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JASA ARTICLE

Personal attenuation ratings versus derated noise reduction ratings for hearing protection devices[a)]

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ABSTRACT:

National and international regulatory and consensus standards setting bodies have previously proposed derating hearing protector ratings to provide a better match between ratings determined in a laboratory and the real-world measurements of attenuation for workers. The National Institute for Occupational Safety and Health has proposed a derating scheme that depends upon the type of protector. This paper examines four real-world studies where personal attenuation ratings (PARs) were measured at least twice, before and after an intervention in earplug fitting techniques. Results from these studies indicate that individualized earplug fitting training dramatically improves a worker's achieved PAR value. Additionally, derating schemes fail to accurately predict the majority of achieved PARs. Because hearing protector fit testing systems are now readily available for use in the workplace, personal attenuation ratings provide a better estimate of worker noise exposures and are able to identify those persons who need additional instruction in fitting hearing protection devices. https://doi.org/10.1121/10.0013418

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I. INTRODUCTION

Hearing protection devices (HPDs) provide a wide range of noise reduction depending upon the design of the protector, the noise spectrum, and the quality of the fit that the user achieves. The performance of an HPD is described by a numerical rating calculated from the attenuation measured in a laboratory with human subjects in diffuse sound field conditions. The real-ear attenuation at threshold (REAT) is measured for several one-third octave band noises, typically 125 to 8000 Hz. National and international standard-setting bodies have developed different hearing protector ratings. In the United States, the Environmental Protection Agency (EPA) specifies that HPDs be measured using ten subjects, with three repeated fittings of the HPD according to the experimenter-fit protocol defined in ANSI S3.19-1974 (ANSI, 1974; EPA, 1979). The experimenter in the testing laboratory fits the HPD on a test subject's head or in the subject's ear canals. Hearing thresholds are measured for the occluded (ears covered) and unoccluded (ears open) condition and the differences at each frequency are used to estimate the Noise Reduction Rating (NRR). The NRR is required to be published on the primary label of every HPD entered into commerce in the United States by the Environmental Protection Agency (EPA, 1979). In this manner, the attenuation of a product is measured for an optimized fit. The NRR, calculated using mean attenuations minus two standard deviations, represents the potential 98th percentile performance capability of a protector. An additional 3 dB is subtracted at the last step of the NRR calculation to account for the variability of the effective attenuation when worn in different noise spectra.

National and international standard-setting bodies have developed different hearing protector ratings. Outside of the United States, the most widely used standard is the International Organization for Standardization (ISO) 4869-2 that specifies the calculation of the Single Number Rating (SNR) and High/Medium/Low (HML) rating (ISO, 2018b). This standard employs the attenuation measurement protocol specified in ISO 4869-1, which requires 16 subjects trained in hearing protector fitting to be tested one time with an experienced subject-fit attenuation test protocol (ISO, 2018a). The mean minus one standard deviation is used to calculate the SNR and HML ratings (see ISO 4869-2 for details). Another rating is the Noise Reduction Rating subject fit (NRR_{SF}) based on an inexperienced or naive subject-fit test protocol where the test subjects fit the HPDs according to the 1997 version of the ANSI S12.6 standard (ANSI, 1997; Franks *et al.*, 2000). Brazil adopted the NRR_{SF} rating, which is calculated using the mean attenuation minus one standard deviation. Australia and New Zealand developed the Sound Level Conversion 80th percentile (SLC_{80}), which

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requires naive subjects for the testing panels. The SLC_{80} rating is also calculated using the mean minus one standard deviation (Australia/New Zealand Standard, 2002).

The purpose of hearing protection is to reduce the exposure levels of potentially harmful sounds. The Occupational Safety and Health Administration (OSHA) adopted the NRR into the hearing conservation amendment regulation (OSHA, 1983). The OSHA Technical Manual (OSHA, 2022) explains the NRR is used for two purposes. First, for regulatory compliance purposes, the NRR is used to estimate the adequacy of hearing protector attenuation for a given noise exposure. If noise is measured with the A-weighting filter, the NRR must first be converted from a C-weighted statistic to an A-weighted statistic by subtracting 7 dB. The result is then subtracted from the A-weighted noise exposure to determine if sufficient attenuation exists to reduce noise exposure to the allowable limits. Second, OSHA strongly recommends applying a 50% correction factor when estimating real-world attenuation when considering whether engineering controls are to be implemented (OSHA, 2022). In this case, the derated NRR accounts for the potential inability of workers to achieve the attenuations measured in the laboratory using the experimenter fit protocol. When applied to A-weighted measurements, 7 dB correction factor is subtracted from the NRR and the result is divided by 2 to achieve the derated NRR, denoted as NRR′, and defined as $NRR' = (NRR - 7)/2$.

Berger *et al.* (1996) and Berger *et al.* (1998) examined 23 occupational studies of hearing protection performance. They found that earplugs were more susceptible to poorer fitting (reduced attenuation) than were earmuffs. Specifically, earmuffs are less influenced by user insertion skills. Formable earplugs were derated less than premolded earplugs because premolded earplugs are more susceptible to incomplete seals with the ear canal walls than formable earplugs. Based upon these findings and laboratory studies that considered the influence of fitting protocols, the National Institute for Occupational Safety and Health (NIOSH) developed a variable derating procedure for different types of hearing protectors to estimate protected noise exposures for a group of workers (Royster *et al.*, 1996; NIOSH, 1998). For earmuffs, the derating factor is 25%, leaving 75% of the NRR. For formable earplugs, the derating is 50% of the NRR. For all other earplugs, the derating is 70%, leaving 30% of the NRR. Laboratory studies conducted after the NIOSH recommendation for a variable derating have generally confirmed these findings (Franks *et al.*, 2000; Murphy *et al.*, 2009; Murphy *et al.*, 2011). NIOSH also proposed that the NRR_{SF} be used to estimate workers' noise exposures if available.

Derating strategies from several countries are presented in Table I. The OSHA derating of 50% reduction of the NRR after conversion to A-weighting is most commonly applied by hearing conservation professionals in the United States. The NIOSH deratings differ from the OSHA deratings in that they apply a variable based on the type of protector and the conversion from C-weighting to A-weighting is applied after the derating factor is applied. The Canadian Standards Association (CSA, 2014) applies similar reduction factors (0.7 for earmuffs and 0.5 for earplugs) and uses a 3 dB C- to A-weighting conversion factor. In Australia and New Zealand, the SLC_{80} hearing protector rating is not derated when applied to an A-weighted noise (Australia/New Zealand Standard, 2002). Similarly, the Brazilian NRR_{SF} rating is not derated for use with A-weighted noise (Brazilian Ministry of Labor, 2003). The SLC_{80} and NRR_{SF} ratings are derived with an inexperienced subject-fit protocol. Prior to January 2021, China derated hearing protectors by using 60% of the SNR (GB/T, 1999, 2009). After 2021, China dropped derating altogether in favor of prescribing the protector based upon the noise exposure. Specifically, for noise levels greater than or equal to 95 dB A-weighted (dBA), the SNR must be greater than 34. For noise levels less than 95 dBA, the protector's SNR can be between 17 and 34. Italy has adopted a variable derating scheme as proposed by NIOSH, except that the derating is applied to the SNR. Germany, France, and the United Kingdom subtract a

TABLE I. Derating schemes from different countries and organizations. This table has been adapted from Table XI.3 in the 6th edition of the AIHA Noise Manual (Berger and Voix, 2022). To convert between C-weighted and A-weighted sound pressure levels, OSHA and NIOSH apply a 7-dB correction factor and the Canadian CSA applies a 3 dB correction factor.

	Earmuffs	Formable earplugs	All other earplugs	Comments
United States OSHA		$(NRR - 7)/2$ for dBA exposure levels		7 dB conversion between C- and A-weighted noise
United States NIOSH	$(NRR \times 0.75) - 7$	$(NRR \times 0.5) - 7$	$(NRR \times 0.3) - 7$	To estimate TWA in dBA
Canada CSA Z94.2[a]	$(NRR - 3) \times 0.7$	$(NRR - 3) \times 0.5$	$(NRR - 3) \times 0.5$	$[(NRR - 3) \times 0.65] + 5$ dual protection 3 dB conversion L_{Ceq} to L_{Aeq}
Australia/ NZ/Brazil		No derating applied. AUS/NZ uses SLC_{80}. Brazil uses NRR_{SF}.		Naive subject fit
China before January 2021		$(SNR \times 0.6)$		SNR
China after January 2021		No derating applied		L_{Aeq} <95 dBA, SNR 17–34 L_{Aeq} ≥95 dBA, SNR >34
Italy	$SNR \times 0.75$	$SNR \times 0.5$	$SNR \times 0.3$	SNR
Germany	SNR-5 dB	SNR-9 dB	SNR-5 dB	SNR-3 dB for custom
France (proposed)	SNR-5 dB	SNR-10 dB	SNR-10 dB	SNR-5 dB for custom earplugs
United Kingdom		SNR-4 dB		SNR

[a]The derating specified in CSA Z94.2 is expressed as an amount to reduce the NRR rather than a multiplier as expressed in Table I.

constant from the SNR. In the discussions that follow, we will primarily use the OSHA recommended derating for A-weighted noise exposure, $NRR' = (NRR - 7)/2$, and provide some discussion of the NIOSH, Canadian, Chinese and Italian derating approaches (Berger and Voix, 2022).

