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Bone Conducted Noise and Mitigation Techniques

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Final Report for October 2004 to September 2008

Approved for public release; distribution unlimited.

Air Force Research Laboratory
711th Human Performance Wing
Human Effectiveness Directorate
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14. ABSTRACT
Very high level noises, up to 150 dB, can cause special problems in hearing protection. In order to achieve a 15 minute exposure within an 85 dB, 8 hour, 3 dB/doubling criteria, the hearing protector must provide 50 dB of overall noise attenuation. The issue becomes the flanking pathway provided by bone conduction with an attenuation at 2 kHz of approximately 40-45 dB. In this case, the flanking pathway becomes the predominate pathway for acoustic energy to stimulate the cochlea. This report describes the basic investigation into the linearity of loudness judgements with bone conducted noise, descriptions of passive and active techniques to mitigate/attenuate bone conducted noise, and recommendations for future research in bone conducted noise.

15. SUBJECT TERMS
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1. INTRODUCTION

Noise has been an unintended by-product of aircraft operations for over 100 years. Pilots and mechanics flying and maintaining aircraft have been at significant risk of hearing loss. The loss of hearing capability seriously degrades voice intelligibility and even a mild or moderate hearing loss has a significant impact on speech intelligibility in noise. This noise can be environmental noise or competing conversations from other people. Approximately 50 percent of the personnel who work on US Air Force flight lines experience significant threshold shifts. This is due not only to the very high noise levels generated by military fighter aircraft as seen in Figure 1, McKinley [5], but also the poor use of existing hearing protection as seen in Figure 2, Bjorn [2]. Bjorn surveyed earplug use on the flight decks of US Navy aircraft carriers where the use of double hearing protection (earmuffs and earplugs in combination) is mandatory due to the extremely high noise levels and 12-16 hour duty days. Bjorn reported that 47 percent never wore earplugs and only 21 percent wore them well enough to give 6 dB or more attenuation.

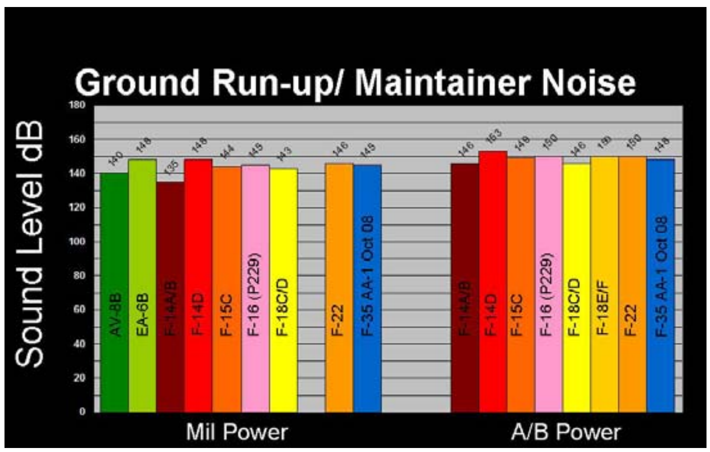

Figure 1: Worst case noise levels at 50 feet for US high performance jet fighter aircraft

The noise levels in Figure 1 would seem to encourage personnel to use the maximum hearing protection available to them. However, as seen in Figure 2, that conjecture is not supported by the reported earplug use on the US Navy flight decks.

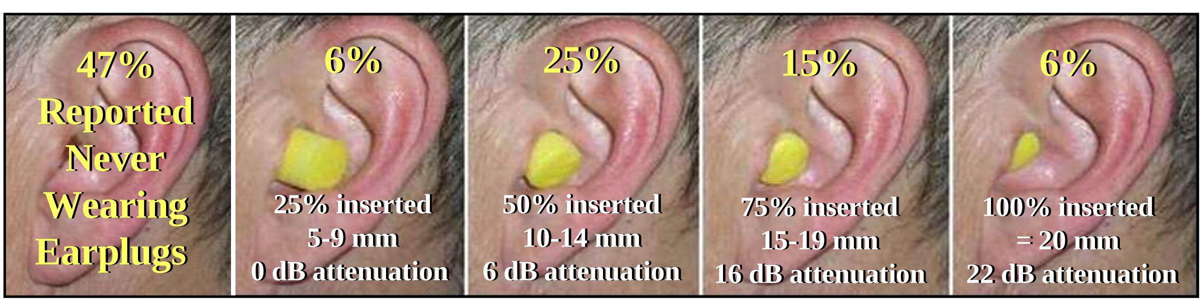

Figure 2: Earplug use rates and depth of insertion on US Navy carrier flight decks (Bjorn, et al., 2005)

There are several possible reasons why the existing hearing protection is not being used and one of them is the possible interference of bone conducted noise interfering with auditory localization while wearing double hearing protection. This leads to the flight deck personnel being unable to localize nearby noise sources such as moving aircraft which can pose a potential threat, Brungart et al. [3].

Bone conducted noise can possibly interfere with auditory localization, speech communication, and can be a possible source of hearing damage risk. Any type of noise, including bone conducted noise can be mitigated using passive, active, or combinations of active and passive technologies. Solutions for protecting personnel in the high level noise fields cannot be validated until bone conducted noise is better understood.

