Communication in Noise with Acoustic and Electronic Hearing Protection Devices

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Abstract
The purpose of the present study was to evaluate communication ability in noise at two signal presentation levels when using acoustic and electronic hearing protection devices (HPDs). Fourteen normal hearing subjects were fitted binaurally with custom acoustic HPDs (ER-15) and custom electronic HPDs (Starkey SA T9). Probe microphone measurements were obtained on 28 ears for three experimental conditions (open ear, acoustic HPD, electronic HPD) at four input signal levels (60, 70, 80, 90 dB SPL). Also, communication in noise was evaluated for three conditions (open ear, acoustic HPD, electronic HPD) at two input signal levels (75 and 90 dB SPL) using the Hearing In Noise Test. Results indicated significantly greater attenuation as well as significantly better communication in noise for the acoustic HPD. Results also indicated that the electronic HPD failed to attenuate any input signal utilized. Although results of behavioral testing indicated that communication ability in noise was not significantly impacted by varying the signal presentation level when utilizing either HPD, a more salient finding may be that utilization of the electronic HPD may place listeners at risk for temporary or permanent sensorineural hearing loss.

Key Words: Hearing protection device, permanent threshold shift, attenuation, temporary threshold shift

Abbreviations: TTS = temporary threshold shift; PTS = permanent threshold shift; HPD = hearing protection device; HINT = hearing in noise test

Sumario: El propósito del presente estudio fue evaluar la capacidad de comunicación en medio del ruido, a dos niveles de intensidad de presentación de la señal, utilizando dispositivos de protección auditiva (HPD) acústicos y electrónicos. A catorce sujetos con audición normal se les adaptó binauralmente un sistema de HPD (ER-15) acústico, y un sistema de HPD (Starkey SAT9) electrónicos, ambos hechos a la medida. Se obtuvieron mediciones con un micrófono de prueba en los 28 oídos, para tres condiciones experimentales (oído libre, HPD acústico, HPD electrónico) con cuatro niveles de presentación de la señal (60, 70, 80, 90 dB SPL). Además, la comunicación en ruido fue evaluada para tres condiciones (oído libre, HPD acústico, HPD electrónico) con dos niveles de presentación de la señal (75 y 90 dB SPL), utilizando la Prueba de Audición en Ruido. Los resultados muestran una atenuación significativamente mejor, así como una mejor comunicación en medio del ruido para los HPD acústicos. Los resultados también indican que los HPD electrónicos fallaron en atenuar cualquier señal de presentación utilizada. Aunque los resultados en las pruebas conductuales indicaron que la capacidad de comunicación en el ruido no se veía influida significativamente por variaciones...
Hazardous noise levels may cause temporary or permanent hearing loss (Abel, Alberti, Haythornwaite, & Riko, 1982). Two basic types of hearing protection devices (HPD) attempt to minimize the deleterious effects of noise on hearing sensitivity: acoustic HPDs and electronic HPDs (Berger, 1986; Lindley, Palmer, Goldstein, & Pratt, 1997). Acoustic HPDs attempt to prevent temporary threshold shift (TTS) and permanent threshold shift (PTS) by providing static attenuation to input signals regardless of signal level (Berger, 1983). Electronic HPDs attempt to prevent TTS and PTS by attenuating input signals that exceed a criterion intensity level; however, input signals below the criterion intensity level are not attenuated and may be amplified (Allen & Berger, 1990; Tye-Murray, 1998).

Properly fitted acoustic HPDs have been shown to effectively attenuate various levels of noise (Abel & Spencer, 1999; Berger, 1986; Mosko & Fletcher, 1971). However, communication ability may be negatively affected when using acoustic HPDs if the signal level is reduced (Mosko & Fletcher, 1971). Conversely, electronic HPDs are designed to provide level dependent attenuation. Variations in the level of the signal should result in variations in the attenuation provided by the electronic HPD. As a result, high level signals may receive similar attenuation from both acoustic and electronic HPDs whereas signals presented at reduced levels may receive less attenuation from electronic HPDs than from acoustic HPDs. Given this, it is reasonable to postulate that communication ability will be less affected by variations in the signal presentation level when utilizing an electronic HPD than when utilizing an acoustic HPD. Thus, the purpose of the present study was to evaluate communication ability in noise at various signal presentation levels when using acoustic and electronic HPDs.

