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An Acoustical Analysis of the Frequency-Attenuation Response of Musician Earplugs

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Abstract

Musician earplugs (MEP) are intended to reduce the risk for noise induced hearing loss among musician populations while providing flat attenuation characteristics. However, survey data suggest that low use rates among musicians are associated with negative listening experiences due to perceived alterations in the spectral characteristics of music. These shortcomings warrant the assessment of how a MEP processes the full frequency and complex spectral nuances of musical sounds. The goal of this study was to assess the influence of musician earplugs on musical stimuli using an acoustic test fixture in order to characterize objectively the influence of custom- and non-custom-fit MEPs on both the attenuation levels and the spectral characteristics of music in and over a wide range of intensity levels in a simulated human ear canal. Our objective measurements inside ear of KEMAR confirm that the spectral characteristics of music are altered by MEPs, regardless of whether the earplug was a non-custom or custom earplug. The findings suggest that the claims used to market MEPs to musicians and music schools are misleading and that the discrepancies for claiming attenuation characteristics in response to musical stimuli are related, in part, to the use of the REAT testing procedure. New testing protocols are recommended.

Keywords: Musician; Musician earplug; Noise-induced Hearing Loss (NIHL); Real-Ear at Threshold Attenuation (REAT)

Introduction

Student musicians, music teachers, and music professionals engaged in ensemble-based activities are potentially at-risk for noise-induced hearing loss (NIHL). The risk stems from these routine activities occurring at sound pressure levels (SPLs) that exceed the permissible exposure limits (PELs) established by the National Institute for Occupational Safety and Health [1]. While neither the OSHA (Occupational Safety and Health Administration) nor NIOSH have yet to develop a hearing conservation standard specifically for such music-related activities, Etymotic Research developed a custom fit earplug trademarked as Musicians Earplugs [2]. The musician earplug (MEP) is designed with a pre-fabricated filter that couples to the lateral-end of a custom-made mold having a bore. The filter is sold with three levels of attenuation (9-, 15-, and 25-dB), and marketed by Etymotic Research as ER-9, ER-15, and ER-25, and by Weston as the ES49 Custom Fit Hearing Protector. These earplugs are marketed to audiologists and musicians with the special claim that these earplugs reproduce sound as it is normally heard, but at a lower intensity, preserving the tonal balance of music [3].

To circumvent the high costs associated with adopting the custom MEP, a non-custom ready-fit version of this product was jointly developed and patented by Etymotic Research and the Aearo Corporation [4]. These non-custom-fit MEPs are labeled and sold by Etymotic Research as ETY-Plugs and the ER-20 High Fidelity Hearing Protector. An online search further revealed that this same product is marketed to musicians directly as the HEAROS High Fidelity Earplugs, the WestStar Earplugs ER 20, the Fender Touring Earplugs, and the Vic Firth VICEARPLUG. Further, the non-custom-fit MEP is marketed directly to public school music programs [5] through a national marketing campaign called Adopt-a-Band [6]. The non-custom-fit version, like their custom-fit counterparts, is marketed with the special claims that these products “replicate the natural response of the ear canal so that when sound enters the earplug, it is reproduced unchanged, exactly as the ear would hear it, only quieter” [7].

A literature review examining these special claims suggests that musicians rate the use of these products negatively [8-12]. In addition to problems with pressure, pain, and discomfort, musicians report low-usage rates of MEPs due to interference with playing ability, distortion of timbre, sonority, and dynamics of the music they and others are playing. Musicians also report difficulty monitoring their own playing, that the custom-fit MEPs are not better than pre-formed, and that the problems created by wearing these products are worse than the fears of hearing loss. Another concern is that musicians perform differently when using MEPs due to the pronounced effect on both the sound level and the spectral characteristics of the musical output of performing musicians [13].

