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Angle-dependent effects for impulsive noise reduction for hearing protectors

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The exposure at the ear in response to a forward-propagating wave depends upon the angle of incidence at the head, the nominal sound pressure level of the impulse and the attenuation of hearing protection (if worn). The unoccluded and occluded responses of an acoustic test fixture equipped with two G.R.A.S. IEC 60711 couplers $^1/_4$-inch microphones were measured in 15° increments for impulses with nominal peak sound pressure levels of 150 and 160 decibels. The attenuation was assessed in a variety of ways: Impulse Peak Insertion Loss (IPIL), change in A-weighted Equivalent Energy, and change in the Auditory Hazard Unit. Generally, the L_{Aeq} was quite similar to the (IPIL). However the change in AHUs predicted less attenuation than was actually observed. The lower performance for AHUs may be attributable to the nonlinear hazard growth for the unoccluded ear.

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1. INTRODUCTION

Directional hearing comes from two aspects of the interaction of progressive sound fields with the human auditory system: interaural time delays and interaural level differences. The delay between the arrivals of a progressive sound wave at the respective ears is the dominant feature used to localize low-frequency sounds. For high frequency sounds, the head acts as a barrier that shadows one ear, resulting in a difference in sound pressure levels at the two ears. Diffraction of the sound field around the head, particularly at 90°, provides a small enhancement of the level observed at the head-shadowed ear.

Murphy *et al.* (2010) reported the performance of hearing protection devices evaluated with an acoustic shock tube and two different acoustic tests fixtures. They reported for the 3M™ PELTOR™ Optime™ 105 and the 3M™ PELTOR™ ComTac™ earmuffs an increased peak impulse noise reduction (the difference between maximum pressures for an external microphone and the ear canal microphone) of the peak sound pressure level when the acoustic shock tube was normal to the exposed ear. The head-shadowed ear for the ComTac earmuff demonstrated about a 15-dB reduction of peak impulse noise reduction between the normal (+90°) and the head-shadowed (-90°) orientations. The Optime 105 did not exhibit such a strong difference between these two orientations, only about 4 to 5 dB.

Hagerman *et al.* (1996) investigated the effect of head orientation in a progressive sound field using loudspeakers positioned in an anechoic room. Hagerman used a variety of sounds with differing spectral and temporal characteristics: drop forge, impact welder and a small caliber pistol. For the small caliber pistol, they observed a slight increase in insertion loss between the center of the head measurement and a microphone positioned in the concha of a subject's ear.

2. METHODS

All measurements were collected at the National Institute for Occupational Safety and Health (NIOSH) Impulse Noise Testing Laboratory. The room dimensions are 14.84 m long, 4.89 m wide and the ceilings are about 3.02 m high and a suspended drop ceiling at 2.44 m above the floor. The room has an acoustic treatment of 5 cm thick plastic-wrapped fiberglass panels suspended from the ceiling approximately 0.20 m below the suspended ceiling and about 0.20 meters away from the walls in order to reduce hard reflections from the walls and ceiling.

A. ACOUSTIC SHOCK TUBE

An acoustic shock tube was used to produce impulses and has been described in detail by Khan *et al.* (2012). Polyester film with a thickness of 0.254 mm (1 mil) was used to produce impulses with peak sound pressure levels (SPL) of 150 and 160 dB SPL. The A-durations (the time between the initial wavefront and return to ambient quiescent pressure) were about 1.5 and 1.3 ms for the 150 and 160-dB impulses, respectively. The shock tube was pressurized to 55-65 kPa and 85 kPa to achieve the 150-dB and 160-dB impulses, respectively.