More recently, studies of larger worker populations have been reported and provided new insights regarding the real-world performance of hearing protectors (Murphy *et al.*, 2009; Smith *et al.*, 2014; Murphy *et al.*, 2016; Gong *et al.*, 2019; Federman and Duhon, 2016; Federman *et al.*, 2021). Real-world performance can now be estimated for an individual worker using fit-testing systems to assess attenuation for a given hearing protector fit. Most fit-testing systems generate a personal attenuation rating (PAR) expressed as an A-weighted attenuation. These studies incorporating HPD fit testing are important in that they illustrate how estimating the protected exposure levels need to be measured and not assumed on the basis of derating the performance of an HPD. HPD fit-testing measures what workers, soldiers, and other HPD users actually achieve.

This paper will compare the PAR values for different earplugs to the corresponding derated NRR. Several datasets collected by the authors and previously published in the literature will be examined. The effect of training the worker in proper fitting techniques will be considered. The PAR values for a given fit of an earplug will be compared to the corresponding derated NRR for the different study cohorts to answer the question, "Do derating schemes accurately predict the actual protection provided for individuals or populations of workers?"

II. METHODS

A. Study selection

Four studies of hearing protector fit testing were selected for re-evaluation of the raw data. The aim of this re-evaluation is to understand the impact of using a derated NRR (or any other single-number rating) in comparison to the achieved and reported PAR values. Studies were selected primarily because of the sample sizes, data availability, and the authors' knowledge of the outcomes that illustrate the applicability of a de-rating scheme to the PAR data. The subject cohort, noise exposure type, inclusion criteria, fit-test system, frequencies used, target PAR, HPD, number of subjects (N), and the instruction provided to the cohort for all studies are described in Table II. The labeled values of the NRR, SNR, HML, NRR_{SF}, and the SLC_{80} ratings for all earplugs provided by the manufacturers are shown in Table III. The quantities that were derived from sources other than directly from the manufacturer are annotated with footnotes below Table III.

The first study was the NIOSH evaluation of the Sonomax custom hearing protector in an automobile stamping factory (Murphy *et al.*, 2007; Davis *et al.*, 2011). NIOSH human subjects review board approved the study (04-DART-02XP). The Sonomax earplug is a custom earplug manufactured using a bladder placed in the ear and filled with a silicon that cures *in situ*. The plant's A-weighted equivalent continuous sound levels (L_{AEq}) ranged from about 80 to 98 dBA. Employees were recruited by the factory's safety personnel to participate for a total of four potential visits by the NIOSH staff over the course of a year. Workers were randomly divided into three groups: an advanced hearing protector group ($N = 70$), a counseled group ($N = 82$), and an uncounseled group ($N = 76$). The advanced hearing protector group was fit with the Sonomax earplug, instructed about how to properly fit the earplug, and fit tested by the manufacturer's representatives. The counseled and uncounseled workers were instructed to fit the earplugs they usually wear and then were fit tested by NIOSH staff. The counseled workers were given instructions on how to fit the earplugs if the first fit test revealed that the noise reduction achieved was too low based upon the worker's reported noise exposure. The uncounseled workers were fit tested, but no additional instruction was given. The tests of the Sonomax earplugs were made with the Sonopass system, a progenitor of the 3M™ E-A-Rfit™ Dual-Ear Validation System. The fit tests of other earplugs were completed using a customized configuration of the original FitCheck system developed by Michael and Associates.

The second fit-testing dataset chosen for re-evaluation was an investigation of the 1996 workers' HPD fitting performance in China's Jiangsu province (Gong *et al.*, 2019; Liu *et al.*, 2020; Gong *et al.*, 2021a; Gong *et al.*, 2021b). The study was approved by the Ethics Committee of the Jiangsu Provincial Center for Disease Control and Prevention (JSJK2015-B009-02) and was approved by 3M Internal Review Board (3M IRB HUM00060704). The investigators used two fit test systems: the 3M™ E-A-Rfit™ Dual-Ear Validation System (E-A-Rfit), and the Michael and Associates FitCheck Solo system. Workers were initially fit tested with their actual earplugs (FitCheck Solo) or with surrogate probed test earplugs (E-A-Rfit). For those workers tested with the E-A-Rfit system, the A-weighted attenuations (PAR_{84}) were used to determine whether the target attenuations were achieved. For workers tested with the FitCheck Solo system, the A-weighted attenuations were compared to the target attenuations. The differences between the E-A-Rfit PAR_{84} and the FitCheck Solo A-weighted attenuation are described in the analysis section. The subsequent analyses in this paper use those respective PAR values. A target attenuation was set as the difference between the noise exposure and the company policy exposure limits. The target attenuations across 15 facilities ranged from 3 to 20 dB. Approximately 53% of the workers ($N = 1061$) either did not achieve the target PAR on the initial fit test or improper fitting technique was observed by the experimenter. These workers were given training in proper fitting techniques and then retested to demonstrate that adequate noise reduction was achieved. In the subsequent analysis and graphs, 878 workers who were tested, trained, and completed the two fit tests with the same model earplug are presented.

The third study was an evaluation of United States Marine Corps (USMC) training recruits who were

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TABLE II. The details of the selected HPD fit-testing studies examined in this paper. The cohort, noise exposure, inclusion criteria, fit test system, test frequencies, PAR, target PAR, HPD, number of subjects, and the intervention are provided. Detailed information can be found in the respective publications.

Fit test study	Cohort	Noise exposure type	Inclusion criteria	Fit test system used	Test frequencies (Hz)	PAR calculation	Target PAR (dB)	HPD	N	Intervention
NIOSH Advanced Earplug Study, 2004/5[a]	Auto-mobile stamping factory workers	Combination of impact and continuous noise, 80 to 98 dBA peaks of 110 dB	Voluntary participation with $100 stipend	Michael and Associates FitCheck system	125, 500, 2000	A-weighted Attenuation at 500, 1000, 2000 Hz	NA	Sonomax custom hearing protector	70	Instructed about proper fitting technique
								Moldex Pura-Fit®	82	Counseled about proper fitting technique
								North DeciDamp Comfit earplugs	76	Uncounseled control group
Chinese Worker Study, 2016[b]	Manufacturing workers in Jiangsu province.	Combination of impact and continuous noise, 80 to 100 dBA	PAR < target on the initial fit test, or improper fitting technique was observed	3M E-A-Rfit Dual-Ear Validation System,	125, 250, 500, 1000, 2000, 4000, 8000	84th percentile PAR from ANSI S12.71	3 to 18 dBA	3M™ 1270 3M™ 1100	733	Individual training to achieve target PAR
				Michael and Associates FitCheck Solo	500, 1000, 2000, 4000	A-weighted Attenuation at 500, 1000, 2000, 4000 Hz	8 to 20 dBA	3M™ 1270 3M™ 1100 3M™ Yellow Neon Honeywell MAX Honeywell MAX-LITE Honeywell Quiet Honeywell AirSoft® Honeywell Bilsom 303 s Moldex SparkPlugs®	145	
USMC Study, 2016[c]	USMC training recruits	Impulse from M16 rifle ~165 dB peak SPL	PAR < 25.0 dB two weeks after initial HPD-use training	Michael and Associates FitCheck Solo	500, 1000, 2000	A-weighted Attenuation at 500,1000, 2000 Hz	25 dBA	Moldex Camo Plugs®	79	Experiential HPD (eHPD) fit-training*
USMC Study, 2021[c]	USMC training recruits	Impulse from M16 rifle ~165 dB peak SPL	PAR < 25.0 dB after initial HPD-use training	Michael and Associates FitCheck Solo	500, 1000, 2000	A-weighted Attenuation at 500, 1000, 2000 Hz	25 dBA	Moldex Camo Plugs®	111	Current training
									105	eHPD fit-training
									105	Integrated training

[a]NIOSH Advanced Earplug Study was approved by the NIOSH human subjects review board (04-DART-02XP).
[b]The Chinese Worker Study was approved by the Ethics Committee of the Jiangsu Provincial Center for Disease Control and Prevention (JSJK2015-B009-02) and was approved by 3 M Internal Review Board (3 M IRB HUM00060704).
[c]The USMC studies were deemed as not human subjects research.