METHOD

Subjects

Fourteen female persons (21 to 24 years of age) with normal hearing sensitivity served as the subjects. Criteria for normal hearing sensitivity was based on a) pure tone air conduction thresholds for each ear between 0 dB HL and 20 dB HL for octave frequencies between 250 Hz to 8000 Hz (ANSI S3.6-1996), b) normal tympanograms bilaterally, and c) unremarkable otoscopy. Qualified subjects had impressions made of each ear. The same impression was used to produce both the acoustic and electronic HPD to minimize physical fit differences between devices. All qualification and experimental tests were conducted in a sound-treated examination room with ambient noise levels suitable for testing with ears uncovered (ANSI S3.1-1991).

Stimuli

The Hearing in Noise Test (HINT) (Nils- son, Soli, & Sullivan, 1994) served as the stimuli. The HINT consisted of 25 lists of 10 English sentences. An adaptive presentation was utilized to determine the sentence reception threshold in terms of signal-to-noise ratio. Speech stimuli and background noise were produced by a compact disc player and routed through a two-channel diagnos-
tic audiometer (GSI-61) to a loudspeaker located in the sound treated examination room. The level of the HINT stimuli was calibrated at the vertex of the listener and was checked periodically throughout the experiment.

**Hearing Protection Devices**

Prior to experimental testing, qualified subjects were fit binaurally with custom acoustic HPDs (ER-15) and custom electronic HPDs (Starkey SA T9). All HPDs were completely in-the-canal devices (no venting) to minimize differences in their respective field to attenuator/microphone transfer functions. The acoustic HPDs were reported to provide relatively flat attenuation for all input signals (Chasin & Chong, 1999). The electronic HPDs were Starkey SA T9 completely-in-the-canal devices with output compression limiting circuitry (HFA-OSPL90 = 90.6 dB SPL; HFA full-on gain = 20.9 dB; kneepoint = 65 dB SPL; compression ratio = 10:1). Each electronic HPD was analyzed electroacoustically prior to testing to ensure proper working order (ANSI-S3.22-1996). The volume control on each electronic HPD remained in the full-on position during all probe microphone and behavioral testing.

**Experiment I: Attenuation Characteristics**

Probe microphone measurements were obtained to ensure proper HPD fit and function and to determine the attenuation characteristics of each device. Probe microphone measurements were obtained binaurally for each subject using standard clinical procedures at four input signal levels (60, 70, 80, 90 dB SPL pure tone sweep) for three experimental conditions (open ear, acoustic HPD, electronic HPD). Probe insertion depth was 30 mm past the tragus for each ear and for each condition.

The probe microphone system measurements consisted of 65 data points measured in 1/12th-octave steps over a frequency range of 200 Hz to 8000 Hz. Data for output levels at the tympanic membrane in the four conditions stored in an Audioscan RM500 were downloaded to a personal computer. Subsequent data analysis was completed to determine the attenuation characteristics of each device.

**Experiment II: Communication in Noise**

Subjects were seated 1 meter from the loudspeaker located at 0 degrees azimuth in the sound treated room. The HINT was administered at sentence presentation levels representative of loud speech (75 dB SPL) and of speech at maximum vocal effort (90 dB SPL) (Cox, 1995) for three experimental conditions (open ear, acoustic HPD, electronic HPD). It should be noted that the HINT protocol utilized in the present study reflected a slight modification of the original HINT protocol in that noise levels were varied and speech levels were fixed.

