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Sound Attenuation of Neoprene Wetsuit Hoods as a Function of Dive Depth and Acoustic Frequency: Hyperbaric Chamber Trials

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14. ABSTRACT

Underwater hearing thresholds were collected from 13 U.S. Navy trained divers while bare headed and while wearing a 7 mm neoprene wetsuit hood. Testing frequencies and depths ranged from 100 Hz to 12,000 Hz and from near surface to 132 feet of sea water (fsw), respectively. All dives were conducted in a small immersion tank in NSMRL's hyperbaric chamber. Wetsuit hood attenuation was calculated from the difference between hooded and unhooded hearing thresholds. The attenuation of underwater sound provided by a 7 mm neoprene wetsuit hood at the threshold of hearing was measured as being from 0 dB to approximately 34 dB. The amount of attenuation is dependent on at least two factors, frequency of the sound and ambient pressure (simulating depth). In general, the lower frequency sounds are attenuated less and the higher frequency sounds are attenuated more when a neoprene wetsuit hood is worn. The greatest attenuation (~20-34 dB) was above 4000 Hz; and almost no attenuation was measured at 100 and 250 Hz. From 500 to 1000 Hz the amount of sound attenuation decreased as the ambient pressure increased.

15. SUBJECT TERMS

Underwater sound, sound attenuation, neoprene hood, diving, hearing function

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Fothergill D.M., Cudahy E.A., Schwaller D. (2004a). The effect of depth on underwater sound attenuation of a neoprene wetsuit hood: hyperbaric chamber trials. Undersea and Hyperbaric Medicine 31, p 317.

This work was conducted while Dr. Fothergill was on assignment leave from the Research Foundation of the State University of New York at Buffalo through an Intergovernmental Personnel Assignment Agreement with the Naval Submarine Medical Research Laboratory, Groton, CT. As a co-principal investigator on this study Dr. Cudahy contributed to the initial inception and design of the study, assisted with data collection, and concurred with the initial results and findings presented in Fothergill et al. (2004a). When Dr. Cudahy passed away in 2012, before the first draft of this report, Dr. Michael Qin took on the task to ensure that Dr. Cudahy's legacy and unpublished work at NSMRL was recorded for prosperity. To that end this report is the first of several on the bioeffects of underwater sound on divers that are dedicated to the memory of Dr. Edward Cudahy.

Executive Summary

The U.S. Navy is interested in strategies that divers could employ to protect them from loud underwater sounds. At the time this research was conducted, the U.S. Navy guidance for diver exposure to underwater sound accounted for the diver wearing a wetsuit hood, but did not account for any changes in the hood's sound attenuation properties with dive depth. Characterizing how the hood's attenuation properties change with depth and frequency is critical to creating appropriate guidance for diver's exposure to underwater sound.

Underwater hearing thresholds were collected from thirteen U.S. Navy trained divers while bare headed and while wearing a 7 mm neoprene wetsuit hood. Testing frequencies and depths ranged from 100 Hz to 12,000 Hz and from near surface to 132 feet of sea water (fsw), respectively. All dives were conducted in a small immersion tank in NSMRL's Genesis hyperbaric chamber. Wetsuit hood sound attenuation was calculated from the difference between hooded and unhooded hearing thresholds.

The acoustic attenuation provided by a 7 mm neoprene wetsuit hood determined using the difference between hooded and unhooded hearing threshold measurements was found to range from 0 dB to approximately 34 dB. The amount of attenuation is dependent on at least two factors, frequency of the sound and ambient pressure (simulating depth). In general, the lower frequency sounds are attenuated less and the higher frequency sounds are attenuated more when a neoprene wetsuit hood is worn. The greatest attenuation (~20-34 dB) was above 4000 Hz; and almost no attenuation was measured at 100 and 250 Hz. At frequencies from 500 Hz to 1000 Hz, where underwater hearing is the most sensitive, the amount of sound attenuation decreased as the ambient pressure was increased.

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1 Introduction

Sonar transmissions and other forms of underwater sound such as that produced by noisy underwater tools are an occupational hazard for U.S. Navy divers (Parvin et al., 2001; Evans et al., 2007; Wolgemuth et al., 2008; and Anthony, 2009). At the time this research was conducted, the U.S. Navy guidance for diver's exposure to underwater sound accounted for the diver wearing a wetsuit hood, but did not account for any changes in the hood's sound attenuation properties with dive depth (U.S. Navy Dive Manual Revision 4 Change A Appendix 1A). Even in the current U.S. Navy Guidance (U.S. Navy Dive Manual Rev 7), a wetsuit hood is considered to provide 15 dB of attenuation, regardless of frequency or depth.

Research by Fothergill, et al. (2004b) found that underwater hearing thresholds (UHTs) at 400 and 500 Hertz (Hz) were increased by approximately 10 decibels (dB) when a 3 millimeter (mm) neoprene wetsuit hood was worn at 1 meter (m) depth. However, for frequencies below 400 Hz, there was no difference in UHTs between unhooded and hooded conditions. Unmanned measurements of the sound attenuating properties of 6-mm thickness neoprene hoods at 10 m depth have been conducted by Parvin, et al. (1994). These authors found little attenuation of sound for frequencies below 200 Hz. However, between 200 and 800 Hz they noted a frequency dependent transmission loss that increased from 1 dB at 200 Hz to 28 dB at 800 Hz. At frequencies above 800 Hz the neoprene attenuated the incident sound by an average level of 28 dB. Similar levels of attenuation by neoprene hoods have also been reported by other investigators during underwater auditory sensitivity tests (Norman, et al., 1971; Montague and Strickland, 1961; Cudahy, et al., 2002).

In the study conducted by Cudahy et al. (2002), the acoustic attenuation of a 7-mm neoprene hood (80% neoprene, 20% nylon) was determined using both physical and psychophysical methodologies. The physical measures of sound attenuation of the wetsuit material were determined using a B&K 8104 hydrophone surrounded by a bracket on which the wetsuit material could be mounted to completely encase the hydrophone. The hydrophone was placed at 2 m water depth and exposed to 12 frequencies between 25 Hz and 32 kHz while the sound pressure levels at the hydrophone were measured with and without the neoprene completely encasing the hydrophone. The difference in SPL yielded the physical attenuation. For the psychophysical measures of attenuation, 22 divers were exposed to the same frequencies at the same depth as for the physical measurements. Each diver performed underwater threshold tests and suprathreshold loudness balance tests using an adaptive tracking methodology while bareheaded and while wearing a hood. Similar to the findings of Parvin et al. (1994), both physical and psychophysical measures showed that a neoprene wet suit hood provided no sound protection below 300 Hz. Between 300 Hz and 4000 Hz the physical attenuation afforded by the hood increased as frequency increased up to a maximum of 30 dB, however at the same frequencies the psychophysical sound protection was 50 to 75% of the physical attenuation. Based on their results, Cudahy et al. (2002) concluded that physical and psychophysical measures of wet suit hood sound protection have a similar pattern across frequency, but physical attenuation is much greater than perceptual attenuation. Furthermore, the sound protection properties of a neoprene wet suit hood are similar at threshold and supra-threshold SPLs.

While the aforementioned studies quantified the sound attenuating properties of current wet suit materials, there are gaps in information, especially in terms of how attenuation varies as a function of dive depth... Furthermore, apart from the preliminary study by Cudahy et al. (2002) there is a paucity of data on the attenuation characteristics of wetsuit hoods at frequencies greater than 8 kHz. It is important to understand wetsuit hood characteristic at higher frequencies and deeper depths since preliminary unpublished studies at the Naval Submarine Medical Research Laboratory, Groton, CT found that divers can hear underwater sound at frequencies as high as 100 kHz (Michael Qin personal communication, 2014) and that the physical attenuation properties of neoprene wet suit material significantly decrease as depth increases (Cudahy and Fothergill NSMRL IRB protocol DOD # 30372). Providing a better understanding of the sound attenuating properties of diving hoods across a wider frequency range and across typical working depths will permit better guidance to be developed to help protect the diver from hazardous underwater sound.

The objective of the current study was therefore to characterize the sound attenuating properties of a typical neoprene wet suit hood worn by U.S. Navy diver's as a function of both frequency and diving depth. The frequency range chosen for testing (100 Hz to 12 kHz) encompasses frequencies over which hearing is most sensitive underwater (approximately 750 Hz) as well as in air (approximately 4,000 Hz) (Parvin et al., 1994) with the specific frequencies chosen to allow for comparison with previous studies of neoprene wet suit hood attenuation (i.e., Parvin et al., 1994, Cudahy et al., 2002, Fothergill et al., 2004b).

2 Methods

2.1 Subjects

Thirteen male U.S. Navy trained divers completed data collection. Female divers were not specifically excluded from participating in the protocol. All subjects had normal hearing (in air audiometric thresholds below 15 dB Hearing Level (HL) at frequencies from 250 to 8000 Hz.) The subjects had a mean ± SD height of 175.9 ± 6.8 cm, weight of 84.3 ± 12.3 kg, and age of 33.1 ± 6.8 years. Subjects wore 7 mm neoprene wetsuits, standardized volume face masks, and a weight belt to achieve negative buoyancy. The protocol was initially approved by NSMRL's Committee for the Protection of Human Subjects (CPHS) under protocol number 30372, and later reassigned to Protocol NSMRL.2001.0003 by NSMRL's Institutional Review Board (IRB).

2.2 Test Conditions

The underwater sound attenuation of a 7 mm thick neoprene wetsuit hood at a given test frequency was indirectly measured from the difference in the level (in dB) between the subjects' underwater hearing thresholds measured with and without a wetsuit hood (i.e. hooded and bare headed dress conditions). The resultant attenuation value is an operational measure of the wetsuit hoods' psychophysical attenuation rather than an absolute measure of the physical attenuation properties of the neoprene material. The neoprene hood used in the testing was commercially available and was of the typical thickness used and purchased by the U.S. Navy for cool/cold water diving in water temperatures between 45°- 60° F such as that found in the waters off of California, Oregon, Washington, New York, the Great Lakes, New England states, Northern Europe and colder waters throughout the world. Hearing threshold measurements were taken with the divers hooded and while bareheaded while they were sitting immersed in an acoustic immersion tank that was located within the NSMRLs Genesis hyperbaric chamber (see section 2.3). The pressure within the main lock of the chamber was varied to allow five depths between 4 and 132 fsw to be tested (see Table 1). At each test depth, ten frequencies between 100 and 12000 Hz were tested, under both hooded and bare headed dress conditions. Each subject repeated these stimulus conditions on a separate day (i.e., Dive 1 and Dive 2). The order of dress condition (bare headed or hooded) was counterbalanced between subjects as well as within a subject between Dive 1 and Dive 2, while the order of the ten frequencies within a given dress condition was presented in a random order. Figure 1 summarizes the test conditions which are described in more detail in the sections below.

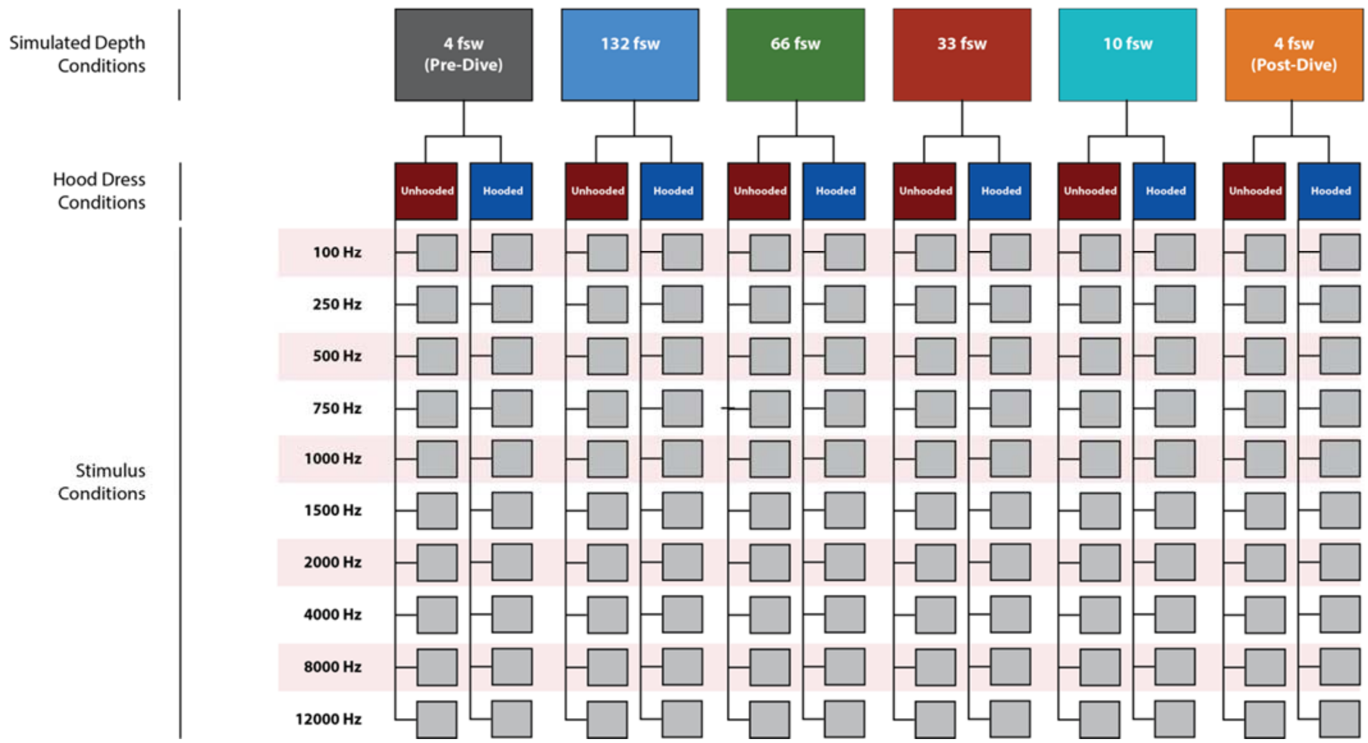

Figure 1: Conditions summary. Depth conditions included: 4 fsw (Pre-Dive), 132 fsw, 66 fsw, 33 fsw, 10 fsw, 4 fsw (Post-Dive). Each subject repeated these testing conditions on a separate day (i.e. Dive 1 and Dive 2). At each depth, the unhooded and hooded dress conditions were tested in a counter balanced order among subjects. The dress condition was also counterbalance within a subject between Dive 1 and Dive 2. At each dress condition, subjects were presented with all ten frequencies in random order.