TABLE III. Hearing protection devices used in the selected fit testing studies and the labeled NRR, SNR, HML, NRR_{SF}, and SLC_{80} ratings. Ratings that do not have a footnote symbol were provided by the manufacturers of the respective products or identified from the manufacturers' websites. The same earplug model was used in both of the USMC studies.

Fit test study	HPD manufacturer and model	NRR dBC	SNR dBC	HML dBC	NRR_{SF} dBA	SLC_{80} dBA
NIOSH advanced earplug study	Sonomax Low Red	9[a]	19	23/16/11	3[a]	NA
	Sonomax High Yellow	14[a]	23[b]	26/19/16[b]	7[a]	NA
	Sonomax High full-block	17[c]	26[b]	28/22/21[b]	23[d]	NA
	Moldex Pura-Fit®	33	36	35/33/31	18[e]	29
	North DeciDamp	29	28	30/24/22	21–22[e]	NA
	Comfit earplugs	26	NA	NA	NA	NA
	Honeywell MAX	33	37	36/35/34	14[f]	26
	Honeywell MAX-LITE	30	34	32/32/31	NA	25
	Honeywell Quiet	26	28	29/25/23	12[f]	20
Chinese worker studies	3M™ 1270	24	25	27/22/20	16[f]	18
	3M™ 1100	29	37	37/34/31	16[f]	21
	3M™ Yellow Neon	33	36	34/34/31	NA	23
	Honeywell AirSoft®	27	30	29/27/25	12–15[e]	26
	Honeywell Bilsom 303 s	29	33	32/29/29	NA	22
	Moldex SparkPlugs®	33	35	34/32/31	18[e]	29
USMC studies	Moldex Camo Plugs®	33	35	34/32/31	18[e]	29

[a]NRR_{SF} values from the NIOSH Compendium of Hearing Protection Devices, circa 2012.
[b]SNR and HML values from BGIA test report from Sonomax.
[c]NRR values from Virginia Tech lab test report provided by Sonomax.
[d]NRR_{SF} values from lab test at Michael and Associates provided by Sonomax.
[e]NRR_{SF} values derived from the Murphy *et al*. (2011) inexperienced subject fit testing.
[f]NRR_{SF} values from the manufacturer tests for Brazil.

completing training at U.S. Marine Corps Recruit Depot (MCRD), Parris Island (Federman and Duhon, 2016). The USMC study was deemed not human subjects research but military program improvement by the Naval Submarine Medical Research Laboratory Institutional Review Board in compliance with all applicable Federal regulations governing the protection of human subjects. In this study, the investigators were interested in determining how the test methodology affected the resulting PAR value. Subjects (N = 320) were evaluated with 1-, 3-, 5-, or 7-frequency tests using the Michael and Associates FitCheck Solo system. While the details comparing the resulting PAR values across frequency cohorts are outside the scope of this paper, those subjects who failed to achieve the target PAR of 25.0 dB (N = 79) were provided with individualized training following the initial fit test. The individualized training, initially coined ear canal muscle memory then renamed experiential HPD (*e*HPD) fit-training, included a brief one-on-one demonstration of how to roll and properly insert the foam earplug. This demonstration was conducted by an expert (occupational audiologist) and was immediately followed by a three-frequency (500, 1000, and 2000 Hz) fit test (i.e., expert fit). The recruits were then asked to replicate the fit using the techniques shown by the expert (i.e., self-refit). FitCheck Solo was used to measure the PARs at all training time points (i.e., initial fit, experimenter fit, self-re-fit). All follow-up training fit tests regardless of cohort (1-, 3-, 5-, or 7-frequency) used the frequencies 500, 1000, and 2000 Hz for the expert and self-refit fit tests. As shown in Tables II and III, the foam earplugs used in the study were the Moldex Camo Plugs®.

The fourth study also used a cohort of USMC training recruits at MCRD, Parris Island undergoing basic training (Federman *et al*., 2021). This USMC study was also deemed not human subjects research. Participants could withdraw at any time, none did so. In this study, the investigators examined how different HPD fit-training formats might affect the noise reduction achieved by the recruits. In order to achieve training groups of approximately 100 recruits each, a total of 798 recruits completed baseline hearing protector fit testing after completing the live, large group instruction regarding hearing conservation and HPD fit-orientation as part of their military basic training. The amount of time between this training and the baseline HPD fit test was not a controlled factor. The recruits whose baseline PAR was greater than the target 25.0 dB were excused from further participation, as they demonstrated the ability to properly fit the issued earplug. Those recruits whose baseline PAR was less than the target PAR (N = 321) were randomly assigned to one of three HPD fit-training methods [current, integrated, experiential (*e*HPD)]. The current training method was a 30-min compilation of military-focused hearing conservation video training modules that included the instruction of how to fit HPDs such as earplugs (N = 111). The *e*HPD fit-training protocol as previously described was conducted with approximately one-third of the recruits (N = 105). The integrated training protocol combined the current and the eHPD fit-training methods (N = 105). The earplugs used in the study were the Moldex Camo Plugs® (see Tables II and III). FitCheck Solo was used to measure PARs with the frequencies 500, 1000, and 2000 Hz.

B. Analysis

For each of the studies, the PAR was calculated by the test system used. The 3M™ E-A-Rfit™ Dual-Ear Validation System computed the PAR for a subject, s, and trial, t, as specified in the ASA/ANSI S12.71-2018 standard. The uncertainties due to the measurement, fit and the spectrum were combined and subtracted from the A-weighted attenuation,

$$\mathrm{PAR}_x(s,t) = \mathrm{FAES_A}(s,t) - \alpha u_{\mathrm{FAES\,A}}(s,t), \tag{1}$$

where

$$u_{\mathrm{FAES\,A}}(s,t) = \sqrt{u^2_{\mathrm{measurement}} + u^2_{\mathrm{fit}}(s) + u^2_{\mathrm{spectrum}}(s,t)}. \tag{2}$$

The E-A-Rfit™ system estimated the percentile for the PAR by adjusting α in Eq. (1). For the median $\mathrm{PAR_{A50}}$, $\alpha = 0.0$. To estimate the $\mathrm{PAR_{A84}}$, one standard deviation below the median, $\alpha = 1.0$. The E-A-Rfit™ system provided $\mathrm{PAR_{A84}}$, whereas FitCheck and FitCheck Solo report attenuation and did not include the variability of repeated measurements, fits or the spectral uncertainties. FitCheck Solo combined the attenuations at each frequency and reported an A-weighted PAR value. Murphy *et al.* (2007) estimated the PAR using an A-weighted attenuation

$$\mathrm{PAR}_N = 10\log_{10}\sum_{i=1}^{N} 10^{(100+\mathrm{Awt}(f_i))/10} - 10\log_{10}\sum_{i=1}^{N} 10^{(100+\mathrm{Awt}(f_i)-\mathrm{REAT}(f_i))/10}, \tag{3}$$

where the $\mathrm{REAT}(f_i)$ are the measured attenuations at the respective frequencies, $\mathrm{Awt}(f_i)$ are the A-weighting values applied to pink-noise spectra of 100 dB in each frequency band.

For each study, the initial PAR values were sorted for the various subject groups. These PARs were then plotted against the ranking of the subject's PAR, lowest to highest values, to create the sorted PAR charts. The retested PAR values for each subject were plotted above the initial PAR and were connected with a line to facilitate comparisons of the PAR for each subject within the study cohort across multiple fit tests. Even though the PAR values from these systems were determined using an A-weighted attenuation [Eqs. (1) and (3)], the units are reported as dB. Estimated exposure levels were reported as dBA. The PAR values as reported by the respective systems ($\mathrm{PAR_{A84}}$ for E-A-Rfit™ and PAR for FitCheck and FitCheck Solo) were shared with the subjects and used to determine subsequent treatment or counseling.

The NRRs (solid lines or gray shaded areas) and the derated NRRs (dashed lines and pink shaded areas) for the tested products were plotted to facilitate comparisons. In Figs. 1–4, the NRRs (dBC) for the earplugs and the derated NRRs (dBA) adjusted for C- to A-weighting are shown with a dashed line.

The second analysis examined how the workers' PAR values changed relative to the derated NRR for their specific HPD before and after training. The OSHA derating of 50% was used to illustrate the effect of derating for the NRR and because it is commonly used by hearing conservation professionals in the United States. In Fig. 5, swarm plots were created in MATLAB to illustrate the PAR minus the derated NRR subtracted from the pre- and post- training PAR values. The points in the swarm plot falling above or below the horizontal line labeled 0 dB indicate the number of persons in the different studies who achieved more or less than the derated NRR.