Two HINT trials were conducted for each condition at each sentence presentation level. An average of the two trials served as the mean HINT score for that subject in the given condition. In the event the HINT score for the first and second trial disagreed by greater than 2 dB, a third trial was performed, and the average of the three trials served as the HINT score. A third trial was necessary on three of eighty-four occasions. Before data collection, an experimental schedule was generated for each subject listing a completely randomized assignment for HPD type, sentence presentation level, and sentence list.

Following HINT behavioral testing, HINT background noise was routed through the loudspeaker in the sound treated room. Probe microphone measurements were obtained at the plane of the tympanic membrane with the loudspeaker of the Audioscan RM500 deactivated thereby allowing the unit to act as a spectrum analyzer. Probe microphone measurements were obtained at two levels (75 and 90 dB SPL) for three experimental conditions (open ear, acoustic HPD, electronic HPD).

**RESULTS**

**Experiment I: Attenuation Characteristics**

Probe microphone responses obtained with the acoustic HPD and with the electronic HPD were each subtracted from the open ear response for each ear to determine the attenuation response provided by each HPD at each input level. A mean attenuation
level was then calculated for each ear by averaging the attenuation values of 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz for each HPD at each intensity level. Attenuation responses (Figures 1a-1d) and attenuation levels (Figure 2) were then averaged across the 28 ears for each HPD at each input level.

A two-way within-subjects analysis of variance was performed to evaluate the effects of intensity level and hearing protection device. The dependent variable was attenuation level. The within-subjects factors were HPD with two levels (acoustic and electronic) and intensity level with four levels (60, 70, 80, and 90 dB SPL). The analysis revealed significant main effects for intensity level \([F (1,27) = 258; p<0.05]\) and HPD \([F (1,27) = 782; p<0.05]\) as well as a significant intensity level x HPD interaction \([F (1,27) = 410; p<0.05]\). To follow up the significant interaction, four paired-samples t-tests were computed to assess differences between HPDs at each intensity level. Results indicated the acoustic HPDs yielded significantly greater attenuation than the electronic HPDs at 60 dB SPL \([t (27) = 30; p<0.05]\), 70 dB SPL \([t (27) = 31; p<0.05]\), 80 dB SPL \([t (27) = 26; p<0.05]\), and 90 dB SPL \([t (27) = 18; p<0.05]\). These results indicated that the acoustic HPDs provided significantly greater attenuation at each input signal level; however, attenuation differences between the HPDs diminished as input signal level increased (Figure 2).

Figure 1a: Mean attenuation responses for acoustic and electronic HPDs for a 60 dB SPL input signal. Error bars represent + 1 standard deviation.

Figure 1b: Mean attenuation responses for acoustic and electronic HPDs for a 70 dB SPL input signal. Error bars represent + 1 standard deviation.

Figure 1c: Mean attenuation responses for acoustic and electronic HPDs for a 80 dB SPL input signal. Error bars represent + 1 standard deviation.

Figure 1d: Mean attenuation responses for acoustic and electronic HPDs for a 90 dB SPL input signal. Error bars represent + 1 standard deviation.

Figure 2: Mean attenuation levels for acoustic and electronic HPDs for input signals of 60, 70, 80 and 90 dB SPL. Error bars represent + 1 standard deviation.
Experiment II: Communication in Noise

Individual HINT scores obtained with the acoustic HPDs and with the electronic HPDs were subtracted from the individual HINT score obtained in the open ear condition in order to determine each subject’s relative HINT score for each device at each level. A positive relative HINT score indicated improved performance relative to the open ear whereas a negative relative HINT score indicated poorer performance relative to the open ear. Individual relative HINT scores were then averaged across fourteen subjects for each HPD at each sentence presentation level (Table 1, Figure 3).