2.2.1 Depth Conditions and Dive Profile

As open-circuit Self Contained Underwater Breathing Apparatus (SCUBA) dives have a normal working limit of 130 feet of seawater (fsw) (U.S. Navy Dive Manual revision 7) we chose to limit our dive depth testing to 5 ATA or 132 fsw. The five depth conditions tested were 4, 10, 33, 66, and 132 fsw. The depth intervals were chosen based upon a combination of the required decompression stops needed to conduct a multi-level dive profile with a maximum depth of 132 fsw and bottom time 40 min as prescribed by the VVAL18 decompression algorithm and the desire to obtain multiple data points on wet suit hood attenuation across the continuum of pressure from 1 to 5 ATA. The 4 fsw depth condition was performed twice, once prior to compressing the chamber and the other after completing measurements at all the other test depths and after the chamber atmospheric pressure had returned to surface levels (see Figure 1). Diving depth was simulated in NSMRLs Genesis hyperbaric chamber (see Experimental Setup). As the divers were immersed in a water tank within the main lock of the chamber with their lung centroid approximately 4 feet below the water line in the tank (see Section 2.3), the aforementioned depth conditions represent actual dive depths rather than chamber simulated depths. Table 1 identifies how this study defines depth conditions in relation to the chamber simulated depth.

Table 1: Conversion of depth condition to chamber simulated depth and pressure.

Depth Condition (fsw)	Chamber Simulated Depth (fsw)	Pressure at Subjects' Lungs (ATA)
4	0	1.12
10	6	1.30
33	29	2.00
66	62	3.00
132	128	5.00

When this study was carried out, the U.S. Navy Dive manual in use (Rev 4) treated any multi-level dive performed greater than 50 fsw as if the total bottom time was conducted at the deepest part of the dive. Consequently, the U.S. Navy Standard Air Tables in Rev 4 of the U.S. Navy Dive manual severely overestimated the required decompression for the multi-level dive profile proposed for the current study. Our preferred approach for testing was to conduct a multi-level dive that would allow 40 min of test time at each test depth, and would follow the shorter air/O_2 decompression procedures generated by the VVAL18 decompression model. As the VVAL18 decompression algorithm had been authorized for Naval Special Warfare use in the U.S. Navy Dive planner (Butler 2000), NSMRL requested and received NAVSEA 00CN approval to use the U.S. Navy Dive planner and VVAL18 decompression algorithm to create the multi-level dive profile described below and shown in Figure 2.

Multi-Level Dive Profile

Descend to 132 fsw at no greater than 75 fsw/min
Stop @ 132 fsw for 40 min then ascend at 30 fsw/min to 66 fsw
Stop @ 66 fsw for 40 min then ascend at 30 fsw/min to 33 fsw
Stop @ 33 fsw for 40 min on air then transfer to 100% oxygen breathing for a further 30 min. After 30 min on O_2 ascend at 30 fsw/min to 10 fsw
Stop @ 10 fsw and continue oxygen breathing for 30 min. After oxygen breathing period breath air for 50 min then ascend at 30 fsw/min to surface.

The risk of decompression illness using the above dive profile was estimated at 1.5%.

The dive profile dictated the order in which the depth conditions were tested; thus, the chamber simulated depths were in this order: 0 fsw, 128 fsw, 62 fsw, 29 fsw, 6 fsw, and 0 fsw (i.e., simulated depth conditions 4 fsw – Pre-Dive, 132 fsw, 66 fsw, 33 fsw, 10 fsw, and 4 fsw – Post-Dive). Figure 2 illustrates the dive profile with testing periods and O_2 breathing periods.

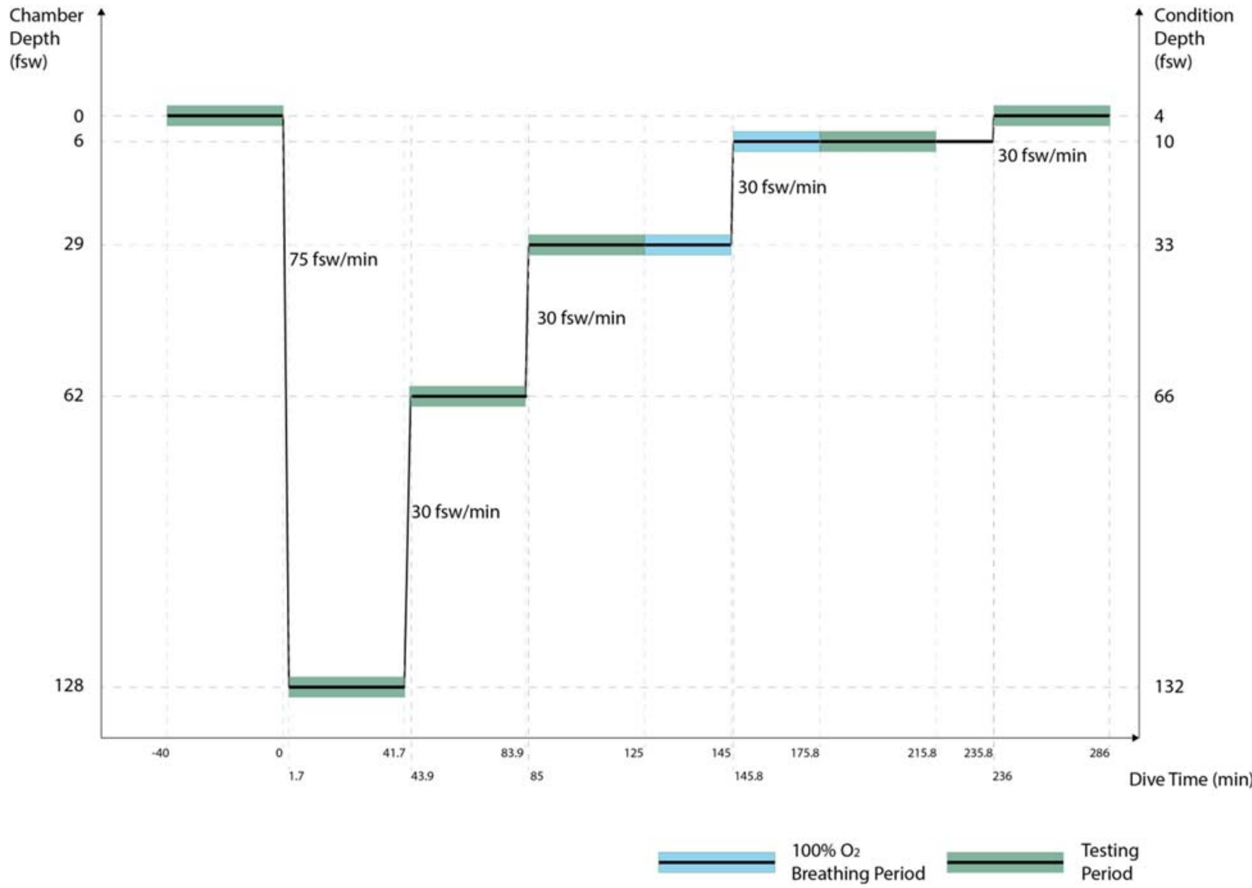

Figure 2: Dive profile. Subjects started each dive in the water tank in the main lock of the chamber with the chamber atmosphere at surface pressure. The chamber then underwent compression at 75 fsw/min to 128 fsw. Decompression, at 30 fsw/min, was then completed between each remaining test pressure, with the final test again being performed in the immersion tank at surface.

2.2.2 Stimulus Frequencies

The ten frequencies tested were 100, 250, 500, 750, 1000, 1500, 2000, 4000, 8000, and 12000 Hz. These stimuli were 1000 millisecond (ms) pure tones with a cosine rise-fall time of 20 ms.

2.3 Experimental Setup

Testing was conducted in an acoustic open air water-filled holding tank located within the main living chamber of the NSMRL Genesis Hyperbaric Chamber. The Genesis chamber is a horizontal cylindrical steel pressure vessel, with an internal diameter of 9 feet and a length of 25 feet with a total floodable volume of 1210 cubic feet. It is capable of pressurization to a depth of 337 feet of sea water (150 psig) at a maximum rate of 75 feet per minute. The chamber is divided into two locks, each of which may be pressurized and controlled independently of the other, but interconnected by means of two 48 inch pressure sealing access hatches. The outer lock is 10 feet long and serves as the entry point to the chamber. The inner lock is 15 feet long and is the main working space within the chamber.

All the dives were performed in the acoustic holding tank shown in Figure 3 which was located in the main lock of the Genesis chamber. The acoustic holding tank was made of aluminum and had nonparallel, asymmetrical sides to reduce standing waves which occur via interference of sound waves reflecting from the various tank surfaces. The inside of the tank was lined with a one inch thick closed-cell foam rubber lining to act as a sound absorber. A riser was placed below one edge of the tank such that there was approximately 2 degree of incline with the chamber floor to ensure that the tank bottom and water surface were also nonparallel.

The tank was filled with water to four inches below its maximum height. Water temperature was maintained at 75-85 degrees Fahrenheit with an immersion heater (that was removed prior to diver testing). The test space was prepared for subjects to sit in the tank according to Figure 3. A transducer was suspended by line from a wooden plank positioned across the top of the tank, such that the transducer's center of mass was 24 inches below the tank's water line. The subjects' head was positioned 18 inches from the face of the transducer.

Diving cylinders were located outside the test tank and provided breathing gas to the subjects via a regulator hose. An underwater response button was in the tank for the subjects.