The third analysis compared the proportion of subject PARs (before and after training) to the protector ratings when adjusted according to the derating schemes given in Table I for various countries. In Table IV, the hearing protector ratings as derated by OSHA, NIOSH, CSA, China (before January 2021), and Italy are presented. These derated values were subtracted from each worker's PAR values pre- and post-training. In Table V, the percentage of the number of negative scores for persons tested with that product and in that instance was calculated as follows:

$$\% = \frac{\mathrm{count}\left\{(\mathrm{PAR}-\mathrm{dR}) \le 0\right\}}{\mathrm{count}\left\{\mathrm{PAR}\right\}} \times 100, \tag{4}$$

where the PAR is the personal attenuation rating, dR is the derated attenuation rating as applied according to the country and type of protector given in Table I, and count{ } tallies the number of members in each of the two sets.

III. RESULTS

A. Hearing protector device deratings

Table IV shows the derated attenuation values for the rating schemes used in the selected studies. The derated OSHA values for use with A-weighted noise measurements were used for comparison in the sorted PAR charts and swarm charts. Use of any derated single number attenuation rating would move the derated line in the following charts by the difference between the OSHA column and other derating scheme columns. Because the derated values can be negative for low-attenuation hearing protectors, such ratings were set to 0 dB.

B. NIOSH advanced hearing protector study

In Fig. 1, the ranges of NRR values for the earplugs worn by each group are shown by the gray-shaded regions in each panel, The NRRs for the Sonomax earplugs varied from 4 to 17 dB (due to the different attenuations of the acoustic filters) and are presented in the upper panel. The derated NRR ranges are shown with the pink-shaded regions towards the bottom of each panel and varied from 0 to 5 dB. Negative values were rounded to 0 dB. The derated NRRs for the other foam and premolded earplugs ranged from 9 to 13 dB and are shown in the two lower panels. The open symbols were the initial PARs measured in February 2004. The filled

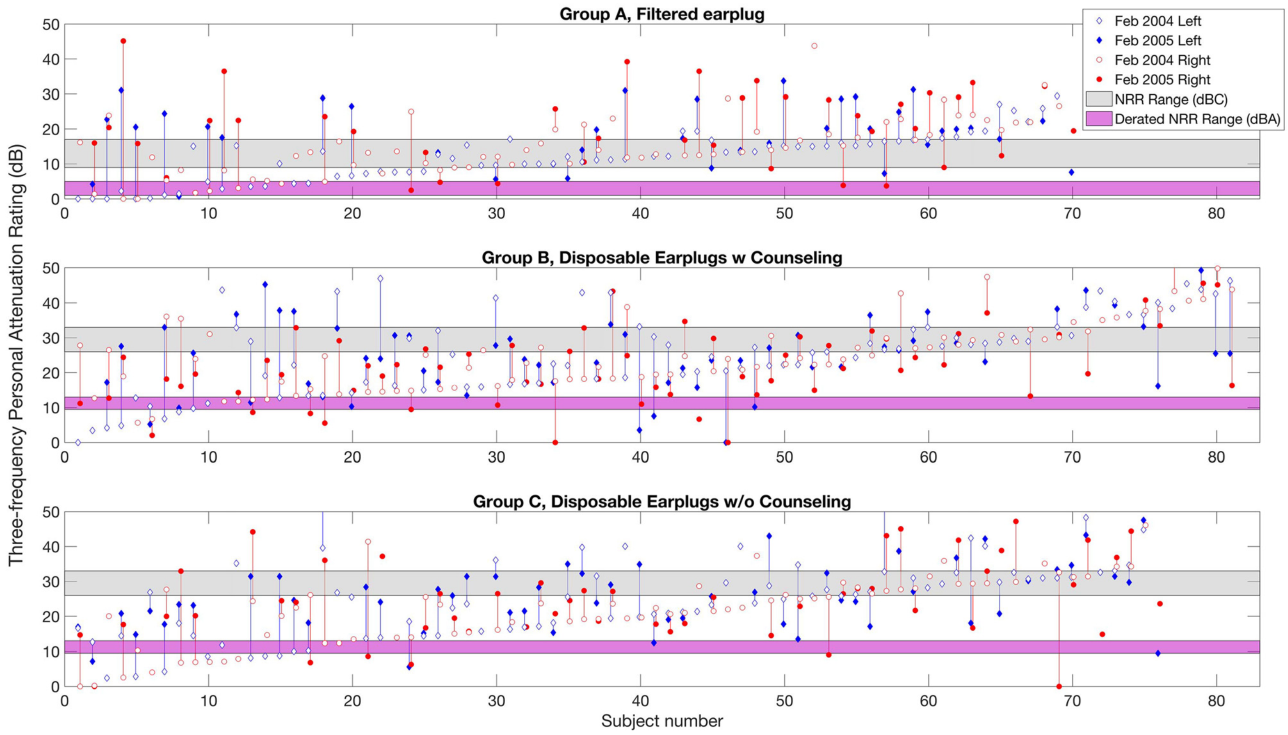

FIG. 1. (Color online) Sorted PAR chart from the NIOSH Advanced Hearing Protector study (Murphy *et al.*, 2007). Fit testing was accomplished with the original FitCheck system modified to test four subjects simultaneously. The open symbols represent the initial fit tests conducted in February 2004. The solid symbols represent the fit tests conducted during the fourth visit to the factory in February 2005. Red circle symbols are the right ear and blue diamond symbols are the left ear. The gray shaded areas between 26 and 33 dB are the range of the NRR values (dBC) for the earplugs worn by the subjects. The pink shaded area towards the bottom of each panel are the range of the derated NRRs (dBA).

symbols were the final PARs measured in 2005. The diamond symbols are the PARs measured for the left ears and the circles are the PARs for the right ears. Not every subject had first and last tests. Two other visits (March and June 2004) are not shown. The red and blue vertical lines connect the open (initial test) and closed (final test) symbols for each subject's test results for their right and left ears. Approximately one fourth of the workers had PARs less than the derated NRRs (i.e., in or below the pink-shaded range).

C. Chinese worker studies

The sorted PAR charts for six types of earplugs are shown in Fig. 2. The E-A-Rfit^{TM} system tested the performance of a surrogate, probed earplug. Of the 1061 workers wo participated in the Chinese Worker Study, 878 workers were trained and re-tested. The target PAR was based on the noise exposure levels of each worker and ranged approximately from 8 to 20 dB. Of those 878 workers shown in Fig. 2, a total 553 workers (63%) had pre-training PARs (blue circles) below the derated NRR. Post-training HPD fit tests (gold diamonds) were conducted with the 878 workers, 868 workers (99%) achieved PAR values above the derated NRR. Specifically, 753 workers (86%) had PARs above 15 dB and 107 workers (12%) had PARs above 25 dB. The derated NRR was not representative of what the trained workers achieved.

D. USMC fit-test study 2016

A total of 320 USMC training recruits were provided a standard hearing conservation orientation and HPD fit training approximately two weeks prior to data collection (Federman and Duhon, 2016). Subjects whose documented PAR values were less than 25.0 dB (N = 79) were provided an additional individualized *e*HPD fit training, which included an expert fit of the issued earplugs. Time permitting, the subjects (N = 35) were instructed to remove and refit the earplugs to replicate the expert fit and complete a third fit test (i.e., self-refit). In Fig. 3, the results of the 35 recruits that completed the initial PARs (blue circles), expert-fit PARs (orange squares), and self-refit PARs (gold diamonds) are shown. Twelve of the 35 subjects (34%) had initial PARs below 13 dB, the derated NRR value. Post-training, at the self-refit fit test one subject (3%) had a PAR below the derated NRR value, while 20 of the 35 subjects (57%) had self-refit PARs above 33 dB, the earplug NRR. Seven of the 35 subjects had self-refit PARs less than 25 dB, the target PAR for the study.