2. BACKGROUND

The first issue was to better understand bone conduction pathways and the attenuation of those pathways. The approach to this issue has been to use a combination of both behavioral studies of bone conducted sound and modeling of the acoustics modes and pathways of the head. Recently, Dietz [4] presented some new information of the bone conduction pathways following a study of the acoustic pathways for bone conducted noise. Figure 3 shows the air conduction, head/bone conduction, and body conduction attenuations. Figure 4 shows the attenuation gains by adding to earplugs a helmet, helmet with goggles, and helmet with a long faceshield.

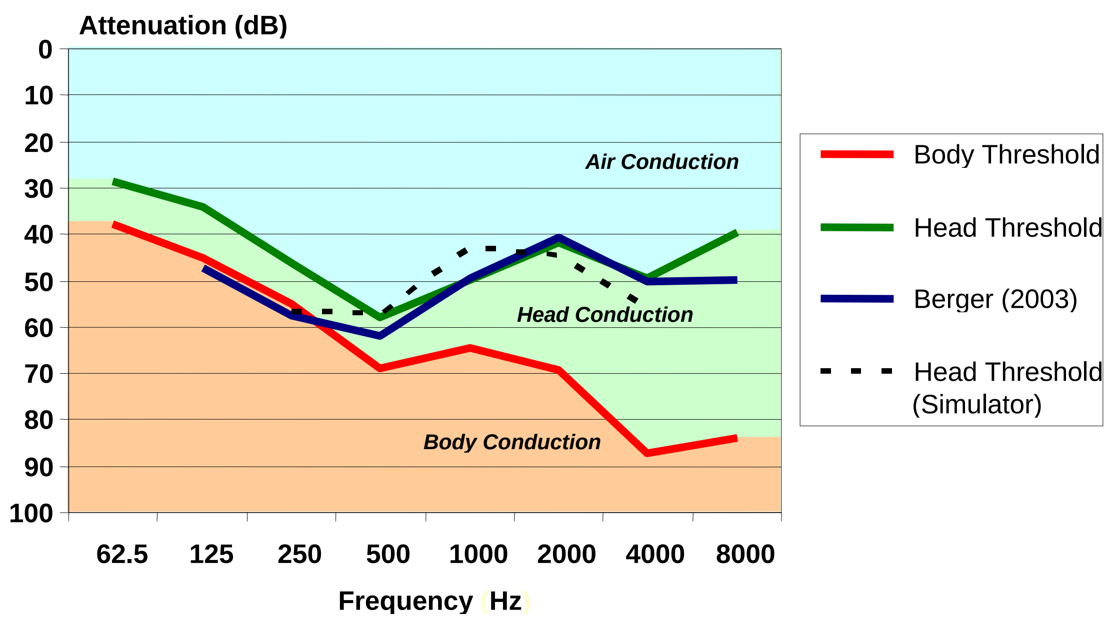

Figure 3: Bone conduction attenuations, head, body, head stimulator, and Berger head (Dietz, 2005)

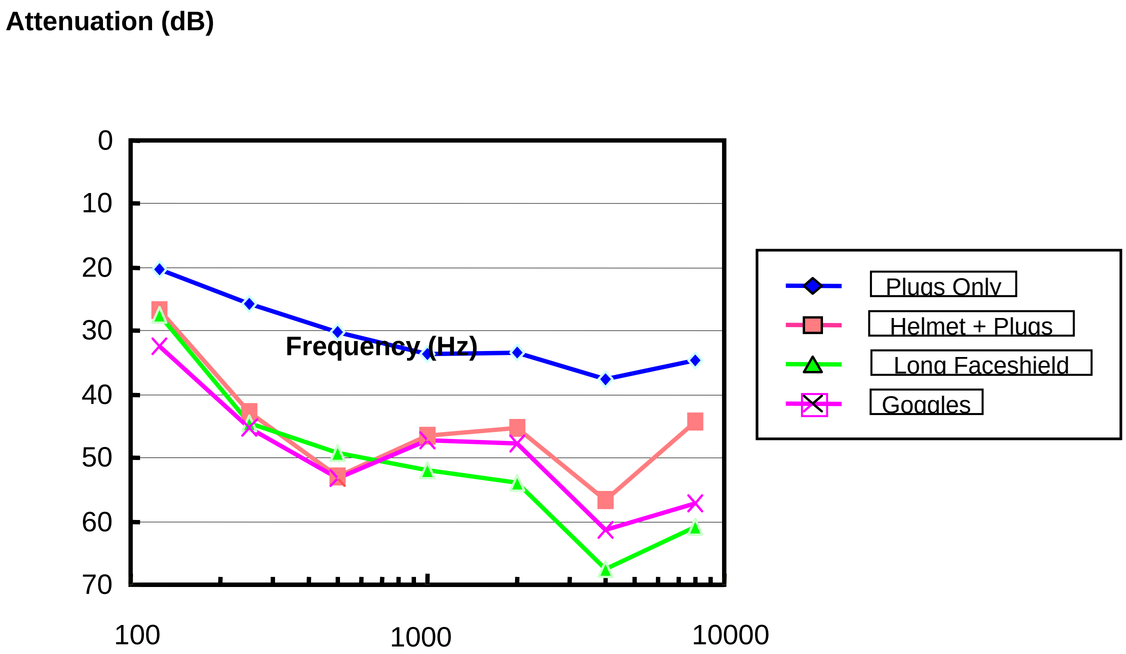

Figure 4: Maximum attenuations of earplugs, helmet w/plugs, goggles, helmet/plugs/face shield(Dietz, 2005)