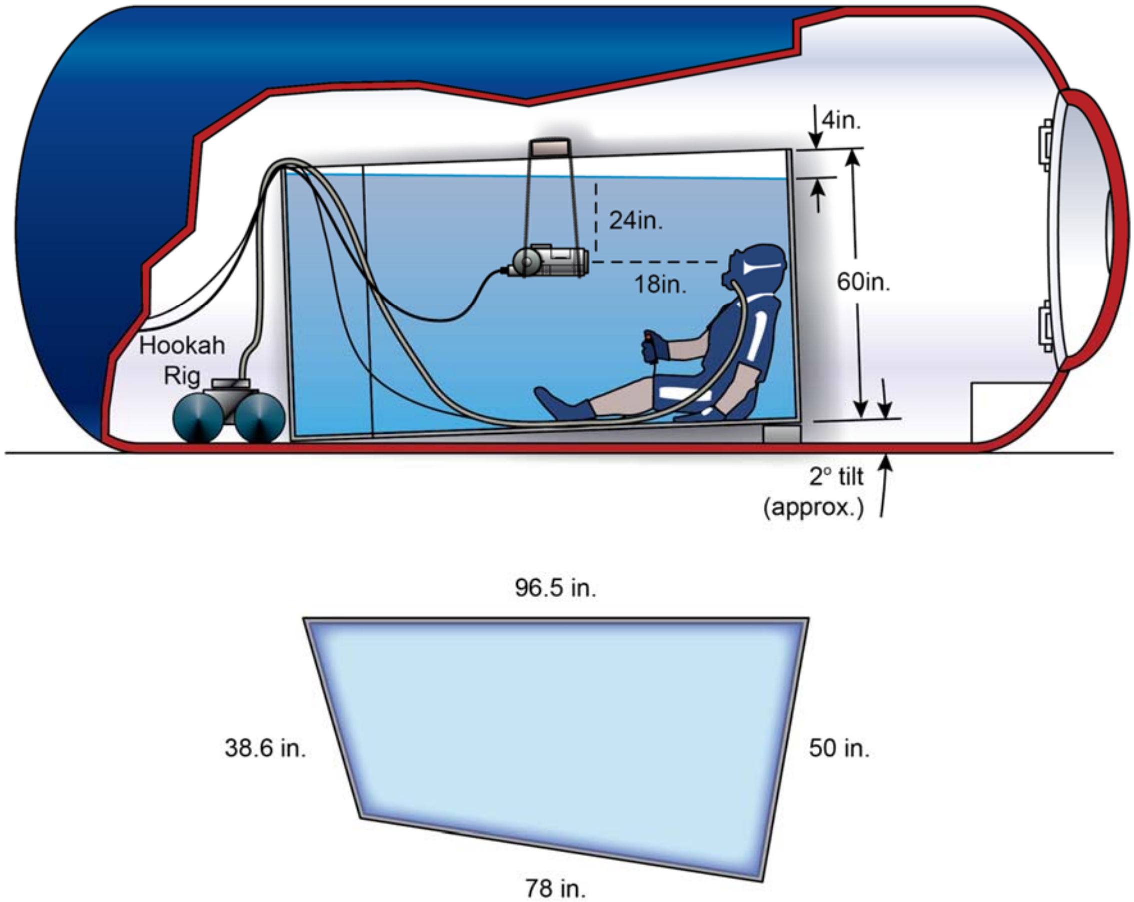

Figure 3: Apparatus and experiment setup. Testing was performed in an acoustic open air water-filled holding tank located within the inner lock of the NSMRL Genesis Hyperbaric Chamber. The holding tank was designed to have nonparallel, asymmetrical sides; its base dimensions are illustrated in the lower figure. Sound stimuli were produced by a USRD J-11S transducer. An underwater response button was placed in the tank for the subjects. A hookah rig was used to supply subjects with air. Subjects placed their head at the correct distance from the transducer by touching their mask to a plumb line positioned 18 inch from the transducer. Diver head positioning was monitored throughout testing by the diver tender who remained outside the tank.

The stimuli were generated by a Tucker Davis Technologies (TDT) WG2 waveform generator, passed through a TDT PA4 programmable attenuator to an Instruments Inc. L6 amplifier, and finally projected into the water by the Underwater Sound Reference Detachment (USRD) J11S Transducer (see Figure 4). Subjects responded with the underwater response button which was interfaced with the data acquisition laptop via a TDT PI2 Parallel Interface. The stimulus presentations and subject responses were monitored with a custom written Turbo Pascal program.

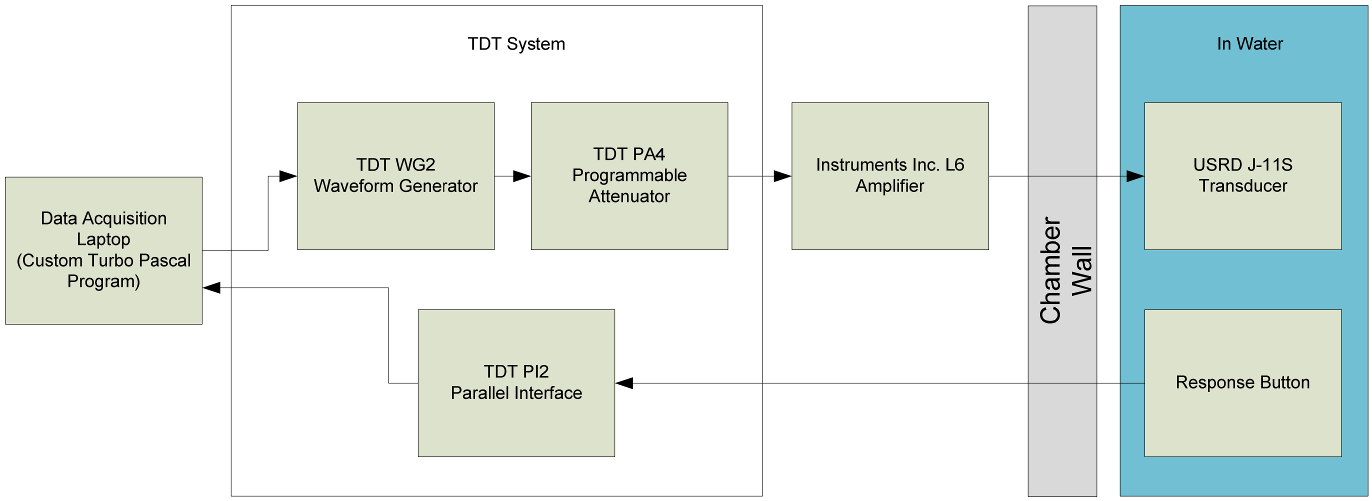

Figure 4: Instrumentation block diagram. A laptop interfaced with a Tucker-Davis Technologies (TDT) system which generated the electronic signals and output them to an amplifier. The amplifier drove a USRD J-11S to generate the underwater sound. The subject responded with an underwater response button.

Prior to subject tests, sound field measurements of this experimental setup were completed to verify the sound levels subjects would be exposed to during the study. Measurements were taken along the midline of the transducer's vertical position at 18, 24 (Position 0), and 30 inches from the face of the transducer, and every six inches above, below, to the left, and right of these points, for a total of 27 sound field measurements. The reported sound level was the highest level recorded at any of those locations.

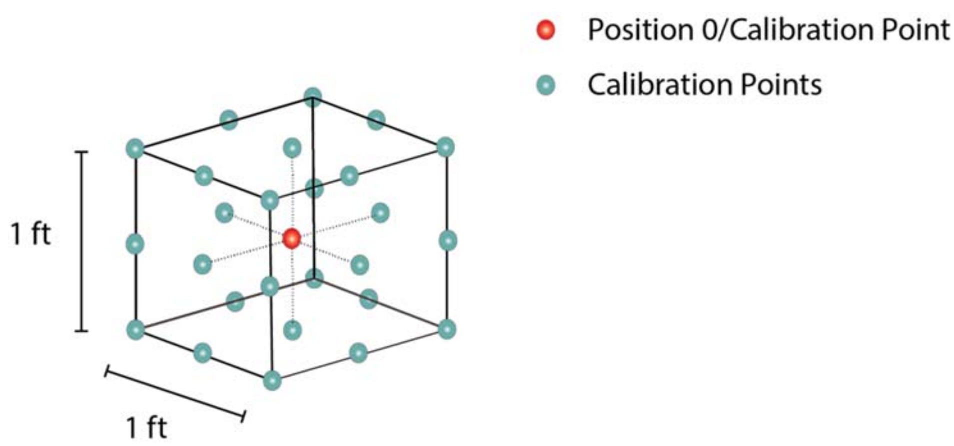

Figure 5: Calibration grid. Position 0 was the planned position at which the center of a subject's head would be located. Sound field measurements were taken at all points indicated on this grid, as well as the midpoints of each line, at surface (i.e. 4 fsw depth condition).

It is important to note that the sound source was only fully calibrated at the 4 fsw depth condition. Calibrated voltage to sound pressure conversion is therefore only possible at this depth. The sound levels were calibrated to ensure the sound exposure would not exceed the SPL limits outlined in the Institutional Review Board protocol (See IRB protocol NSMRL.2001.0003). The transducer used was known to be less efficient at depth, so the investigators and the Committee of Protection of Human Subjects were confident that if the levels were set at surface, they would not be exceeded at depth. As hood attenuation was calculated from the difference in UHTs between the hooded and bare headed dress conditions, absolute sound pressure levels were not needed to calculate hood attenuation values; therefore attenuation results for the remaining chamber pressures tested can be reported. A quick calibration of fewer locations within the tank was performed at all the depths. These data are in Appendix A. The recorded sound levels show that the sound field varied with depth enough that we cannot make conversions of UHTs to sound pressure levels, but the sound field was consistent enough to be safe for the subjects.

2.4 Procedure

Each subject began testing at 4 fsw simulated depth. At each test depth, the testing order for the hooded versus unhooded condition was counterbalanced across subjects. Each subject performed UHT tests at the six simulated depth conditions detailed in the dive profile (see Figure 1 and Figure 2). At each depth, both the unhooded and hooded dress conditions were tested; for each dress condition, all ten stimulus frequencies were tested in random order. The order of the frequencies was generated by the Turbo Pascal program. See Figure 1 for a tree map of all the test conditions (i.e., simulated depth, hood dress, and frequency) of this protocol.

All subjects were briefed on the protocol during the informed consent process, including the dive profile, dive procedures, and all conditions under which they would set UHTs. All depth conditions were completed according to the dive profile (see Figure 2). During the testing periods at each simulated depth, subjects set UHTs for all stimulus frequencies, unhooded and hooded.

Each subject completed this protocol twice with the repeat dive performed on a separate day (i.e., Dive 1 and Dive 2).

2.4.1 Underwater Hearing Threshold Test

Underwater hearing thresholds were measured using a modified Békésy procedure similar to that described by Marshall and Heller (1998) for measuring in air thresholds. At each frequency, a series of pure tone stimuli each of 1-second duration with a rise-fall time of 20 ms and with an inter-tone interval of 1 second (i.e., 50% duty cycle) was presented. The first tone began 20 dB above the estimated underwater hearing threshold and tracked adaptively initially in 5 dB step sizes. The divers responded by pressing and then releasing an underwater button each time they heard a tone. After a button press, the sound pressure level (SPL) of the subsequent tone decreased until the subject could no longer hear the tone. At this point, the SPL was increased until the tone is heard again and the diver responded by pressing and releasing the underwater button. After the first two reversals, the step size was reduced from 5 to 2 dB. This process was repeated until the standard deviation for the amplitude of the sound stimuli varied by 3.06 dB or less. At least 10 reversals were recorded for each frequency and the thresholds were calculated from the average of the last 8 reversals recorded (i.e. the last 4 minima and 4 maxima as calculated using Equation 1).The above described up-down adaptive tracking psychophysical procedure was modified from the Békésy procedure for underwater use. Specifically, the number of tones, the tone duration, inter-stimulus interval and calculation of threshold values were chosen through previous pilot studies to minimize the test length while obtaining reliable and repeatable threshold measurements. As the divers were breathing from an open circuit demand regulator they would tend to "skip breath" or conduct repeated breath holds during the threshold tests to minimize exhale bubble and regulator noise interfering with detection. The total time required to complete the 10 test frequencies was less than 20 min which resulted in less than 40 min to obtain the unhooded and hood thresholds at each test depth.

$$Threshold = \frac{1}{n}\sum_{i=1}^{n} y_i$$

Equation 1: Threshold calculation. n is the number of reversals considered in the calculation, in this case $n = 8$. y_i is the individual reversal SPL.

3 Data Analysis

The threshold values in dB re 1 V (calculated as described above) were gathered by the Turbo Pascal program and recorded in laboratory logbooks, then transcribed into Microsoft® Office Excel. These data were sorted by subject, hood dress, depth condition, and stimulus frequency. Attenuation was calculated as the threshold of the unhooded condition subtracted from the threshold of the hooded condition.

To determine if there was any systematic bias in the attenuation values between Dive 1 and Dive 2, the data was first analyzed using a three-way (Dive 1 vs Dive 2, x frequency x depth condition) repeated measures ANOVA. As this analysis found no significant main effect of Dive day (see Results section), each subject's attenuation values at a given frequency and depth were averaged across Dive 1 and Dive 2 prior to conducting a two-way repeated measures ANOVA to determine the main effects of depth and frequency on wet suit hood sound attenuation. The pre-4 fsw and post-4 fsw condition on each dive were treated as separate conditions for this analysis. Subsequent planned comparisons across depth and frequency conditions were performed using paired t-tests with Bonferroni corrections for multiple comparisons.

For all stimulus frequencies, each of the twelve subject's attenuation values were modeled as a function of depth condition via linear regression analysis. Such analysis served to give insight on a) whether attenuation is depth dependent, as will be evidenced by the linear regression slopes, and b) whether there is attenuation afforded by the wetsuit hoods, as will be evidenced by the linear regression y-intercepts.