E. USMC fit-test study 2021

A total of 798 USMC training recruits completed an initial (baseline) HPD fit test using the FitCheck Solo fit-test system (Federman *et al.*, 2021). Those recruits who failed to achieve a 25-dB PAR (N = 321) were randomly assigned to

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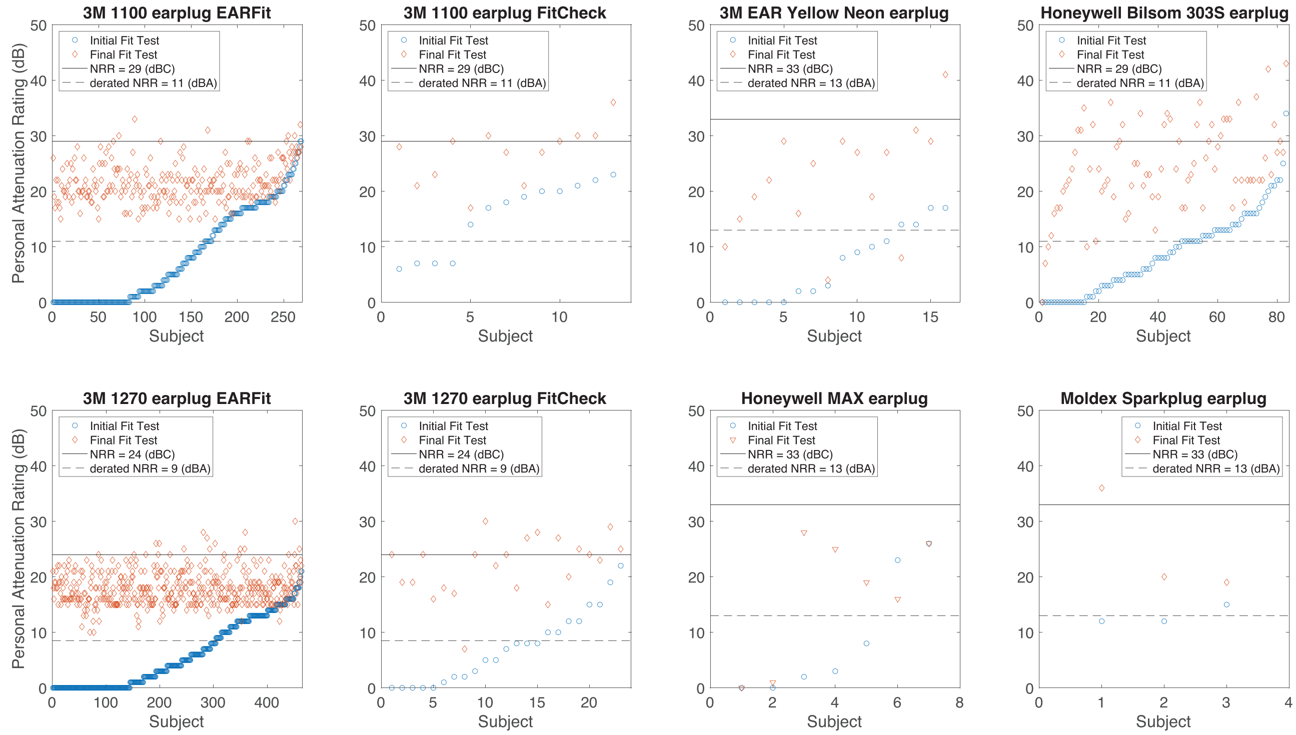

FIG. 2. (Color online) Sorted PAR charts from the Chinese worker studies (Gong *et al.*, 2019; Liu *et al.*, 2020; Gong *et al.*, 2021a; Gong *et al.*, 2021b). The different panels separate the results from the subjects based upon the earplugs and fit-test systems used in these studies. The solid lines in the panels indicate the respective NRR and the dashed lines indicate the derated, C-A corrected NRR for each earplug tested. The E-A-Rfit™ system was used to test the workers in the two panels on the left. The FitCheck Solo system was used to test the workers in the other six panels. Initial fit tests are indicated with blue circles and the final fit tests are indicated with gold diamonds.

one of the three training cohorts (current, integrated, experiential [eHPD]).

In Fig. 4, the initial self-fit tests, expert (when applicable) and self-refit PAR results are shown. The initial PARs are shown as blue circles, the expert-fit PARs are shown as orange squares, and the self-refit PARs are shown as gold diamonds. The solid line is the 33 dB NRR for the Moldex Camo Plugs®. The dashed line is the 13 dBA OSHA-derated NRR. For the *current* training protocol, 24 recruits (22%) had PARs less than the OSHA derated NRR and the 18 recruits (16%) had PARs less than the derated NRR after training. Before the *experiential* training, 32 recruits (30%) had PARs less than the 13 dB OSHA-derated NRR. After the *experiential* training, all of the recruits (100%) had

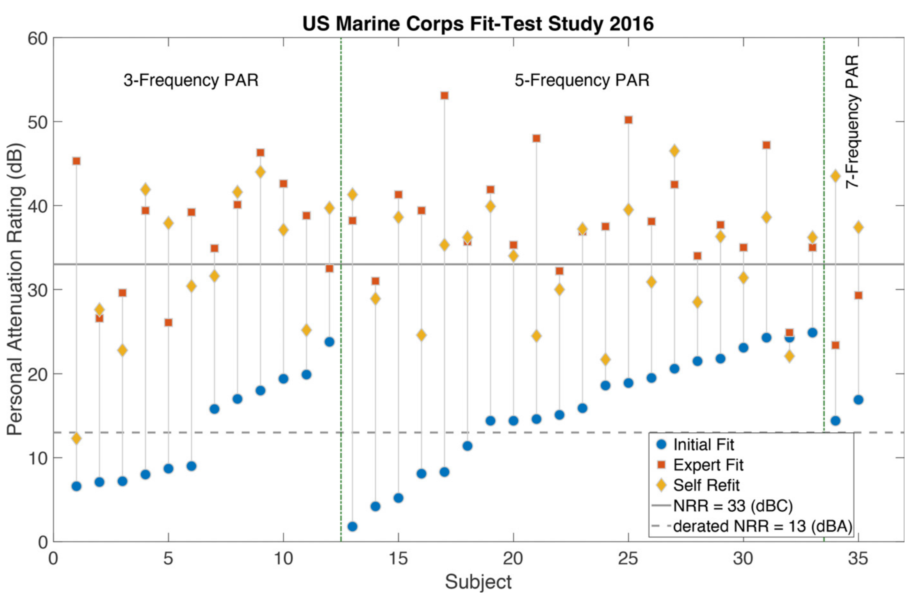

FIG. 3. (Color online) Sorted PAR charts from the USMC fit testing study (Federman and Duhon, 2016). For each section of this plot, the initial fit test is shown as the blue circles. The expert fit PARs are shown in orange squares and self-refit PARs of the earplug are displayed as gold diamonds. The horizontal solid line is the NRR (33 dBC) of the Moldex Camo Plugs® and the dashed line is the derated NRRs (13 dBA). The PAR results measured with 3-, 5-, and 7-frequencies are separated with a vertical line from 0 to 60 dBA.

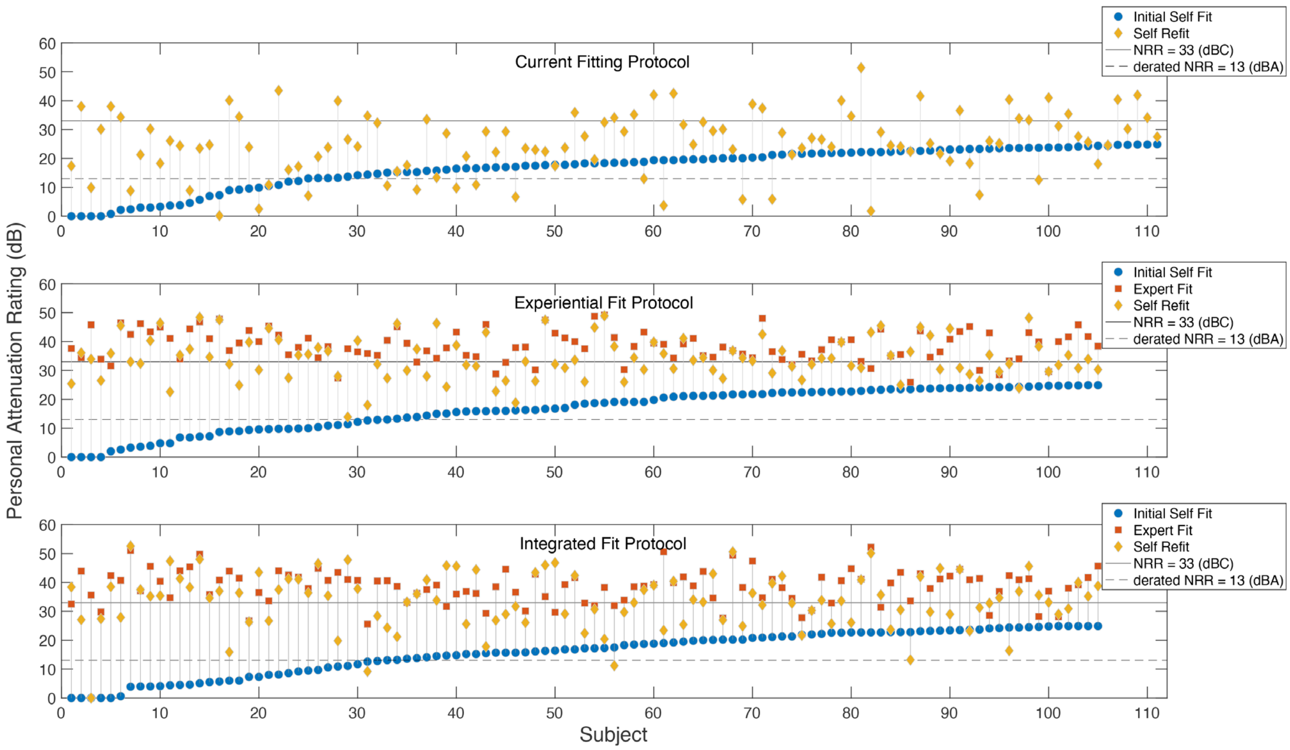

FIG. 4. (Color online) Sorted PAR charts from the USMC fit testing study (Federman *et al.*, 2021). The three panels illustrate the result of the different training methods. The upper panel shows results from the current video-based instruction group. The middle panel shows the results for the experiential (eHPD) training protocol. The lower panel shows the results from the integrated fitting protocol that combined the video and experiential training. For each panel, the initial fit test is shown as blue circles. For the experiential and integrated protocols, the subjects were tested immediately after having been fit by the experimenter (orange squares), and then the subjects were asked to remove the earplug and self-refit the earplug (gold diamonds). The horizontal solid line is the NRR (33 dBC) of the Camo Plugs® and the horizontal dashed line is the derated NRRs (13 dBA).

