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Original Article

Individual Fit Testing of Hearing Protection Devices Based on Microphone in Real Ear

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ABSTRACT

Background: Labeled noise reduction (NR) data presented by manufacturers are considered one of the main challenging issues for occupational experts in employing hearing protection devices (HPDs). This study aimed to determine the actual NR data of typical HPDs using the objective fit testing method with a microphone in real ear (MIRE) method.

Methods: Five available commercially earmuff protectors were investigated in 30 workers exposed to reference noise source according to the standard method, ISO 11904-1. Personal attenuation rating (PAR) of the earmuffs was measured based on the MIRE method using a noise dosimeter (SVANTEK, model SV 102).

Results: The results showed that means of PAR of the earmuffs are from 49% to 86% of the nominal NR rating. The PAR values of earmuffs when a typical eyewear was worn differed statistically ($p < 0.05$). It is revealed that a typical safety eyewear can reduce the mean of the PAR value by approximately 2.5 dB. The results also showed that measurements based on the MIRE method resulted in low variability. The variability in NR values between individuals, within individuals, and within earmuffs was not the statistically significant ($p > 0.05$).

Conclusion: This study could provide local individual fit data. Ergonomic aspects of the earmuffs and different levels of users experience and awareness can be considered the main factors affecting individual fitting compared with the laboratory condition for acquiring the labeled NR data. Based on the obtained fit testing results, the field application of MIRE can be employed for complementary studies in real workstations while workers perform their regular work duties.

1. Introduction

The objective of an effective hearing conservation program is to minimize the health risks associated with noise exposure, and to prevent hearing loss. One of the main elements of this program is the provision of suitable hearing protection devices (HPDs) to workers exposed to industrial noise and monitoring their suitable usage [1,2]. HPDs are commonly used during the short-term period before the noise is effectively reduced by implementation of engineering controls, or when engineering or administrative controls are not feasible [3,4]. The willingness of workers to use HPDs as passive earmuffs is associated with some important factors such as worker preference and their efficiency. Unreliable nominal noise reduction data presented by the devices are considered the main barrier to rely on hearing protectors as an effective noise control measure. Numerous studies have reported that the reliability of the labeled data to estimate the real noise attenuation of HPDs is poor [5,6].

The noise reduction rating (NRR) is a single-number, laboratory-derived rating that the US Environmental Protection Agency proposed to be shown on the label of each hearing protector. The National Institute for Occupational Safety and Health (NIOSH) proposed the derating method to compensate for known differences between the laboratory-derived noise attenuation values and the noise protection provided by a hearing protector in the real world. Based on the recommended protocol, the labeled NRRs shall

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be derated as follows: (1) earmuffs—subtract 25% from the manufacturers' labeled NRR; (2) formable earplugs—subtract 50%; and (3) all other earplugs—subtract 75% from the manufacturers' labeled NRR. Moreover, for calculating the effective noise exposure to the wearer of a hearing protector at the workplace, the Occupational Safety and Health Administration (OSHA) also derates the NRR by 50% for all types of hearing protectors. Therefore, the NRR cannot be used as a measure of field noise attenuation even when various derating schemes are used to account for the differences between the laboratory and real-world NRR [7]. An individual HPD fit-testing method estimates the amount of noise attenuation that a worker achieves from a given HPD in a particular wearing way and at a particular time and determines whether the worker has sufficient noise protection [8,9].

Real-ear attenuation at threshold (REAT) is the gold-standard technique of fit testing presented by ISO 4869-1 [10,11]. REAT, as a subjective method, was performed by evaluating audiometric hearing threshold levels on an individual with (occluded) and without (unoccluded) hearing protectors [10]. The difference between the occluded and unoccluded thresholds in one octave band is equivalent to the noise attenuation or exact insertion loss (IL) in decibels acquired by the HPDs [11]. NRR values for hearing protectors were calculated using ILs in one octave band. One of the main drawbacks of the REAT method is that the measurement of hearing threshold is a time-consuming task. Furthermore, it should be repeated for each ear and can have some differences in the standard deviation values of the attenuation results [9,12]. It should be noted that accurate REAT measurements require individuals with normal hearing and a very quiet booth so that the open-ear thresholds are not masked and contaminated [13]. This method relies on optimum fitting under laboratory conditions and group statistics to predict performance of hearing protector. The calculated noise attenuation rating is therefore generally higher than the measured noise attenuation rating in the field [14].