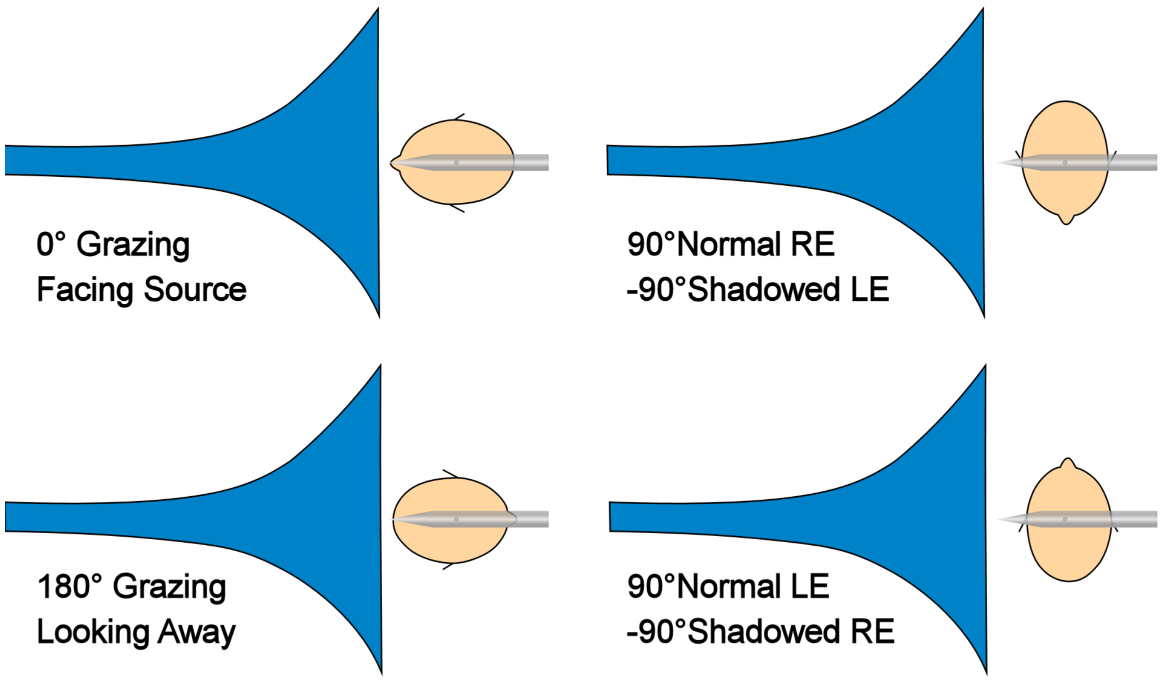

Figure 1: The orientation of the catenoidal horn of the shock tube (blue), the acoustic test fixture (beige) and the blast probe (silver). Positive angles indicate when the right or left ear is oriented towards the mouth of the shock tube and negative angles indicate when the ear is shielded by the head.

B. ACOUSTIC TEST FIXTURE AND BLAST PROBE

A binaural acoustic test fixture (ATF) used for all measurements was built by the French German Research Institute of Saint Louis (ISL). The ATF is equipped with two GRAS IEC 60711 ear simulators and ¼-inch microphones. The 3% distortion upper limit for the microphone used in the ear simulator is 169 dB SPL or a peak level of 172 dB. The ATF was positioned about 0.75 m in front of the catenoidal horn of the shock tube and centered on the shock tube axis. A GRAS 67SB probe microphone was positioned 0.10 m above the ATF and the microphone element was centered using a laser line above the center of rotation of the ATF. The ATF was rotated in 15° increments from -180° to 180° while the blast probe was pointed at the throat of the catenoidal horn and not moved throughout the measurements. In the figures displaying the data, the positive angles correspond to the right and left ears being oriented towards the shock tube and the negative angles are indicate the head-shadowed conditions with the ear oriented away from the source. Figure 1 illustrates four different cases. When the ATF is facing the mouth of the shock tube, the angle is at 0°. When the right ear is normal at 90° to the shock tube, the left ear is shielded at -90° and vice versa.

C. HEARING PROTECTION DEVICES

Four different model hearing protection devices were used in this study: 3M™ E-A-R™ Classic™ foam earplugs (Classic), 3M™ Combat Arms™ version 4 earplugs (Combat Arms), 3M™ PELTOR™ ComTac™ III earmuffs with gel cushions (ComTac III), and David Clark Model 27 earmuffs (DC27). The Classic earplugs are a formable polyvinyl foam earplug and were inserted 13 mm into the ATF's ear canals. The Combat Arms earplugs are a premolded, triple flanged earplug with a rocker switch that can open or close a valve that provides level-dependent attenuation based upon the level of the external stimulus. The ComTac III earmuff is an electronic level-dependent earmuff that provides amplification of low-level sounds and begins to limit the output of the earmuff speakers above approximately 82 dB SPL. For high-level impulses and stimuli, the ComTac III electronic circuits will saturate and yield a response similar to when the electronics are turned off.

D. ANALYSIS

Each protector was fitted on the ATF and was not removed throughout the particular test condition. The Combat Arms earplugs were tested in the closed-filter and open-filter conditions. The ComTac III earmuffs were tested with the electronics turned off and the electronics turned on. We collected a series of open-ear responses for the 150-dB and 160-dB conditions that were used to estimate the noise reduction of the protector due to the impulse. Although the acoustic shock tube was capable of creating impulses of higher and lower peak impulse levels, the higher levels exceeded the design specifications for the ¼-inch microphones of the test fixture. This method differed from what was done earlier by Murphy *et al.* (2010) who determined just the nonlinear peak reduction from outside the protector to the ear canal ear simulator.

At each protector condition and angle, three impulses were recorded for the 150 and 160-dB impulses. The peak sound pressure levels, L_{Peak}, and equivalent 8-hour A-weighted levels, L_{Aeq8}, were determined. As well, the impulses were analyzed by the Auditory Hazard Assessment Algorithm for Human (AHAAH) model for the warned and unwarned ear conditions (Price & Kalb, 1991; Price, 2007). The AHAAH model was run in MATLAB and has been used previously to analyze results for impulse noises (Murphy *et al.*, 2009). Because the Auditory Hazard Units (AHUs) are given as a maximum of linear summations of the estimated upward displacement for 23 sites along the basilar membrane, the warned and unwarned AHUs were transformed into a dB value as follows,

$$L_{\mathrm{Warned/Unwarned}} = 10\log_{10}(\mathrm{AHU}/10^{-5}), \quad (1)$$

where the AHU are computed by the AHAAH model and the 10^{-5} AHU is the smallest result typically returned by the AHAAH model (Fedele *et al.*, 2013). The differences between the open-ear and unoccluded AHU levels, $\Delta\bar{L}_{\mathrm{Warned}}$ and $\Delta\bar{L}_{\mathrm{Unwarned}}$, are shown in the subsequent plots to allow a more direct comparison with changes in L_{Peak} and changes in L_{Aeq8}.