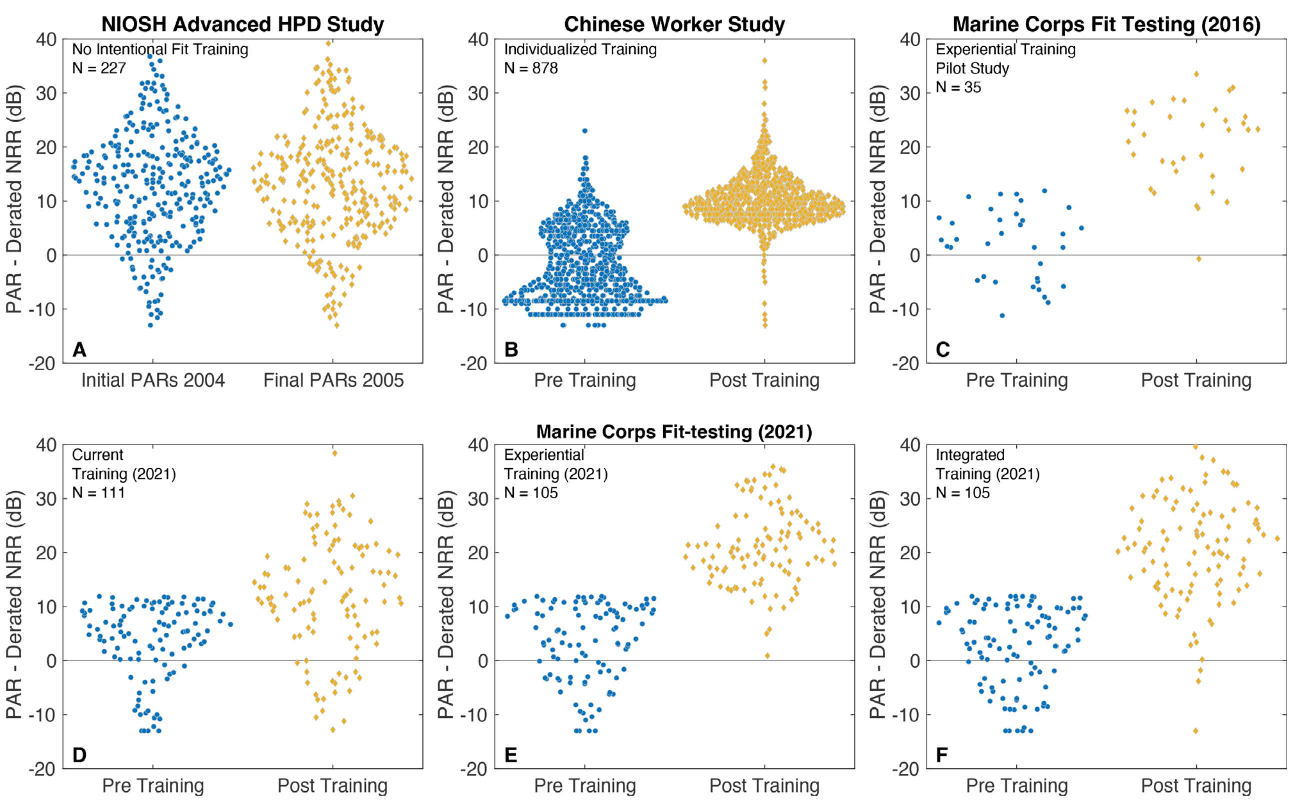

FIG. 5. (Color online) Pre-training and Post-training swarm plots illustrate the effect (or lack of effect) of training on the PARs relative to the derated NRR. OSHA derating and C-A correction was applied. The blue symbols are the initial fit tests before training. The gold symbols are the post-training PARs.

TABLE IV. The derated attenuation ratings for the products used in the referenced studies for a selection of countries. C-weighting to A-weighting corrections were applied to the OSHA, NIOSH, and CSA ratings as indicated in Table I.

HPD Manufacturer and Model	OSHA (dBA)	NIOSH (dBA)	Canada CSA (dBA)	China before January 2021 (dBC)	Italy (dBC)
Sonomax Low Red	1	0	2	11	6
Sonomax High Yellow	4	0	3	14	7
Sonomax High solid	5	0	4	16	8
3 M™ 1270	9	0	6	15	8
3 M™ 1100	11	8	13	22	19
3 M™ Yellow Neon	13	10	15	22	18
Honeywell MAX	13	10	15	22	19
Honeywell MAX-LITE	12	8	14	20	17
Honeywell Quiet	10	1	7	17	8
Honeywell AirSoft®	10	1	7	18	9
Honeywell Bilsom 303 s	11	8	13	20	17
Moldex SparkPlugs®	13	10	15	21	18
Moldex Camo Plugs®	13	10	15	21	18
Moldex Pura-Fit®	13	10	15	22	18

self-refit PARs greater than the 13 dB OSHA-derated NRR. Before the *integrated* training protocol, 32 recruits (30%) had initial self-fit PARs less than the OSHA derated NRR of 13 dB. After the *integrated* training protocol, only three recruits (3%) had PARs less than 13 dB. (i.e., 0-, 9-, and 11-dB PARs). Note that negative PARs are plotted as 0 dB in the sorted PAR chart. These results demonstrate the importance of providing individualized training that focuses on proper HPD fit techniques to the recruits.

F. Comparison of PARs with derated NRR

In Figs. 1–4, the NIOSH study initial/final PARs and other studies' pre-/post-training PARs for the subjects in the four studies are displayed. In Fig. 5, the OSHA derated NRRs of the respective earplug were subtracted from the PARs and plotted as a swarm chart. The distribution of the subjects' results along the X-axis is intended to convey the density of the distribution of attenuations minus the derated PARs. If the subject's PAR matched the derated NRR, the difference would be 0 dB. Several observations can be made from these swarm charts.

In the NIOSH Advanced HPD study, there was essentially no difference between the initial and final PARs in the study. The design of the NIOSH study was not intended to provide a training experience, rather it aimed to evaluate the longitudinal performance and acceptance of the Sonomax earplug. The counseled group did not exhibit any significant differences from the uncounseled groups. The workers in the counseled group were fit tested and given instruction regarding how to better fit the earplugs. If the counseled subjects achieved a low PAR, they were counseled about other possible earplugs they could use and retested. The subjects were free to revert to their original earplugs of choice.

In the Chinese worker studies, the training in hearing protector fitting and selection was highly successful in helping workers to achieve the target PAR for their exposures. Of the 876 workers, 135 workers (15%) had pre-training PARs greater than 15 dB. In contrast, 753 workers (86%) had post-training PARs greater than 15 dBA and 107 workers (12%) had post-training PARs greater than 25 dB. Only 8 workers (0.9%) had post-training PARs less than the derated NRRs.

In Figs. 5(C)–5(F), several notable findings are evident in the results from the USMC 2016 and 2021 fit test studies. First, panel (C) of the USMC 2016 swarm plot shows that, of the 79 subjects referred for individualized HPD fit-training, 35 completed all components (expert-fit and self-refit) of the *e*HPD fit-training method. The upper limit for the difference between the pre-training PAR and the derated PAR value (13 dB) is about 12 dB. Recruits who failed to achieve a 25.0 dB PAR in the USMC studies, were identified for subsequent training. Similarly, the lower limit for the USMC 2016 study is −13 dB because any negative PARs are rounded to 0 dB. This pattern is also seen in the USMC 2021 study [panels (D), (E), and (F)] pre-training charts for the three groups, with the swarm of points also exhibiting an upper limit for the differences between initial PAR values and the derated NRR of about 12 dB. We should also note that in both the USMC 2016 and 2021 studies, more of the subjects had PARs between 13 and 25 dB than there were subjects below 13 dB. Second, the experiential and integrated training protocols in the 2021 study were considerably more effective in moving the PARs from unsatisfactory to satisfactory than the current training protocol (Federman *et al.*, 2021). For the current training cohort, 55 of 111 recruits (50%) were below the target PAR of 25 dB after training. For the experiential and integrated training cohorts, 9 (9%) and 17 (16%) recruits were below the target PAR after training, respectively.

