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Evaluation of Hearing Protector Fit Test Systems

William A. Ahroon & JR Stefanson

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14. ABSTRACT

The objective of this project was to conduct an evaluation of five Hearing Protection Device (HPD) Field Attenuation Estimation Systems (FAES) and measure the improvement in device attenuation following training in the proper use of hearing protection devices. Soldiers, civilians, and contractors enrolled in the Army Hearing Program at five U.S. Army installations each exhibiting a Significant Threshold Shift during annual audiometric monitoring comprised a convenience sample for a repeated-measures design. Personal Attenuation Ratings (PARs) were collected before and after earplug retraining. PARs were measured using five different HPD FAES: the NIOSH HPD Well-Fit™, the Michael & Associates FitCheck™, the Howard Leight VeriPRO®, the 3M™ E-A-Rfit™ and the Workplace Integra INTEGRAfit®. Retraining how to fit the hearing protection improved PARs measured by each HPD FAES. HPD FAES provide a valuable tool to assess the hearing protection provided to individual Soldiers during annual audiometric examinations, especially when retraining on fitting the HPD is advised.

15. SUBJECT TERMS

hearing protection, earplugs, fit testing, field attenuation estimation system

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14. Abstract (continued)
The HPD FAES could be useful at the unit level in the unit's Hearing Conservation Office for group or individual instruction.

Summary

The objective of this project was to conduct a “round-robin” evaluation of five Hearing Protection Device (HPD) Field Attenuation Estimation Systems (FAES) and measure the improvement in device attenuation following training on their use. Soldiers, civilians, and contractors enrolled in the Army Hearing Program at five U.S. Army installations each exhibiting a Significant Threshold Shift (STS) during annual audiometric monitoring comprised a convenience sample for a repeated-measures design. Personal Attenuation Ratings (PARs) were collected before and after re-training. PARs were measured using five different HPD FAES: the NIOSH HPD Well-Fit™, the Michael & Associates FitCheck™, the Howard Leight VeriPRO®, the 3M™ E-A-Rfit™, and the Workplace Integra INTEGRAfit®. Re-training how to fit the hearing protection devices improved PARs measured by each HPD FAES. HPD FAES provide a valuable tool to assess the hearing protection provided to individual Soldiers during annual audiometric examinations, especially when re-training on fitting the HPD is advised. The HPD FAES could be useful at the unit level in the unit’s Hearing Conservation Office for group or individual instruction. The cost of these systems does not exceed the “micro-purchase threshold” and therefore can be purchased using the unit’s Government Commercial Purchase Card (Federal Acquisition Regulation [FAR] 13.301).

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Introduction

Noise-induced hearing injuries (NIHIs) are endemic among U.S. Soldiers. Noise-induced hearing loss (NIHL) and tinnitus (ringing in the ear) are the two most prevalent injuries suffered as a result of deployment in support of Operation Iraqi Freedom and Operation Enduring Freedom in Iraq and Afghanistan, respectively. According to the 2018 Veterans Benefits Administration (VA) Annual Report, hearing loss and tinnitus are the most prevalent service-connected disabilities for all Veterans, with over 3.2 million veterans receiving compensation for service-connected auditory system injuries (Veterans Benefits Administration, 2015). Theodoroff et al. (2015) report that hearing loss and tinnitus are the most prevalent injuries among veterans from Operation Iraqi Freedom, Operation Enduring Freedom, and New Dawn. Ahroon et al. (2011) reviewed data extracted from the Defense Occupational and Environmental Health Readiness System - Hearing Conservation (DOEHRS-HC) database over a 10-year period from 1998 to 2007. They report that more than 5% of Soldiers in 32 military operational specialties have suffered NIHIs and therefore, the Army has not met its requirement of protecting 95% of all Soldiers.

While the results of this database analysis suggested that Soldiers who are regularly exposed to impulses have more hearing loss than Soldiers without regular exposure, even those in jobs without regular exposure (e.g., mechanics and vehicle crewmen) show unacceptable rates of hearing loss. NIHIs not only cost the military and VA billions of dollars a year (Veterans Benefits Administration, 2015) but also reduce the quality of life for many military and veteran populations.

The best defense against hazardous industrial noise is engineering controls (i.e., reducing or eliminating noise levels at the source). However, quiet battlefields generally do not exist, nor does the capability to reduce noise to safe levels within most modern weapon systems, aircraft, and ships. Therefore, many Soldiers, Airmen, Sailors, and Marines are routinely exposed to extreme noise produced by the nature of their military environments. Mitigation of these loud noises is imperative to preventing damage to the auditory system and ultimately to the success of a given mission. HPDs are usually considered the last line of defense against hazardous noise and are often necessary for modern industrial and military hearing conservation programs. However, if hearing protection is not worn correctly, their performance can be compromised and protection from noise may be negated entirely. The acoustic seal of an HPD with the ear canal (for earplugs) and the head (for earmuffs and helmets) is critical to achieve and maintain for maximum air-conduction attenuation; even the smallest "leak" will reduce the steady-state noise protection provided by an HPD.

