# Bone Conduction: Head Mapping of Frequency Responses

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***Abstract* – The versatility of bone conduction allows them to be used in various scenarios where air conduction headphones is problematic, such as underwater or needing to leave the ears unobstructed. A common placement for transducer is behind the ear at the mastoid portion of the temporal bone. However, there is potential for other locations to be used. This paper analyzes the viability of other locations on the skull as potential placements for bone transducers. Frequency responses of the chin angle, collarbone, forehead, inion, mastoid, temple, and vertex were measured in this study. Via analyzing these frequency responses, it was determined that the mastoid still remains the best choice when considering power efficiency. However, placing the transducer on the inion or forehead offers better speech comprehensibility due to lower variance in their frequency response.**

## 1. INTRODUCTION

Bone conduction technology is steadily making its way into the consumer market as an alternative type of headphones. Headphones utilizing bone conduction have many advantages over their air conducting counterparts. Because bone conduction does not transmit via the ear drums the user's ears can remain uncovered. This is useful in military applications, where crews need to be able to reliably communicate with each other while maintaining situational awareness in harsh, noisy environments. When sealed within a waterproof assembly, bone conducting headphones can also be used underwater. This is advantageous over conventional underwater headphones, which rely on creating a sealed pocket of air in the ear canal that can cause discomfort at higher pressures. All in all, the versatility of bone conduction allows them to be superior in both common and uncommon applications. One particularity of bone conduction however is that bone conducts lower frequencies better than air does, as demonstrated in previous studies by Stenfelt, S. [1]. A corollary of this is that music played from bone conducting headphones will sound different from music played via conventional air conduction. The transmitted sound is also dependent on the user's bone density, skull shape, and where the bone transducer is placed on the skull. A common location where bone transducers are placed is at the mastoid behind the ears. However, there is potential for other areas to be used. This paper aims to analyze how the sound perceived by a user will change with respect to the location of the transducer on the skull. It is hypothesized that different locations on the skull will transmit certain frequencies better than others. For example, placing the transducer at a certain location might be better for listening to classical music, while another location would be better for making phone calls. Ultimately, it should be possible to find recommendations on when each location of the skull is best for various scenarios.

## 2. RELATED WORK

Similar experiments have been performed in the study "Bone conduction microphone: Head sensitivity mapping for speech intelligibility and sound quality" by Tran, P. et al. [2] In this experiment, a transducer was strapped to various locations on the head and participants were asked to describe the speech intelligibility and quality. The locations undertaken by this study were the forehead, temple, mastoid, vertex, inion, chin angle, and collarbone. Speech intelligibility was defined as the degree of confidence to which the speech was clearly understood. Speech quality was defined as the degree to which the speech was pleasant to hear. After hearing a recorded speech, participants would be asked to provide a numerical score for intelligibility and quality. At the end of these tests, the average intelligibility and quality scores were calculated for each location. It was found that the forehead had scored the highest for both intelligibility and quality. The caveat of this however is that the data from each experiment was qualitative and dependent on the participant's assessment. In another study by Qin, X. and Usagawa, T. [3] quantitative measurements were obtained for the loudness and acceleration of four transducers using different actuator types. One of the actuator types required placing it in the inner ear canal. While the other three were placed on the human mandible. The study did not investigate the effects that location had on the measurements, but instead focused on the effects of actuator type.

In comparison to the two previous works mentioned, what this paper does differently is that first rather than a qualitative assessment by participants, a quantitative assessment is performed by analyzing the frequency responses of the received sound. Secondly the same transducer is used for all experiments, with the primary focus being the how the transducer location affects the sound.

# 3. METHODOLOGY

## 3.1 Instrumentation

The transducer being used is an 8-Ohm 1-Watt bone conduction transducer by Adafruit Industries. The type of actuator it uses is a vibrating rectangular plate. Figure 1 provides a photograph of this particular transducer.