4 Results

A total of twenty five dives were conducted using the dive profile shown in Figure 2, exposing two people (one subject and one tender) on each dive (total man dives = 50). One subject exhibited signs consistent with decompression illness 2 hours and 45 min after surfacing from their first dive and was subsequently treated on a USN Treatment Table 6 (observed incidence of decompression illness =2 %). As this subject did not complete a second dive and had several missing data points from the first dive, this subject's data were excluded from the analysis. Several subjects also had missing threshold data due to either, a) not hearing the pure tones when presented with the highest allowable sound exposure level, b) not reaching a threshold criterion, or c) running out of time at a given dive depth to complete all the test frequencies. Out of the 1440 potential attenuation values (12 subjects x 2 dives x 10 frequencies x 6 depth conditions) in the experimental data set there were only 22 missing values for which an attenuation value could not be derived. A three-way repeated measures analysis (Dive 1 vs Dive 2, x Frequency x depth) of the data found that the attenuation values on Dive 1 were not significantly different from those on Dive 2 (main effect of Dive $F_{1,5} = 680$, $p=0.1715$). Furthermore, none of the two-way interactions with Dive or the three way interaction (Dive x Frequency x Depth) were significant. As there were missing data that resulted in only 6 subjects being included in this repeated measures analysis, an additional three way repeated measures ANOVA was conducted on the data set without the 132 foot depth condition. This latter analysis permitted an additional 3 subjects to be included in the repeated measures ANOVA model (n=9) and confirmed the same non-significant results for the main effect of dive ($F_{1,8} = 3.5$, $p=0.0982$) and the non-significant two-way/three-way dive interactions. Figures comparing Dive 1 with Dive 2 attenuation values across the frequency range are plotted for each depth condition in Appendix C: Dive 1 versus Dive 2 Attenuations by Depth Condition.

Given that there were no differences in the attenuation values between Dive 1 and Dive 2, each individual subject's Dive 1 and Dive 2 attenuation values at a given depth and frequency condition were averaged prior to perfoming additional analysis. If only a single attenuation value was available for a depth and frequency condition on a given subject, that value was used in the analysis. A two-way repeated measures ANOVA of these data showed strong significant main effects for Depth ($F_{5,55} = 3.8$; $p<0.01$) and for Frequency ($F_{9,99} = 26.6$; $p<0.000001$), and a significant two-way interaction between Depth and Frequency ($F_{45,495} = 36.8$; $p< 0.000001$). The mean change in wetsuit hood attenuation with frequency across each of the depth conditions tested is illustrated in Figure 6. Note that standard error of the means were not plotted here; refer to Appendix B for a breakdown of Figure 6 data by depth condition with standard error of the means. The changes in hood attenuation with frequency appear to be sigmoid in nature. At low frequencies (i.e. <500 Hz), the wet suit hood offers very little sound attenuation. From 500 Hz – 4000 Hz, hood attenuation values appear to vary as a function of frequency and depth. At frequencies above 4000 Hz, hood attenation values are the greatest and appear to be less frequency and depth dependent.

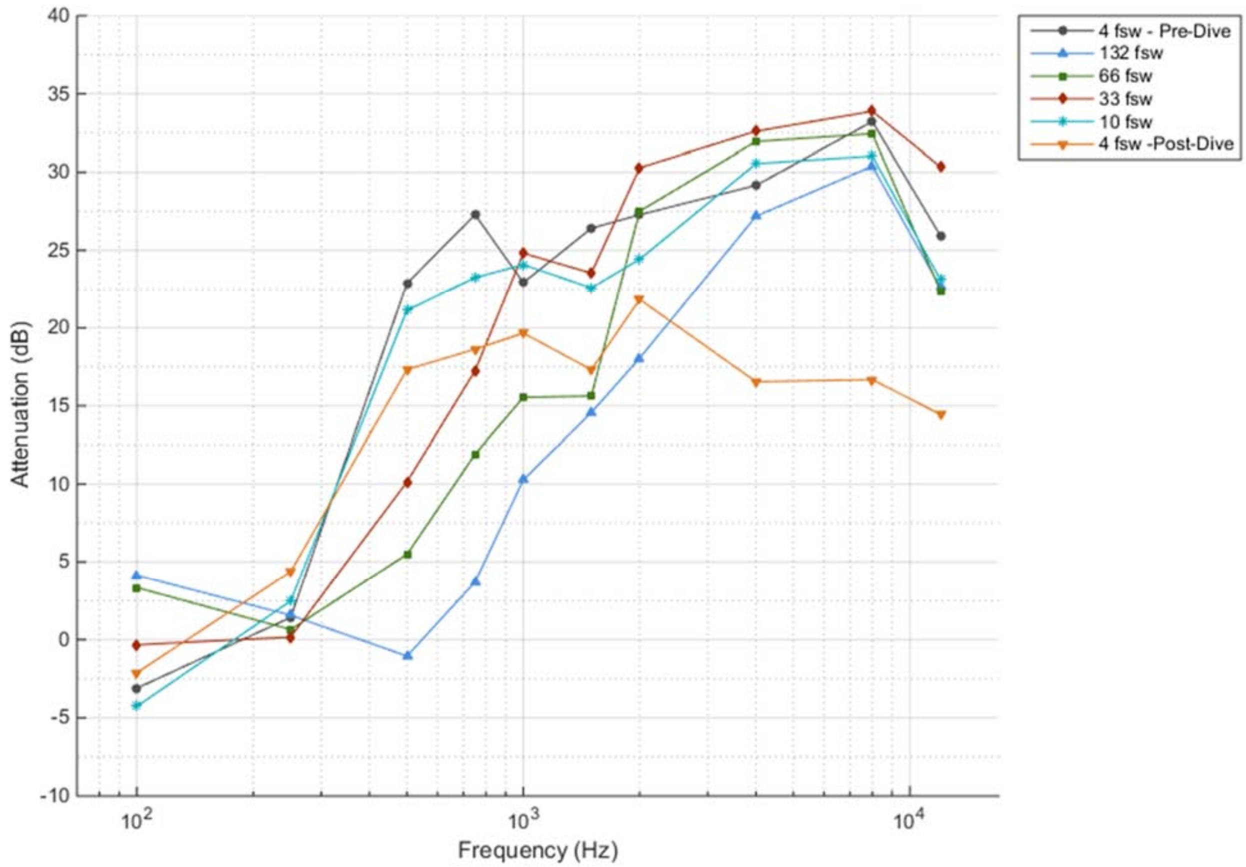

Figure 6: Overlay plot showing mean values for wetsuit hood attenuation as a function of frequency for the different depth conditions. Each subject's Dive 1 and Dive 2 attenuation for each depth condition and frequency were averaged. Error bars are omitted for clarity

The depth dependence of hood attenuation is illustrated in Figure 7 which plots attenuation values as a function of the simulated depth for each frequency separately. Again it is noted that for the lowest frequencies tested (i.e., 100 and 250 Hz), attenuation was close to 0 dB across all depths. From 500 Hz – 4000 Hz, attenuation exceeds 20 dB at the shallowest depths at all frequencies within this band. As the depth increases, the hood attenuation values decrease almost linearly with depth, with the lowest frequencies within the 500 – 4000 Hz band showing the greatest decreases in attenuation with depth. At frequencies of 4000 Hz and above, hood attenuation values are between 20 and 34 dB and vary relatively little with changes in depth between 4 fsw and 132 fsw.

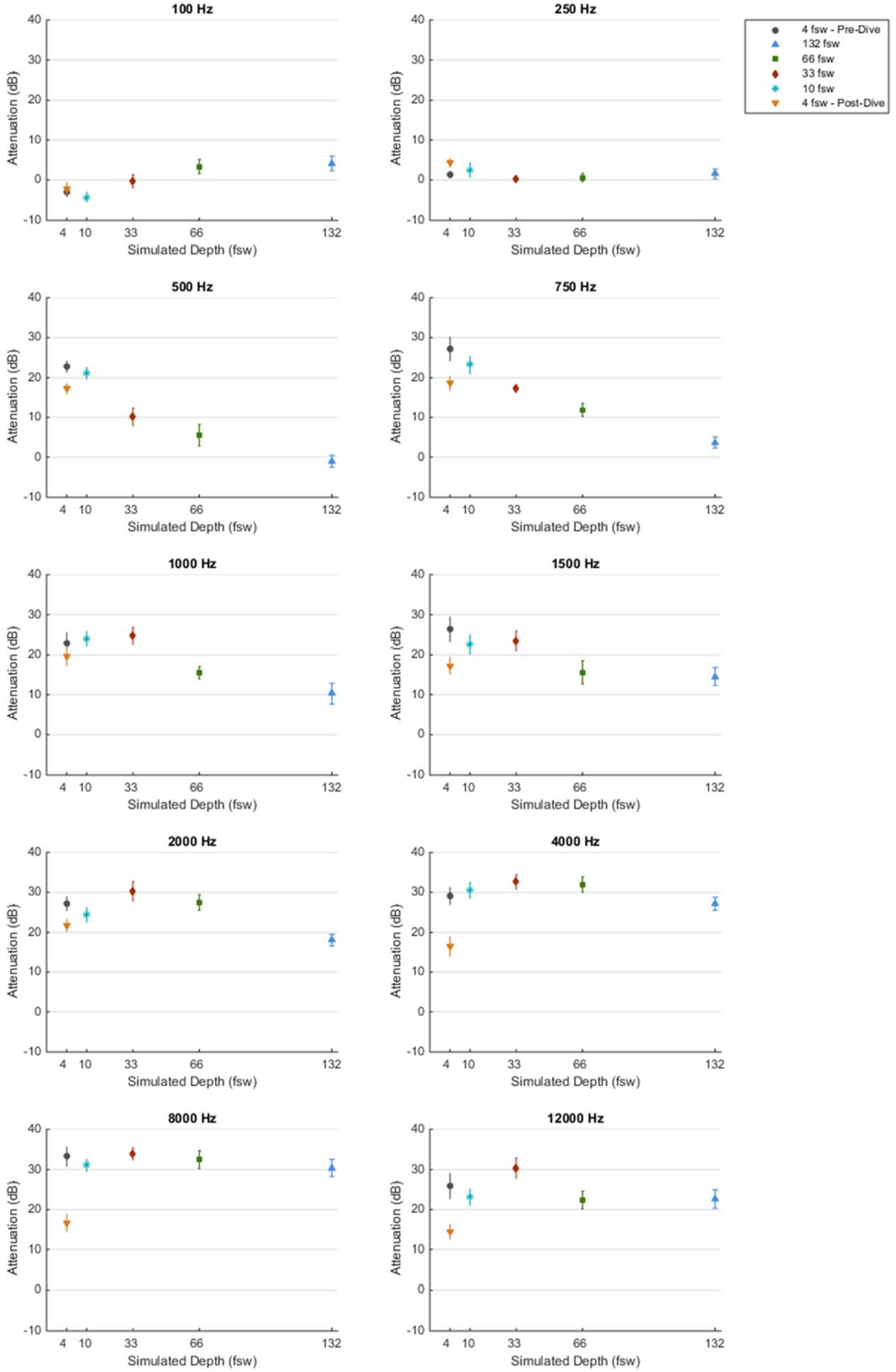

Figure 7: Wetsuit hood attenuation as a function of depth and sound frequency. Data are mean attenuations and standard errors of the mean (error bars) calculated across all subjects' using the average attenuation calculated for their two dives for each frequency and depth condition.

To explore the depth dependence of hood attenuation further, each subject's data, at each frequency, was modeled as a linear regression as a function of depth (all 4 fsw data was used in the calculation of line-of-best-fit). The resulting individual regressions are denoted by the grey lines in Figure 8. The mean of individual subject regressions and a 95% confidence area in the mean was then calculated and plotted. Confidence bounds were calculated from the coefficients of all subject regressions completed for a given frequency.