For each of the impulse levels, angles, and HPD conditions, the changes in the dependent measures were determined as the difference between the averaged unoccluded and occluded conditions at the same angle and level: ($\Delta\bar{L}_{\mathrm{Peak}}, \Delta\bar{L}_{\mathrm{Aeq8}}, \Delta\bar{L}_{\mathrm{Warned}}$, and $\Delta\bar{L}_{\mathrm{Unwarned}}$. Because the ATF was binaural, the right and left ears were treated separately. As one ear turned towards the source, the other ear was moving into the head-shadowed region. In the graphs that follow, the ears have been transformed so that the positive angles represent the ear being exposed to the source and negative angles are the angles that are head-shadowed. This transformation provides a check for the consistency of the results from both ears.

3. RESULTS

The results for the open-ear response will be discussed first and then the occluded conditions for the protectors.

A. OPEN-EAR ATF RESPONSE

The peak sound pressure levels for the open ear of the ATF are shown in Figure 2. The positive angles on the abscissa are when the ATF ear is turned towards the shock tube, the negative angles are when the ear is head-shadowed. The red and blue lines are for the right and left ears, respectively. The circles were for the 150-dB impulses and the squares were for the 160-dB impulses. By way of comparison, the curves measured for the azimuthal head related transfer function by Mehrgardt and Mellert (1977) are shown for the 500 Hz (solid black line) and 800 Hz (dashed black line) frequencies.The ATF impulse data and the continuous tone transfer function data reported by Mehrgardt and Mellert both exhibited a small peak at -90°. This peak increased in amplitude between the 150 and 160-dB impulse levels and between the 500 and 800 Hz tonal signals. The acoustic shock tube waveform and spectra change with impulse level as the shock wave becomes more sharply formed. In Murphy *et al.* (2015), the 168-dB impulses exhibited less roll off above 125 Hz and the open-ear transfer function creates a maximum at about 3000 Hz. Although these data are more circumstantial and correlative in nature, the increases at -90° may be understood as a diffraction effect as the waveform propagates around the ATF. The slightly increased high frequency energy may be responsible for the higher peak at 160 dB than at 150 dB.

B. DAVID CLARK MODEL 27 RESPONSE

The response of the David Clark Model 27 earmuff, a passive protector, is illustrated in Figure 3. This figure displays the reductions for all four metrics. The peak level reductions, $\Delta\bar{L}_{\mathrm{Peak}}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{\mathrm{Aeq8}}$, are dashed-dotted lines. The reductions of warned auditory hazard levels (see Eq. 1), $\Delta\bar{L}_{\mathrm{Warned}}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{\mathrm{Unwarned}}$, are dotted lines (see Eq. 1). Each point is the average of three impulses presented in the open-ear and occluded conditions. As the exposed ear rotates toward the shock tube impulse source (0 to 180 degrees) the level differences under the muff increases slightly by 2 to 4 dB. In the head-shadowed area, the levels are reduced by about 2 dB.

C. 3M™ E-A-R™ CLASSIC™ RESPONSE

The level reductions for the 3M™ E-A-R™ Classic™ earplugs are plotted in polar coordinates to facilitate comparisons between the various metrics. The reductions for the 150-dB impulses are plotted in the left panel and the reductions for the 160-dB impulses are plotted in the right panel of Figure 4. The solid lines are the peak-level reductions, $\Delta\bar{L}_{\mathrm{Peak}}$. The dash-dotted lines are the $\Delta\bar{L}_{\mathrm{Aeq8}}$ reductions for the equivalent 8-hour A-weighted levels. The dashed lines are the warned