The disparity between the special claims and what musicians report, we conjecture, stem from the possibility that MEPs do not reduce music equally across the frequency range, provide adequate attenuation, or both. Currently, the data used to support the validity of the special claims are predicated on the Real-Ear Attenuation at Threshold (REAT) test procedure (ANSI S12.6-1997) [14], a subjective method of determining the attenuation of a hearing protector by subtracting the open-ear hearing threshold from the occluded ear threshold. Historically, the REAT was designed to provide estimates obtained by listeners with normal-hearing sensitivity in a laboratory setting, based on subjective unoccluded and occluded hearing thresholds of non-musician subjects at octave frequencies ranging between 125 and 8000 Hz. To date, there is insufficient evidence that

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REAT testing adequately quantifies whether a hearing protector preserves the tonal balance of music, reduces sounds equally across the frequency range associated with music, and reproduces musical sounds for the user as heard in an unoccluded condition. The evidence is based on the fact that the REAT procedure includes neither music stimuli nor musicians as test subjects. Music is characterized by complex spectral characteristics, most of which are concentrated in the low frequencies (i.e., <100 Hz). Research has shown that the REAT procedure has known limitations for accurately assessing occluded perception of frequencies below 500 Hz, due to masking by physiological noise [15].

Together, these shortcomings warrant the assessment of additional methods for understanding how an MEP processes the full frequency and complex spectral nuances of musical sounds. This is the goal of the present study. Specifically, our goal is to assess the influences of earplugs on the spectral characteristics of musical stimuli using an acoustic test fixture (i.e., KEMAR; Knowles Electronics Manikin for Acoustic Research) [16]. Using this approach, we are able to characterize objectively the influence of custom- and non-custom-fit MEPs on both the attenuation levels and the spectral characteristics of music in and over a wide range of intensity levels in a simulated human ear canal. Findings from the present study will be used to direct future studies related to the influences of acoustic alterations of MEPs on perception.

Methods

Earplugs

A custom-fit MEP was ordered from Westone Laboratories from earmold impressions taken on the right ear of KEMAR, along with three attenuating filters (ER-9, ER-15, ER-25). For the non-custom-fit earplug, we used a single ER-20 earplug obtained from Etymotic Research.

Musical stimuli

The stimuli used in this study were digital music recordings of ensemble-based activities at the College of Music, University of North Texas (UNT). The recorded music represented a cross section of genre, ensemble size, and performance venue. Ten musical segments, each between 20 and 25 seconds in duration, were placed in a single wav file (16-bit, 44100 Hz sampling rate) with a two-second silent interval inserted between each musical segment (Figure 1). The inclusion of the silent interval allowed us to analyze the implications of each recording in additional detail.

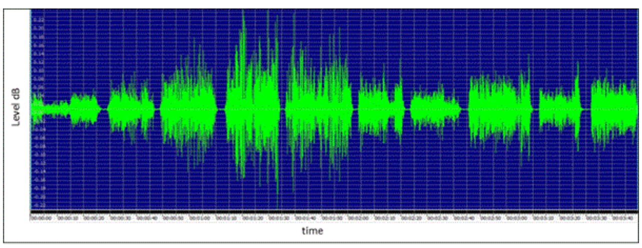

Figure 1: Waveform depicting the 10 short musical segments used as stimuli for this study.

Procedures

We recorded and analyzed the musical stimuli presented to KEMAR without and with the four MEPs (ER-9, ER-15, ER20, ER-25). KEMAR-based recordings of the musical stimuli took place in a multi-use music studio housed within the UNT College of Music. The studio measured 5.9 m (l) x 4.2 m (w) x/3.0 m (h), had a carpeted floor, concrete-block walls with acoustic damping material covering one third of each wall area, and a suspended ceiling with standard 2 feet x/2 feet acoustical panels. This multi-use music studio contained a table, 2 chairs, audio-visual equipment, and a measured reverberation time of 1.246 seconds for the frequencies of 500, 1000, 2000, and 4000 Hz.