A two-way within-subjects analysis of variance was performed to evaluate the effects of signal presentation level and hearing protection device. The dependent variable was relative HINT score. The within-subjects factors were HPD with two levels (acoustic and electronic) and sentence presentation level with two levels (75 and 90 dB SPL). The analysis revealed a significant main effect for HPD [F (1,13) = 10; p<0.05]. However, main effects for sentence presentation level [F (1,13) = 1; p>0.05] and for the sentence presentation level x HPD interaction [F (1,13) = 2; p>0.05] were not significant. These results indicated that communication in noise was significantly better when utilizing the acoustic HPD than when utilizing the electronic HPD at each sentence presentation level.

DISCUSSION

Experiment I: Attenuation Characteristics

Probe microphone measurements were obtained at the plane of the tympanic membrane to ensure proper HPD fit and function and to determine the attenuation characteristics of each device. Results of the present study confirmed that the acoustic HPDs provided relatively static attenuation at each input signal level while the amount of gain

<table>
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<tr>
<th>Signal Level</th>
<th>Condition</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Relative HINT Score</th>
<th>Standard Deviation</th>
</tr>
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<td>1.6</td>
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<tr>
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<td>-0.4</td>
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<tr>
<td>90 dB SPL</td>
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<td>-3.2</td>
<td>0.9</td>
<td></td>
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<tr>
<td></td>
<td>Acoustic HPD</td>
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<tr>
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<td>Electronic HPD</td>
<td>-2.6</td>
<td>1.1</td>
<td>-0.6</td>
<td>1.3</td>
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Figure 3: Mean relative HINT scores for the acoustic and electronic HPDs for input signals of 75 and 90 dB SPL. Error bars represent + 1 standard deviation.
provided by the electronic HPDs decreased as input signal level increased. Results of the present study further indicated that the electronic HPD failed to attenuate at any input signal level utilized. For example, the acoustic HPDs provided approximately 10 dB of attenuation for all input signal levels whereas the electronic HPDs provided 20 dB of gain for 60 dB SPL inputs and 5 dB gain for 90 dB SPL inputs (Figure 2). In fact, in situ levels for the electronic HPD approached or exceeded damage criterion levels for input signals that would typically pose no risk to hearing sensitivity. Consequently, utilization of the electronic HPD may place listeners at risk for temporary or permanent sensorineural hearing loss.

Attenuation results obtained at 60 and 70 dB SPL were expected given the fact the acoustic HPDs provided static attenuation of approximately 10 dB while the electronic HPDs provided dynamic, level-dependent gain. However, attenuation results obtained at 80 dB SPL and 90 dB SPL were not expected due to the fact that the electronic HPD utilized output compression limiting with a compression threshold of 65 dB SPL.

Figure 4 displays the mean output levels of the electronic HPD measured at the tympanic membrane and in a 2cc coupler using a 2000 Hz stimulus presented at various input signal levels. Results of coupler testing revealed that the input signal levels of 80 dB SPL yielded output levels of 89.5 dB SPL while input signals of 90 dB SPL yielded output levels of 90.5 dB SPL (Figure 4). These results suggested that the electronic HPD would effectively limit output sound pressure levels for high intensity input signals such as 80 dB SPL and 90 dB SPL. However, the absolute SPL output in a real ear has been shown to be approximately 5 dB greater than that measured in a 2cc coupler for a 2000 Hz signal (Hawkins, Cooper, & Thompson, 1990). Consequently, output levels for the 80 dB SPL and 90 dB SPL input signals could be greater during in situ testing as compared to coupler testing. Further analysis of Figure 4 reveals that input levels of 80 dB SPL yielded a mean output level of 92 dB SPL at the tympanic membrane while input signals of 90 dB SPL yielded output levels of 94 dB SPL at the tympanic membrane. These results suggest that differences between the real ear and the coupler may have resulted in increased in-situ sound pressure levels thereby decreasing the attenuative properties of the electronic HPD.