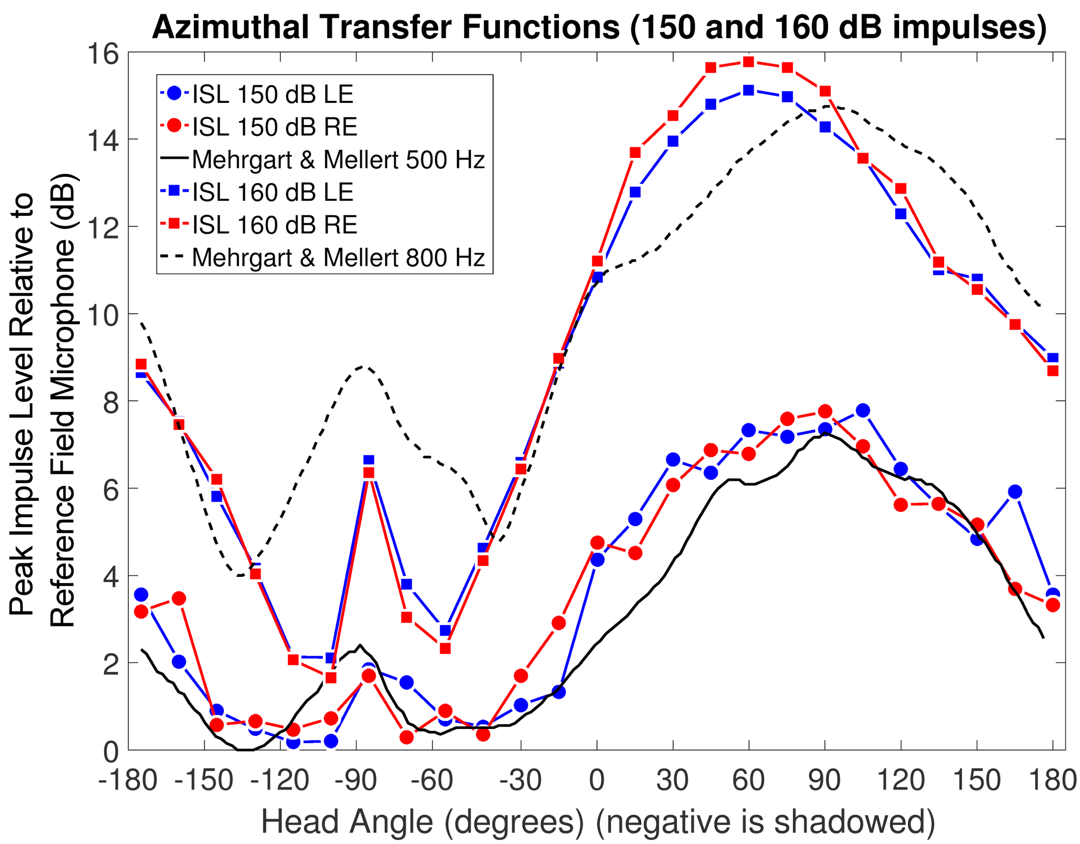

Figure 2: Open-ear response of the ISL acoustic test fixture. The red symbols represent the right ear of the ATF and the blue symbols represent the left ear of the ATF. The circles were measured with 150-dB impulses and the squares were measured with 160-dB impulses. Superimposed upon the two sets of curves are the azimuthal transfer functions measured by Mehrgardt and Mellert (1977) for the 500 Hz (solid black line) and 800 Hz (dashed black line).

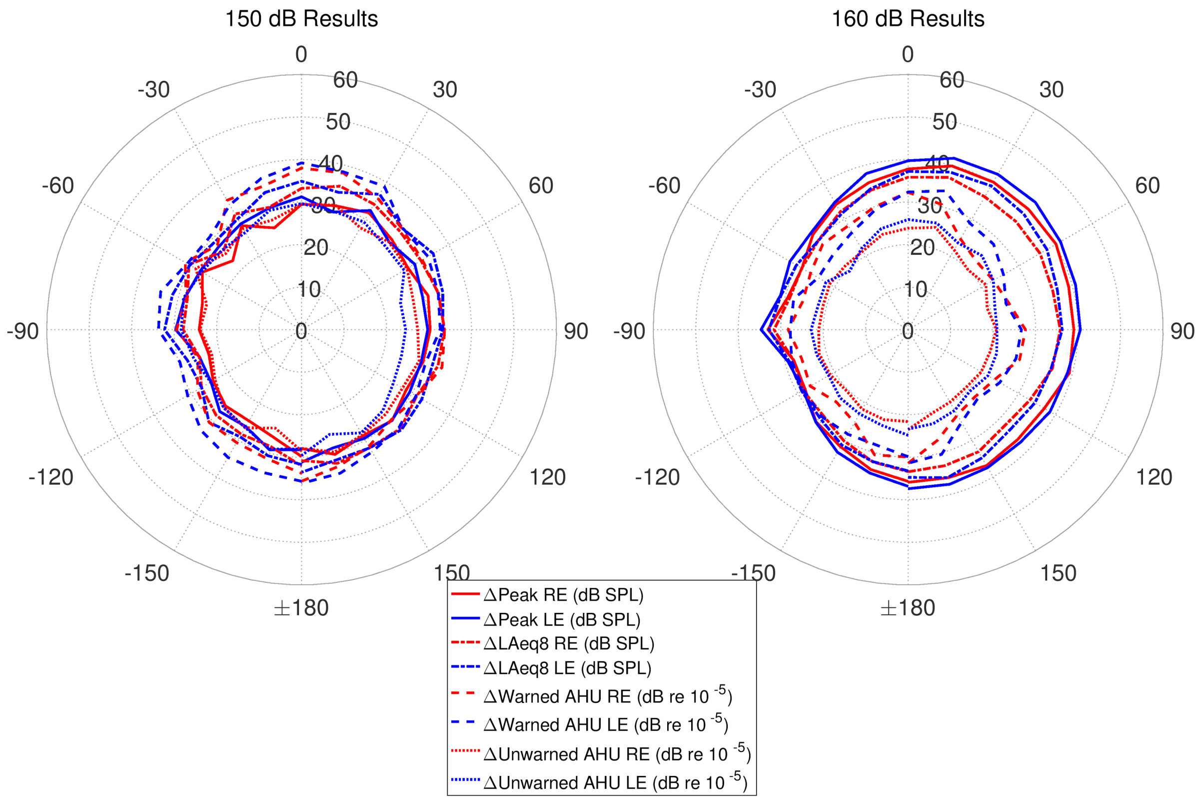

Figure 3: The reductions of various metrics for the David Clark Model 27 earmuffs for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue. The top of the polar plots are the face of the fixture pointed at the impulse source. The angles from 0 to 180 degrees are with the source on the exposed side of the head. The left ear data have been transposed through the sagittal plane to emphasize the symmetry of exposed and head-shadowed ears.