During testing, the musical stimuli were presented simultaneously from eight loudspeakers positioned in 45-degree increments relative to 0-degrees azimuth. The loudspeakers (Tannoy 800A) were positioned at an equal distance of 1 meter relative to the center-head position of KEMAR and at a height of 1.5 meters. We recorded the influence of the MEP only in the right ear of KEMAR. Separate recordings of the musical stimuli were made for five conditions that included the unoccluded condition and four occluded conditions (ER-9, ER-15, ER-20, ER-25). Each condition was retested at nine presentation levels, between 85 dB and 109 dB in 3-dB intervals. The presentation levels were determined by presenting pink noise through the loudspeaker array and measuring the sound pressure levels (+1 dB) at 1000 Hz using a sound level meter (Larson-Davis 800B). All five conditions were recorded, as illustrated in Figure 2, before proceeding to the next presentation level, in order to control for influences of presentation level across conditions. Because the experimental procedure required removal and reinsertion of earplugs prior to recording each condition, all artifacts associated with insertion anomalies or custom-fit MEP filter-to-body connections would be noted during the acoustical analysis. Photographs were taken of each condition to verify fit. During the recording process, the amplified output from KEMAR (Etymotic Research microphone preamplifier model ER-11) was routed to a personal computer and saved as a monaural wav file (16-bit resolution, 44100 Hz sampling rate).

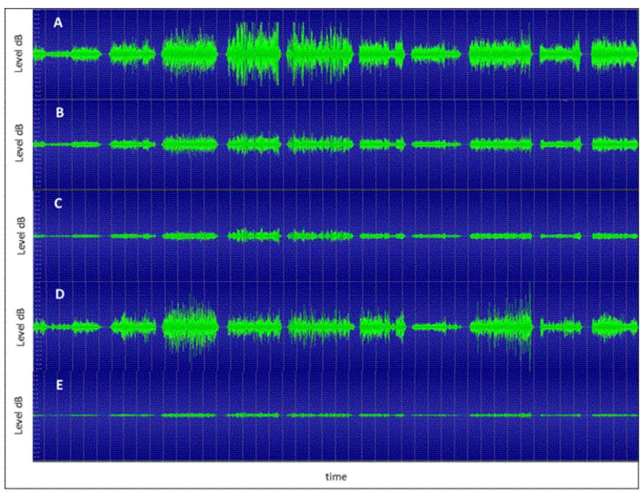

Figure 2: Wave files of the musical stimuli recorded through each of the ear plugs placed on KEMAR at 91 dB SPL. Panels A=unplugged; B=ER-9; C=ER-15; D=ER-20; and E=ER-25.

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Acoustical analyses

Spectral analyses of each KEMAR-recorded condition were determined by estimating the frequency content using a Fast-Fourier Transformation (FFT) algorithm written in Matlab. Each wav file was analyzed using a 1024-sample FFT, yielding a spectral line resolution of 43.07 Hz (i.e., sampling rate of 44100 Hz/1024-sample FFT). We employed the use of a rectangular window, based on the findings of Maddage and colleagues [17]. Specifically, these authors revealed that a rectangular (i.e., uniform) window best captured the pseudo-random-dynamic properties of music, compared to a more traditional smoothing window (i.e., hamming). To reduce the effect of spectral leakage between windows, the FFT was overlapped by 75%. The use of the additional overlap provided a high-resolution output in both the frequency and time domains.

Leq/Dose: A limitation of the rectangular window is its inability to capture the amplitude characteristics of a signal adequately. To overcome this limitation, a second Matlab algorithm was written to calculate the time average level, or equivalent continuous noise level (Leq), for each condition. Specifically, the algorithm calculated the A-weighted sound pressure level (dBA) in octave bands using a Kaiser-window filter for anti-aliasing for a given input wav file. The equation used to calculate dBA was:

$$L = 10\ \log \sum_{i=1}^{n} 10^{Li + Ki/10}$$

where L represented the combined level in dB SPL, n the number of bands being combined, i the ith band, Li the octave band level, and Ki the A-weighted correction to simulate human auditory sensitivity for the octave frequencies ranging between 31.5 and 8000 Hz, per ANSI S1.4a-1985 (R2006) [18].