To assess performance (i.e., attenuation) of HPDs, the best-practice method used by industry is real-ear-attenuation at threshold (REAT) testing that is conducted in laboratories that follow the American National Standards Institute's (ANSI) and Acoustical Society of America's (ASA) procedures described in ANSI/ASA S12.6-2016 (Acoustical Society of America, 2016). The Noise Reduction Rating (NRR) of a hearing protector is computed in accordance with the Code of Federal Regulation 40 CFR § 211.207. The current Environmental Protection Agency (EPA) rule requires an old version of this standard, ANSI S.3.19-1974 (American National Standards Institute, 1974) to be used for calculating the Noise Reduction Rating (NRR), which is a single number that theoretically reflects the attenuation capabilities of the HPD. The EPA mandates the NRR be listed on HPD packages sold by manufacturers (U.S. Environmental Protection Agency, 1978). A common misconception by consumers is that a higher NRR is equivalent to more protection, which is not necessarily true in real-world environments (Berger, 1993). Several reasons can be attributed to the laboratory NRR being far above the average user's actual attenuation achieved during field conditions. The inherent equation to calculate an NRR is population based and measures the performance of the HPD when used by a group of highly trained and motivated users tested in a laboratory setting. Therefore, the NRR is not a reliable real-world prediction of attenuation afforded to an individual and further, may be a substantial overestimate and perilous when used to assess an individual's daily noise exposure (Berger, 1993). As such, NRR de-rating schemes have been developed by the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) in attempts to more accurately predict or estimate HPD attenuation during field conditions (Franks et al., 2003; Kroes et al., 1975; Occupational Safety and Health Administration, 2013; U.S. Department of Health Human Services, 1998). However, the various NRR de-rating schemes are still simply blind guesses at an individual's protection level and are completely meaningless (Franks et al., 2000).

The only sure way to know how much protection a person receives from a given HPD is to "fit-test" that individual. Fit-testing individuals also affords the ability to tailor the hearing protection to the individual's occupational environment. Many Warfighters need to be equipped with HPDs that can attenuate high levels of noise (e.g., during weapons training and aboard aircraft, ships), while others may only need to reduce levels slightly (e.g., continuous noise levels just above 85 A-weighted decibels [dBA]. While both require the use of HPDs, and in fact are mandated per Army Regulation (AR) 40-501 Standards of Medical Fitness, it is necessary to equip a Soldier with the correct hearing protection to attain maximum protection in the former case and low-level protection in the latter case. While low-level noise exposures are rarely associated with immediate NIHIs, the long-term effects can be latent and dramatic after prolonged subjugation to the noise exposure. The effects of overprotection can also be serious and lead to missed safety alarms, unnoticed equipment malfunctions, and reduced communication ability. These effects may cause the wearer to become frustrated and stop using the HPD altogether thereby increasing exposure to potentially hazardous noise and future injuries. Therefore, an individual's occupational noise environment should be considered during HPD selection, and fit-testing can be a valuable tool to assist with the HPD selection.

The purpose of the current project was to evaluate four commercially available fit-test systems and one from a government agency. The various systems were sent to Army audiology clinics around the country to be used for a period of 2 months. After this time, the systems were rotated in a round-robin style so that each system was evaluated by each clinic involved. The systems were employed as an adjunct to the clinics' normal hearing conservation programs during hearing protection training and re-training procedures.

Background

The first hearing protector fit-testing system was developed under a contract with the National Institute for Occupational Safety and Health (Michael et al., 1975). Michael et al. (1975) developed a fit-test system for evaluating the "on-the-job" performance of inset-type hearing protection (i.e., earplugs). The goal was to develop a circumaural earphone system that would provide the necessary noise isolation normally required by a sound-attenuating, diffuse-field chamber in accordance with the current ANSI standard test method (ANSI S3.19-1974) (American National Standards Institute, 1974). After three commercially available headphones were evaluated and rejected, a circumaural HPD was selected and modified for use. The modifications involved fitting the HPD with earphone drivers and validating the performance of the system for sound attenuation, frequency response, and maximum sound pressure level. Following the fabrication and validation of the “field-method headphones,” a standard array of 1975 era laboratory equipment was collected for ANSI S3.19 and “field-method” testing. Using 20 experienced listeners, five earplugs were evaluated with both methods, using two unoccluded and two occluded measurements across the third-octave band center frequency test signals. A modified Békésy procedure was used. The results indicated high correlations of the unoccluded and occluded thresholds between the diffuse-field and headphone-field methods.

Studies evaluating the effectiveness of HPDs in field studies after the Michael et al. (1975) report chiefly used United States or international standard test methods (e.g., ANSI S3.19, ANSI S12.6, ISO 4869-1) or variations of the same. Within the last few decades, however, specialized HPD fit-test systems have been developed by a number of commercial entities.

In the mid-2000s, a number of reports were published describing requirements for individual fit-testing (Behar & Wong, 2010; Berger, 2007; Hager, 2007; Stephenson et al., 2011; Witt, 2007a, 2007b). Individual fit-testing HPDs has been conducted for more than a decade and is considered a best practice for hearing conservation programs promoted by industry leaders such as NIOSH and the National Hearing Conservation Association (OSHA/NHCA/NIOSH Alliance, 2008). Several commercial vendors have developed various types of HPD field attenuation estimation systems (FAESs) designed to be used in real-world environments.

There have been several reports on the use of HPD FAES. Hager (2011) described the technologies associated with seven HPD FAES technologies, including four of the five used in the present evaluation. (Those not tested in this evaluation were: QuickFit, a web-based tool by NIOSH [https://www.cdc.gov/niosh/mining/content/quickfitweb.html], the Phonak Communications SafetyMeter, a HPD FAES for Phonak custom-molded earpieces, and using a standard audiometer, which might be problematic since the space under the audiometer headphones may not be sufficient for earplugs that normally protrude from the entrance of the ear canal. This is especially important if the earplug is insufficiently inserted.) Hager (2011) also noted that there is no standardized formula to calculate personal attenuation ratings (PAR). Schulz (2011) presents the PAR calculation methods for the 3M™ E-A-Rfit™, the VeriPRO®, and FitCheck™.