Military personnel noise environments represent most of the noise exposure conditions to which people are routinely exposed. The overall noise levels can be as high as 150 dB for exposure times which exceed 15 minutes per day [5]. Many national and international hearing conservation programs have adopted a noise exposure criterion of 85 dBA for 8 hours with a 3 dB/doubling exchange rate. This same noise exposure criterion is in both DOD and USAF standards. Attenuation requirements of approximately 50 dB are derived using this noise exposure criterion based on the need to adequately protect the majority of the users [5]. This attenuation need exceeds the bone conduction limits to attenuation reported by many researchers [1] especially in the region around 2kHz.

The goal of adequately protecting personnel in these types of environments cannot be accomplished without a better understanding of the bone conduction flanking pathways and the accompanying mitigation strategies which logically follow. Additionally, susceptibility to bone conducted noise may have a component of non-linearity when compared to air conducted noise exposure criteria. This non-linearity may have two parts, the first due to physics associated with the intensity of the noise (>130 dB) and the second due to non-linear response to bone conducted stimulation of the cochlea. Finally, double hearing protection, the normal prescription in very high noise exposure conditions, seems to significantly interfere with auditory localization possibly due to confusion with bone conducted sound [3].

3. METHODS

The objective of the study was to identify the magnitude of the potential non-linearity in the loudness perception of bone conducted noise. This was thought to be an important factor in establishing the potential damage risk from bone conducted noise and also establishing the amount of required mitigation/attenuation of bone conducted noise in intense military noise environments. Three experiments were conducted, linearity of loudness perception, passive attenuation of bone conducted noise, and a demonstration of active attenuation of bone conducted noise.

Experiment 1 – Linearity of Loudness Perception

Listeners

Seven normal hearing listeners (4 females and 3 males), aged 19 to 25 years (mean age = 21.7 years) were paid for their participation in the study. All subjects had audiometric thresholds of 15 dB HTL or better at all audiometric octave frequencies from 250 to 8000 Hz and had a satisfactory otoscopic examination of the external earcanals and tympanic membranes. The listeners had participated in similar auditory experiments in this laboratory.

Stimuli

The signals used in this study were 1/3 octave-band, 250ms noise bursts centered at 2 kHz with 25ms on/off cosine-squared ramps. These signals were used due to the improved transmission/less attenuation at 2 kHz to bone conducted sound. The stimuli were generated digitally by a Tucker-Davis Real-Time Processor. The air conducted stimuli were presented via deep insert, custom-molded earplugs fitted with an integrated earphone and microphone (the microphone was not used in this study). The levels of the earplug-presented stimuli were calibrated using a Brűel & Kjær artificial ear with a 2cc coupler. A photo of the inserted earplug is shown in Figure 5. The bone conducted stimuli were presented via the ambient loudspeakers in a reverberation chamber shown in Figure 6. The earplug/earmuff combination was expected to provide enough attenuation of the ambient sound so that the predominant signal at the cochlea was the bone conducted noise.

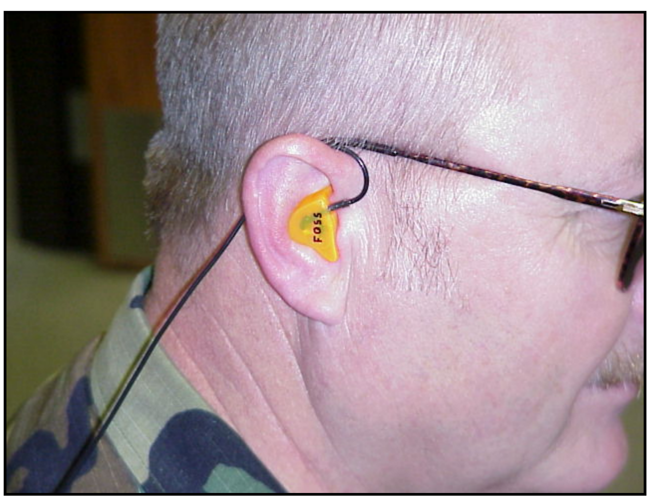

Figure 5: Deep insert custom molded earplug with integrated earphone and microphone

Apparatus

The sound attenuation of the earplugs and earplug-earmuff combination were measured in the ANSI 12.6 Real Ear Attenuation at Threshold (REAT) [7] facility located at the Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio, USA. The loudness judgments were conducted in a 1500 cubic foot reverberation chamber with a high intensity sound system, shown in Figure 6, to generate the high ambient level, 2 kHz signals required for this study. The subjects were provided with deep insert custom molded earplugs and earmuffs in order to achieve significant levels of bone conducted sound when compared to attenuated levels of air conducted sound. The earplugs, sealing to the second bend in the earcanal, attenuated ambient noise approximately 35-40 dB at 2 kHz while maintaining the ability to present acoustic stimuli un-attenuated directly to the listener.