Results

Influence of presentation level on spectrum of music

Figure 3 shows the spectral characteristics of the music stimuli across the nine presentation levels measured in the unoccluded condition. As expected, much of the acoustic energy in this music was in the low frequencies. In addition to showcasing the influence of ear canal resonance, the data show remarkable stability of the spectral characteristics over the nine repeated measures and across intensity levels.

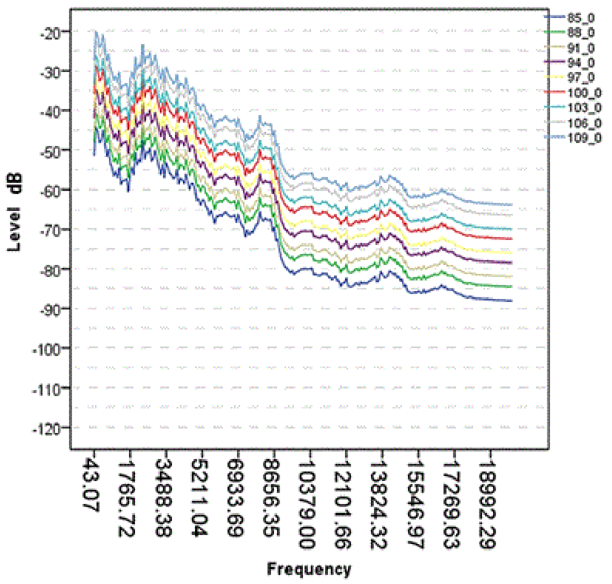

Figure 3: Spectral characteristics of music at nine presentation levels as measured unoccluded in KEMAR.

The spectral characteristics of the music stimuli for the nine presentations levels and across the four MEP conditions are shown in Figure 4. Similar to measurements of the unoccluded condition, the spectral characteristics of the music stimuli were highly stable within each of the four MEP conditions. Because the MEP was removed and reinserted prior to each presentation level, this finding also demonstrates that the spectral characteristics within each MEP condition were not influenced by 1) repeated or varied insertions of MEPs, 2) or anomalies due to disconnection and reconnection of filters to MEP earplug. However, comparisons across MEP condition show that each earplug type produced a unique spectral profile. These data show that each MEP condition had a unique influence on the spectral characteristics of the music.

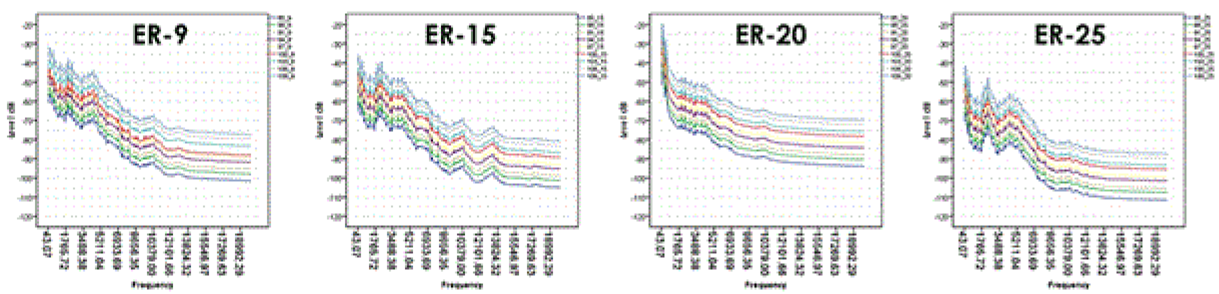

Figure 4: Spectral characteristics of music as measured in KEMAR at 9 presentation levels.

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Attenuation levels

As shown in Table 1, the mean attenuation levels across the nine presentation levels for the ER-9 and the ER-15 were significantly higher (p<0.01) than published rates by about 3.5 dB and 1 dB respectfully. The ER-25 and the ER-20 attenuation levels across the nine presentation levels were statistically lower (p<0.01) than published levels. The mean attenuation level across the nine presentation levels for the ER-20 was 4.8 dB, much lower than the reported 12 dB NRR level and markedly lower than the manufacturer-claimed 20 dB of attenuation for an earplug inserted correctly.