The recent development of measuring equipment that can determine HPDs' performance under field conditions along with reasonable accuracy and speed has facilitated the individual fit testing. One of the main objective techniques of HPDs fit testing is microphone in real ear (MIRE) [14]. Field application of MIRE (FMIRE) has been also developed to make rapid and accurate fit testing of the HPDs in occupational settings [9,15]. The MIRE technique is performed by placing a microphone in the ear canal to measure the sound level at the eardrum. The noise attenuation of a hearing protector can be determined from the difference of the sound levels in the ear canal with and without HPDs and is termed IL (measured in dB). The MIRE can also be performed through two microphones, one placed inside the ear canal underneath a hearing protector, and the other simultaneously placed outside the ear. In this mode, the noise attenuation is the difference between the sound levels measured simultaneously by the internal and external microphones, and is termed noise reduction (NR; measured in dB) [7].

However, NR levels are different from IL values by factors that are defined as the transfer function of the open ear (TFOE; e.g., IL = NR + TFOE). TFOE is the amplification relative to the undisturbed sound field caused by ear canal and pinna resonances and the effect of head presence. Individual-specific TFOE factors can be measured with MIRE measurements and extracted from the estimated TFOE values for ears mentioned in the international standard method, ISO 11904-1 [7,16].

In general, the MIRE method had greater speed and efficiency than the REAT method. Its results also had smaller frequency-specific standard deviations than the REAT method. It should be mentioned that the MIRE technique is an objective approach that does not depend on the human responses [12,17].

As mentioned earlier, if local individual fit data are not available, the international institutes proposed using the derating methods to compensate for known differences between the labeled noise attenuation values and the real noise protection obtained by a hearing protector [13,18]. In developing countries such as Iran, occupational health experts also reported that unreliable NR data of HPDs are considered the main challenge to achieve an efficient hearing conservation program. This study aims to evaluate the actual NR data of the commercially available HPDs based on the MIRE method. The results of this study can provide local individual fit data and propose the native derating pattern of the HPDs.

2. Materials and methods

Five commercially available earmuff protectors used by Iranian workers in noisy workplaces were selected to assess the actual noise attenuation data under the reference conditions. Based on the ethical and legal considerations, the protectors studied were nominated as manufacturer models A, B, C, D, and E. Thirty workers participated in the study (age, 25 $\pm$ 3.5 years). Each worker was asked to sign an informed consent form prior to experiments. Three samples of each earmuff were tested. Each sample was tested for all workers and the measurements were repeated three times. This experimental study was performed according to the recommendations of the standard methods [10,16]. The standards describe the procedure for measuring IL in the MIRE technique and it presents the specifications regarding the participants, instrumentation, test signal, sound field etc. [12,16]. As recommended by American National Standards Institute (ANSI S12.6-2008), a brief training program was conducted for all workers. Moreover, workers fit HPDs themselves without assistance [10]. The experiments were performed in a custom-built acoustic lab at Hamadan University of Medical Sciences (Hamadan, Iran).

2.1. Experimental setup

The test room characteristics included semireverberant space with T60 < 1.6 seconds and low background noise level according to the standards specifications [10]. The MIRE technique was performed by placing a microphone in the ear canal to measure the sound level at the eardrum. In this regard, the microphone is proximal to the ear canal and the probe is in the ear canal. The noise attenuation of a hearing protector can be determined from the difference of the sound levels in the ear canal with and without HPDs and is termed IL (in dB). Schematic of the experimental setup for measuring IL in one octave band is shown in Fig. 1. It should be noted that this figure was reproduced from SV 102+Data sheet 2016 which is available at website: http://www.svantek.com.

Measurements based on the MIRE technique were performed using the SVANTEK SV 102+, Class 2 dual-channel dosimeter (SVANTEK SP. Z O.O., Warsaw, Poland). An SV 25S microphone, Type 2, has been also designed together with SV 102+ dosimeter that specifies methods for the determination of sound level in the ear canal by different lengths of probes, easily controlled and placed in repeatable position. An SV 25S microphone measured sound level in the ear canal by a probe that was placed at the entry of the ear canal. The length of the probe was selected as 16 mm to ensure maximum comfort and to protect from contact with the eardrum [19]. Calibration of the SV 25S microphones was performed with an SV30/SV31 acoustic calibrator. For all real-ear measurements, the proper placement of the probe tube is important. The tip of the probe tube must be placed within approximately 5 mm of the eardrum to avoid standing waves and to assure that the high-frequency components of the response are accurately measured.