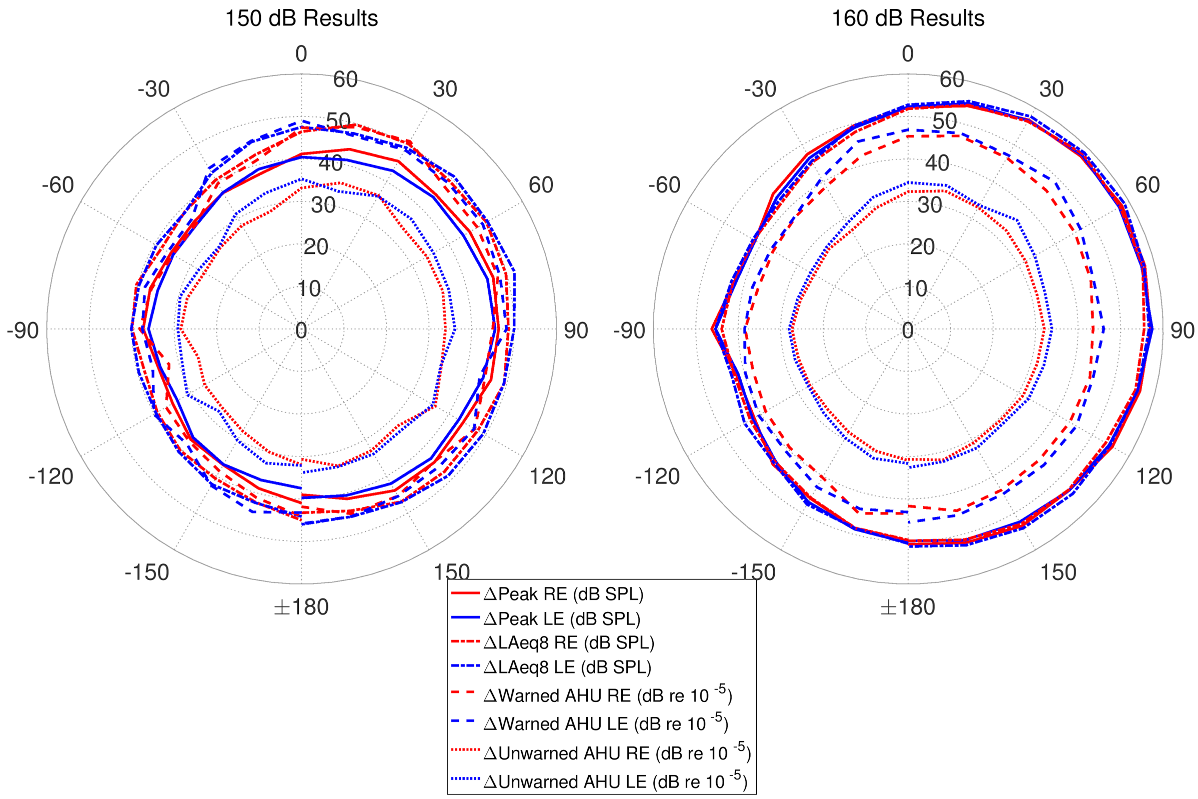

Figure 4: The reductions of various metrics for the E-A-R Classic foam earplug for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue.

reductions, $\Delta\bar{L}_{\text{Warned}}$, and the dotted lines are the unwarned reductions, $\Delta\bar{L}_{\text{Unwarned}}$, in the auditory hazard levels (see Eq. 1).

For the 150-dB impulses, the $\Delta\bar{L}_{\text{Aeq8}}$ results are remarkably similar to the warned AHAAH reductions, $\Delta\bar{L}_{\text{Warned}}$. The $\Delta\bar{L}_{\text{Peak}}$ are less by about 5 dB in the exposed front quadrant, 0° to 90°. The unwarned AHAAH reductions, $\Delta\bar{L}_{\text{Unwarned}}$, range from 30 to 39 dB re 10^{-5} AHU. For the 160-dB impulses, the $\Delta\bar{L}_{\text{Peak}}$ and $\Delta\bar{L}_{\text{Aeq8}}$ results are nearly identical. The increase at -90° is more prominent than for the 150-dB impulses corresponding to the increased response for the open-ear results in Figure 2. The $\Delta\bar{L}_{\text{Peak}}$ and $\Delta\bar{L}_{\text{Aeq8}}$ reductions range from about 40 dB to almost 60 dB. The reductions of the AHAAH warned responses, $\Delta\bar{L}_{\text{Warned}}$, range from about 40 to 48 dB AHU (dashed lines). However, the reductions of unwarned AHAAH responses, $\Delta\bar{L}_{\text{Unwarned}}$, are significantly lower ranging from about 28 dB to 33 dB (dotted lines). All of the metrics indicate an increased attenuation in the frontal exposed quadrant, likely due to the increased level for the open-ear response.