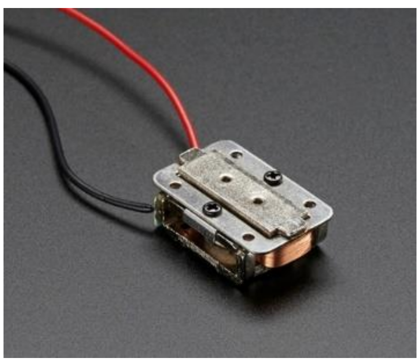

**Figure 1. Bone transducer by Adafruit Industries**

The transducer cannot operate on its own and must be driven by an amplifier. The amplifier being used is a TPA2012 audio amplifier module, also manufactured by Adafruit Industries. The amplifier in turn is powered by a 9-volt battery, and the input signal comes from a connected 3.5mm audio jack. This audio jack then connects via cable to an ASUS laptop that is controlling the audio playback. Figure 2 presents the schematic for this circuit. Figure 3 is a photograph of this circuit after it has been fully assembled.

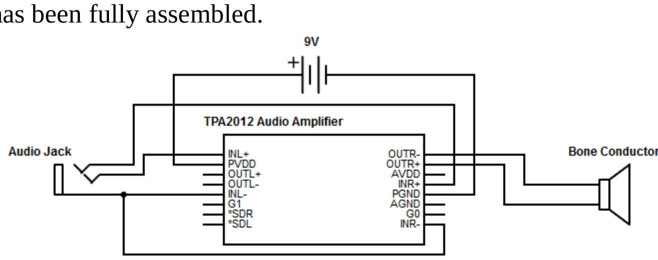


**Figure 2. Schematic for bone transducer circuit**

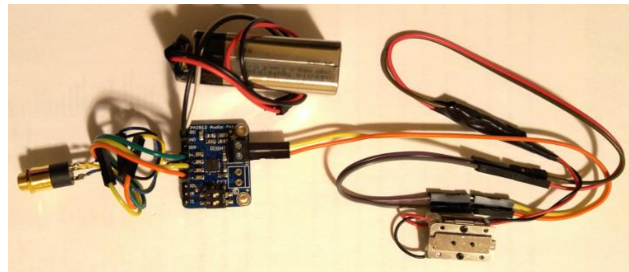

**Figure 3. Assembled bone transducer circuit**

The receiver being used to measure and record sound is a small electret microphone. The microphone is soldered to a 3.5mm mono plug that then connects to the laptop. Normally a capacitor and pull-up resistor is required when using an electret microphone. However, in this case the functionality of these components are provided by the internal circuitry at the microphone jack of the laptop. Figure 4 presents the schematic for this microphone circuit. Figure 5 is a photograph of the assembled circuit.

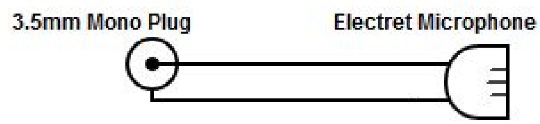


**Figure 4. Schematic for microphone circuit**

**Figure 5. Assembled microphone circuit**

## 3.2 Setup

In order to analyze the effects of transducer location on perceived sound, the general idea is to place the transducer at various location on the head, and then measure the sound that is heard at the ear. In order to measure the sound heard at the ear, the ideal would be to place a receiver at the cochlea. This is where auditory information is first received by the neurons. However, there does not exist a noninvasive and nonsurgical method of placing such a receiver in the cochlea. As such the inner ear canal will be used instead, the reasoning being that the inner ear canal is close enough to the cochlea that the difference in sound is negligible. The receiver that is then to be placed inside the inner ear canal is the small electret microphone. Earplugs were inserted after the microphone to block out noise from the surrounding environment. The transducer was then placed at seven different locations on the head and neck area: right chin angle, right collar bone, forehead, inion, right mastoid, right temple, and the vertex. Figure 6 provides a diagram of the transducer locations that were tested. Figure 7 provides a photograph of the physical setup on a participant.