G. Comparison of percentages for workers below derated ratings

Table V shows the estimated percentage of persons with PAR values below the derated HPD rating for each protector in the studies reported.

TABLE V. Estimated percentage of persons with PAR values below the derated HPD rating for each protector in the studies reported. Five derating methods from the U.S., Canada, China (as previously applied), and Italy were applied to the NRR or SNR and tested against the PAR values for all subjects. The rounded percentages are given. The first and second numbers in each cell correspond to the initial pre-training and final post-training PAR percentages.

		% < derated NRR			% < derated SNR	
Study	Protector	OSHA	NIOSH	CSA	China	Italy
NIOSH Advanced Hearing Protector Study	DeciDamp	14/9	9/4	17/10	32/21	21/13
	Pura-Fit®	10/12	7/7	12/15	33/36	17/24
	AirSoft®	6/22	0/11	6/22	12/33	12/22
	Quiet®	13/50	7/0	33/50	53/63	47/50
	MAX-LITE	13/19	10/5	27/24	33/38	33/33
	Sonomax Fullblock	14/9	0/0	19/13	64/46	45/28
	Sonomax Red	4/2	0/0	7/4	33/26	30/24
Chinese Worker Studies	1270	66/0	51/0	71/1	89/6	79/26
	1100	60/0	53/0	63/0	93/54	85/16
	Yellow Neon	75/19	63/13	88/19	100/44	100/31
	MAX	71/29	71/29	71/29	71/57	71/43
	SparkPlugs®	67/0	0/0	67/0	100/67	100/0
	Bilsom® 303S	57/5	46/2	70/7	92/24	88/12
USMC Studies 2016, 2021	Camo Plugs® (2016)	34/3	31/0	46/3	80/3	57/3
	Camo Plugs® Current	22/16	18 /13	29 /18	64/30	40/20
	Camo Plugs® Experiential	30/0	23/0	35/1	59/3	48/1
	Camo Plugs® Integrated	30/3	25/2	38/4	68/9	50/6

IV. DISCUSSION

As demonstrated by data in these selected studies and shown in Figs. 1–4, as well as similar data reported in the literature (Murphy *et al.*, 2016; Franks *et al.*, 2000; Michael and Bloyer, 1999; Michael *et al.*, 1976; Green *et al.*, 1989; Joseph *et al.*, 2007, Murphy *et al.*, 2011), population-based statistics (e.g., NRR, derated NRR, SNR, HML, NRR_{SF}, etc.) fail to characterize the HPD fitting performance that individual workers achieve. The derated HPD ratings are predictive for a small percentage of subjects who were tested regardless of the earplug. For untrained subjects, the derating may overestimate the attenuation for as many as 25% of the workers. For well-trained subjects, 90% to 100% of the workers were able to achieve more attenuation than predicted by the derated value. The Murphy *et al.* (2007) study did not include training, and the final PARs exhibit no significant difference with the initial PARs (Fig. 5, upper left panel). This suggests that personal/individual feedback is important to users who are not achieving adequate protection. Whether the success of the feedback is due to learning the "feel" of a correct fit or the quantitative verification of the attenuation is unknown. However, Federman *et al.* (2021) demonstrated the efficiency of expert fit as feedback to the individual.

As stated previously, NRRs are used for two purposes in a hearing conservation program: (1) to estimate the adequacy of hearing protector attenuation for a given noise exposure and (2) estimating field attenuation when considering whether engineering controls are to be implemented.

In the hierarchy of controls (NIOSH, 2015; Murphy, 2016), the most effective controls are to eliminate the noise hazard, to substitute quieter tools and processes through strategic use of Buy Quiet and Quiet by Design procurement process programs, and to control noise hazards through maintenance and acoustic isolation or rework of the noisy equipment. For these reasons, the OSHA derating approach makes some sense. That is, the noise levels with the engineering noise control in place are compared to the current noise levels minus the derated NRR. For the purpose of estimating adequacy of HPD attenuation, derating provides a relatively inaccurate prediction of the performance of the group. Regarding the latter purpose, derating provides an indicator of the minimum protection that the majority of the population will achieve. By its nature, such ratings are influenced heavily by the protection achieved by the 10% to 20% of the population that are wearing the HPDs poorly. Because HPDs are assumed to be worn poorly, the estimated protected levels will be higher than it could be if HPDs were properly fit to the head or in the ear canals.

Regarding the former purpose, derating provides a relatively inaccurate estimate of the performance of the group. At best, derating represents the attenuation of poorly trained workers. As has been demonstrated by the Chinese worker studies and the USMC studies, derating grossly underestimates the performance of subjects who are trained in the proper fitting techniques with individual feedback. One purpose of the OSHA Hearing Conservation Amendment is to mandate that noise-exposed workers are trained in the selection, care, and proper use of HPDs to mitigate their noise exposures (OSHA, 1983).

In 2009, the EPA proposed a revised hearing protector labeling rule that used the ANSI/ASA S12.6-2008 standard with the Method A experimenter trained REAT protocol and the ASA/ANSI S12.68-2007 standard to calculate a range of attenuations that reflect the potential range of performance (EPA, 2009; ANSI, 2008; ANSI, 2020). Noise reduction depends upon the test panel subjects and the noise spectrum in which the HPD is worn, and the EPA proposed to use the 80th and 20th percentiles to describe the range of attenuation achieved by the test panel. Public comments on the proposed rule available at the docket EPA-HQ-OAR-2003–0024 proposed that the 80th percentile was not substantially different from the current NRR and that the 90th percentile would yield more realistic and achievable ratings. The EPA justified its selection of the Method A protocol as being more descriptive of the capabilities of the protector compared with using the Method B inexperienced subject-fit protocol. Specifically, inexperienced subjects would inevitably become experienced after the first few series of product tests (EPA, 2009, p. 39155, §VI.A.4).

From a practical perspective, the Method A protocol would better describe a hearing conservation program where employees are trained with individual feedback in the proper use and selection of protectors. The goal of such a program should be to achieve the best possible protection and not the compromised performance described by naive subjects. For example, Murphy *et al*. (2011) tested four models of earplugs with naive subjects using three different instruction sets: manufacturer written instructions, a detailed video describing the fit process, and individualized training with an experienced user. For each earplug, the individualized training produced a statistically significant improvement over either the written or video instructions. These effects were also observed by Federman *et al*. (2021). In this study, a mean improvement of approximately 9 dB was documented for personnel who received individualized HPD fit training with an expert either as the primary method of training or combined with video training, compared to video training alone. Joseph *et al.* (2007) demonstrated a similar improvement when evaluating inexperienced subjects for groups or small groups of subjects. An improvement of 8 to 11 dB for the provision of enhanced training suggests that the EPA's proposed choice of an experimenter-trained testing protocol would yield a more useful rating. Specifically, the experimenter-trained protocol is achievable by many workers if they are trained and evaluated to ensure that they are obtaining the target attenuation.

A. Under-protection and over-protection

Proper selection and training are critical to ensure that workers are not over-protected or under-protected. Over-protection can occur when the protected exposure levels are below 70 dBA and under-protection occurs when protected exposure levels exceed 85 dBA. When workers are over-protected, the ability to hear warning signals, to communicate with other workers, and to hear important sounds can be significantly impaired. Consequently, workers will tend to remove the hearing protection or intentionally fit the protection poorly, compromising any potential protection afforded by the protectors. Under-protected workers experience increased exposure and a greater risk of noise-induced hearing loss.

The studies considered in this paper represent two different noise environments: manufacturing and military exposures. In the manufacturing environment, noise exposures are significantly lower than the highest exposure for military personnel. Franks (1988) claimed that 92% of the exposures in the manufacturing sector are less than 95 dBA. In the NIOSH Advanced HPD Study, the highest TWAs (98 dBA) were typically for maintenance workers. Measurements around some of the stamping machines had peak levels of 115 dB SPL and maxima in the 1000 Hz frequency band. Most workers had TWA exposures between 80 and 90 dBA. The PARs achieved by the autoworkers were highly variable. Generally, the protection the workers achieved was adequate based upon the TWA estimates of the exposure. However, a significant portion of the workers issued the Sonomax hearing protector rejected the product because of low attenuations and protector discomfort. The workers preferred the foam earplugs over the custom earplug with adjustable filters because the impact noise was attenuated more by the foam earplugs.