Brueck (2012) compared two HPD FAE systems: the objective 3M™ E-A-Rfit™ and the subjective VeriPRO®. The measurements of the objective system produced octave-band results with “lower mean attenuation results than the manufacturer’s data and generally a wider standard deviation, which is consistent with the expected real world performance” (p. 8). However, the compressible-foam earplug results showed higher than expected attenuation than the push-in type earplugs “when tested with the objective system” (p. 8) and suggested that the probe of the test earplugs may have aided the test subject in the insertion of the compressible-foam earplugs. Discussing the results from the subjective (VeriPRO®) system, this author notes that (1) the “system is relatively imprecise” (p. 17) and that (possibly related) “the subject required a degree of skill and concentration to perform the loudness balance" (p. 14). However, it was reported that the "attenuation results appear comparable to the expected real world performance of the earplugs" (p. 17).

Trompette et al. (2015) compared four HPD fit-test systems, 3M™ E-A-Rfit™, Howard Leight's VeriPRO®, and Cotral's CAPA© (a pure-tone audiometer-based procedure), and compared the results with those obtained using the REAT method approved by ISO 4869-1 (International Organization for Standardization, 1990). They note that the 3M™ E-A-Rfit™ and Contral CAPA© results agree with the REAT measurements. However, the results from the VeriPRO® measurements did not agree with the benchmark REAT measurements and suggest, "Some of the test subjects were incapable of properly using this system" (p. 93).

Murphy et al. (2016) evaluated HPD fit on 126 off-shore oil-rig inspectors and engineers during their annual hearing conservation training. Using the NIOSH HPD Well-Fit™ HPD FAES, Murphy et al. found that, before FAES training, less than 50% of the workers achieved the company target of 25 dB of protection (measured by the HPD FAES). Following refitting and re-training in the use of earplugs, approximately 85% achieved a PAR of at least 25 dB. Byrne et al. (2017), in a four-laboratory study, compared three HPD FAES; the NIOSH HPD Well-Fit™, the Michael & Associates FitCheck™, and the Howard Leight VeriPRO®. REAT measurements also were made in accordance with ANSI/ASA S12.6-2008 (Acoustical Society of America, 2008) and compared with the fit-test results. The results of the study found the A-weighted attenuation calculated by two of the FAES, HPD Well-Fit™ and FitCheck™, to be within approximately ±2 dB agreement with the laboratory REAT method (i.e., ANSI S12.6-2008), and that VeriPRO® generally underestimated the A-weighted attenuation compared to the laboratory method.

Methods

The goal of this study was for uniformed Army audiologists to use, within the context of the Army Hearing Program, various HPD FAES and provide information on the use and performance of the systems and changes in hearing protector performance following HPD fit re-training if indicated by initial fit-test results.

The Army Hearing Program (Department of the Army, 2015) includes annual monitoring audiometry for all Soldiers. If a significant threshold shift (STS) is detected during the annual visit, the Soldier is counseled on hearing conservation including reinstruction on the proper use of hearing protection, and another audiogram is collected after 14 hours in (relative) quiet. If the STS is still present at this retest, a final audiometric examination is conducted by a certified audiologist who reestablishes the Soldier's baseline audiogram if the STS persists (see Figure 1). The subjects in this study consisted of Soldiers, civilians, or contractors who showed an STS on the retest from their annual audiometric screening visit and the HPD FAES was used during the counselling and fit/refit of hearing protection. (Normally, a second retest would be conducted by a certified audiologist and, if an STS was still present, the Soldier's baseline audiogram would be reestablished in accordance with the Army Hearing Program.)