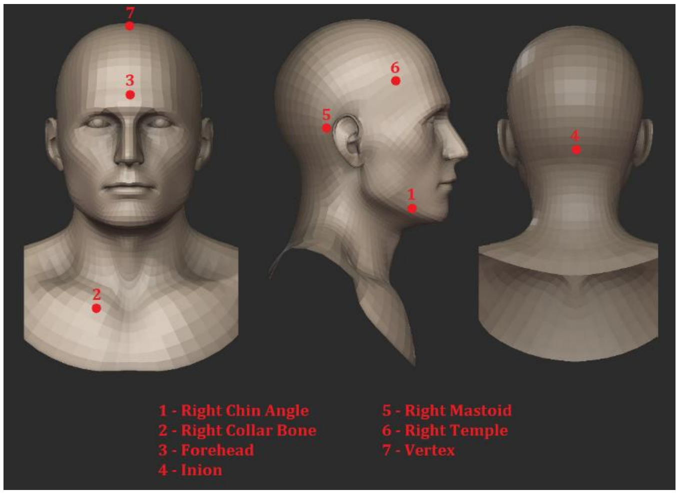


**Figure 6. Locations being tested for bone conduction**

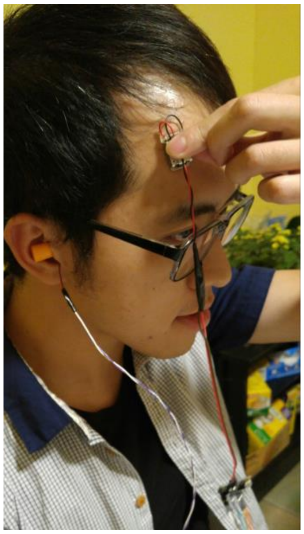

**Figure 7. Bone transducer and microphone setup**

### 3.3 Evaluation Procedure

For each of the seven locations, the transducer was used to play a ten-second long chirp ranging from 10 Hz to 8000 Hz. The sound heard at the ear is then recorded by the electret microphone in the inner ear canal. The recording is then analyzed to acquire the frequency response for that location. From frequency response, the entire spectrum from 10 Hz to 8000 Hz is then split into the three categories of Low, Medium, and High frequencies. Low is defined as the frequencies in the range 10 Hz to 300 Hz. Medium is defined as the frequencies in the range 300 Hz to 3400 Hz. High is defined as the remaining frequencies in the range 3400 Hz to 8000 Hz. For each of the categories, the mean and variance of the frequency responses are tabulated. This information will be assessed to provide characteristics of the sound at that location.

For the test, it is important to note that the transducer and microphone have a combined frequency response of their own that will skew the result of the recorded sound. The combined frequency response of the transducer and microphone can be determined by placing the microphone directly on the transducer. To aid in this visualization, Figure 8 shows the combined frequency response of the microphone and transducer. Figure 9 shows the frequency response measured at the mastoid. Take note in how the general shape of Figure 9 resembles Figure 8. In order to correct the skew, the combined frequency response of the microphone and transducer is subtracted from whatever frequency response is measured during the test. The resulting difference between the two frequency responses is then taken as the frequency response of that location on the head. Figure 10 contains the result after subtracting the frequency response in Figure 9 by Figure 8.