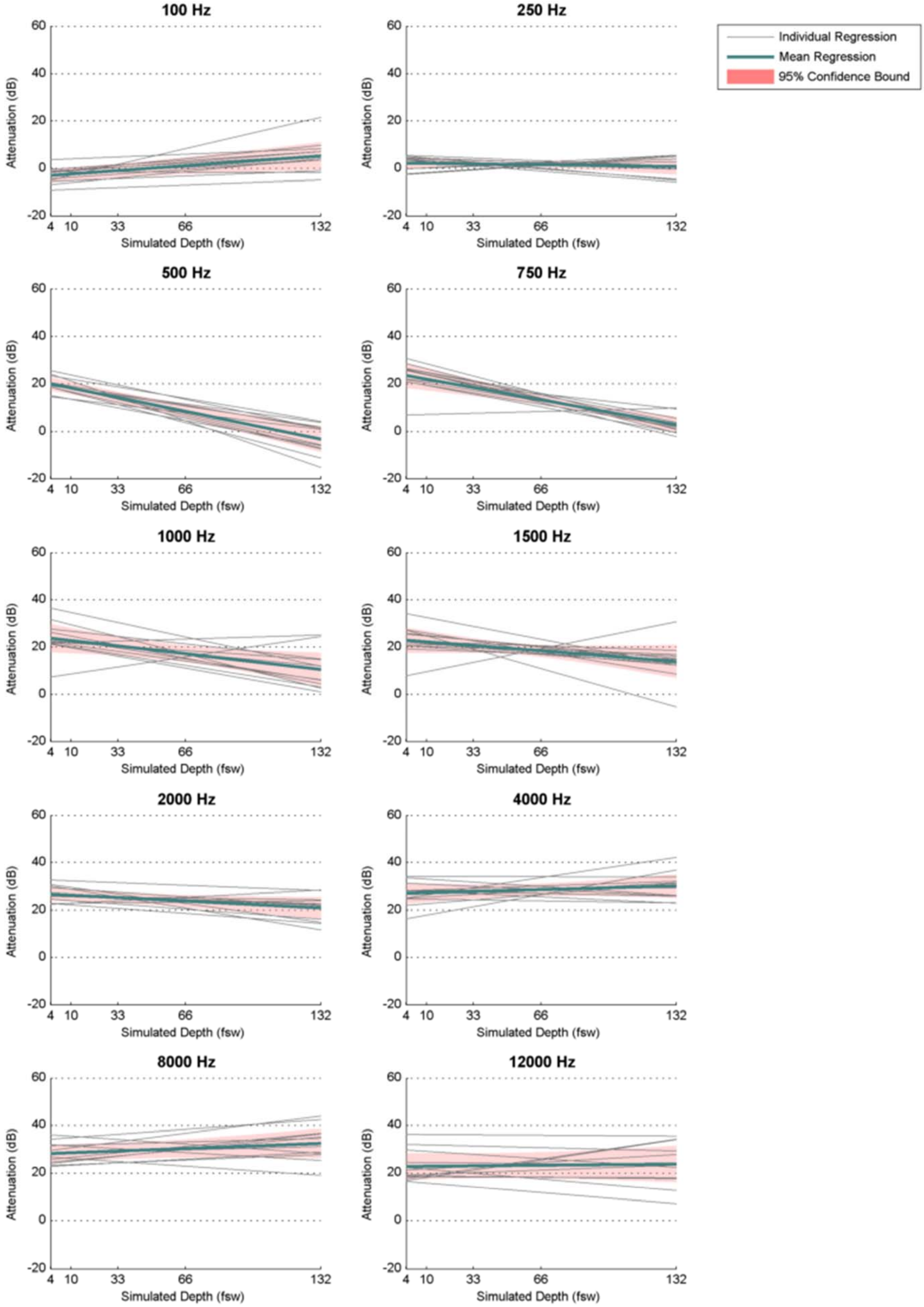

Figure 8: Linear regression analysis of wetsuit hood sound attenuation as a function of dive depth. At each frequency, each subject's attenuations were modeled with a linear regression as a function of depth, plotted as grey lines. The mean of all subject regressions was calculated and plotted in green. Bounds for 95% confidence in the mean regression are plotted in red.

Statistical analysis of the linear regressions presented in Figure 8 is reported in Table 2. At each frequency, the mean and p-value for a one sample t-test of the first and zeroth-order coefficients for twelve subject linear regressions are reported. The first order coefficients represent the regression slopes and the zeroth order coefficients represent regression y-intercepts. The regression slopes give insight into whether there is an effect of depth on attenuation (i.e. if the slope is zero, or close to zero, there is no depth dependence). The t-tests between slopes for twelve subject regressions at each frequency are reported to gain a measure of significance for the observed slopes. Similarly, the regression y-intercepts give insight into whether there is attenuation present at the tested frequencies (i.e. if the y-intercept is zero, there is no attenuation, if the y-intercept is 20, the regression suggests there is approximately 20 dB of attenuation at depths near the surface). The t-tests between y-intercepts for twelve subject regressions at each frequency are reported to provide a measure of significance for the observed attenuation values.

Table 2: Linear regression analysis of the wetsuit hood attenuation values as a function of dive depth for each frequency tested. At each frequency, mean p-values for a one sample t-test were calculated across all subjects for the first and zeroth order coefficients of subject linear regressions. Values highlighted red are lower than a p-value of 0.005 (Bonferroni correction to α = 0.05 with the completion of 10 t-tests), and can be considered statistically significant differences.

Frequency	Mean First Order Coefficient (slope)	p-Value First Order Coefficient (slope)	Mean Zeroth Order Coefficient (y-intercept)	p-Value Zeroth Order Coefficient (y-intercept)
100	0.06	1.20E-03	-2.97	1.06E-02
250	-0.01	0.455	2.23	2.07E-02
500	-0.18	2.28E-07	19.93	3.24E-10
750	-0.16	6.47E-06	23.47	3.79E-08
1000	-0.10	4.42E-03	23.66	1.40E-07
1500	-0.07	3.98E-02	22.79	6.69E-08
2000	-0.04	1.17E-02	26.74	1.60E-11
4000	0.02	0.262	27.05	9.33E-10
8000	0.03	8.87E-02	28.27	1.98E-10
12000	0.01	0.702	22.83	1.10E-07

As shown in Table 2, the frequency region showing the greatest depth dependence was from 500 – 1000 Hz. Within this frequency region, the values for the first order coefficient (i.e., slope) were all statistically significant. A significant first order coefficient was also noted for 100 Hz. However, on inspection of the 100 Hz data in Figure 7 and Figure 8, it can be seen that the slight but significant positive slope for attenuation with depth for this frequency is the net result of the effects of slightly negative attenuation values being recorded for the shallow depths (i.e., 4 fsw and 10 fsw) in combination with slight positive attenuation values recorded at 66 and 132 fsw. In general however, the magnitude of attenuation to 100 Hz was less than 5 dB across the entire depth range. Furthermore, the non-significant y-intercept value for 100 Hz shown in Table 2 implies that hood attenuation values close to the surface are not detectibly different from zero.

While the results showed that there were no significant differences detected in the attenuation values between dives, there is evidence to suggest that the wetsuit hood sound attenuation properties may change over the course of a dive. Figure 9 reveals that the hood attenuation values obtained at 4 fsw at the end of the dive were lower for certain frequencies than when they were measured at the beginning of the dive. To explore this phenomenon in more detail, a two-way repeated measures ANOVA was performed on the 4 fsw attenuation values (averaged across Dive 1 and Dive 2) to ascertain if there was a significant difference between the pre and post-dive 4 fsw attenuation values across the frequencies range tested. This analysis revealed a significant main effect for pre versus post attenuation values ($F_{1,11} = 20.2$, $p<0.001$) as well as a significant frequency x pre versus post interaction ($F_{9,99} = 7.8$, $p<0.000001$). Inspection of the data shown in Figure 9 reveals that the significant two-way interaction is a result of the two curves deviating from each other at the higher frequencies. Further planned comparisons confirmed that while hood attenuation was similar between pre and post dive tests for the majority of frequencies up to 4,000 Hz, at 4,000 Hz and higher the post dive attenuation values at 4 fsw were significantly lower than the 4 fsw pre-dive attenuation values (see Figure 9 and Table 3).

Table 3: Absolute differences in the mean wetsuit hood attenuation between the 4 fsw Pre-Dive and 4 fsw Post-Dive trials. Statistically significant differences between the means are shown highlighted in red ($p< 0.005$ for Bonferroni correction to $\alpha = 0.05$ with the completion of 10 t-tests).

Frequency	Difference Between Means	p-Value
100	1.0	0.501
250	2.9	5.99E-02
500	5.5	2.19E-03
750	8.7	2.95E-02
1000	3.3	0.167
1500	9.1	1.30E-02
2000	5.5	3.96E-02
4000	12.6	2.60E-03
8000	16.6	1.86E-04
12000	11.5	2.30E-03

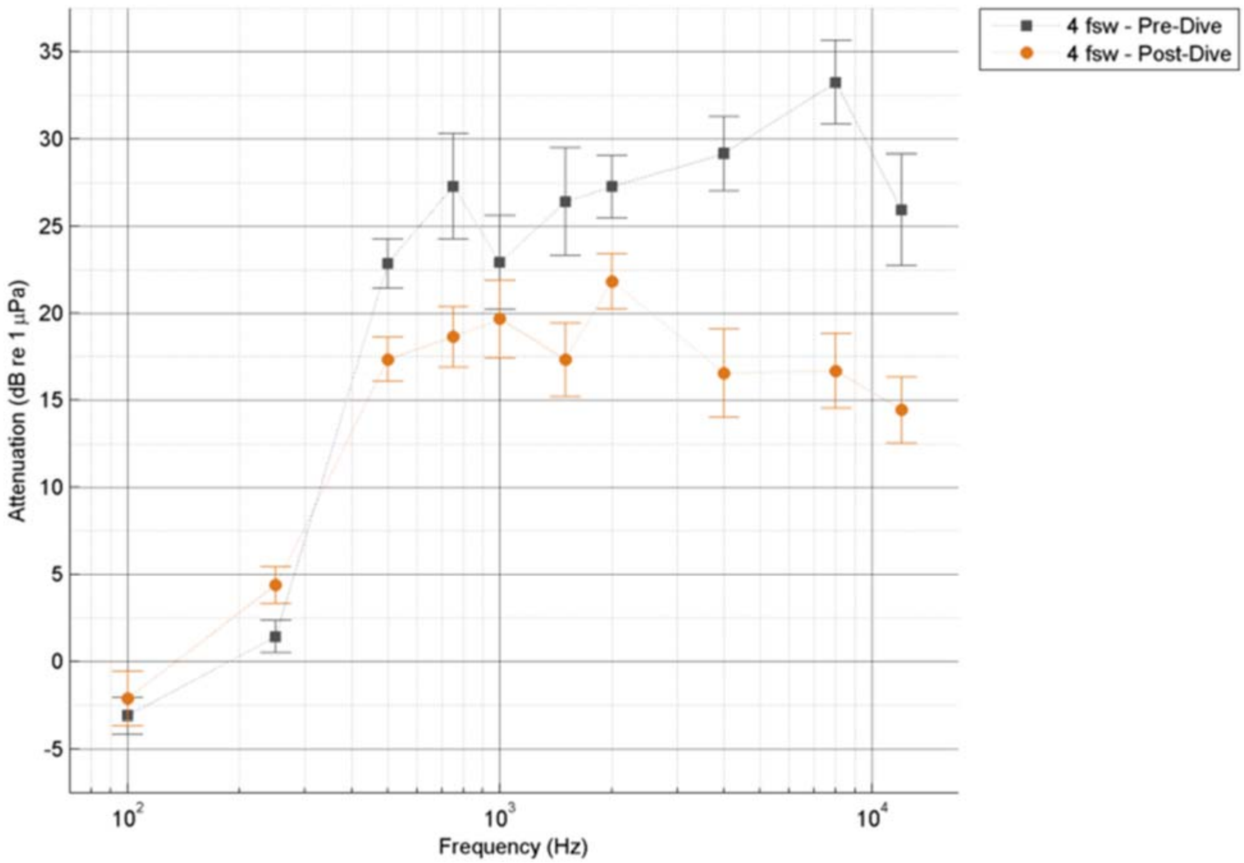

Figure 9: 4 fsw Pre-Dive and 4 fsw Post-Dive wetsuit hood attenuation as a function of sound frequency. Means of each subject's Dive 1 and Dive 2 were calculated. Of those values, the mean and standard error of the mean attenuation across subjects as a function of frequency for the 4 fsw Pre-Dive and Post-Dive was then calculated and plotted.

4.1 Results Summary

The depth and frequency dependence of the amount of sound attenuation provided by a neoprene wetsuit hood are summarized in the Figures 10-12. Using the results of the linear regression analysis shown in Table 2, the attenuation property observed at each test frequency were sorted into one of three categories: no attenuation and no depth dependence, attenuation with depth dependence, and attenuation with no depth dependence. The results are shown in Figure 10. Table 2 shows that the attenuation for frequencies from 500 to 1000 Hz significantly decreased with increasing depth, whereas for frequencies between 1500 and 12000 Hz, attenuation was depth independent. Note that although statistical analysis showed significant depth dependent attenuation for 100 Hz, this depth dependence was due to a small but statistically significant positive attenuation slope rather than a negative slope. Since a wetsuit hood offers little attenuation for 100 Hz frequencies across the depth range studied, this frequency was assigned to the upper left quadrant in Figure 10 (i.e., no attenuation and no depth dependent attenuation).

Means and standard error of the means for all individual regression slopes (i.e., our depth dependence measure) and y-intercepts (i.e., attenuation measure) (see Table 2) are reported as a function of frequency in Figure 11 and Figure 12, respectively. Both mean and standard error of the mean calculations are made for the twelve individual regression lines plotted in Figure 8. Figures 11 and 12 provide a visual and analytical construct to easily characterize wetsuit hood attenuation characteristics as a function of frequency and depth. Note that in Figure 11 the data points (frequencies) farthest from the 0 dB attenuation/fsw line show the greatest level of depth dependent attenuation. In Figure 12 the data represent the amount of attenuation provide by the wetsuit hood as function of frequency at depths at or near surface. From the point of view of providing the maximum sound protection to the diver across a wide range of depths and sound frequencies, the ideal wetsuit hood characteristics would show high positive attenuation values across all frequencies in Figure 12 in combination with low or near 0 regression slopes across the entire frequency range in Figure 11.