Figure 6: AFRL's high intensity reverberation chamber – 142 dB max overall sound pressure level capability

Procedure

Each experimental block consisted of an attenuation/threshold determination followed immediately by 30 loudness matching judgments, six at each level. Each block lasted approximately 20 minutes in total. Each subject completed 10 blocks per condition. The first condition used only the deep insert custom molded earplugs with seven subjects participating. The second condition used the deep insert custom molded earplugs in combination with large volume earmuffs with three subjects returning to participate.

Threshold Determination In order to determine the amount of attenuation achieved with the custom molded deep insert earplugs or the combination of the earplugs and earmuffs, an ANSI 12.6 "Method A" (experimenter supervised fit) Real Ear Attenuation at Threshold [7] type measurement was performed at 1, 2 and 4 kHz (Note that this study did not meet the requirements of ANSI 12.6 for number of subjects and range of frequencies). The first condition was the open condition, which measured the unoccluded hearing thresholds. Following the open condition, subjects were asked to insert the custom-molded deep insert earplugs with or without earmuffs and track their occluded thresholds. In order to preserve the earplug or earplug and earmuff fit for the remainder of the block, subjects were always tested open first then closed. The difference in thresholds between the open and closed was reported as the attenuation achieved by the custom molded deep insert earplugs with and without the earmuffs.

Loudness Matching Following the threshold determination, subjects were escorted to the ANSI 12.42 MIRE facility and asked not to remove the custom molded deep insert earplugs or earmuffs. The subjects were then presented with alternating noise bursts. One noise burst originated from the loudspeakers in the reverberation chamber, the other originated from the earphone transducers in the custom molded deep insert earplugs. In this manner, alternating stimuli were presented 1) ambient sound sources attenuated by the custom molded deep insert earplugs with and without the earmuffs and 2) an air conducted sound presented via the custom molded deep insert earplug earphone transducer. Prior to the start of the loudness matching the stimuli levels were roughly matched using the attenuation value at 2 kHz from the attenuation measurement. On each trial, the subject was presented with the alternating noise bursts and asked to use a knob to adjust the level within the earplug until the intervals between the loudspeaker presented ambient noise (bone conducted) and the air conducted stimuli presented via the earphone in the earplug seemed to be of equal loudness. Although the levels were matched initially by the experimenter for each trial in which the subject was asked to match the levels, a random offset +/- 5-10 dB was introduced in order to force the subject to have to adjust the level in some manner. Once the match was achieved the subject pressed a button to indicate that the levels were matched and the next trial began. Due to exposure limitations in the human use protocol, five different levels were tested from 70dB to a maximum of 110 dB. This 110 dB limitation was about 20 dB less than the maximum 1/3 octaveband levels experienced by aircraft maintenance personnel and could have an effect on the loudness judgments for stimuli from 110-130 dB. This is an area for possible future research.

Experiment 2 – Passive Mitigation of Bone Conducted Noise

The second experiment was conducted in accordance with ANSI S12.6-1997 “Method A” (experimenter supervised fit) Real Ear Attenuation at Threshold [7].

Listeners

Ten normal hearing listeners (5 females and 5 males), were paid for their participation in the study. All subjects had audiometric thresholds of 15 dB HTL or better at all audiometric octave frequencies from 250 to 8000 Hz and had a satisfactory otoscopic examination of the external earcanals and tympanic membranes. The listeners had participated in similar auditory experiments in this laboratory.

Hearing Protection Device – Passive

The hearing protector used in this experiment was a helmet designed by Creare with special attention to mitigating bone conducted noise. The helmet liner and padding system was designed to minimize the mechanical transmission of acoustic energy to the head. The helmet also had a face shield to reduce coupling of acoustic energy via the face and nasal cavities. The helmet was also integrated with large volume passive earcups provided by Creare and deep insert custom molded solid hard silicone passive earplugs designed by AFRL.

Experiment 3 – Demonstration of Active Attenuation of Bone Conducted Noise

A third experiment or more correctly, a demonstration, of active noise reduction of bone conducted noise was performed. This demonstration involved the author as the test subject. The demonstration was conducted in the AFRL MIRE facility in a 105 dB overall sound pressure level pure tone diffuse sound field. The subject was given control which allowed adjustment of the phase and gain characteristics of the active cancellation system. The active cancellation system was a prototype designed and provided by Infoscitex.

4. RESULTS AND DISCUSSION

Experiment 1 – Linearity of Loudness Perception

Mean real-ear attenuation values for the deep insert custom molded earplugs and the deep insert custom molded earplugs with earmuffs are shown in Figures 7 and 8, respectively. Figure 7 shows that the earplug only condition was close to the bone conduction limit but was not sufficient to indicate that bone conducted noise was the predominant pathway Berger [1], Nixon [6]. Both Nixon and Berger reported the limit at 2 kHz being an average of 40 dB. The 40 dB attenuation for the double protection condition shown in Figure 8 suggests that the bone conduction pathway had become the predominant path for the 2 kHz ambient acoustic energy.