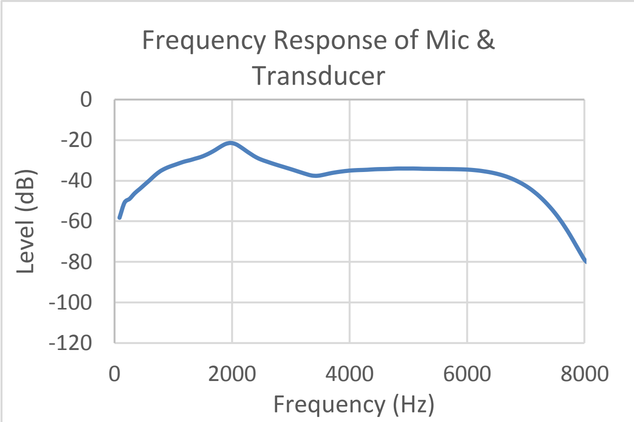


**Figure 8. Combined frequency response of transducer and microphone**

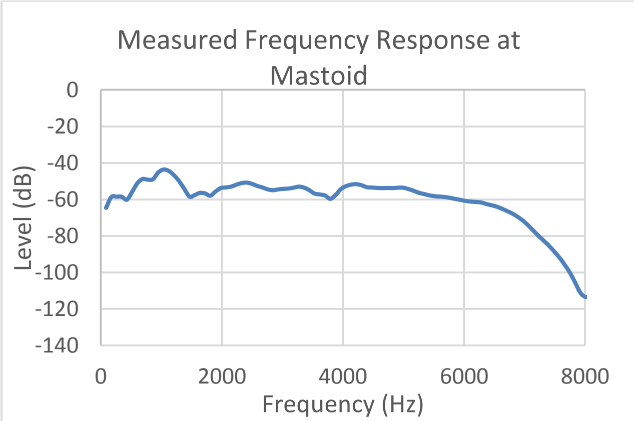


**Figure 9. Frequency response recorded at the mastoid**

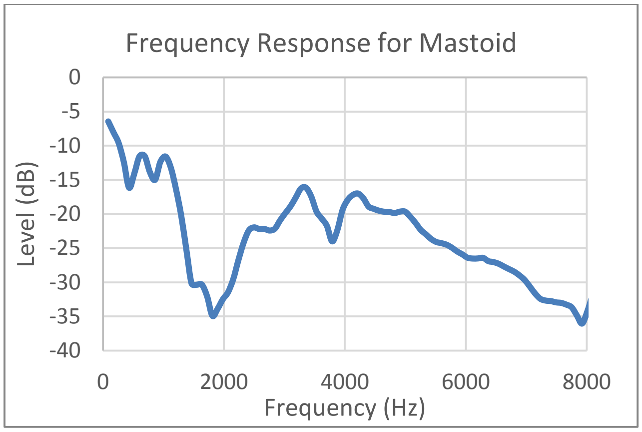


**Figure 10. Frequency response of mastoid after removing skew caused by microphone and transducer**

### 3.4 Participants

A total of five participants had taken part in this experiment. The first four participants consisted of two males and two females, all aged 22-24. The fifth participant was a male in his late 50's. All of the participants were considered to be in good health, with no prior history of any hearing impairment nor any sustained injuries to the skull.

## 4. MEASUREMENTS

The frequency responses for each of the seven locations were averaged across the participants and are shown in Figures 11 to 17. For each category of Low, Medium, and High frequencies, Table 1 lists the mean frequency responses of each location. Table 2 lists the variance of the frequency responses. Table 3 ranks the seven locations based on their mean frequency response in each category. A rank of 1 indicates the highest mean frequency response, a rank of 7 indicates the lowest mean frequency response. Table 4 then ranks the locations based on their variance. A rank of 1 indicates the lowest variance, a rank of 7 indicates the highest variance.