Differences associated between the real ear and the coupler may have also impacted the effective compression ratio of the electronic HPD. For example, varying the input signal level from 70 dB SPL to 90 dB SPL resulted in a 2 dB increase in sound pressure level in the coupler and in a 4 dB increase in sound pressure level at the tympanic membrane at 2000 Hz (Figure 4). As a result, the compression ratio of the electronic HPD decreased from 10:1 when measured in a 2 cc coupler (20 dB change in input / 2 dB change in output) to 5:1 when measured at the tympanic membrane (20 dB change in input / 4 dB change in output). Therefore, each 10 dB increase in input above the compression threshold (65 dB SPL) resulted in a 1 dB increase in output in the coupler and in a 2 dB increase in output at the tympanic membrane. Consequently, coupler measurements may have over-estimated the impact of the compression limiting circuitry.

Experiment II: Communication in Noise

The present study evaluated communication ability in noise at two signal presentation levels when using acoustic and electronic HPDs. Results indicated that listener communication ability was significantly better with the acoustic HPDs than with the
electronic HPDs. However, varying the signal presentation level did not result in a significant change in communication ability with either HPD.

The decreased communication ability in noise exhibited when using the electronic HPDs may be attributed to the output compression circuitry utilized in the device. As previously mentioned, measurements of the HINT background noise were made at the plane of the tympanic membrane for each condition. The HINT background noise, which was spectrally matched to the long-term average of the speech spectrum of the sentence stimuli (Nilsson et al., 1994), should reflect the spectra of the sentences in each condition. Analysis of mean spectral responses revealed more low frequency energy (10 to 15 dB) with the electronic HPDs than the acoustic HPDs (Figure 5). Consequently, the potential for the upward spread of energy along the basilar membrane was greater when utilizing the electronic HPD than when utilizing the acoustic HPD. The increased spread of energy towards the basal end of the basilar mem-

brane could have produced greater masking of the higher frequency speech cues necessary for intelligibility; thereby resulting in poorer performance with the electronic HPD. Thus, it is possible that performance with the electronic HPD may have been improved had multi-channel architecture been employed or had a signal processing strategy been utilized that restricted low-frequency amplification at increased input levels (i.e. BILL processing).

Distortion present in the output signal may have also contributed to the decreased communication ability in noise exhibited when using the electronic HPD. The non-linearity of the electronic HPDs could have resulted in the creation of harmonic and intermodulation distortion. Output compression systems are designed to produce less harmonic and intermodulation distortion than systems utilizing peak clipping. However, some degree of harmonic and intermodulation distortion remains inevitable in instruments utilizing output compression. Thus, distortion could have been present in the output signal of the electronic HPD that would not have been present when utilizing the acoustic HPD. Therefore, it is possible that the existence of harmonic and intermodulation distortion in the output signal of the electronic HPDs may have further contributed to differences in communication ability in noise between the devices.

Results of the present study also indicated that decreasing the signal presentation level did not negatively impact communication ability in noise when utilizing either HPD. This finding was expected for the electronic HPD given the level-dependent nature of the device. However, the results obtained with the acoustic HPDs were not in agreement with previous research. Previous studies indicate that providing static attenuation to lower level signals may result in decreased communication ability in quiet (Davis & Silverman, 1960) and in noise (Mosko & Fletcher, 1971).

It is possible that the similar communication performances exhibited at each level were in part attributed to the amount of attenuation provided by the acoustic HPD. In the present study, input levels of 75 dB SPL were attenuated by 10 dB with acoustic HPDs, thereby resulting in an in-situ level of approximately 65 dB SPL. In previous studies, input levels of 70 dB SPL were attenuated...
ated by 25 dB with acoustic HPDs, thereby resulting in an in-situ level of approximately 45 dB SPL. However, normal hearing listeners do not have decreased communication ability until signal presentation levels approximate 50 to 55 dB SPL (Davis & Silverman, 1960). Therefore, it is possible that communication ability was not negatively affected by level in the present study because in-situ levels were sufficient for accurate identification. Similarly, communication ability was affected by level in previous studies because in-situ levels were not sufficient for accurate identification. Given this, it is reasonable to postulate that the static attenuation provided by the acoustic HPD was not sufficient to negatively impact communication at the reduced input signal levels utilized in the present study. However, it is possible that communication ability may have been negatively affected had the amount of static attenuation provided by the acoustic HPD been increased or had the presentation level of the signal been further reduced.