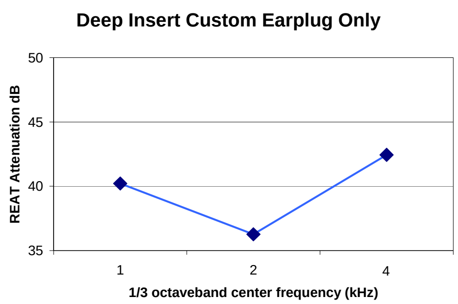

Figure 7: Earplug only attenuation

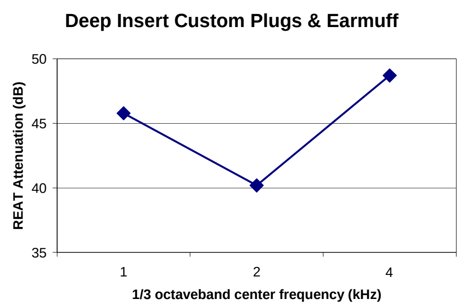

Figure 8: Combination earplug & earmuff attenuation

Figure 9 shows the mean loudness judgment data for the two conditions where the x-axis is the ambient noise generated by the reverberation chamber loudspeakers and attenuated by the earplugs & body – tissue/bone and the y-axis is the air conducted noise presented via the earphone in the custom molded deep insert earplugs. The left panel shows the mean loudness judgment data from the earplug only condition (red line/circles). The black line is the expected function if the relationship between air and bone conducted noise loudness judgments was linear and that the bone conduction limit had been exceeded by the attenuation of the earplug. The results demonstrate a small deviation from linearity.

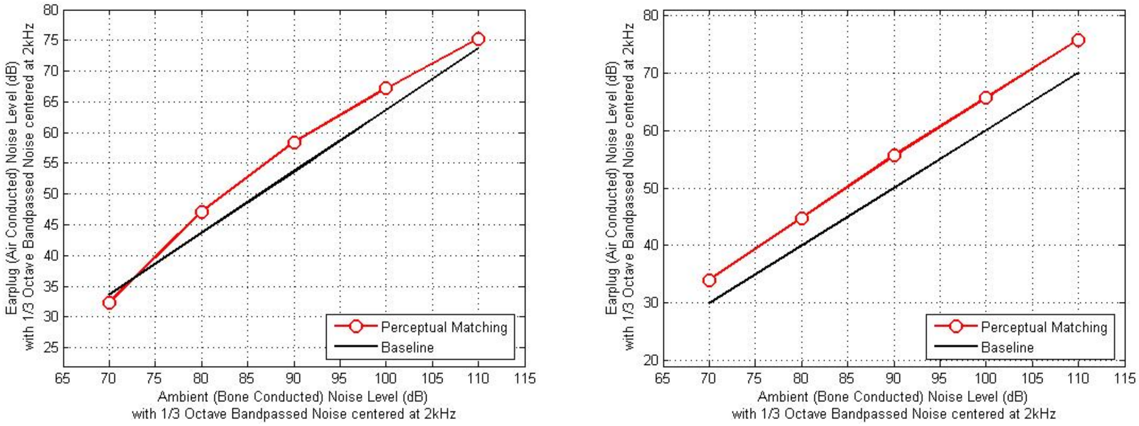

Figure 9: Loudness judgment mean data earplug only 7 subjects(left) and earplug & earmuff 3 subjects(right) ambient noise earmuff attenuation + bone conduction vs air conduction – std error .29 dB left & .36 dB right

The right panel of Figure 9 shows the mean loudness judgment data for the 3 subjects in the double protection condition. Once again, the black line shows an ideal linear function and the red line/circles is the measured data. The data show an offset but also appear to be linear. The offset could be an indication of lower sensitivity to the bone conducted stimuli when compared with the air conduction stimuli.

Figure 10 shows the individual subject loudness judgment data when using only the deep insert custom molded earplugs. The mean real-ear attenuation and standard deviation (labeled as REAT) at 2 kHz for each subject is also shown at the bottom of each panel. In Figure 10, five of the seven subjects showed loudness judgment functions that were very close to linear while two subjects showed loudness judgment functions that were up to 5 dB away from linear. The variation of the loudness judgments did not seem to be correlated with the REAT attenuation at 2 kHz. This was possibly due to the single hearing protection not exceeding the bone conduction limits so that the air conducted signal was still the predominant signal.

Figure 11 shows the individual subject loudness judgment data for the condition using the hearing protection combination of deep insert custom molded earplugs and a large volume earmuff. The mean and standard deviation for the real-ear attenuation at 2 kHz for each subject is also shown. In Figure 11, the double hearing protection condition, one subject displayed linear loudness judgments while the other two subjects displayed loudness judgments with an offset and/or a slightly steeper slope. Once again, there did not seem to be a correlation between the REAT attenuation at 2 kHz and the linearity of the loudness judgments.