Fig. 1. The schematic setup for measuring insertion loss of the hearing protection devices (Courtesy SVANTEK).

Location of the loudspeaker relative to the individual is another important consideration while obtaining real-ear measurements. Based on the recommendation, the distance between the loudspeaker and the worker was chosen as 1.0 m. The artificial omni sound source with 12 matched loudspeakers and remarkable output power of 115 dB (developed by BSWA Technology Co. Ltd. Beijing 100029, China) was used. The test signal was continuous pink noise with a sound pressure level of 90 dB (±1 dB) at the listener's hearing zone. The data were acquired using a dual-channel acoustic dosimeter in a short time of about 60 seconds for any fit test on each ear to obtain data at seven standard test frequencies from 125 Hz to 8 kHz. It should be noted that each worker wore five HPDs, and therefore, five time measurements were performed based on the MIRE technique for each worker. Moreover, the actual attenuations of the earmuffs along with wearing a typical safety eyewear (with medium frame, 3 mm) were also measured. It should be mentioned that five workers were employed to participate in this part of experiments.

2.2. Determination of personal attenuation rating

The ILs in one octave band for each HPD were used to calculate the noise attenuation rating called the personal attenuation rating (PAR) [20]. The PAR is calculated in a manner similar to the Noise Level Reduction Statistic for use with A weighting as defined in ANSI S12.68-2007 except that it is calculated individually for each user and reported as a mean of PAR values [21]. Mean of PAR values can be directly subtracted from A-weighted sound levels to estimate protected noise levels or exposures. In this study, a pink noise measuring 100 dB (sound pressure level) in each one-third octave test band was assumed. Each of these test bands was A-weighted and then summed to give an overall A-weighted exposure level. Next, the measured noise attenuation data in decibel in each of the seven bands were subtracted from the A-weighted level in the corresponding band. The resulting differences were summed to give an overall A-weighted level under an HPD. Finally, the PAR was calculated as the difference between the overall A-weighted unprotected exposure level and the overall A-weighted protected level [8,9].

2.3. Determination of the workers' TFOE

The MIRE can also be performed through two microphones, one placed inside the ear canal underneath a hearing protector, and the other simultaneously placed outside the ear. In this mode, the noise attenuation is the difference between the sound levels

Fig. 2. Schematic setup for measuring noise reduction of the hearing protection devices (Courtesy SVANTEK).

Table 1
PAR values of the earmuffs compared with the labeled noise reduction rating

Manufacture types	NRR (dB)	PAR (dB)		PAR/NRR (%)
		Mean ± SD	Range	
A	20	17.2 ± 3.4	9.0–22.0	86
B	25	12.3 ± 4.4	7.6–24.7	49
C	25	14.4 ± 3.9	8.2–22.3	58
D	26	18.9 ± 5.0	9.6–26.0	69
E	30	15.2 ± 3.5	9.3–20.8	51

NRR, noise reduction rating; PAR, personal attenuation rating.

measured simultaneously by the internal and external microphones, and is termed NR (in dB) [7]. The experimental setup for measuring NR of the HPDs is shown in Fig. 2. It should be noted that this figure was reproduced from SV 102+Data sheet 2016 which is available at website: http://www.svantek.com. The location of the outer microphone was fixed at a distance of 15 cm from individuals' ear. As mentioned, NR levels are different from IL values by factors that are defined as the TFOE (e.g., IL = NR + TFOE). In this regard, the values of TFOE of the studied workers in one octave band were calculated.

The TFOE factors can also be extracted from the estimated TFOE values for ears mentioned in the international standard method, ISO 11904-1. However, the recommended values can vary from one population to another. Importantly, in real situation of workplaces, the workers have exposure to fluctuating noise from various industrial sources, and therefore, measurement of ILs of HPDs during work activities is impossible. However, NR using the MIRE technique can be measured through two microphones, of which one is placed inside the ear canal underneath a hearing protector and the other is simultaneously placed outside the ear. Hence, the main application of the TFOE factors is calculation of ILs using NR data in actual conditions of workplaces. The data were analyzed using SPSS 21 software (SPSS Inc., Chicago, IL, USA). The statistical significance was set as $p < 0.05$.