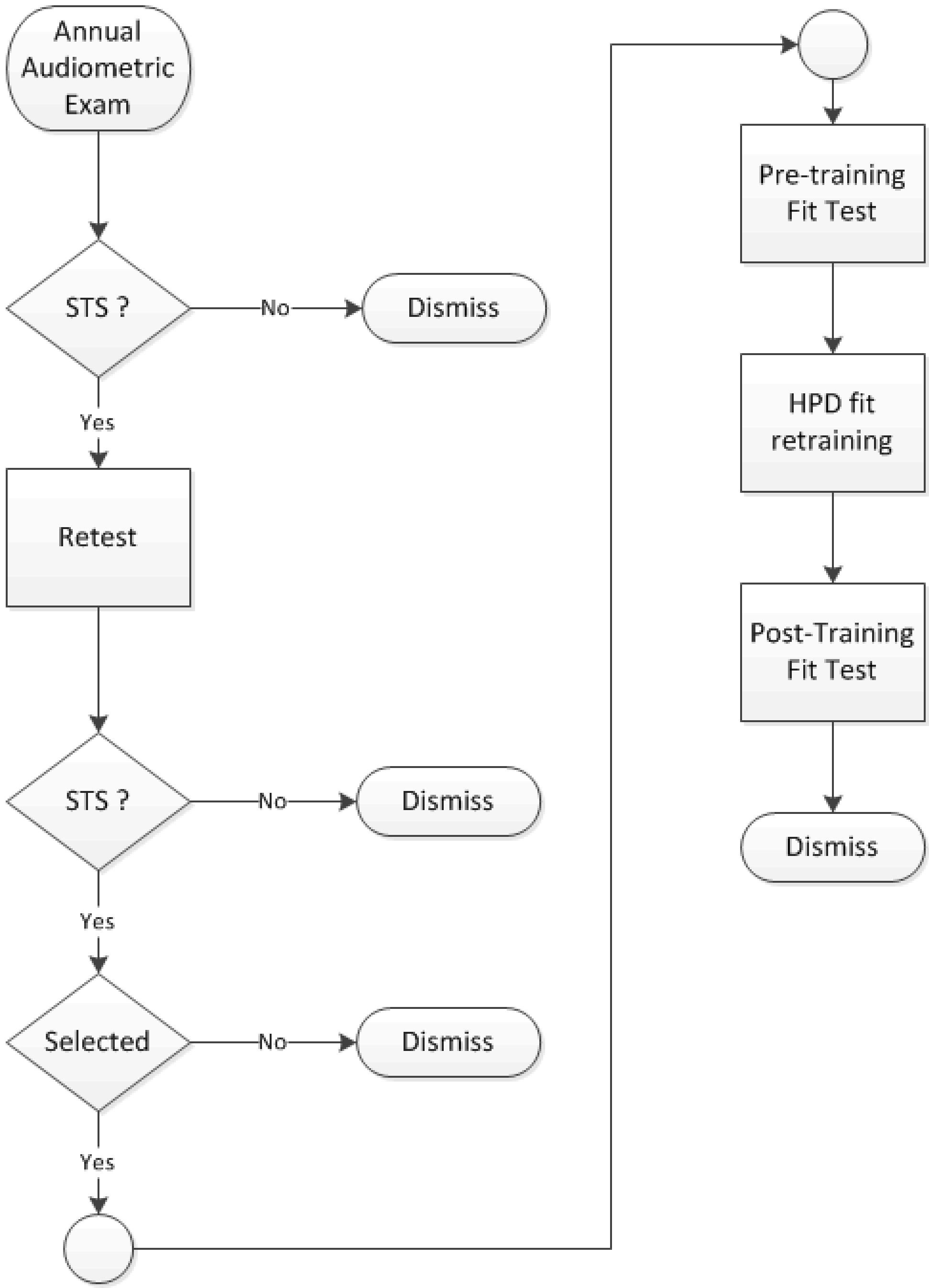

Figure 1. Flowchart of the process followed for each participant.

Participants

U.S. Army Soldiers at any unit or tenant activity at Fort Bliss, Fort Bragg, Fort Campbell, Fort Hood, or Fort Polk were eligible subjects for this study, as were any civilians or contractors enrolled in a hearing conservation program at any of these posts during the duration of the test activity. This study was approved by the U.S. Army Aeromedical Research Laboratory Determination Official, which determined that this activity did not constitute research as defined under the human subjects protection regulations.

Equipment

Five HPD FAE systems were incorporated into the Army Hearing Program, one at each of the five Army installations and employed during hearing protector re-training procedures. Training was not standardized but consisted of normal routine procedures administered by the audiologist or an experienced Council for Accreditation in Occupational Hearing Conservation (CAOHC) accredited hearing technician. Each system was deployed for approximately two months and rotated in a “round-robin” style exchange so that each of the five clinics involved had a chance to evaluate each system. A Dell Latitude E6510 laptop computer and laser printer were distributed to control and print reports for each HPD FAES. The laptops and printer did not rotate with the HPD FAES system. The software for each system was preloaded and tested for correct operation before being distributed. The schedule is presented in Table 1.

Table 1. Schedule of HPD FAES Evaluations

HPD FAES	Period 1	Period 2	Period 3	Period 4	Period 5
E-A-Rift™	Fort Hood	Fort Bragg	Fort Bliss	Fort Polk	Fort Campbell
FitCheck™	Fort Campbell	Fort Hood	Fort Bragg	Fort Bliss	Fort Polk
HPD Well-Fit™	Fort Polk	Fort Campbell	Fort Hood	Fort Bragg	Fort Bliss
INTEGRAfit®	Fort Bliss	Fort Polk	Fort Campbell	Fort Hood	Fort Bragg
VeriPRO®	Fort Bragg	Fort Bliss	Fort Polk	Fort Campbell	Fort Hood

Each FAES calculates a PAR that is used as the measured performance of the HPD. The PAR is a single number that reflects the amount of attenuation a user receives from a given HPD at that moment in time. However, each FAES calculates PAR based on unique formulae; therefore, PAR values from different FAES may not be directly comparable.

E-A-Rfit™ (3M Corporation).

The 3M™ E-A-Rfit™ HPD FAES (Figure 2) uses a Field-Microphone in Real Ear (F-MIRE) procedure in which a dual-element microphone samples noise external to the ear and inside a specially designed probed earplug surrogate (Figure 3). The E-A-Rfit™ software compensates for the difference between the probed earplug surrogate and the standard earplug based on laboratory ANSI/ASA S12.6-2008 (Acoustical Society of America, 2008) measurements.

The individual participating in the FAES F-MIRE evaluation is seated approximately 16 inches in front of a speaker (Figure 3). During the F-MIRE evaluation, a broadband noise is presented through the speaker at 85 dBA for approximately 8 seconds and the noise from both microphones is sampled. The samples are then analyzed into seven octave bands (0.125 to 8.0 kilohertz [kHz]), and the differences between the octave-band levels are the insertion losses of the earplug. The insertion losses from 0.125 to 4.0 kHz are used to compute the PAR. The current configuration of the E-A-Rfit™ is a dual-ear system that simultaneously collects F-MIRE data from both ears. Further information on the 3M™ E-A-Rfit™ Validation System can be found at the 3M Hearing Conservation web site at http://www.e-a-rfit.com/.