Another possible explanation for the similar communication performances exhibited at each level could be the relatively flat attenuation response provided by the acoustic HPDs. The acoustic HPDs utilized in the current study provided relatively flat attenuation as a function of frequency and are commonly utilized by persons desiring good sound quality such as concert-goers and musicians. Performance differences may have been more evident at reduced presentation levels had the acoustic HPDs provided a more typical attenuation pattern. For example, acoustic HPDs such as earmuffs, foam earplugs, and custom earplugs provide significantly greater attenuation in the high frequency region than in the low frequency region (Berger, 1983). As a result, the audibility of high frequency speech cues necessary for intelligibility is reduced thereby resulting in degraded communication ability. Therefore, it is possible that the relatively flat attenuation response provided by the acoustic HPDs in the present study may have further contributed to the acoustic HPDs resistance to variations in signal presentation level.

CONCLUSIONS AND CLINICAL IMPLICATIONS

Results of the present study indicated that the acoustic HPDs were more effective attenuators than the electronic HPDs for input signals at or below 90 dB SPL. In addition, the electronic HPD failed to attenuate any input signal utilized in the present study. As a result, in-situ levels approached or exceeded damage criteria for effective hearing conservation when utilizing the electronic HPD. Results of behavioral testing indicated varying the signal presentation level from 90 dB SPL to 75 dB SPL did not significantly affect communication ability in noise when using either HPD, however, communication in noise was significantly better when using the acoustic HPD than when using the electronic HPD.

Successful communication in noise with acoustic HPDs may be dependent on the amount of signal variation and on the amount and spectra of the attenuation provided. Conversely, successful communication in noise with electronic HPDs appears to be resistant to the effects of signal level variation at least for signals at or below 90 dB SPL. These findings suggest that listeners exposed to varying levels of noise and speech, such as concert-goers, bartenders, waiters/waitresses, athletes and fans in noisy stadiums, may preserve their communication ability by using either an acoustic or electronic HPD. However, listeners utilizing electronic HPDs may be at risk for TTS or PTS. Therefore, although results of behavioral testing indicated that communication ability in noise was not significantly impacted by varying the signal presentation level when utilizing either HPD, a more salient finding may be that the utilization of electronic HPDs may place listeners at risk for temporary or permanent sensorineural hearing loss.

Future research should further investigate the efficacy of electronic HPDs. Specifically, attenuation and communication ability with electronic HPDs should be evaluated at various gain settings. In addition, studies should attempt to determine if the utilization of different circuitry options with adjustable compression characteristics result in improved attenuation and communication ability. If so, hearing aid users who also need effective hearing conservation may opt to purchase multiple memory hearing aids with
one memory being dedicated to serving as an electronic HPD.

Lastly, appropriate fit and function of any HPD should be verified before distributing the devices to the client. Results of the present study revealed a relatively large standard deviation (4 dB) for the mean attenuative properties of the acoustic HPDs, thereby suggesting that the attenuation levels varied from 6 dB to 15 dB. Inappropriate fit and function of the acoustic HPDs could result in insufficient attenuation to the end user and could be detrimental to the client’s hearing and/or communication ability. Appropriate fit and function of electronic HPDs is necessary for proper hearing protection as well. Electronic HPDs function similar to hearing aids, therefore, excessive gain or acoustic leaks due to improper fit of the electronic HPD could cause a TTS or PTS (Macrae, 1994). Thus, both acoustic and electronic HPDs should be verified for appropriate fit and function before distribution.

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REFERENCES