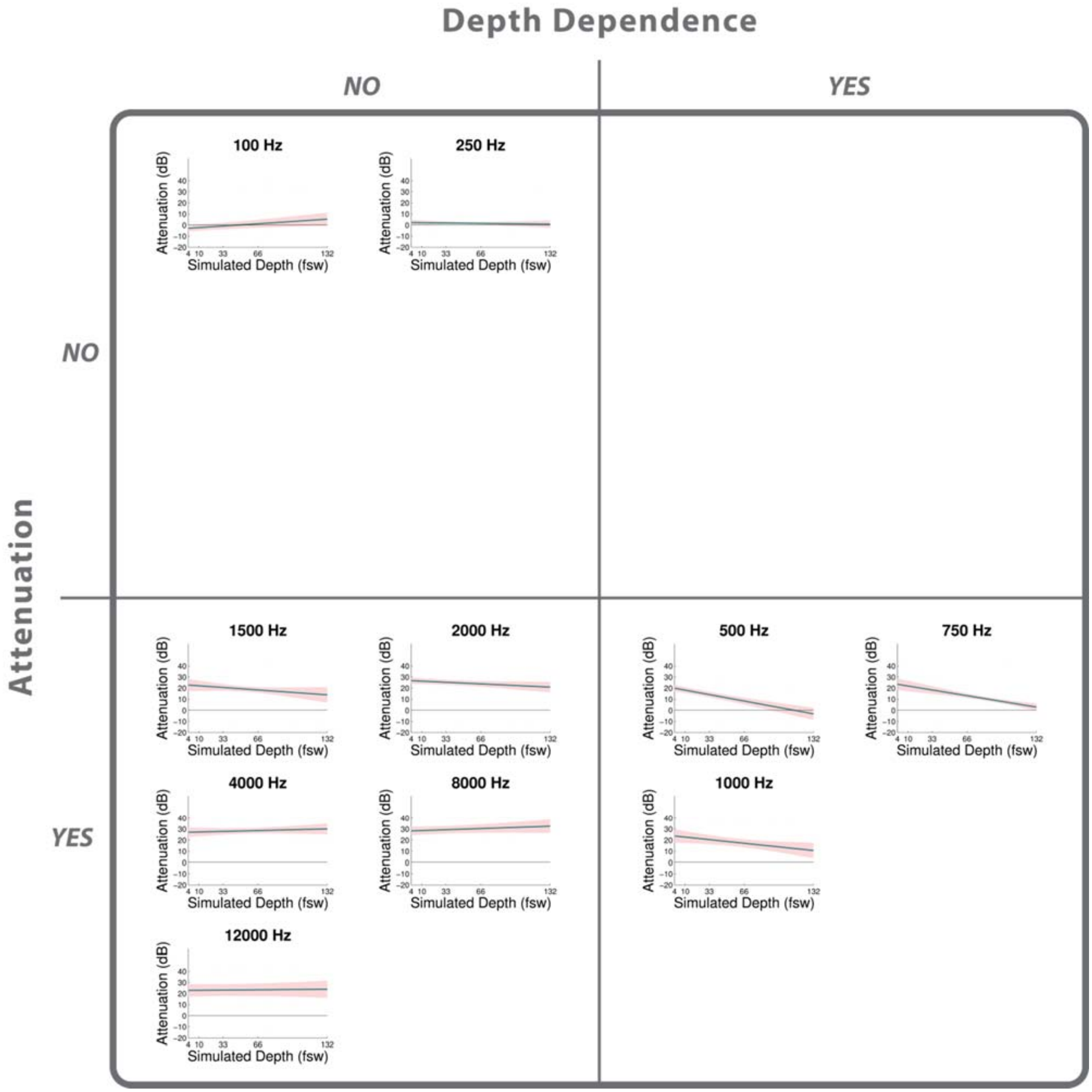

Figure 10: Depth dependence vs. attenuation quad chart. Stimulus frequencies under evaluation are categorized to show the depth dependence and attenuation properties observed based upon the regression models from Figure 8 and linear regression analysis shown in Table 2.

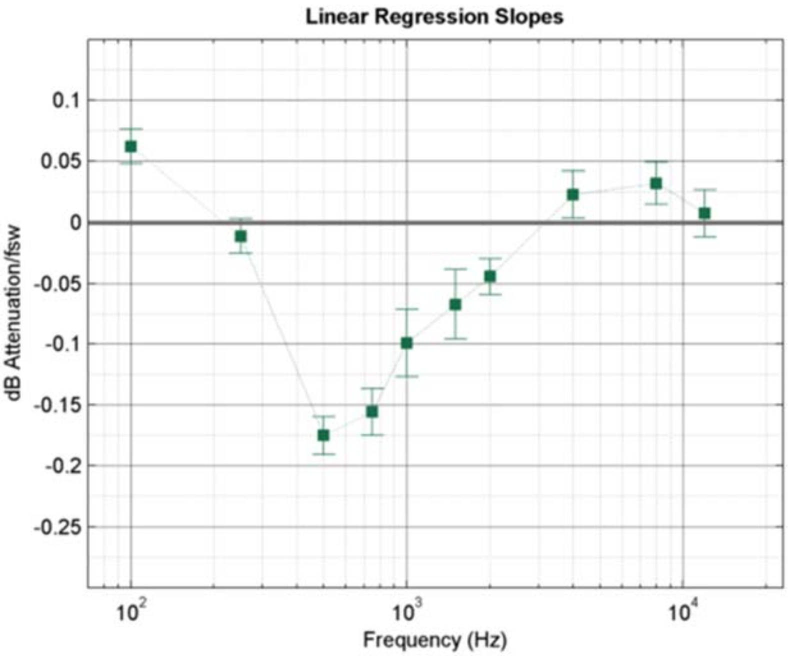

Figure 11: Mean and standard error of the mean of linear regression slopes. Means and standard error of the means were calculated from slopes of the twelve subject linear regressions plotted by frequency in Figure 8.

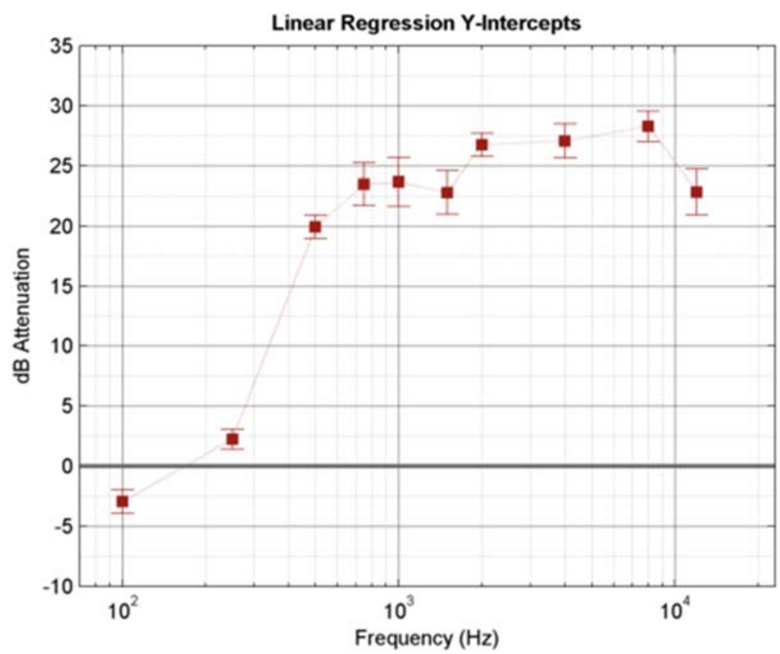

Figure 12: Mean and standard error of the mean of linear regression y-intercepts. Means and standard error of the means were calculated from y-intercepts of the twelve subject linear regressions plotted by frequency in Figure 8.

5 Discussion

This report describes the psychophysical sound attenuating characteristics of a 7 mm neoprene wetsuit hood and demonstrates how wetsuit hood sound attenuation changes as a function of frequency and depth. Furthermore, we present a useful method to easily and separately visualize the degree of depth dependence and amount of sound attenuation as a function of frequency. From this analysis, we identified three distinct frequency bands which exhibit different attenuation characteristics. These bands were characterized as having 1) no attenuation (100 – 250 Hz), 2) depth dependent attenuation (500 – 1000 Hz), and 3) depth independent attenuation (1500 – 12000 Hz).

The lack of attenuation at low frequencies was also observed by Fothergill et al. (2004b) and Cudahy et al. (2002) who found that at a shallow depth (3m) and at frequencies below 400 Hz, neoprene hoods of between 3- and 7 mm thick offered no sound protection. Cudahy et al. (2002) also confirmed that there was no attenuation at these low frequencies using a physical measure of sound attenuation in which the monitoring hydrophone was completely encased in neoprene.

Possibly the earliest published measurements of wetsuit hood sound attenuation were carried out by Montague and Strickland (1961). Using seven experienced divers underwater threshold measurements at frequencies between 250 and 6000 Hz were collected while the divers were bare headed and while wore neoprene hoods of different thicknesses were worn. The experiments were conducted at a single depth (390 cm) in a fresh water pond. Similarly to the current experiment there was little attenuation at the lowest frequencies, but between 20 and 30 dB attenuation at frequencies above 1000 Hz. They also reported that there was little difference in the attenuation between hoods of different thicknesses.

Parvin and Nedwell (1995) mention that they have generated an unpublished set of measurements on wetsuit hood attenuation. In their 1995 report on underwater sound perception and the development of an underwater noise weighting scale, they provide a comparison of noise produced during the operation of a small compressed air rock drill, measured inside and outside a diver's hood. The frequency band of measurement was from 25 Hz – 16 kHz; the depth of testing was not specified. Results showed that the wetsuit hood provided no attenuation below 250 Hz, increasing sound attenuation from 250 Hz to 2 kHz (range 0 to 30 dB), and approximately 40 to 50 dB at the highest frequencies (4 kHz – 16 kHz).

It should be born in mind that the attenuation measurements reported by Parvin and Nedwell (1995) reflect the physical properties of the hood rather than psychophysical attenuation reported in the current study. While the general pattern of wetsuit hood attenuation across frequency appears similar between physical and psychophysical measures of attenuation the absolute values of attenuation will likely be greater for the physical measurements. This is because the diver's head is not completely encased by the hood and mask, thus allowing for transmission of sound through bone conduction via portions of the face not coved by the hood or mask.

Shortly after the work published by Parvin and Nedwell (1995), the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, UK designed and constructed an underwater hearing laboratory in which they tested the psychophysical acoustic attenuation of neoprene wet suit hoods with both male (n=12) and female (n=6) divers in a 3m x 3m x 3m specially built tank. Details of the testing facility are provided in the ISVR MSc Dissertation by Raggatt (1997). The frequency range tested was from 200 Hz to 8 kHz. The results over this frequency range were comparable to the pattern of results found for the 4 fsw pre and 4 fsw post dive results shown in Figure 9. The absolute attenuation ranged from 0 dB at 200 Hz and 250 Hz rising to 15 dB at 500 Hz and 20 dB at 800 Hz. At 1 kHz the attenuation was approximately 25 dB and a showed a gradual 5 dB decline with frequency from 1 kHz to 8 kHz similarly to that shown by the 4 fsw post dive results in Figure 9. Interestingly, Raggatt (1997) reported that a 5 mm hood did not provide significantly more attenuation than that of a 2.5 mm thick neoprene hood.

Previous research on hood attenuation has focused on a single depth (usually shallow) and thus there is limited published data to show how wetsuit hood attenuation changes across the depths commonly encountered by the working diver. The current study found that the only frequency region where a neoprene hood showed depth dependent attenuation was between 500 Hz and 1000 Hz. Interestingly, this frequency region corresponds to those frequencies over which the wet headed ear is most sensitive (i.e., has the lowest underwater thresholds) (Parvin and Nedwell 1995). Given this fact, and the lack of sound attenuation from hoods at low frequencies and the decreasing attenuation with depth from frequencies between 500 and 1000 Hz, particular care should be taken when specifying guidance to hazardous underwater sound within this frequency range.

Current U.S. Navy Guidance (U.S. Navy Dive Manual Rev 7); considers a wetsuit hood to provide 15 dB of attenuation, regardless of frequency or depth. This is too liberal in some instances and too conservative in others. To better protect divers' hearing, and to avoid needlessly restricting dive operations based upon non-hazardous sound exposures, the U.S. Navy needs additional data to construct more accurate underwater sound exposure guidance. The current guidance was written based on studies done at a 10 foot depth or shallower and with frequencies ranging from 25 to 4000 Hz. Until now, there was limited knowledge of hood attenuation at frequencies >4 kHz and how hood attenuation is affected by dive depth. With data from this study (and several studies performed after it at the Naval Submarine Medical Research Laboratory) a much more accurate guidance can now be written.