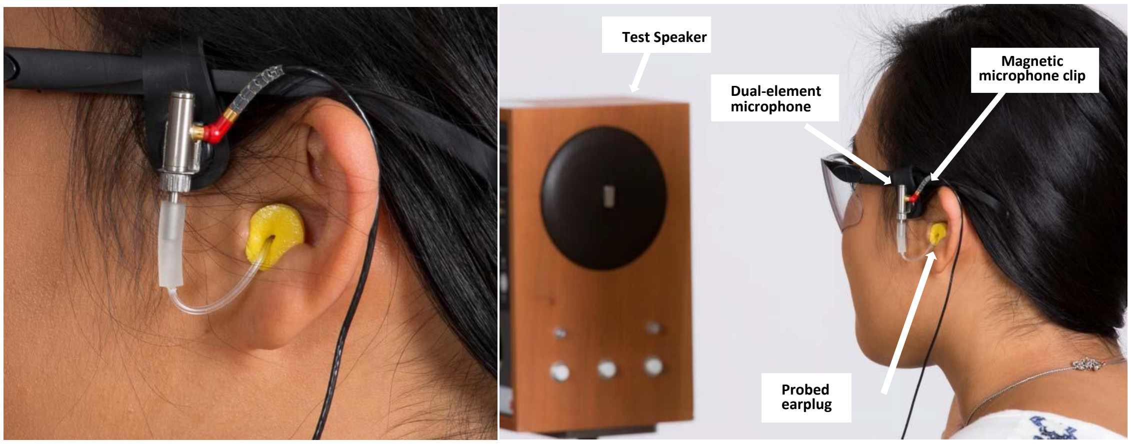

Figure 2. 3M™ E-A-RFit™ Dual-element microphone with probed premolded earplug (left), subject positioned in front of speaker for F-MIRE measurement (right).

Figure 3. E-A-Rfit™ control box with speaker (left), E-A-Rfit™ surrogate preformed (top right) and expandable foam (bottom right) earplugs.

FitCheck™ (Michael & Associates).

The FitCheck™ system (Figure 4) from Michael & Associates, Inc. was the first commercially available HPD FAES. It employs a modified Békésy psychophysical procedure. A 250 milliseconds (ms) tone burst is presented (50% on/off duty cycle) through custom noise-isolation earphones. The subject is asked to press a hand-held response button when the tones are heard and release the button when he/she does not hear the tones. After four reversals (two peaks and valleys), the threshold is computed as the mean of the four up and down traces. When the reversals met the standard of no valley above a peak and the range of the peaks and valleys less than 20 dB, the frequency of the tone was advanced to the next frequency. From thresholds determined during unoccluded (open, no earplugs) and occluded (closed, earplugs in) runs, the subject's PAR was computed. During this test plan, measurements and PAR calculations were made binaurally at test frequencies of 0.5, 1.0, and 2.0 kHz.

The equipment used by the FitCheck™ FAES consists of a Dell Latitude laptop computer with appropriate software, custom noise-isolation headphones, subject response switch, custom attenuation control box with power supply and appropriate digital control and analog stimulus cables. Additional information is at http://michaelassociates.com/products/fitcheck-for-insert-type-hearing-protectors/.

Figure 4. Fitcheck™ control box with circumaural noise-isolation headphones.

HPD Well-Fit™ (National Institute for Occupational Safety and Health).

The NIOSH HPD Well-Fit™ FAES (Figure 5) can use several different psychophysical procedures. A method of adjustment procedure was used in this study. With this procedure, a third-octave noise burst is presented, initially at a clearly audible level. The subject uses the scroll wheel on the computer mouse to adjust the noise bursts until they are "just barely audible" and then presses the left mouse button. The intensity of the signal is then increased by a random amount between 10 and 20 dB and the subject again performs the adjustment. After three threshold determinations within a range of 6 dB, the arithmetic average of the three determinations is computed. During this study, measurements were made binaurally at test frequencies of 0.5, 1.0, and 2.0 kHz, first measuring unoccluded thresholds followed by occluded thresholds. The difference between the average occluded and unoccluded thresholds is the noise protection of the hearing protection devices from which the PAR is computed.

The equipment used by the NIOSH HPD Well-Fit™ FAES consists of a Dell Latitude laptop computer with appropriate software, custom noise-isolation headphones, and a computer mouse with scroll wheel. The headphones used by the HPD Well-Fit™ FAES were obtained from Michael & Associates and were identical to those used by the FitCheck™ FAES. The HPD Well-Fit™ software has been licensed to Michael & Associates, Inc. and is now commercially available as FitCheck Solo™ (http://michaelassociates.com/products/fitcheck-solo-tm/).

Figure 5. HPD Well-Fit™.

INTEGRAfit® (Workplace Integra).

The INTEGRAfit® FAES (Figure 6) also uses a modified Békésy psychophysical procedure. Open and occluded thresholds are measured at only a 500 Hz pure-tone test signal. Unlike the FitCheck™ system which presents the tone bursts continuously, the INTEGRAfit® FAES presents three 500 Hz tone bursts and the subject is expected to press the response button if the tone bursts are heard. Following a response by the subject (i.e., pressing the response button), the level of the tone bursts is decreased (in 2 dB increments) until the subject fails to respond. During some intermediate (i.e., catch) trials, no signal was presented. When the subject fails to respond, the software increased the level of the signal by 2 dB. After three reversals, the threshold of the 500 Hz signal was calculated. The difference between the occluded and unoccluded thresholds allows the computation of the subject's PAR. It should be noted that, although a test at 500 Hz is a good indicator of a hearing protector seal leak, it likely is a poor choice from which to identify PAR. The INTEGRAfit® was the only single-frequency HPD FAES evaluated.