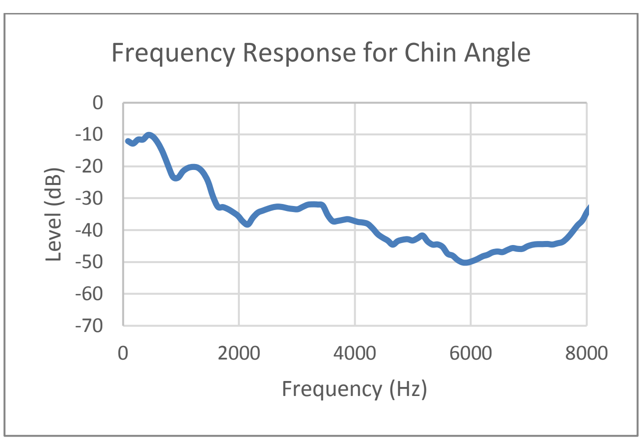


**Figure 11. Average frequency response for chin angle**

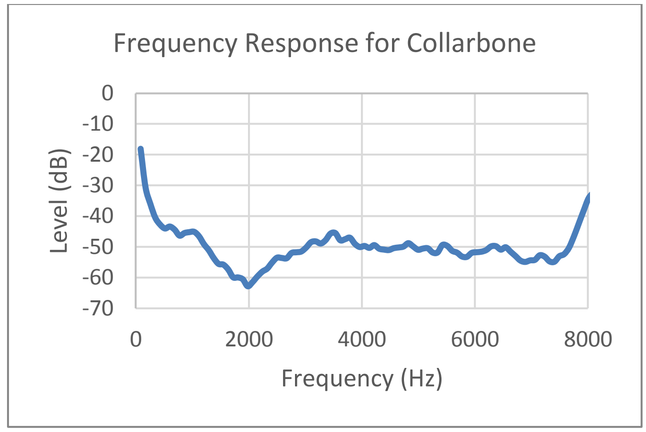


**Figure 12. Average frequency response for collarbone**

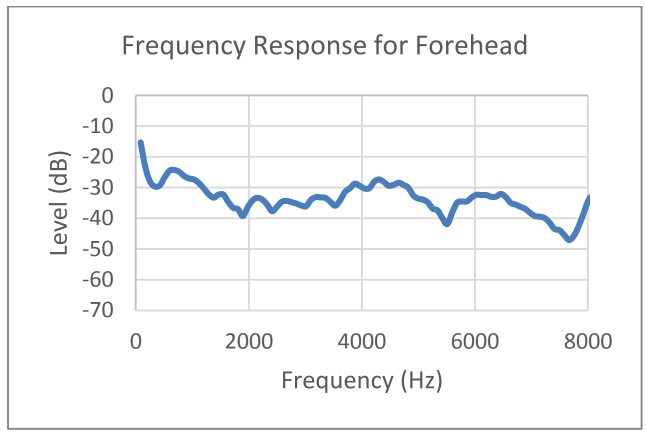


**Figure 13. Average frequency response for forehead**

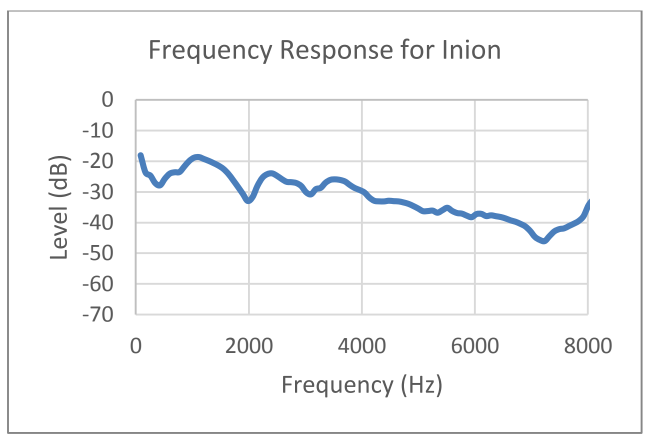


**Figure 14. Average frequency response for inion**

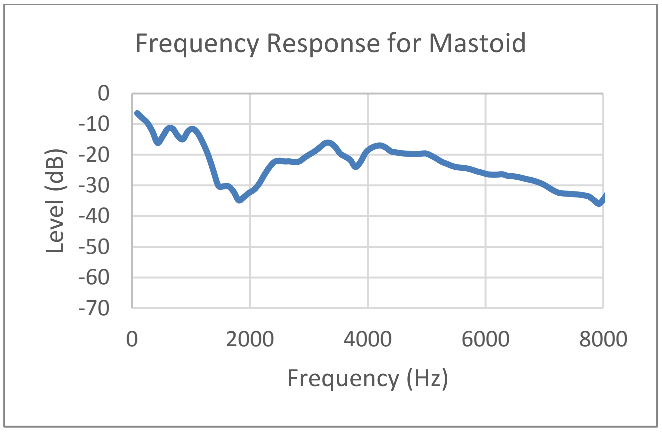


**Figure 15. Average frequency response for mastoid**

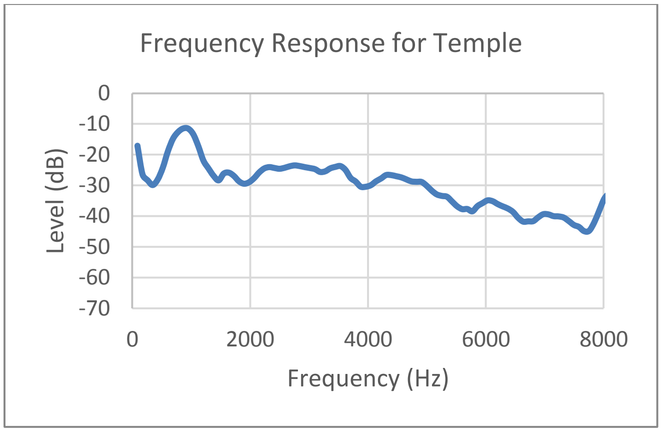


**Figure 16. Average frequency response for temple**

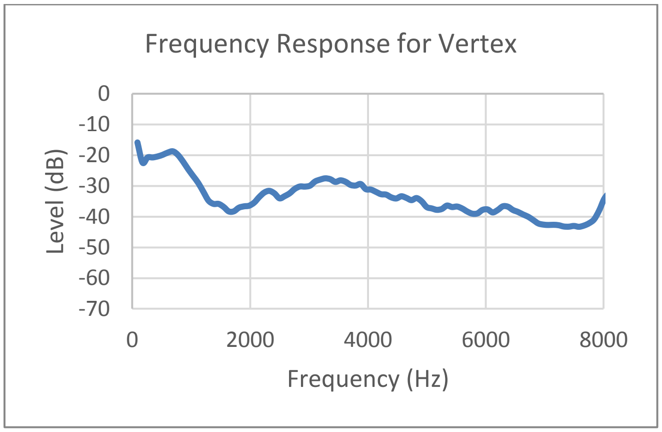


**Figure 17. Average frequency response for vertex**

**Table 1. Mean frequency responses (dB) for each frequency range**

| Location | Low | Medium | High |
|---|---|---|---|
| Chin Angle | -11.50 | -25.55 | -40.97 |
| Collarbone | -35.35 | -52.46 | -50.75 |
| Forehead | -25.40 | -31.16 | -34.94 |