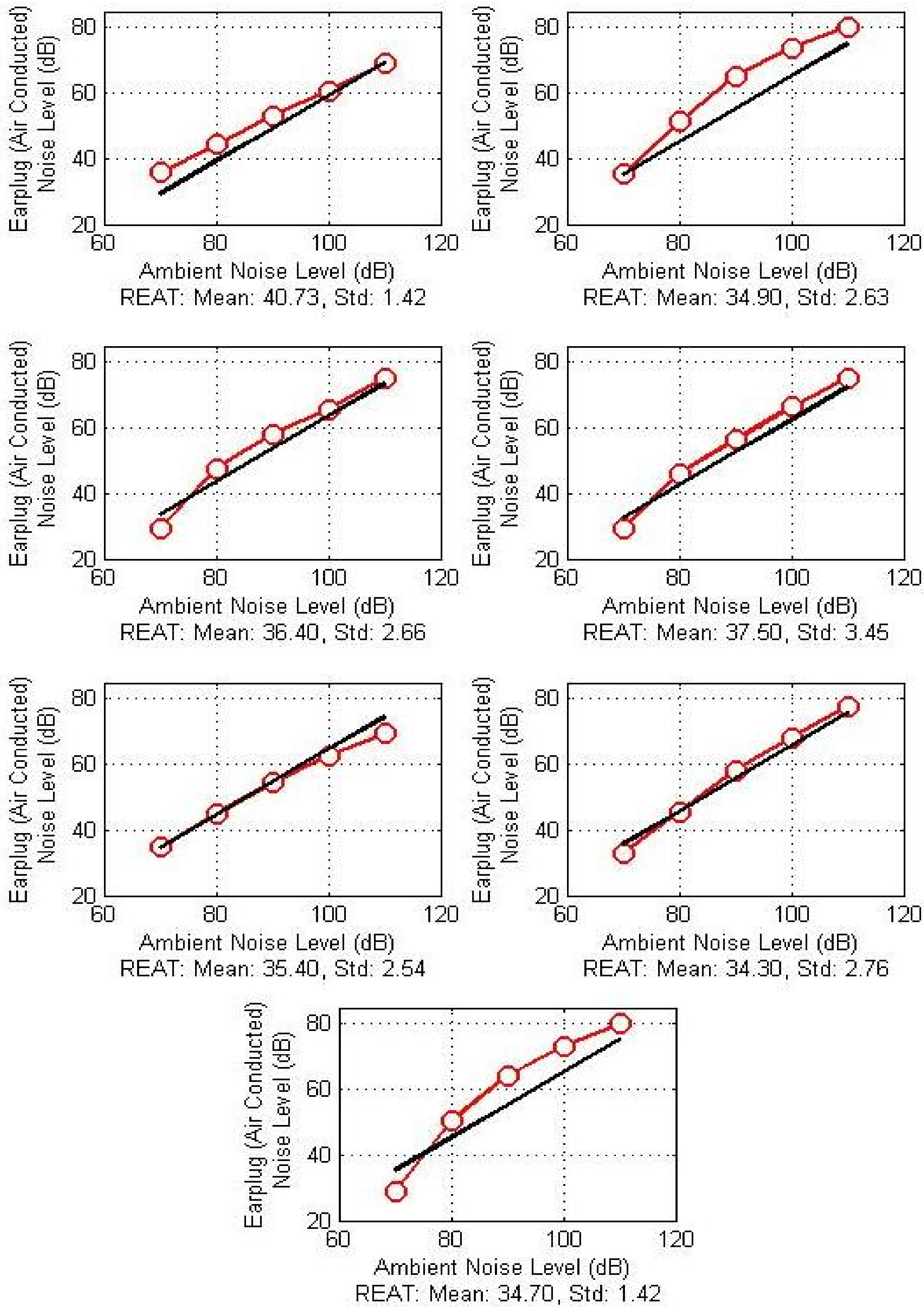

Figure 10: Seven individual subjects' loudness judgments for the earplug only condition

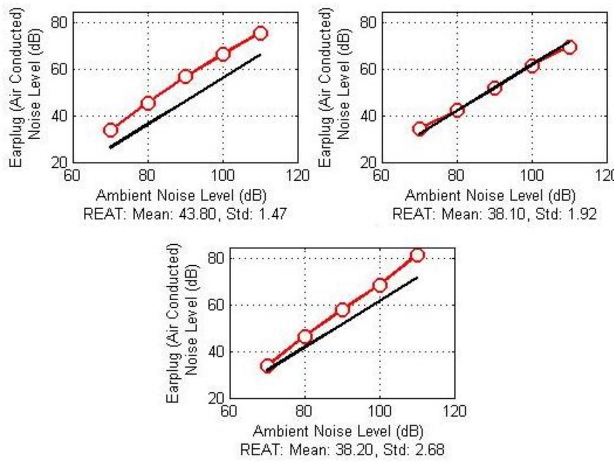

Figure 11: Three individual subjects' loudness judgments air conduction vs bone conduction-double protection – deep insert custom earplugs and earmuffs

The second set of loudness judgment functions with double hearing protection, earmuffs in combination with the custom-molded deep insert earplug are shown in Figure 12. The top and bottom right panels of Figure 12 seem to indicate a possible reduced sensitivity to bone conducted noise. As also seen in Figure 12, comparing the loudness judgments for the same subjects of the earplug only condition to the earplug and earmuff condition, it does not appear that the loudness judgments of bone conducted noise are significantly different from loudness judgments of air conducted noise. Further study is needed at higher sound pressure levels to explore the effects of the 110-130 dB exposure range.