The equipment used by the INTEGRAfit® FAES consists of a Dell Latitude laptop computer with appropriate software, custom noise-isolation headphones, subject response switch, custom attenuation control box with power supply and appropriate digital control and analog stimulus cables. INTEGRAfit® is currently compatible with iOS for use on an Apple iPad.

Figure 6. INTEGRAfit® control box and circumaural noise-isolation headphones.

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VeriPRO® (Howard Leight by Honeywell).

Unlike the other three FAES that used a psychophysical procedure that estimated thresholds, the VeriPRO® (Figure 7) used a loudness balancing procedure in which the subject was asked to adjust the loudness of a pulsing tone in one ear to be the same loudness as the same stimulus presented in the other ear. In this procedure, the loudness balance procedure was conducted above threshold at approximately 60 dBA (unoccluded) or at 100 dBA when occluded. First, the subject was asked to perform the loudness balance with no earplugs in either ear. Next, the subject was instructed to insert an earplug into the right ear and perform the loudness balance task again. Finally, the subject inserted an earplug into his/her left ear and repeated the loudness balance procedure for a third time. From these three measurements using pure tone stimuli at 0.250, 0.5, 1.0, 2.0, and 4.0 kHz, the PAR was calculated.

The equipment used by the VeriPRO® FAES consisted of a Dell Latitude laptop computer with appropriate software, custom noise-isolation headphones, and custom USB-controlled audio processor. The manufacturer’s information on the VeriPRO® may be found at the web site https://www.howardleight.com/veripro.

Figure 7. VeriPRO® control box and circumaural noise-isolation headphones.

Results

The five HPD FAES were relatively new tools for the audiologists and hearing technicians at each of the hearing conservation sites involved. Each FAES had unique features and characteristics, of which the users had to become accustomed. The use of each system was not standardized because they were inserted into actual hearing conservation programs and used as needed for HPD training. For that reason, various subjects were tested on a before and after HPD training basis depending on clinic time available and the need to do so. In addition, the number of subjects tested varied with each system, again because the study was not standardized since it was dependent on available clinic time and the need for HPD re-training. Figure 8 displays the mean PARs before and after HPD fit re-training for each of the HPD FAES. Each of the subjects exhibited a significant threshold shift during annual audiometric testing. Table 2 presents this information in tabular form.

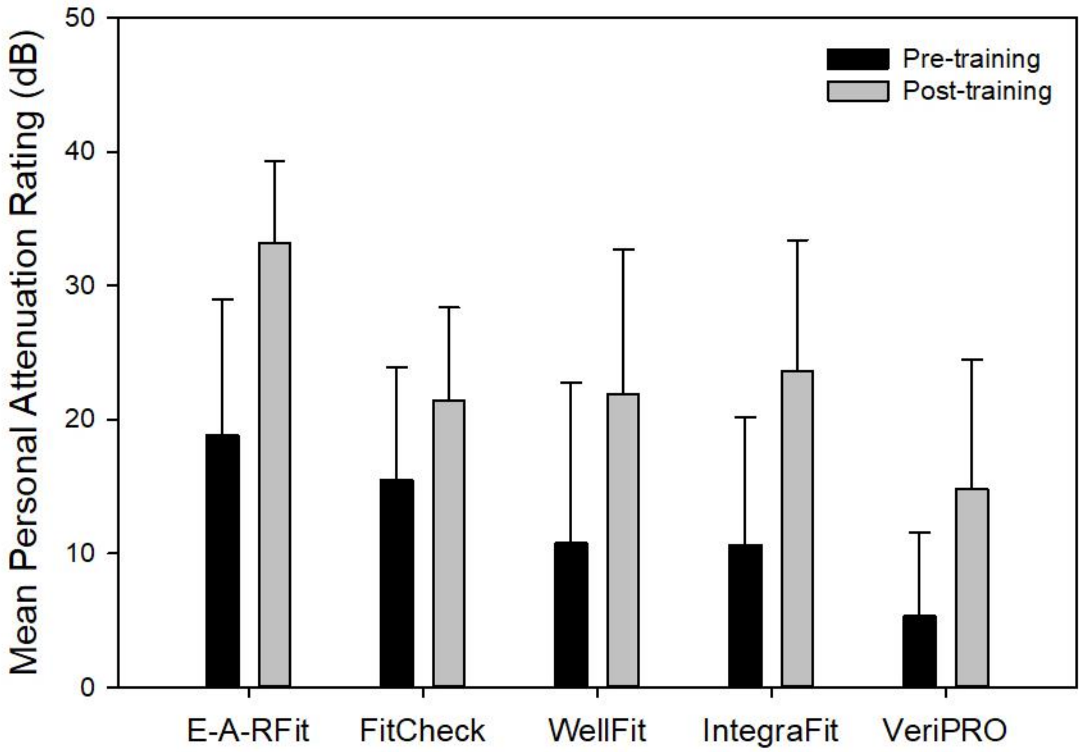

Figure 8. Mean Personal Attenuation Ratings before and after training for each of the Hearing Protection Device Field Attenuation Estimation Systems.