3. Results

The PAR values of the earmuffs were determined based on the difference between the overall A-weighted unprotected exposure level and the overall A-weighted protected level of all workers. The PAR values of the tested hearing protectors compared with the labeled NRR are shown in Table 1. As shown in Table 1, the means of PAR were from 49% to 86% of the nominal NRR. Fig. 3 illustrates the comparison of the actual and labeled (nominal) ILs in one octave bands for the tested HPDs. The graphs showed that very slight noise attenuations occur at the low frequencies.

The PAR values of earmuffs along with wearing a typical safety eyewear are presented in Table 2. The PAR values of earmuffs when a typical eyewear was worn differed statistically ($p < 0.05$). It is revealed that a safety eyewear (with medium frame, 3 mm) can reduce the PAR values of the earmuffs by approximately 2.5 dB.

The variability in PAR values from between individuals, within individuals, and within earmuffs values based on the standard deviations is shown in Table 3. The between-individual variability shows the differences in IL achieved by each worker. The within-individual variability shows the difference in IL achieved by each fitting for any worker. In other words, it represents the effect of earmuff refitting. The within-earmuff variability represents the changes in IL achieved by each earmuff of any manufacturer. The results showed that the variability values were relatively stable. The variability in PAR values between individuals, within individuals, and within earmuffs was not statistically significant ($p > 0.05$). These findings confirm the importance of measuring variability for HPDs, rather than relying on single measurements.

As mentioned, TFOE is the amplification relative to the undisturbed sound field caused by ear canal and pinna resonances and the effect of the head presence. The TFOE for workers was calculated based on the difference between IL and NR values in one octave band. Mean of TFOE values for the studied workers in one octave band frequency is presented in Fig. 4. It should be noted that workers are often exposed to fluctuating noise in real workstations during normal working conditions. Therefore, the NR values (in dB) can only be determined using the MRIE method in workrooms. In the next step, based on the calculated TFOE values, the NR values can be used to calculate the IL (in dB) of the hearing protectors.

4. Discussion

The labeled NR data presented by the manufactures are one of the main challenging issues of occupational experts for employing a hearing conservation program. For earmuffs, NIOSH proposed that a subtraction of 25% from the manufacturers' labeled NRR and OSHA also derates the labeled NRR by 50% for all types of hearing protectors. Our results showed that means of PAR values were from 49% to 86% of the labeled NRR. The results confirmed that the noise protection data of the tested hearing protectors were approximately similar to OSHA and NIOSH derating patterns [7]. Occupational health experts can use the individual fit data obtained from the current study for workers who have fitting from poor to acceptable conditions.

The comparison of the actual and labeled (nominal) ILs of the tested HPDs in one octave band showed a considerable difference, especially in low-frequency noise. Some causes can describe the difference between the results of MIRE and labeled data from REAT at lower frequencies. First, due to physiological noise masking, the workers overestimate HPD attenuation during REAT tests. Second, noise leakage due to poor fitting is most effective in low-frequency band [9]. Henrique et al [22] reported that noise leakage can occur at frequencies ranging from 125 Hz to 2,000 Hz due to the nature of the foam lining of the cup. They also indicated that a Vaseline coating between the head surface and the cushion improved the noise ILs at low frequency. The quality and ergonomic aspects of the cushion of the hearing protector are responsible for the comfort in the contact between the cup and head of the worker, so it is necessary to try to produce new materials for the cushion along with less noise leakage [23]. The lack of speech intelligibility is another reason why workers may not fit hearing protection completely. Therefore, new studies emphasize on the development of electronic earmuffs that enable conversation but filter out the noise for special jobs [24].

Some of industrial activities require the combined use of eyewear and hearing protection. The results indicate that the actual noise attenuation rating along with the use of eyewears can reduce noise by approximately up to 2.5 dB. Sergio and Caporali [25] also reported that use of earmuff along with protective eyewear had a significant effect (5%) on earmuff IL.