One interesting observation from the current study is that the attenuation values at the 4 fsw - Post-Dive condition were found to be lower than the 4 fsw - Pre-Dive condition in the 4000 - 12000 Hz frequency range (see Figure 9). However, when the subjects repeated the dive on a separate day, the second dive 4 fsw Pre-Dive attenuations were back to Pre-Dive levels seen in the first dive (see Appendix C: Dive 1 versus Dive 2 Attenuations by Depth Condition). We have a few possible explanations for this effect. First, the hood may not have fully recovered its thickness by the time subjects completed the 4 fsw - Post-Dive test, meaning that its attenuation properties were temporarily altered as a result of undergoing compression at depth. It is possible that during the compression phase of the dive some of the air trapped in the closed cell neoprene may have been compressed and then replace by water (which will not attenuate the sound) as the neoprene expands during decompression. Once the hood has dried out overnight its attenuating properties would return to normal.

A second possibility is that the subjects' middle ear may have experienced an impedance change over the course of testing, i.e., the middle ear pressure might not have been fully equalized to ambient pressure during the 4 fsw – Post Dive condition. It is known that differences in middle ear pressure can significantly affect hearing thresholds (Erlandsson et al., 1980). One factor that could contribute to middle ear disequilibrium is the oxygen breathing period conducted at 33 fsw and 10 fsw before the 4 fsw –Post Dive test. During the oxygen breathing period the air within the middle ear will begin to be replaced by 100% oxygen resulting in a partial pressure difference in the amount of oxygen in the middle ear compared to that in the external ear canal and within the body tissues. When the diver is placed back on air during the threshold testing the high oxygen level in the middle ear will be gradually adsorbed potentially resulting in a reduction in the volume of gas in the middle ear and a negative middle ear pressure until the diver equalizes their ear through opening of the Estuation tube. It should be noted that it was necessary to include the 33 fsw and 10 fsw oxygen breathing periods in the current dive profile in order to avoid lengthy air decompression procedures. One counterargument is that underwater hearing is more dependent upon bone conduction than the traditional route of sound transmission through the tympanum and middle ear bones (Montague, & Strickland, 1961, Hollien & Feinstein 1975). As direct bone conduction of sound bypasses the middle ear any changes in middle ear pressure will likely have less impact on underwater hearing thresholds than they would for in air thresholds. Furthermore, mitigation of negative middle ear pressure is easily and quickly resolved through either a swallowing maneuver or a Valsalva maneuver, which all divers are trained to do on detecting pressure in their ears. Therefore it is unlikely that the divers will have maintained a significant decrease in middle ear pressure throughout the 4 fsw – post-dive testing period.

A third possibility is that subjects were experiencing cognitive fatigue due to the demands of the previous underwater sensory threshold testing performed during the dive prior to conducting the 4 fsw post-dive condition. While it is certainly possible that the divers may have experienced some level of cognitive fatigue the general pattern of the threshold responses shown in Appendix C and Figure 9 do not support either a random or constant bias in attenuation differences between the pre and post 4 fsw trials across the entire frequency range tested. Rather, the decrease in wetsuit hood attenuation during the 4 fsw post dive test is largely limited to the high frequency range with little difference in attenuation values at the lower frequencies. This pattern of results suggests that the phenomenon may be more related to physical factors rather than cognitive fatigue. This thesis could easily be tested by repeating the current dive profile while conducting physical measures of wet suit hood sound attenuation.

Despite the above mentioned differences in attenuation between the 4 fsw conditions within a given dive, there were no significant differences detected between the attenuation values obtained between Dive 1 and Dive 2. Further illustration of the repeatability of the results can be seen in Appendix C Dive 1 versus Dive 2 Attenuations by Depth Condition. From these results we infer that the methodology for assessing the sound attenuation properties of wetsuits hoods using underwater hearing thresholds was a reliable one that resulted in consistent and repeatable attenuation values across different dive days.

The mechanism by which neoprene hoods provided acoustic attenuation has been attributed to the mechanical damping effect of the hood on the scull which would theoretically reduce bone conduction transmission of underwater sound (Smith 1969). However, acoustic damping due to the pressure release effect of the neoprene material is also likely to play a role. The neoprene material will likely reflect certain frequencies but absorb others which may partially explain why lower frequencies are attenuated less than higher frequencies. Indeed the pressure release effect of wearing a neoprene wet suit on the sound field incident to a diver has be noted and measured by Stevens et al. (1997) at low frequencies. Between 250 Hz and 350 Hz neoprene was found to attenuate the incident sound field by 8-10 dB.

There are a number of study limitations that should be born in mind when interpreting the current data set. Firstly, the threshold data were obtained within a small tank rather than in a body of open water. While the tank was specially designed to minimize standing waves from surface reflections the sound field will be somewhat different to that in a free field open water environment. In order to verify the current results, these data should be compared to measurements conducted in an open water environment.

Secondly, the maximum depth tested was 132 fsw. While the attenuation of the higher frequencies was found to change little with depth these frequencies may exhibit depth dependence at depths greater than we were able to test. Similarly, the frequency range tested was limited to between 100 and 12000 Hz. As it is known that divers can hear high frequency sound underwater well into the ultrasound range (Sagalovich 1967) additional work is need to characterize wetsuit hood sound attenuation properties at frequencies >12 kHz.

6 Summary

The attenuation of underwater sound provided by a 7 mm neoprene wetsuit hood determined using the difference between hooded and unhooded hearing threshold measurements was found to range from 0 dB to approximately 34 dB. The amount of attenuation is dependent on at least two factors, the frequency of the sound and ambient pressure (simulating depth). In general, lower frequency sounds are attenuated less and higher frequency sounds are attenuated more when a neoprene wetsuit hood is worn. The greatest attenuation (~20-34 dB) was above 4000 Hz; and almost no attenuation was measured at 100 and 250 Hz. At frequencies from 500 Hz to 1000 Hz, where underwater hearing is the most sensitive, the amount of sound attenuation decreased as the ambient pressure was increased.

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Appendix A Calibration Data

The SPL at all depth and stimulus conditions was measured for three points (A, B, and C in Figure 13) of the calibration grid described in Section 1.3.

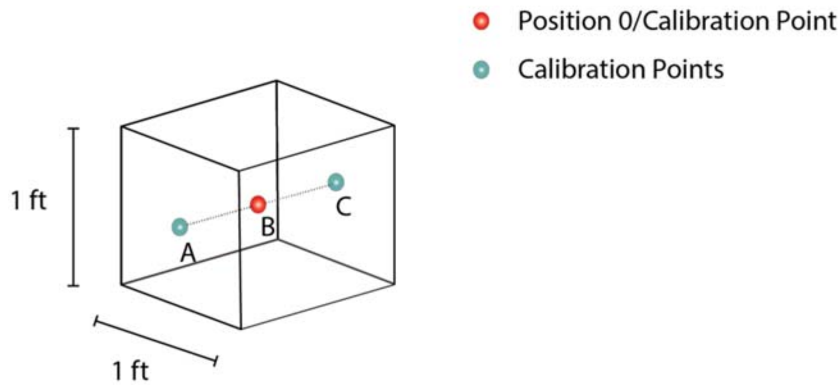


Figure 13: Calibration points at depth. At all depth conditions, SPL measurements were made for points A, B, and C. Position 0/Point B was the approximate planned location of the center of a subject's head.

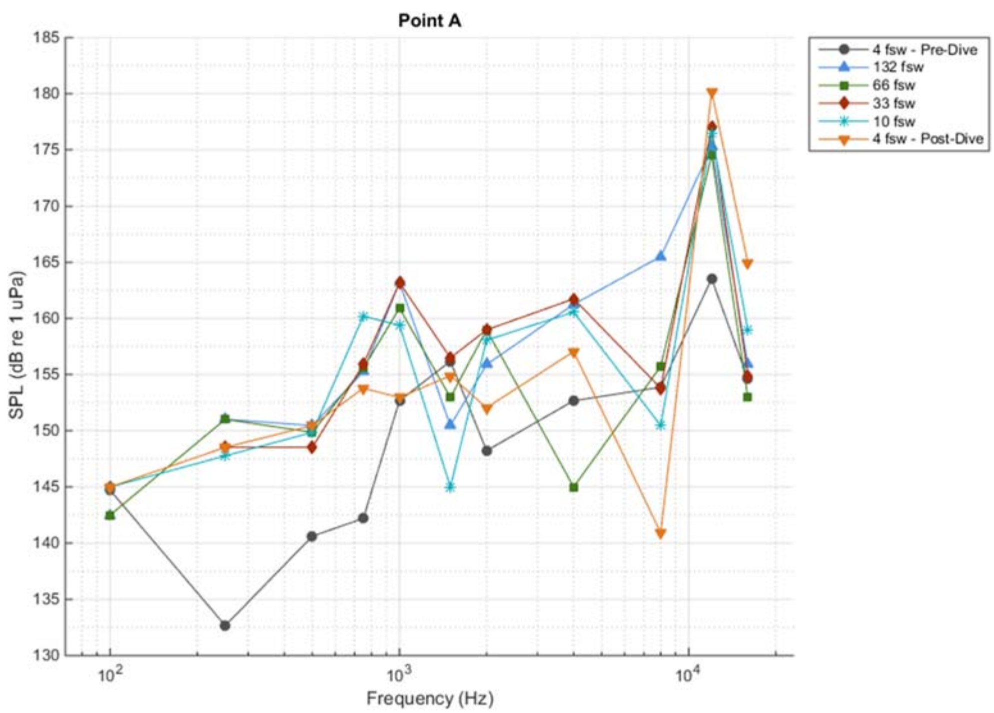


Figure 14: SPL at calibration point A at each test depth as a function of frequency.

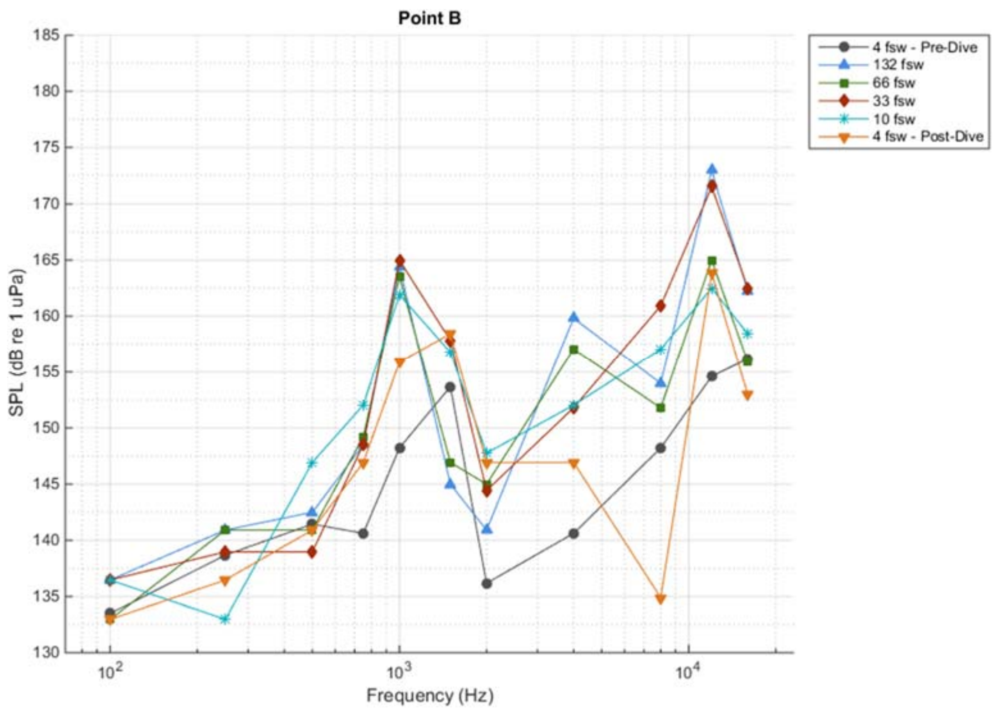


Figure 15: SPL at calibration Point B at each test depth as a function of frequency.