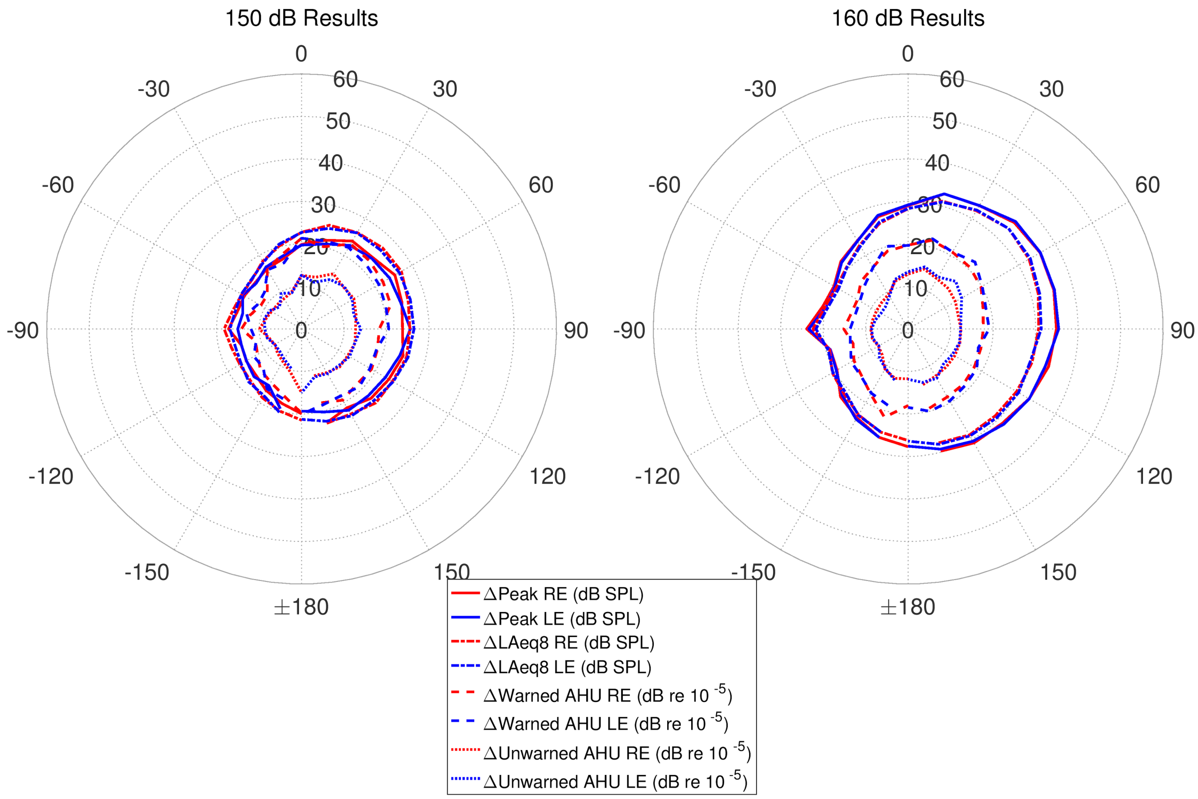

Figure 5: The reductions of various metrics for the Combat Arms Single-Ended (open) earplug for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue.

D. 3M™ COMBAT ARMS™ SINGLE-ENDED RESPONSE

The 3M™ Combat Arms™ Single-Ended earplugs were tested first in the open filter condition (Figure 5) and then in the closed filter condition (Figure 6). For the 150-dB impulses and the filter open, the reductions for $\Delta\bar{L}_{\text{Peak}}$, $\Delta\bar{L}_{\text{Aeq8}}$ and $\Delta\bar{L}_{\text{Warned}}$ were comparable, about 10 dB on the head-shadowed side and about 20 dB on the exposed side. The $\Delta\bar{L}_{\text{Unwarned}}$ yielded between 8 and 15 dB hazard reduction. For the 160-dB impulses and the filter open, the impulse peak insertion loss (IPIL) was greatest 20 to 35 dB and the $\Delta\bar{L}_{\text{Aeq8}}$ reduction was similar to the $\Delta\bar{L}_{\text{Peak}}$ for the head-shadowed conditions, but less when the ear was more exposed, only about 30 dB. The $\Delta\bar{L}_{\text{Warned}}$ reductions were between 15 and 20 dB while the $\Delta\bar{L}_{\text{Unwarned}}$ reductions were between about 9 and 15 dB.

