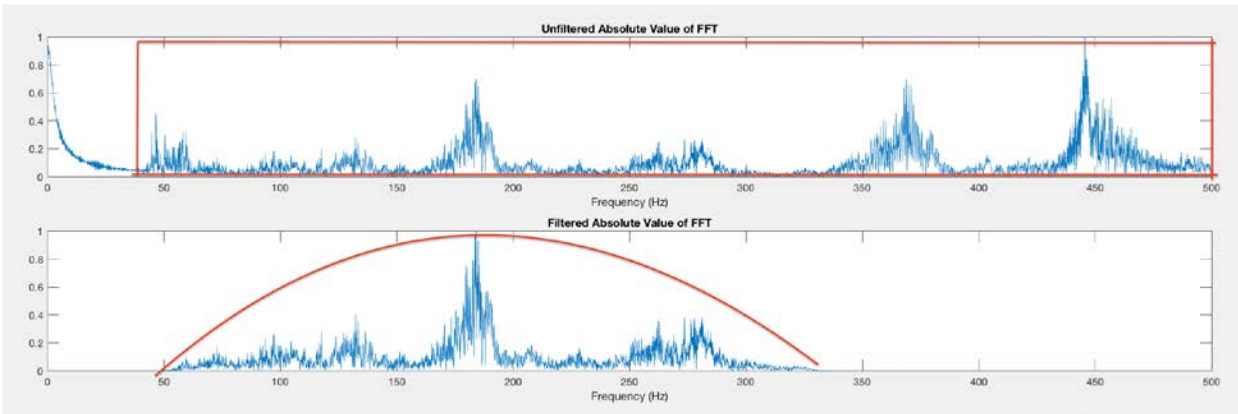

Figure 7: Areas highlighted used for determining the amount of noise present in FFT with a) being the unfiltered FFT and b) being the filtered FFT

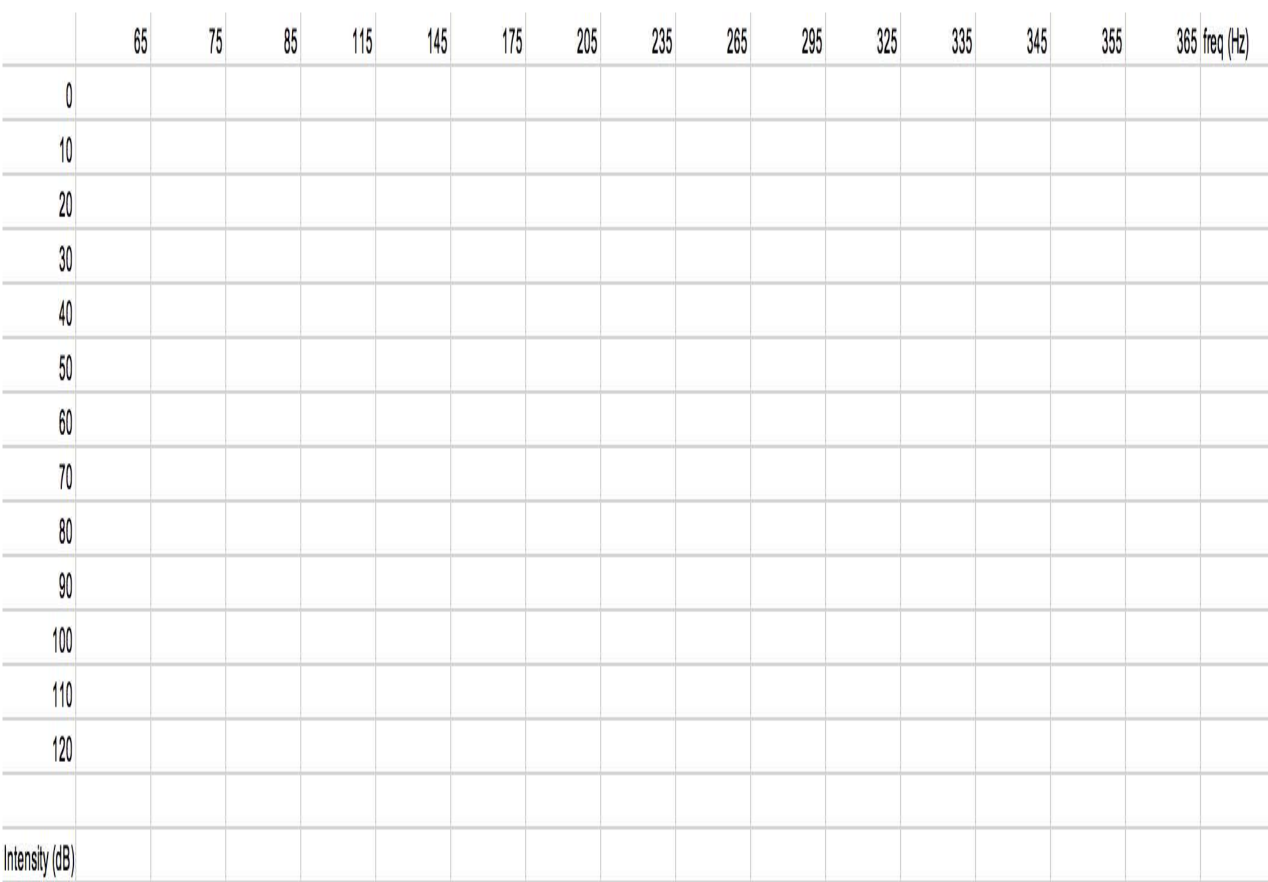

Figure 8: Audiogram used to determine range of frequencies and intensities that could be heard using device