MEP Type	dB Mean (SD)	t	df	Sig	Mean Difference	95% CI	
						Lower	Upper
ER-9	12.7718 (.795)	14.226	8	.000	3.7718	3.1604	4.3832
ER-15	16.1757 (.471)	7.477	8	.000	1.1757	.8131	1.5384
ER-25	23.4805 (.730)	-6.242	8	.000	-1.5195	-2.0809	-.9582
ER-20	4.8658 (.443)	-102.36	8	.000	-15.1342	-15.4752	-14.7933

Table 1: Statistical comparisons based on one sample t-test.

Attenuation characteristics

Figure 5 shows the influence of each MEP condition on the spectral characteristics of the music stimuli by graphically contrasting the unoccluded condition to the occluded conditions at the 97 dB presentation level.

The resultant attenuation curves for each of the 4 MEP conditions, derived from graphing the differences between the unoccluded and the occluded conditions, are shown in Figure 6. Here, the data clearly show that the MEPs do not reduce music equally across frequency.

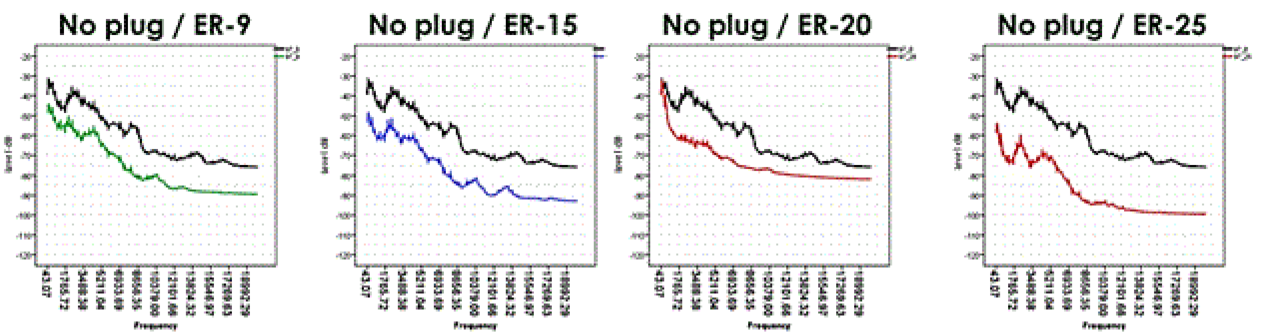

Figure 5: Frequency responses of MEPs compared to no plug condition as measured in KEMAR at 97 dB presentation level.

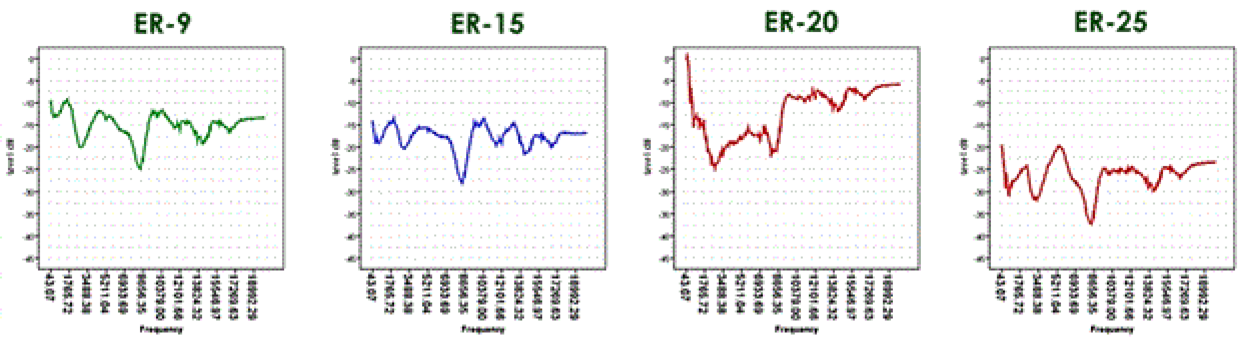

Figure 6: Attenuation responses for MEPs.