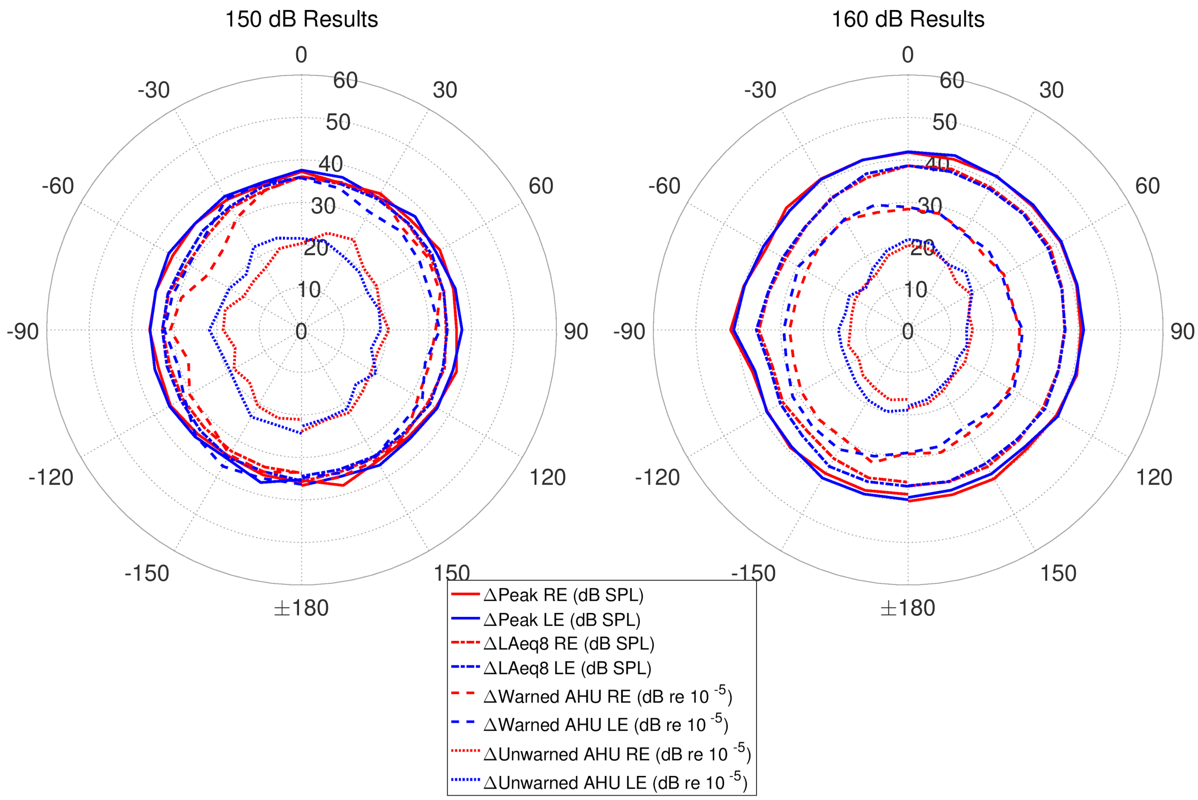

Figure 6:* *The reductions of various metrics for the Combat Arms Single-Ended (closed) earplug with the filter closed for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue.

E. 3M™ PELTOR™ COMTAC™ III RESPONSE

The 3M™ PELTOR™ ComTac™ III earmuffs are an electronic level-dependent earmuff. When external signals exceed approximately 82 dB SPL, the electronic level-limiting circuits begin to take control and reduce the amount of amplification provided to external ambient sounds. For impulses such as gunshot noise or the impulses produced by the acoustic shock tube, the microphones go into saturation almost instantaneously, effectively forcing the device into its passive protection (Figure 7) and then in the closed filter condition (Figure 8). Although the two figures are not plotted directly on top of one another, the responses for all four metrics are very comparable. For the 150-dB impulses, the reductions in peak levels, $\Delta\bar{L}_{\mathrm{Peak}}$, equivalent 8-hour A-weighted levels, $\Delta\bar{L}_{\mathrm{Aeq8}}$, and warned AHAAH, $\Delta\bar{L}_{\mathrm{Warned}}$, responses range between about 17 and 30 dB. The unwarned reductions, $\Delta\bar{L}_{\mathrm{Unwarned}}$, range between 10 and 20 dB. For the off condition, the pressure level of the charge for the shock tube was varied by the operator slightly and resulted in somewhat more noisy responses of the protector. For the on condition, the protection in the exposed quadrant (ear towards the source) is increased by 5 to 10 dB for the 150-dB impulses and 160-dB impulses. While the warned AHAAH reductions, $\Delta\bar{L}_{\mathrm{Warned}}$, are similar to the $\Delta\bar{L}_{\mathrm{Peak}}$ and $\Delta\bar{L}_{\mathrm{Aeq8}}$ reductions for the 150-dB impulses, the 160-dB warned AHAAH reductions, $\Delta\bar{L}_{\mathrm{Warned}}$, are about 10 dB less than the $\Delta\bar{L}_{\mathrm{Peak}}$ and $\Delta\bar{L}_{\mathrm{Aeq8}}$ reductions.