| Inion | -24.47 | -23.74 | -34.26 |
| Mastoid | -11.11 | -22.56 | -24.37 |
| Vertex | -25.62 | -21.91 | -32.45 |
| Temple | -19.98 | -31.00 | -35.59 |

**Table 2. Variance of frequency responses (dB) for each frequency range**

| Location | Low | Medium | High |
|---|---|---|---|
| Chin Angle | 0.91 | 53.58 | 31.31 |
| Collar Bone | 95.42 | 46.97 | 14.60 |
| Forehead | 29.38 | 22.30 | 19.90 |
| Inion | 12.35 | 20.20 | 35.08 |
| Mastoid | 13.87 | 86.26 | 28.22 |
| Vertex | 21.28 | 45.49 | 45.76 |
| Temple | 4.86 | 51.62 | 22.28 |

**Table 3. Skull locations ranked by mean frequency response for each frequency range. (Rank 1 is highest mean)**

| Rank | Low | Medium | High |
|---|---|---|---|
| 1 | Mastoid | Vertex | Mastoid |
| 2 | Chin Angle | Mastoid | Vertex |
| 3 | Temple | Inion | Inion |
| 4 | Inion | Chin Angle | Forehead |
| 5 | Forehead | Temple | Temple |
| 6 | Vertex | Forehead | Chin Angle |
| 7 | Collarbone | Collarbone | Collarbone |