Otic Solutions:Bone Conduction Hearing Aid Survey

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Section 1: Overall Design

	1	2	3	4	5
Overall fit /comfort……	☐	☐	☐	☐	☐
Battery life…………	☐	☐	☐	☐	☐
Transducer placement ..	☐	☐	☐	☐	☐
Value (performance vs cost)	☐	☐	☐	☐	☐

Figure 9: Sample Questionnaire used to test effectiveness and quality of other aspects of device

Discussion

From Figure 5 we see that the average frequencies recorded were for an average adult male which was around 61-71Hz range which made it reasonable to set the lower cutoff to be 72 Hz. In addition, these recordings were taken in the presence of noise in order to get a more realistic frequency measurement. We repeated the measurements for a female subject which ended up being around 322 Hz. Thus, our frequency range was determined and to confirm that this was indeed the accurate range for human speech, we compared with literature values and both were in agreement.

The next figure, Figure 6 shows the simulation of the bandpass filter that we implemented by taking oscilloscope measurements mentioned in the methods sections. To ensure that the impulse response was functioning properly and indeed applying a bandpass filter, the slopes of the impulse response were calculated of both the cutoff ends. Generally speaking the higher the slope of these cutoff ends (slope > 2.0) the better the impulse response. For our specific case, the slopes of both ends were 3.6 which indicates that our impulse response was a fairly accurate result with very little roll off of the frequencies.

Another analysis that was done was computing the SNRs before and after the filter. Figure 7 shows the methods in which the snr function basically determines the ratios for each of the FFTs. As we see in a) the way in which to calculate the SNR before filtering is by determining the peak of the signal, and then calculating the area of the noise level present in the signal and essentially diving the signal by the noise to get an SNR. Similarly, for after the filter in b) the same procedure is taken however one drastic difference is that the area of the noise is significantly smaller with it being a semi-circle. When comparing the SNRs we see that the values went up by approximately 30 dB from 10 dB to 40 dB which indicates a huge increase in the quality of the signal.

The next analysis was conducting a hearing test where different frequencies at different intensities and basically testing of whether or not the subject could hear was recorded as seen in Figure 8. Once the test was concluded, the results of both a normal person as well as using the device were plotted for two separate measurements; frequencies and intensity. From comparing the plots of these two subject, we can be able to measure the distance between the normal and the device results and determine how much to adjust the device itself. This adjustment would entail changing the gain of the amplifier via the formula:

□□ = 10□□□□2 − 10□□□□1

Formula 2: Equation for determining amount of adjustment to gain

In addition, determining the frequency different will allow for the adjustment of the resistors in the hardware bandpass filter.

The final analysis that was performed was providing a questionnaire for subjects who tested the device as seen in Figure 9. The questions that were the most useful was the placement of the transducer which as mentioned in the methods section was tested in 5 different ranges and the survey indicated that the range directly behind the ear was the most convenient and also the best sounding. The other question that was quite useful was the battery performance which allowed for us to retain the existing battery as it wasn’t consuming too much power and was an appropriate size.

Conclusion

The main purpose of this design project was to create a novel hearing aid that could be used without the need of fully formed ears. Bone conduction technology can be that source for creating these devices as demonstrated in this research. A bone conduction hearing aid was not only created and demonstrated to work, but also further characterization and analysis indicated that the device not only functioned properly but also by minor adjustments such as adjusting the gain to the amplifier and altering the cutoff frequencies of the bandpass filter, the quality and effectiveness of the device increased drastically. Future work with this device would focus on ultimately making the entire internal components on a PCB board which can be customized to be as thin and small as possible and in addition, simply to scale down to make it even more appealing and smaller in size as well. Further in-depth analysis of each component of the device can also be done to provide more data for determining accuracy as well.

References

[1] Lewin, Sheryl. “What Is Atresia?” *Microtia Ear Surgery*, 2018, microtiaearsurgery.com/hearing-loss/what-is-atresia.

[2] “Medpor Surgery Cost and Insurance Information.” *Ear Community - Microtia and Atresia Support Group*, 2018, earcommunity.org/microtiaatresia/surgical-options/techniques/medpor/cost-and-insurance/.

[3] “Bone Conduction: How It Works.” *Goldendance Bone Conduction*, Goldendance Co., Ltd., 2018, www.goldendance.co.jp/English/boneconduct/01.html.

[4] Tayyab, Muhammad. “Human Ear: Outer Ear, Middle Ear, Inner Ear, Hearing.” *SimpleBiology*, 2016, simplebiologyy.blogspot.com/2014/11/human-ear-outer-ear-middle-ear-inner-ear-Hearing.html.

[5] “Types of Hearing Loss.” *HEARnet Online*, hearnet.org.au/hearing-loss/types-of-hearing-loss.

[6] “Microtia & Atresia.” *Ear Community - Microtia and Atresia Support Group*, 2018, earcommunity.org/microtiaatresia/

[7] “Goldenhar's Syndrome.” *California Ear Institute*, 17 Aug. 2007, www.californiaearinstitute.com/ear-disorders-goldenhars-syndrome-bay-area.php.

[8] “Understanding the Causes of Microtia.” Reinisch Plastic Surgery Reinisch Plastic Surgery - Microtia Reconstruction Specialist, www.drjohnreinisch.com/microtia/causes

[9] "BAHA Cost and Insurance Information." *Ear Community - Microtia and Atresia Support Group*, 2018, earcommunity.org/hearing-loss/baha-technology/baha-cost-and-insurance-information/