The results showed that measurements based on the MIRE method resulted in low variability. The main advantage of the MIRE method is its objectiveness, so this removes possible errors caused by human perception [13]. The nonsubjective nature of the MIRE test led to results with good reproducibility and a small standard deviation, indicating that it has high precision for evaluation of noise attenuation of HPDs [13]. As mentioned, the REAT method requires the individual to hear, listen, and respond to test tones in

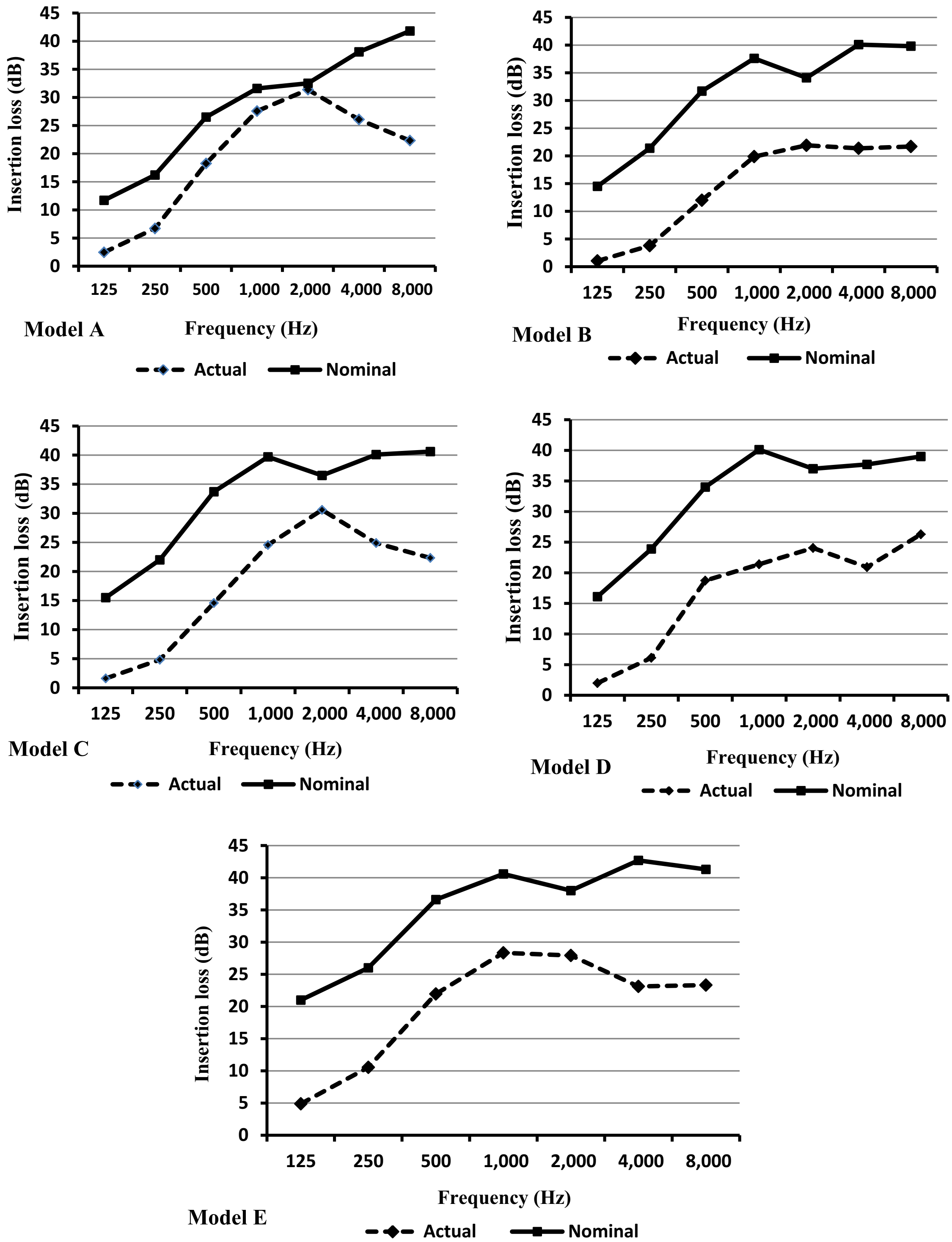

Fig. 3. Actual insertion losses compared with the nominal insertion losses for the tested hearing protectors.

an active fashion, and thus may be problematic for workers with impaired hearing, test anxiety, attentional issues, or other confounders [26].