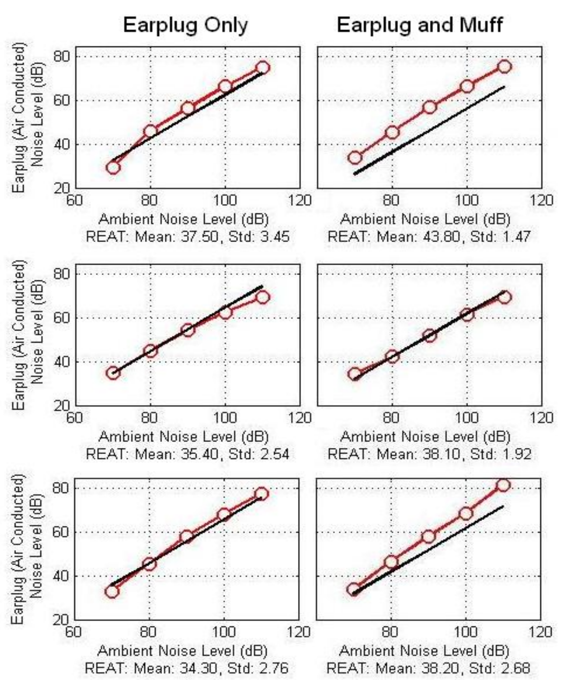

Figure 12: Comparison of three subjects' loudness judgments with single and double hearing protection

Experiment 2 – Passive Mitigation of Bone Conducted Noise

Mean real-ear attenuation of the Creare bone conduction helmet with and without a face shield and AFRL deep insert custom molded solid earplugs is shown in Figures 13.

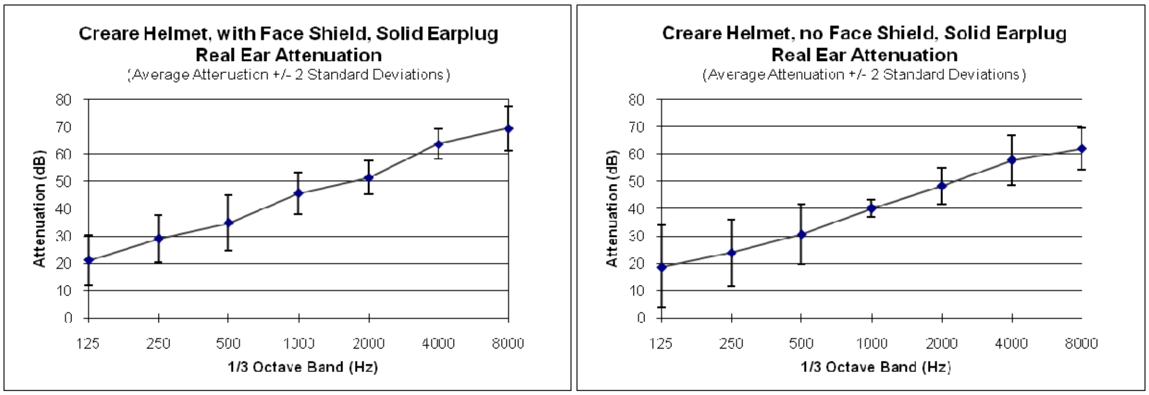

Figure 13: ANSI S12.6-1997 Real-ear attenuation with passive helmet and deep insert custom earplugs with (left chart) and without (right chart) face shield

The Table 1 shows the mean and standard deviation of numerical attenuation data in decibels for the helmet with and without the face shield.

Table 1: Attenuation provided by Creare Helmet with solid earplugs and with (upper table) and without face shield (lower table)

Creare Helmet, with Face Shield, Solid Earplug

Octave Band Attenuation Data

Freq (Hz)	125	250	500	1000	2000	4000	8000
Mean	21	29	35	46	51	64	70
Std dev	5	4	5	4	3	3	4
Mean - Std dev	17	25	30	42	48	61	65
Mean - 2*SD	12	20	25	38	45	58	61

Creare Helmet, without Face Shield, Solid Earplug

Octave Band Attenuation Data

Freq (Hz)	125	250	500	1000	2000	4000	8000
Mean	19	24	31	40	48	58	62
Std dev	8	6	6	2	3	5	4
Mean - Std dev	11	18	25	39	45	53	58
Mean - 2*SD	4	12	20	37	42	49	54

The face shield provides a moderate, 2 to 8 dB, improvement in attenuation as seen in Table 2. The values are in dB and were computed by taking the differences in the mean attenuations at the test frequency bands.