Discussion

Our objective measurements inside ear of KEMAR confirm that the spectral characteristics of music are altered by MEPs, regardless of whether the earplug was non-custom or custom earplug. Thus, MEPs do not attenuate musical stimuli in a way that reduces levels equally across frequencies. These results help explain why musicians 1) complain that the ER-15 distorts the timbre of music [9], 2) report the most important factor for non-use is sonority of their own instrument [8], 3) don't like the ER-15 because they change the natural sound of the instrument [12], and 4) can't communicate musically when using the ER-20 [11]. This also offers an important hypothesis regarding why the spectral characteristics of musical output changes when musicians use and perform using ER-15 earplugs [13].

The findings from this study are critically important because they suggest that the special claims used to market MEPs to musicians and music schools are misleading. We believe that the discrepancies for claiming flat attenuation characteristics in response to musical stimuli are related, in part, to the use of the REAT procedure. While the current study did not assess perception of timbre, dynamics, or other factors that may be considered critically important to musicians, the protocol did involve music stimuli along with an objective analytic technique sufficient for understanding how an earplug changes the spectral nuances associated with music. The Environmental Protection Agency (EPA) states that "Any manufacturer wishing to make claims regarding the acoustic effectiveness of a device, other than it noise reduction ratings, must demonstrate the validity of such claims, including the presentation of test data and the specific methods used to validate the claims" (Federal Register/Vol. 74, No 149, pg 3986). The REAT procedure is not a valid procedure for supporting the existing claims used in marketing MEPs to audiologists, musicians, and music schools.

The findings are also important because they show that the non-custom-fit MEPs sold under the name of ER-20, ETY, HEAROS, Fender Touring, and VICEARPLUG do not protect the user at the stated levels. The deficiency of attenuation provided by the ER-20 earplug is further illustrated in panel D of Figure 2. Marketing materials report an NRR of 12 but claim that the user can expect 20 dB of attenuation when the plug is used correctly [2]. In addition to showing the dramatic influence of the ER-20 on the spectral characteristics of the music stimuli, the protocol used in this study also revealed that the ER-20 offers less than 5 dB of attenuation while utilizing a best-fit scenario. The disparity in attenuation levels, we believe, is explainable by the fact that the REAT procedure does not measure or account for energy levels below 125 Hz. or between octaves as specified in the REAT procedure. Highlighting the significance of this measurement deficiency, and as shown in Figure 5, the ER-20 earplug failed to attenuate sounds at frequencies below 100 Hz. The authors believe that these findings point to a critical need for measurement protocols and reporting standards for earplugs specifically marketed to musicians, public schools, and schools of music. This standard should oblige manufacturers to provide data that are essential for understanding how an earplug responds to musical sounds and in a manner that the average lay user can understand and apply to their everyday listening environment.

Conclusions

Attention towards hearing conservation in musician populations has greatly increased over the past decade. Research and education [19], along with national recommendations through the Health Promotion in Schools of Music project [20], have led to recent and historically significant changes to the health and safety accreditation standards for over 600 college and university music programs accredited by the National Association of Schools of Music [21]. Because college level programs are now obligated to educate future music professional about hearing health, students majoring in music education will bring and apply this knowledge into the public school setting. While these national initiatives offer unprecedented opportunities for those interested in the relationships between music and hearing health, the results of this study demonstrate an urgent need for robust protocols designed specifically for evaluating and labelling earplugs intended for and marketed to musicians. The REAT testing protocol is not a valid test for developing critical information about how an earplug modifies musical stimuli or how musicians perceive these changes. New protocols should incorporate music, musicians, and context specific scenarios that included perceptual testing. More broadly, the results of this study should prompt critical examinations of other hearing conservation protocols used for music but were developed for use in industrial audiology. New testing protocols and innovations will have a positive impact on the on-going transformation of the music discipline.

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