**Table 4. Skull locations ranked by variance of frequency responses for each frequency range (Rank 1 is lowest variance)**

| Rank | Low | Medium | High |
|---|---|---|---|
| 1 | Chin Angle | Inion | Collarbone |
| 2 | Temple | Forehead | Forehead |
| 3 | Inion | Vertex | Temple |
| 4 | Mastoid | Collarbone | Mastoid |
| 5 | Vertex | Temple | Chin Angle |
| 6 | Forehead | Chin Angle | Inion |
| 7 | Collarbone | Mastoid | Vertex |

# 5. ANALYSIS

From inspecting the graphs shown in Figures 11 to 17, a general trend can be observed – the frequency responses are higher at low frequencies, and lower at high frequencies. This is conclusive with previous studies that bone conducts lower frequencies better than it can for high frequencies [1]. From the rankings shown in Table 3, the mastoid on average has a higher level of frequency response compared to other locations on the skull. This is expected as the mastoid is the closest to the ear. In contrast, the collarbone has the lowest mean frequency response because of how far away it is from the ear. If only the intensity of sound is being considered, placing the transducer at the mastoid is always the best option. However, this assessment changes when the variance of the frequency response is taken into consideration. Of particular interest is the results after ranking the locations based on their variance, as shown in Table 4. For the Medium range frequency category, the inion ranked the highest, with the forehead coming in second. The Medium range, 300 Hz – 3400 Hz, is significant because this corresponds to the voice frequency band. The voice frequency band is the range of frequencies that are normally used in the transmission of speech. Recall that from the study by Tran, P. et al. [2] it was observed that the forehead had the highest speech intelligibility score. This can now be further explained with the fact that the forehead has one of the lowest variance in frequency response within the voice frequency band. Because of the lower variance, sound is more uniform within this range and speech does not undergo fluctuations in sound intensity. The result is more comprehensible speech.

The final thing of importance is to note the behaviour of the frequency responses at 2000 Hz. For all seven locations, the frequency response drops to a local minimum at 2000 Hz. This dip is most pronounced in the frequency responses for the collarbone, mastoid, and vertex – as shown in Figures 12, 15, and 17. The fact that this happens at every location infers that this phenomenon is independent of location and is instead intrinsic to the properties of the bone around the ear. Upon cross-referencing these results with previous studies, it was found that this phenomenon is known as the Carhart's notch [4]. In the study by J. Tonndorf [5], it was suggested that the frequency of the notch varies depending on the natural resonance frequency of ossicular chain of the participant. The ossicular chain is a set of small bones located in the middle ear. This frequency is normally in the 1600-1700 Hz range, however any bone conduction disorders such as in the case of otosclerotic patients will decrease the mobility of the ossicular chain. This is what causes the notch to shift to 2000 Hz. However, it is important to note that at this point there is insufficient information to be able to make any comments about the bone conduction health for the participants involved in this study. The frequency responses graphed in Figures 11 to 17 are just the averages taken across all the participants. Individually, the location of the Carhart notch for some patients were above 2000 Hz, and others were below it. Incidentally, they all ended up being centered around 2000 Hz.

# 6. CONCLUSION

This study demonstrated how the frequency response of sound changes with respect to various placement locations for a bone transducer. Bone transducers are commonly placed behind the ear on the mastoid. This is the optimal choice when trying to maximize power efficiency, i.e. perceived sound intensity versus power output of the transducer. However, this may does not provide the best results for speech comprehensibility. Within the voice frequency band, the mastoid has the highest variance in frequency response. This will cause fluctuations in sound intensity that can make speech harder to understand. The better choices for placing the bone transducer are at the inion and the forehead. These two locations have the lowest variance in their frequency responses, and as such the sound intensity will not fluctuate as greatly. The benefit of using the forehead is that it also has a lower variance at higher frequencies compared to the inion. The recommendation is to place transducers on the forehead in cases of telephony and voice communication, this provides superior speech comprehensibility. For cases outside the voice frequency band, such as listening to music, the transducer can instead be placed on the mastoid which offers better power efficiency. Moving forward, results from this study can be further refined by acquiring data from more participants. Furthermore, safely extending the upper bound on the chirp to 20,000 kHz will provide additional insight into bone conduction for the full range of human hearing.

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