Table 2: Additional attenuation added by face shield to Creare Helmet with solid earplugs

Creare Helmet attenuation difference due to face shield

Octave Band Attenuation Data

Freq (Hz)	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Mean	2	5	4	6	3	6	8

The Creare helmet with face shield and solid earplug data can also be compared with the bone conduction limits shown in the literature. Figure 14 shows a significant increase of the attenuation of approximately 10 dB in the 2 kHz test band, 5 dB in the 4 kHz test band, and nearly 20 dB in the 8 kHz test band. The improvement at 2 kHz would most likely be significant in reducing the overall noise level for users in very high noise environments.

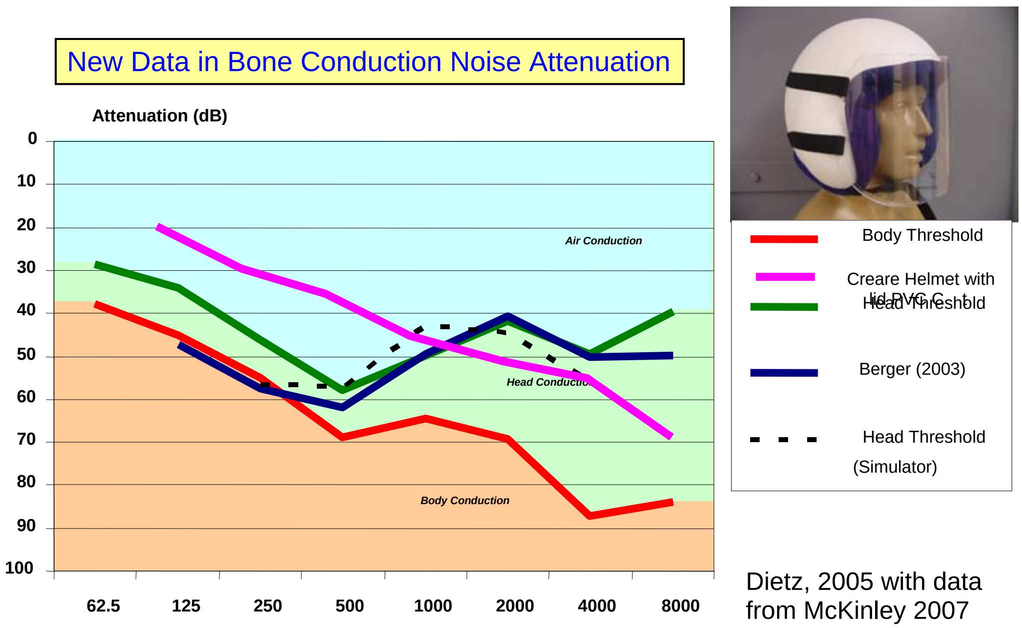

Figure 14: Attenuation of bone conducted noise with passive helmet and deep insert custom earplugs

These data show that at least some of the bone conducted noise is being mechanically coupled to the head and that some other portion of the bone conducted noise is being acoustically coupled via the face and nasal cavities. These findings were thought to be important relative to the design and development of new hearing protection systems for use in very high noise environments.

Experiment 3 – Demonstration of Active Attenuation of Bone Conducted Noise

This demonstration was a success in that the author perceived a reduction in the level of the signal which was being actively cancelled. However, the gain and phase characteristics required for the cancellation were different for each ear and were manually adjusted relative to the perceived noise level. Additionally, the cancellation demonstration was only accomplished for pure tones. Clearly, this was just a demonstration of concept, but additional investigation may be warranted for applications where a passive bone conduction helmet may not have reasonable user acceptability and a lighter, smaller solution is needed.

5. CONCLUSIONS

Bone conducted noise is a critical issue relative to hearing protection and noise exposure in the extreme (140-150 dB) noise environments associated with the operation of high performance military aircraft. Current double hearing protection, earmuffs and earplugs, most likely exceed the bone conducted limits. In this series of three experiments: the loudness judgments of suspected bone conducted noise in the 70 dB to 110 dB range were concluded to be comparable to the loudness judgments of air conducted noise for the double hearing protection condition and therefore linear; the combination of a passive bone conduction helmet with face shield and solid custom molded earplugs was shown to exceed the currently published bone conduction limits, and a very limited concept demonstration of active attenuation of bone conducted noise was accomplished.

Consideration of bone conduction pathways and effects on attenuation performance of hearing protectors should be a part of future developments of high performance hearing protection systems for use in high noise environments. Passive solutions are generally less costly but larger in size and weight than the potential active solutions (if the technical challenges can be overcome with the active systems).

6. RECOMMENDATIONS FOR FUTURE RESEARCH

Further investigation of bone conducted noise and tissue conducted noise is warranted. A follow-on effort has been funded by AFOSR to investigate the loudness judgments of air conducted noise and suspected bone/tissue conducted noise in the 110-130 dB range. Additionally, in order to assess potential hearing damage risk of bone conducted noise, a second experiment was required and has been planned and designed. 20 subjects will participate in the study of TTS generated by air conducted noise at the 2 kHz 1/3 octaveband vs TTS generated by bone conducted noise. The 2 kHz 1/3 octaveband noise levels will be measured/matched by both loudness matching and physical measurement of the sound field under the custom molded deep insert earplug near the tympanic membrane. A third experiment was also approved investigating the interactions of bone/tissue conducted noise in auditory localization.

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