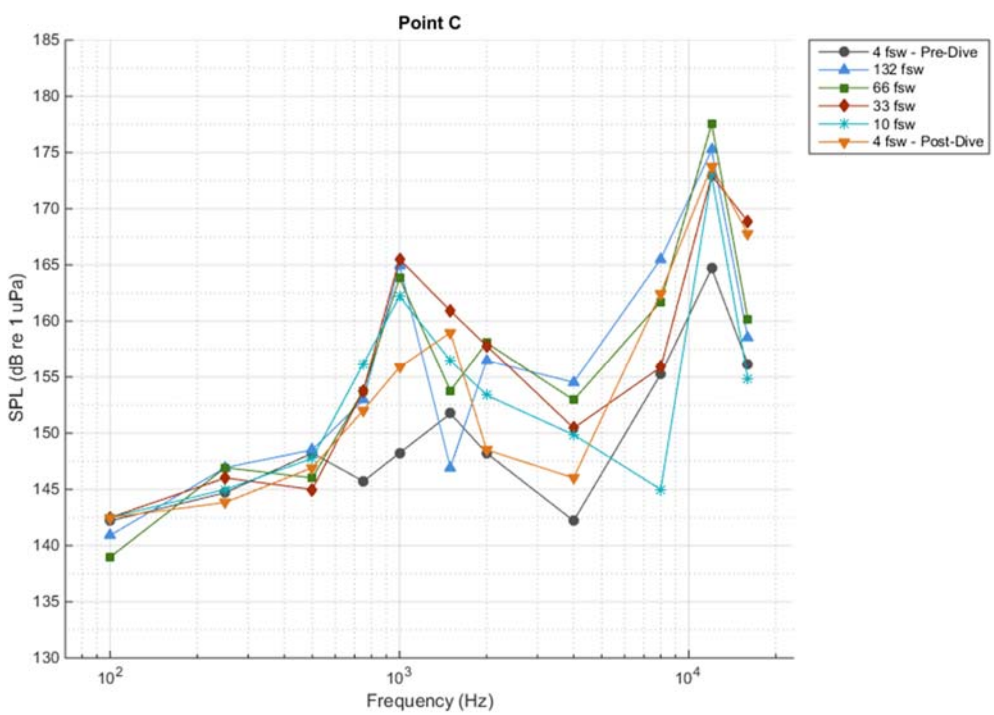


Figure 16: SPL at calibration point C at each test depth as a function of frequency.

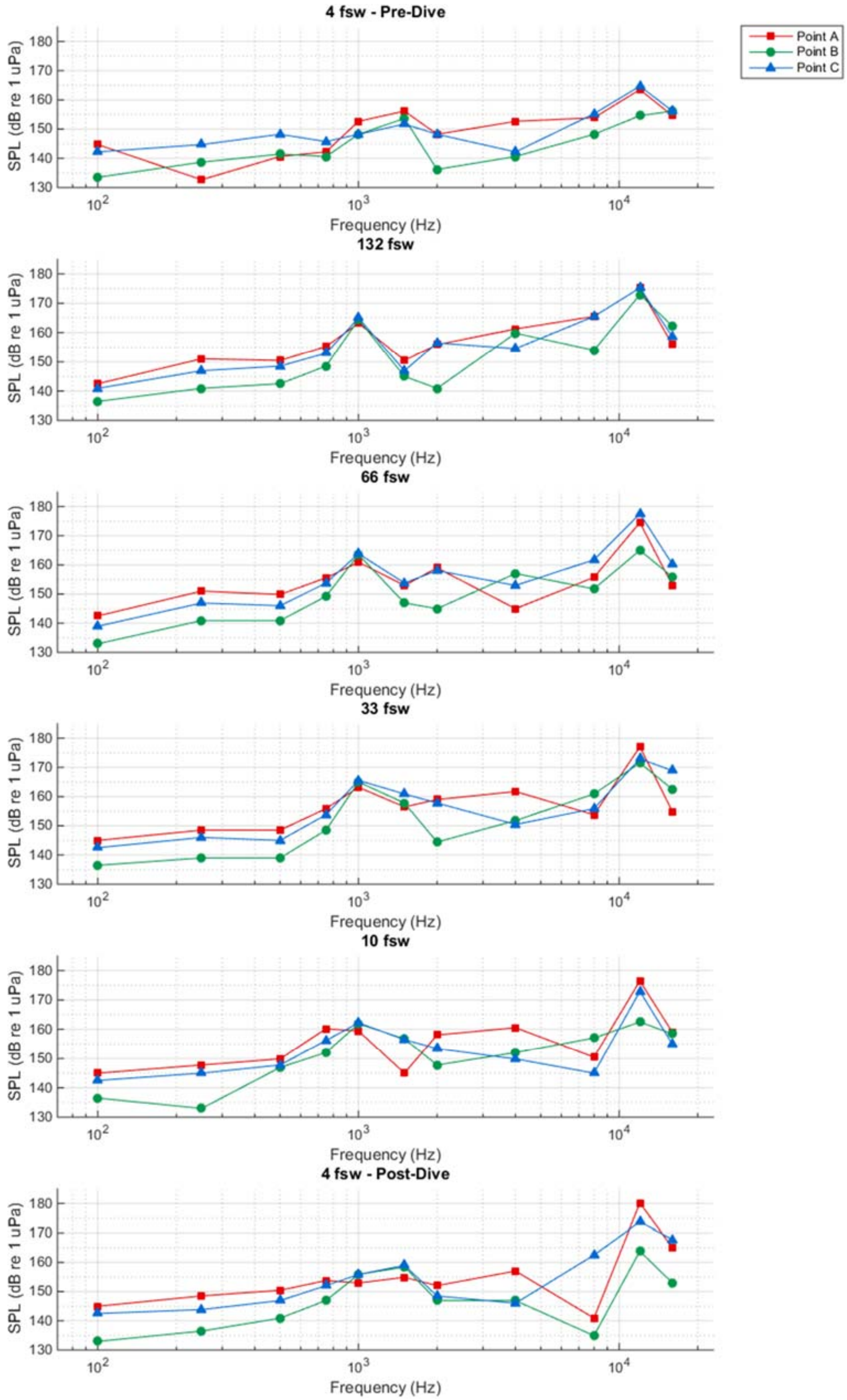
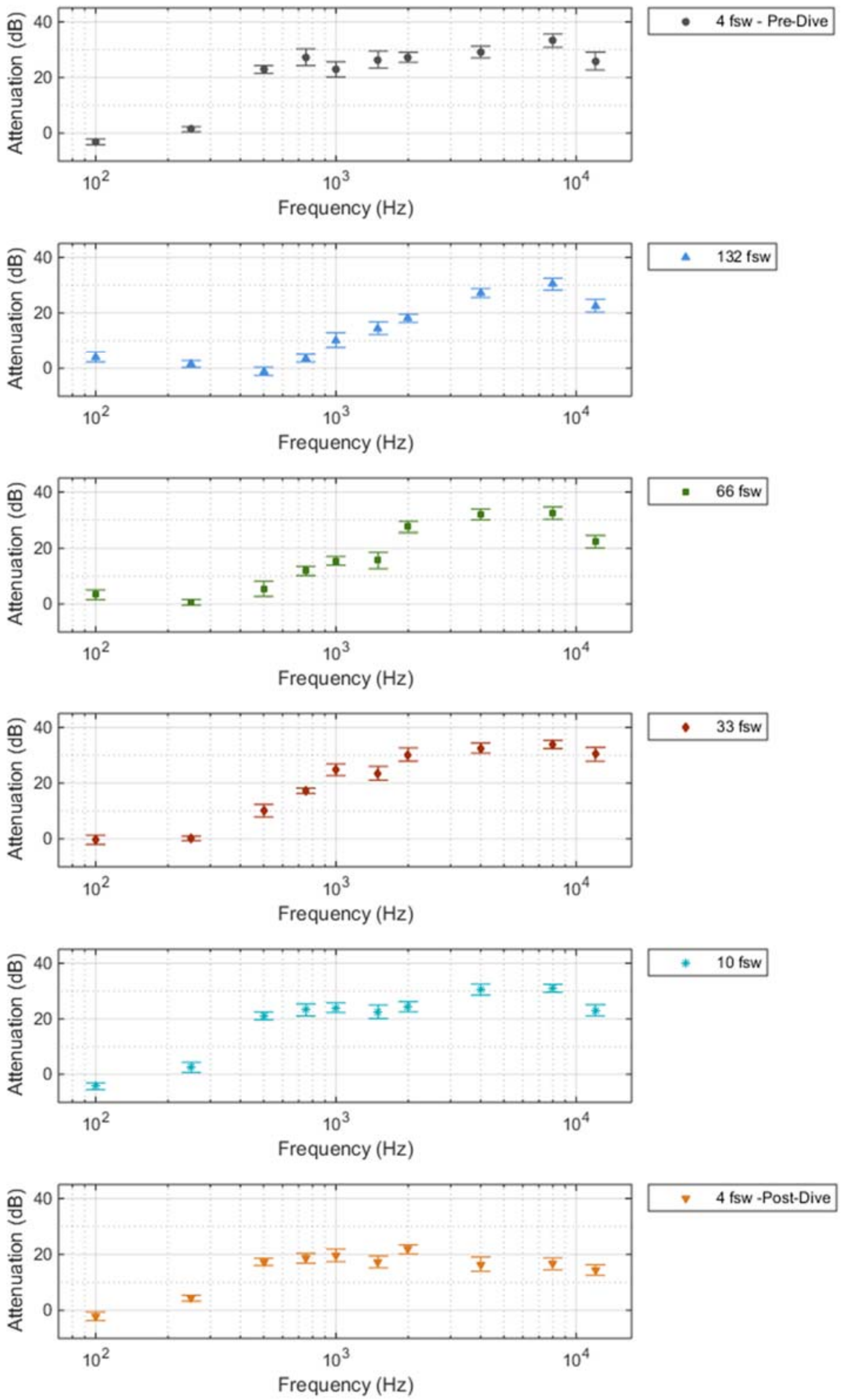


Figure 17: SPL by depth condition at calibration points A, B, and C.

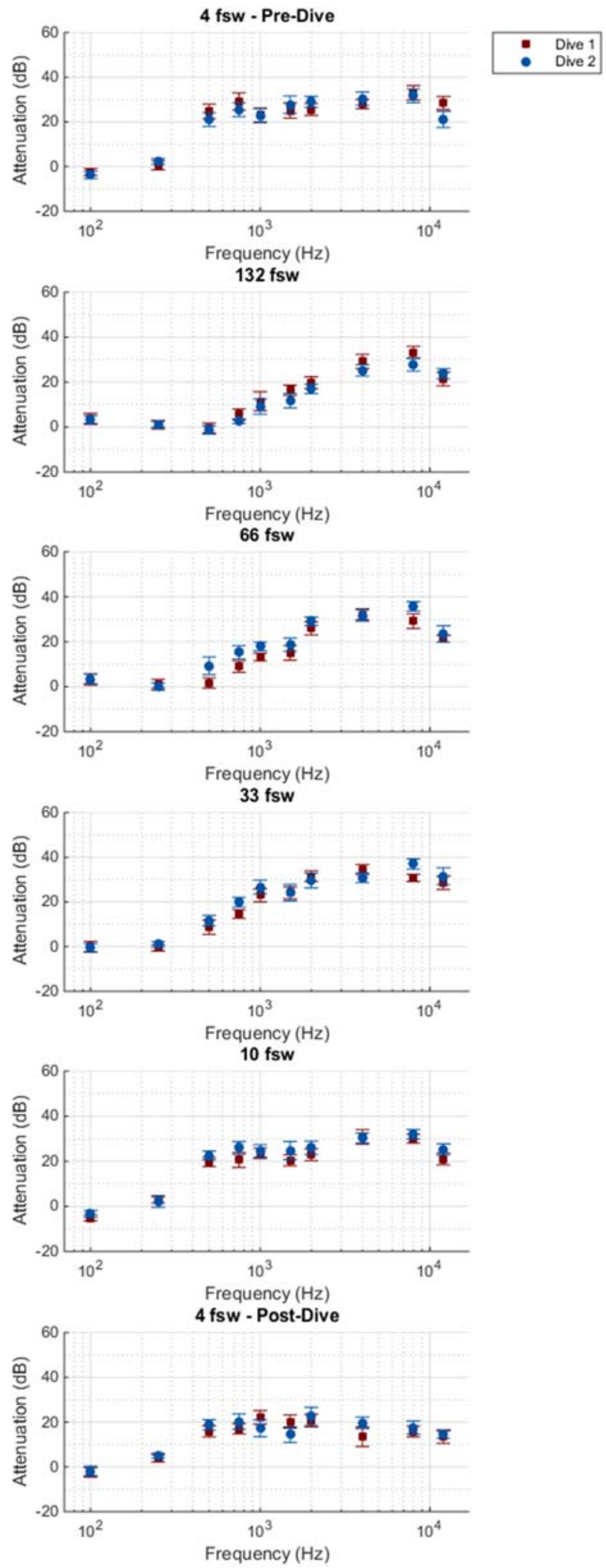
Appendix B Attenuation by Depth Condition

Means of each subject's Dive 1 and Dive 2 attenuations were calculated. Of those values, the mean and standard error of the mean attenuation across subjects as a function of frequency was then calculated and plotted for all depth conditions below (n=12).



Appendix C Dive 1 versus Dive 2 Attenuations by Depth Condition

Data are means and standard error of the means (error bars) for Dive 1 and Dive 2 (n=12).



Appendix D 4 fsw Pre-Dive versus Post-Dive Attenuation by Subject

Data are means of each subject's Dive 1 and Dive 2 attenuation values for the 4 fsw – Pre-Dive and 4 fsw – Post-Dive at each frequency.