In contrast for the military noise environment, typical small-caliber firearms produce peak impulse levels of 150 to 175 dB SPL (Schulz *et al*., 2013). The USMC fit testing studies chose a target PAR of at least 25.0 dB in anticipation that peak impulse levels of 165 dB SPL would be reduced to 140 dB SPL or less (U.S. Army Public Health Command, 2013). According to the MIL-STD 1474D, the USMC recruits could be exposed to 2000 rounds daily with single-level hearing protection (U.S. Department of Defense, 1997). For single-level hearing protection, the standard assumes that the attenuation of earplugs is 29 dB. The impulse noise exposure standards are currently undergoing revision and perhaps the 140-dB limit is not sufficiently protective.

If Service Members wear hearing protection that reduces peak noise levels to "safe" levels, then their awareness of their environment could be compromised. Specifically, earplugs alter the spectral cues of the pinna used in localization. For some high-level exposures, such as operations in tanks, helicopters, etc., double hearing protection may be required (Jokel, 2019). However, double hearing protection (earplugs plus earmuffs) yields the poorest performance for localization, as earmuffs essentially eliminate the pinna cues, further degrading localization performance.

As stated previously, over-protection compromises a worker's ability to hear environmental cues, under-protection places workers at risk for noise-induced hearing loss. Applying any single number rating to a population or many heterogeneous populations is fraught with inaccuracies. Applying a derated noise-reduction single number rating to many heterogeneous populations leads to an increased risk of over-protection as well as the risk of under-protecting a portion of the population (as shown in Table V).

B. The essential need for HPD training

In this paper and in other studies, many workers did not achieve the target attenuation (Berger *et al*., 1996;

Berger *et al.*, 1998; Joseph *et al.*, 2007; Murphy *et al.*, 2016; Schulz, 2011). However, with training, most workers achieved the target attenuation. Once workers are trained and have demonstrated the ability to fit the protector correctly, derating is no longer required. The worker's PAR can be used to estimate exposure and as evidence that hearing protector fits the worker.

Individualized training is essential for workers to achieve the best fit for their issued and preferred HPDs. Laboratory studies have demonstrated that trained subjects achieve better attenuation performance than naive subjects (Berger *et al.*, 1998; Murphy *et al.*, 2004; Joseph *et al.*, 2007; Murphy *et al.*, 2009; Murphy *et al.*, 2011). The selected studies presented in this paper also validate the need for individualized fit training. Chinese workers who were individually trained demonstrated retention of the ability to properly fit earplugs six months after the initial training (Gong *et al.*, 2019; Liu *et al.*, 2020).

Copelli *et al.* (2021) reported that workers with the lowest PARs tended to exhibit the greatest improvement following training. Bone conduction limits the maximum amount of attenuation achieved by hearing protection in frequencies at and above 2000 Hz. A person achieving more than a 30 dB PAR is already approaching the maximum attenuation for earplugs in frequencies above 2000 Hz. Any deeper insertion of the earplug will improve the low-frequency performance, but still be limited by the bone conduction limit of about 42 dB at 2000 Hz (Berger *et al.*, 2003). In contrast, persons with poorly fit earplugs can increase attenuations by 25 or 30 dB with improved fitting techniques. Derating applies the same proportional reduction regardless of the protector and quality of fit.

Finally, derating is not consistent with the intent of the OSHA regulation for hearing conservation. That is, the regulation is to protect workers against the harmful effects of noise exposure. When an evaluation of a worker population defaults to a derated hearing protector rating, all workers are assumed to be performing equally badly. Training is not really training if there is no effort to quantify performance. A worker's fit-test PAR is the only way to assess who is or is not achieving an appropriate fit. Derating cannot identify who needs to be trained nor can it identify who may have too much attenuation.

C. Potential biases and limitations

The four studies reported herein are considered to represent a convenience sample that was available to the authors. A comprehensive systematic review of the effectiveness of hearing protector fit-testing and training is currently undergoing peer review with the Cochrane Policy Institute (Morata *et al.*, 2021). These four selected studies could be biased to higher attenuations because the workers and recruits were brought to the testing location and asked to insert the protector the way that they would normally wear the product. In the Casali and Park (1991) and Green *et al.* (1989) studies, workers were escorted directly off the production line and the performance of the protectors were tested as they were being worn on the job. In Berger *et al.* (1996), candid and scheduled fit-tests of the E-A-R™ Classic™ earplug exhibited small differences (a few tenths of a decibel) and allowed the attenuations to be pooled. In this study, the tests were all scheduled and the subjects fitted their own earplugs. The potential for slightly greater attenuations exists for scheduled tests.

Selection bias exists in the NIOSH advanced hearing protection study. Subjects were not randomly recruited. The factory's occupational safety and hygiene group announced the fit test study to the entire facility. Workers who volunteered to participate in the study received a $100 stipend if they completed the entire study ($25 per visit). Workers were randomly assigned to the different training groups. Because the Sonomax group had the custom earplugs manufactured *in situ*, they received more in-depth training about the earplug's care and use. The other cohorts used products they were familiar with. The counseled group were given extra information about fitting their protectors. If the product they chose did not fit correctly, they were offered a different earplug and were retested to ensure a proper fit.

The employees in the Chinese worker studies were often curious to learn how they should wear the earplugs. The companies that participated in those studies were already interested in improving their workers' hearing protector performance and could be biased towards doing more to protect their workers. There is potentially a bias in the Chinese worker studies' data to consider that the workers all received individualized training.

The USMC studies had less selection bias. The 2016 USMC fit test study tested recruits ($N = 320$) who were randomly selected by local leadership from all base-wide battalions, then randomly assigned by study personnel to their specific test groups. Selection and randomization were blinded to both parties. Specifically, participant selection was completed by non-study personnel, and group assignment was made by study personnel with no knowledge of any subject demographics. The subjects who failed to achieve the 25.0 dB PAR were selected for further training.

The 2021 USMC fit test study tested recruits who were randomly selected by local leadership from all base-wide battalions during basic training. Recruits who failed to achieve the 25.0 dB PAR were randomly assigned to one of the three training protocol groups. In order to create intervention cohorts of approximately 100 recruits, the pass/fail rate from Federman and Duhon (2016) was used to identify the total number of persons required to test. This resulted in a total of 798 recruits being initially tested. Like the 2016 USMC study, random assignment to one of the three training cohorts was done by study personnel blinded to any subject demographic information.

The E-A-Rfit™ and the FitCheck Solo fit test systems were used to collect the data that have been presented in this analysis of PARs. While both systems report an A-weighted attenuation, the PARs are not calculated in the same manner. The E-A-Rfit™ includes two terms when reporting the

84th percentile PAR. The first term is an estimate of spectral uncertainty that describes how the measured noise reduction would be affected according to the noise spectra where the protector is worn. The high frequency attenuation of HPDs is typically greater than low frequency. Consequently, a range of PARs is estimated when E-A-Rfit™ applies the attenuations to a database of noises. The second term is the repeatability of the fit. Each fit of an earplug or earmuff can be slightly different, and each measurement of a fit can have some variability. E-A-Rfit™ applies corrections for the repeatability when reporting the 84th percentile PAR. In contrast, FitCheck Solo estimates the PAR using an A-weighted attenuation method (Murphy *et al.*, 2016). No adjustment for the spectral variability is provided. The PAR from FitCheck Solo would be comparable to the 50th percentile PAR reported by E-A-Rfit™. The differences in PAR estimates can be seen in Fig. 2 for the 3M 1260 and 1100 earplugs. The PARs from E-A-Rfit™ are generally lower than those for the FitCheck Solo system. Murphy (2013) considered different methods for estimating PAR. The ASA/ANSI S12.71 (2018) standard specifies a method for determining PAR. The E-A-Rfit™ fit test system is currently the only commercially available product that incorporates the corrections as specified in ASA/ANSI S12.71. Regardless of any inherent differences in the PAR calculation, PARs will provide a better estimate of the protection workers achieved and therefore a better estimate of exposure.

V. CONCLUSIONS

The fit of the HPD is the most important factor in hearing protector attenuation. Effective use incorporates both attenuation and comfort of the HPDs for the user. The convenience or accessibility to protection and the cost of purchasing HPDs for the workforce are also important factors. The growing body of literature is rich and provides practical evidence supporting the notion that individuals, including those who have been trained in hearing protection fitting and those who have not, get a wide range of attenuation levels. In some cases, even from one fit to another with the same protector, individual attenuation levels are inconsistent. Derating schemes have become marginalized due to their inability to predict real world attenuations and consequently noise exposures. Not only do hearing protector fit-testing systems provide an attenuation estimate at the level of the individual worker, noise exposure estimates using PAR values will be more accurate than relying on derating schemes. In addition to the increased accuracy for epidemiologic research, individuals who fail to achieve a desired PAR can be provided immediate training to ensure that their hearing is adequately protected. Regardless of any inherent variance in how fit testing systems calculate PAR values (Byrne *et al.*, 2017, Murphy, 2013), they are all superior to the estimated derated NRR value.

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