One advantage of the MIRE is that it can be used to test noise attenuation over a wide range of sound levels to explore the potential level-dependent attenuation of certain devices [27]. Because of the recent development of systems that can measure individual performance under field conditions with reasonable accuracy and speed, the concept of individual fit testing is now feasible. As mentioned, Berger et al [14] developed field MIRE as an alternative approach for objective fit testing in occupational settings. This new approach presents a novel advantage that it can be conducted in real condition of the workplaces when workers are being exposed to industrial noise during normal working conditions. Using FMIRE, noise levels are recorded in the ear canal under the hearing protector, as well as those outside the HPDs. The

Table 2
Personal attenuation rating (dB) of the earmuffs when eyewear was also worn

Manufacture types	With eyewear	Without eyewear
A	13.8 ± 1.9	16.5 ± 1.9
B	9.7 ± 1.4	12.7 ± 4.6
C	14.8 ± 1.8	17.2 ± 2.2
D	16.4 ± 4.6	18.0 ± 5.4
E	14.0 ± 2.5	16.2 ± 3.5
Total	13.7 ± 3.6	16.2 ± 4.2

Data are presented as mean ± SD.

Table 3
Variability in the PAR values (dB) between individuals, within individuals, and within earmuffs based on the standard deviation

Manufacture types	Within earmuffs	Within individuals	Between individuals
	Mean (min–max)	Mean (min–max)	Mean (min–max)
A	1.1 (0.2–1.6)	0.4 (0.2–0.8)	1.2 (0.9–1.4)
B	1.2 (0.7–1.7)	0.4 (0.1–0.7)	0.8 (0.7–0.9)
C	0.7 (0.4–1)	1.1 (0.1–1.5)	1 (0.8–1.1)
D	0.7 (0.2–1.4)	0.8 (0.1–1.2)	0.9 (0.8–1.0)
E	0.9 (0.5–1.3)	0.7 (0.1–1.5)	0.8 (0.4–1.2)

PAR, personal attenuation rating.

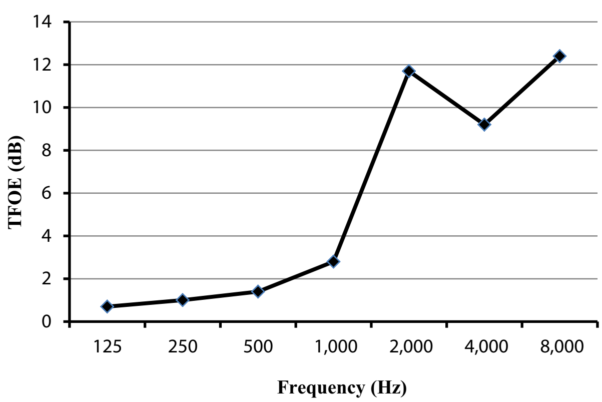

Fig. 4. Mean of the real transfer function of the open ear (TFOE) values for the workers in one octave band.

difference is termed the NR. In this regard, based on the obtained TFOE values, the NR values acquired by FMIRE can be used to calculate the IL (in dB) of the hearing protectors. The results of this study can be followed by using FMIRE for complementary studies on performance of HPDs in real condition of workplaces with actual noise sources.

5. Conclusions

This study provided local individual fit data. The results proposed a native derating pattern for the labeled NRR of the HPDs. These data can be employed by occupational health experts to achieve an effective hearing conversion program. It can be concluded that the main factors affecting individual fitting are the ergonomic aspects of earmuffs and different levels of users experience and awareness compared with the laboratory condition of manufactures for acquiring the labeled NR data. It was observed that the size of some earmuff cups was slightly smaller than the dimensions of workers' auricles. Moreover, a number of workers have higher skill for earmuff fitting than others. This study can be followed by employing FMIRE for complementary studies on performance of HPDs in real workstations while workers perform their regular work duties. Our study also has some notable achievements: MIRE as an objective method was used for performance evaluation of the current earmuffs used in typical industrial workplaces, especially in Iran. We also determined the actual noise attenuation ratings of the current earmuffs used by the Iranian workers. For first time, mean of the actual TFOE values for typical cases in one octave band frequency was presented, which is comparable with the estimated values recommended by the International Standard Organization.

Conflicts of interest

The authors have no conflict of interests to declare.

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