Pre-training PARs ranged from 5.3 dB (VeriPRO®) to 18.8 dB (E-A-Rfit™). Post-training PARs using these systems were 14.8 and 33.2 dB, respectively. The greatest percent improvement from pre- to post-training was for subjects using the VeriPRO® (179% or 9.5 dB), which may be due to the low pre-training PAR (5.3 dB). As noted above, the greatest PAR improvement was for the E-A-Rfit™ (14.4 dB, 77%). The least improvement was observed in subjects using the FitCheck™ system (38% or 5.9 dB).

The results of Student t-tests for repeated measures (i.e., dependent samples) also are listed in Table 2. As noted above, these subjects were selected because their annual audiometric examinations showed an STS following their retest. For those subjects who were selected for HPD fit-testing before and after training on the proper fit of HPDs, all HPD FAE Systems resulted in improved PAR means. Fifteen (15) of the 119 subjects showed poor PARs following re-training and 23 showed less than 5 dB PAR improvement. Table 3 presents the distribution of PAR ratings across the units and HPD FAE systems. Thus, nearly one-third of the subjects receiving earplug-fit re-training did not appreciably improve their PAR scores.

As mentioned above, some individuals were not tested more than once based on either of two factors: 1) they did not require additional training due to high initial PAR values or 2) sufficient time was not available for retesting the individual. Table 4 presents the average PAR of individuals tested with each of the FAES without re-training (i.e., only individuals fit-tested one time).

Table 2. Average PAR Values Before and After HPD Rre-training with Each HPD FAES

HPD FAES	**Average PAR** Pre-Training	**Average PAR** Post-Training	**Average PAR Improvement**	**Average % PAR Improvement**	**Subjects (*n*)**	***t***	***p***
E-A-Rfit™	18.8	33.2	14.4	77%	11	3.63	0.005
FitCheck™	15.5	21.4	5.9	38%	19	3.37	0.003
HPD Well-Fit™	12.8	23.7	10.9	85%	19	4.54	0.000
INTEGRAfit®	11.2	23.7	12.5	112%	37	7.10	0.000
VeriPRO®	5.3	14.8	9.5	179%	33	4.80	0.000
Overall*	11.2	21.8	10.6	94%	119	10.65	0.000

* Weighted values

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Table 3. Summary of Individual Device and Unit PAR Results

Device	**Installation**	**PAR < 0 dB**	**0 dB ≤ PAR < 5 dB**	**PAR ≥ 5 dB**	***n***
E-A-Rfit™	1			1	1
E-A-Rfit™	2				
E-A-Rfit™	3			7	7
E-A-Rfit™	4	1	2		3
E-A-Rfit™	5				
Total		1	2	0	11

Device	**Installation**	**PAR < 0 dB**	**0 dB ≤ PAR < 5 dB**	**PAR ≥ 5 dB**	***n***
FitCheck™	1	1	1		2
FitCheck™	2	1		1	2
FitCheck™	3	1	3	4	8
FitCheck™	4	2	2	3	7
FitCheck™	5				
Total		5	6	8	19

Device	**Installation**	**PAR < 0 dB**	**0 dB ≤ PAR < 5 dB**	**PAR ≥ 5 dB**	***n***
INTEGRAfit®	1		1	7	8
INTEGRAfit®	2				
INTEGRAfit®	3		1	1	2
INTEGRAfit®	4	1	3	15	19
INTEGRAfit®	5	1	1	6	8
Total		2	6	29	37

Device	**Installation**	**PAR < 0 dB**	**0 dB ≤ PAR < 5 dB**	**PAR ≥ 5 dB**	***n***
HPD Well-Fit™	1				
HPD Well-Fit™	2				
HPD Well-Fit™	3	3	1	11	15
HPD Well-Fit™	4		1	2	3
HPD Well-Fit™	5	1			1
Total		4	2	13	19

Device	**Installation**	**PAR < 0 dB**	**0 dB ≤ PAR < 5 dB**	**PAR ≥ 5 dB**	***n***
VeriPRO®	1	1	1	14	16
VeriPRO®	2				
VeriPRO®	3		1	1	2
VeriPRO®	4	1	4	8	13
VeriPRO®	5	1	1		2
Total		3	7	23	33

Table 4. Average PAR Value With No HPD Rre-training with Each FAES

HPD FAES	PAR	Subjects
E-A-Rfit™	24.7	163
FitCheck™	25.1	91
HPD Well-Fit™	19.7	109
INTEGRAfit®	19.1	27
VeriPRO®	9.4	138
Overall Average	19.5	528

Subjective Results: Audiologist Feedback

Audiologists gave their comments, opinions, and also recorded some Service Members' comments while evaluating each FAES. Although each system has unique features, all the equipment helped subjects to understand what a proper fit feels like. One Service Member reported that "Soldiers want to have faith in their equipment and this system assists with that." He used the example of going through basic training and entering the gas chamber, "you think the gas isn't bad when you have the mask on, but you really don't realize how much you are being protected until you pull the mask off." During some of the Service Members' fittings, the audiologist noted a hearing protector appeared to be a poor fit but the system showed a good fit. The opposite was true also, visual appearance was a good fit, but the FAES measured poor attenuation, therefore demonstrating visual inspection of HPD fitting alone is not adequate for HPD performance evaluations. The HPD FAES may be used as a tool in the field to measure HPD performance in an objective and consistent method. With this tool, audiologists and hearing conservationists have the ability, for the first time, to test and select a hearing protector that is best suited for the individual and their particular environment (i.e., aviators, mechanics, tankers, etc.).

Discussion

The results of this evaluation suggest each of the HPD FAES is beneficial for HPD training procedures. The performance capability of a given HPD is identified by the FAES for an individual fit. However, the fit of the HPD may be different each time it is donned thereby affecting the performance depending on the fitting technique employed by the user. As a result, the attenuation provided by the HPD will vary between fits, but the FAES identifies a PAR which may be used as a good "estimate" of what a user is able to achieve with a given HPD. Each FAES may also be used as a tool to improve fitting techniques by providing objective measurements rather than relying on appearance alone. One audiologist commented on a particular user, "It appeared as though the user had a poor fit by visual inspection but the FAES measured a very good PAR." Alternatively, if a FAES was not available, the user would have been instructed to re-fit the HPD for a better fit which was not necessary due to the high PAR value initially achieved.

The Soldiers tested using each HPD FAES except the E-A-Rfit™ were able to use the earplugs that they were issued (or selected). However, the E-A-Rfit™ required the use of surrogate plugs (see Figure 3) and the subject selected the surrogate that was most similar to the issued/selected earplug. For example, if the subject normally wore the Howard Leight triple-flange SmartFit® earplug, he or she might select the 3M™ surrogate for the 3M™ UltraFit™ earplug, thus adding to the uncertainty of the PAR measurement. Four of the five HPD FAES used threshold measurement procedures during the occluded and unoccluded measurements and therefore required a relatively quiet space for testing. The Howard Leight VeriPRO® system, however, used a loudness balance procedure where the subject performed three loudness balance assessments, first with both ears unoccluded, second with the earplug in the right ear, and finally with both ears occluded. Like the 3M™ E-A-Rfit™ FAES , one advantage of the loudness balance procedure is that the sounds at 60 dBA (when unoccluded) and at 100 dBA (when occluded) do not require a space as quiet as those required for threshold measurements. The manufacturer claims that the VeriPRO® system can be used with background noises up to 73 dB SPL However, as noted above, Brueck (2012) indicated that the loudness balance task may be difficult for some subjects to perform, leading to imprecise results. Hager (2011) notes that individuals with hearing loss may have difficulty performing loudness balance, even though it is not a particularly difficult listening task, Indeed, many of the studies of the VeriPRO® have used trained listeners who are not a typical individual who might be tested annually while enrolled in a hearing conservation program. Trompette et al. (2015) reported that the VeriPRO® system requires more time and greater concentration than either the 3M™ E-A-Rfit™ or CAPA© (audiometer-based) systems, a general observation shared by Mitchem (2012).

The quickest assessments are conducted using the 3M™ E-A-Rfit™ F-MIRE system, which calls for no subject responses. The INTEGRAfit® system measures unoccluded and occluded thresholds at only 500 Hz and the VeriPRO® system can be configured to use loudness balance at only 500 Hz (i.e., “Quick Check”).

The NIOSH HPD Well-Fit™ HPD FAE system (now FitCheck Solo™) is the only FAES that does not require any external processors, interfaces, or response buttons. It uses only the laptop with a mouse with scroll wheel and a set of high-quality headphones. The 3M™ E-A-Rfit™, FitCheck™, INTEGRAfit®, and VeriPRO® all require a response button and/or an interface box.

Biases and Limitations

The limitations of this study result from its sample population, convenience samples at each participating Army post. The greatest limitation faced by all uniformed Army audiologists in clinics is time. Given their workloads as the head of the Army Hearing Program at their installation, there is limited time that can be dedicated to re-training on hearing protector fit. Their responsibilities include hearing readiness, clinical hearing services, operational hearing services, and hearing conservation.

Conclusion

HPD Fit-testing has become a "best practice" for hearing conservation programs (OSHA/NHCA/NIOSH Alliance, 2008) and several HPD FAES are commercially available. The purpose of this project was to evaluate five HPD fit-testing systems, E-A-Rfit™, FitCheck™, HPD Well-Fit™, INTEGRAfit®, and VeriPRO®. Each system was sent to Army audiology clinics to use as a tool in the HPD re-training process. After two months, the systems were rotated between the clinics until each system was evaluated by each clinic involved. The results of the evaluation suggest that HPD FAES are useful in hearing protection training procedures and add value to hearing conservation programs by enabling the hearing conservationist to assess and properly assign HPDs to individuals based on their 'fit-test' results.

The use of an HPD FAES during annual audiometric screening for individuals enrolled in a hearing conservation program could significantly improve the proper use and selection of HPDs to prevent hearing injuries. It would be appropriate, as a next step, to fully integrate HPD fit-testing into a selected post's monitoring audiology component of Army Hearing Program and determine the efficacy, timeliness, and HPD use improvement as a result of periodic fit-testing.

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Appendix A. Acronyms and Abbreviations

ANSI	American National Standards Institute
ASA	Acoustical Society of America
HPD	Hearing Protection Device
EPA	Environmental Protection Agency
FAES	Field Attenuation Estimation System
F-MIRE	Field-Microphone in Real Ear
NIHL	Noise-Induced Hearing Loss
NIHI	Noise-Induced Hearing Injury
NIOSH	National Institute for Occupational Safety and Health
PAR	Personal Attenuation Rating
SPL	Sound Pressure Level
STS	Significant Threshold Shift
USAARL	U.S. Army Aeromedical Research Laboratory

U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

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Army Futures Command
U.S. Army Medical Research and Development Command