4. DISCUSSION

These results provide new information regarding the performance of different types of HPDs as a function of angle. The use of an IPIL metric seems to provide a reasonable approximation of the change in equivalent 8-hour A-weighted energy. The AHAAH model in the unwarned condition yielded results that were consistently different by 10 to 20 dB. The $\Delta\bar{L}_{\mathrm{Warned}}$ reductions agreed somewhat with the reductions of other metrics ($\Delta\bar{L}_{\mathrm{Peak}}$, and $\Delta\bar{L}_{\mathrm{Aeq8}}$) for the 150-dB impulses, however it did not agree with the peak and energy metrics for any of the 160-dB impulse measurements.

The source of the differences for the AHAAH is likely due to the nature of the AHAAH metric. The AHAAH model has two nonlinear elements, the middle ear muscle contraction (MEMC) and the stapes suspension provided by the annular ligament. For the warned AHAAH model, the MEMC is assumed to be fully activated and it provides about 15 to 20-dB reduction in "risk" by attenuating the impulsive energy transmitted to the cochlea. The prevalence and ability of the MEMC to be classically conditioned as claimed by the developers of the AHAAH model have been recently investigated by Flamme *et al.* (2016; 2017). Flamme *et al.* (2017) have examined the National Health and Nutrition Examination Survey (NHANES) data to assess the prevalence of acoustic reflex responses at 1000 and 2000 Hz using frequentist and Bayesian methods to identify the occurrence of a valid reflex response. They reported less than 80% of subjects in the NHANES data (N=15,106) exhibited consistent reflex responses at elicitor levels of 105 dB. Flamme *et al.* (2016) reported on measurements of the MEMC elicited by non-acoustic stimuli: eye closure and air puff stimulation of the temple and nares. They did find that their method of monitoring the level of a click stimulus presented to the ear for increased levels was effective. For maximal eye closure effort, they demonstrated about a 95% prevalence in subjects (N = 60) with normal hearing, contralateral reflexes and cranial nerve function. For the air puff, the prevalence ranged between 70% and 98% with all subjects and conditions having a response being about 96%. Preliminary

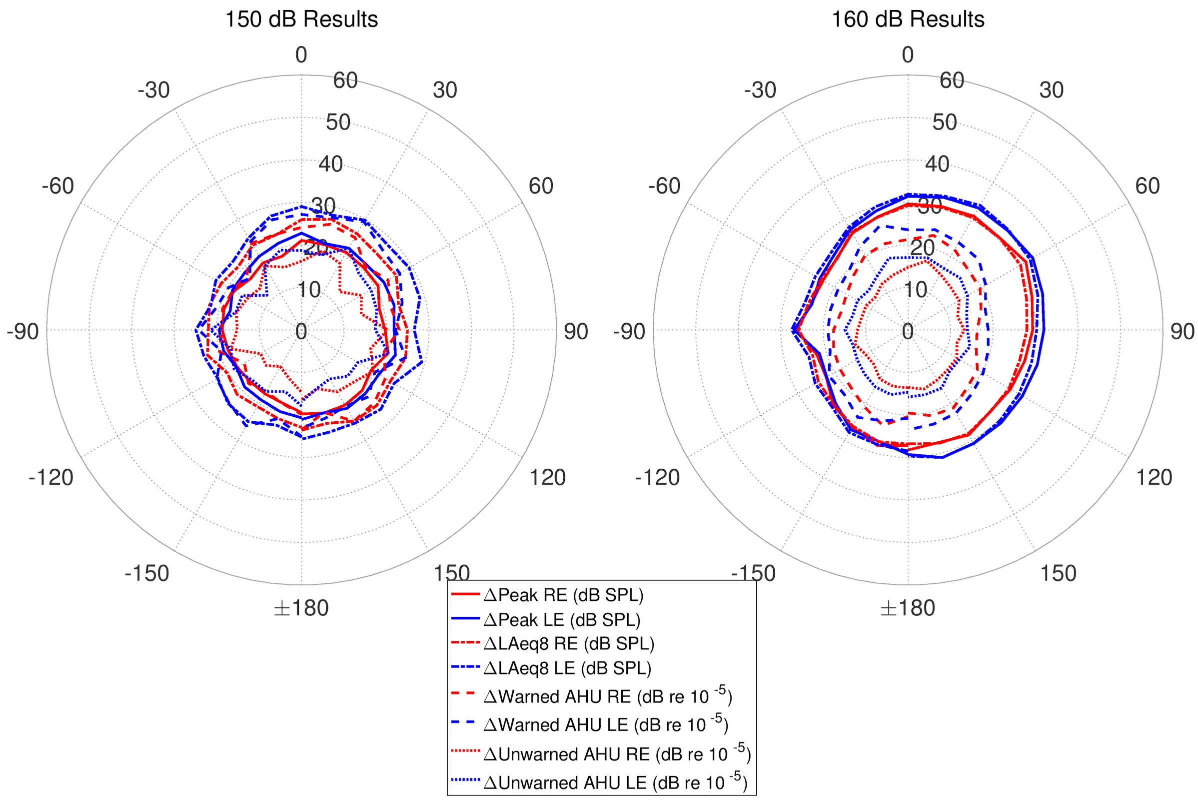

Figure 7: The reductions of various metrics for the PELTOR ComTac III earmuff with the electronics turned OFF for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue.

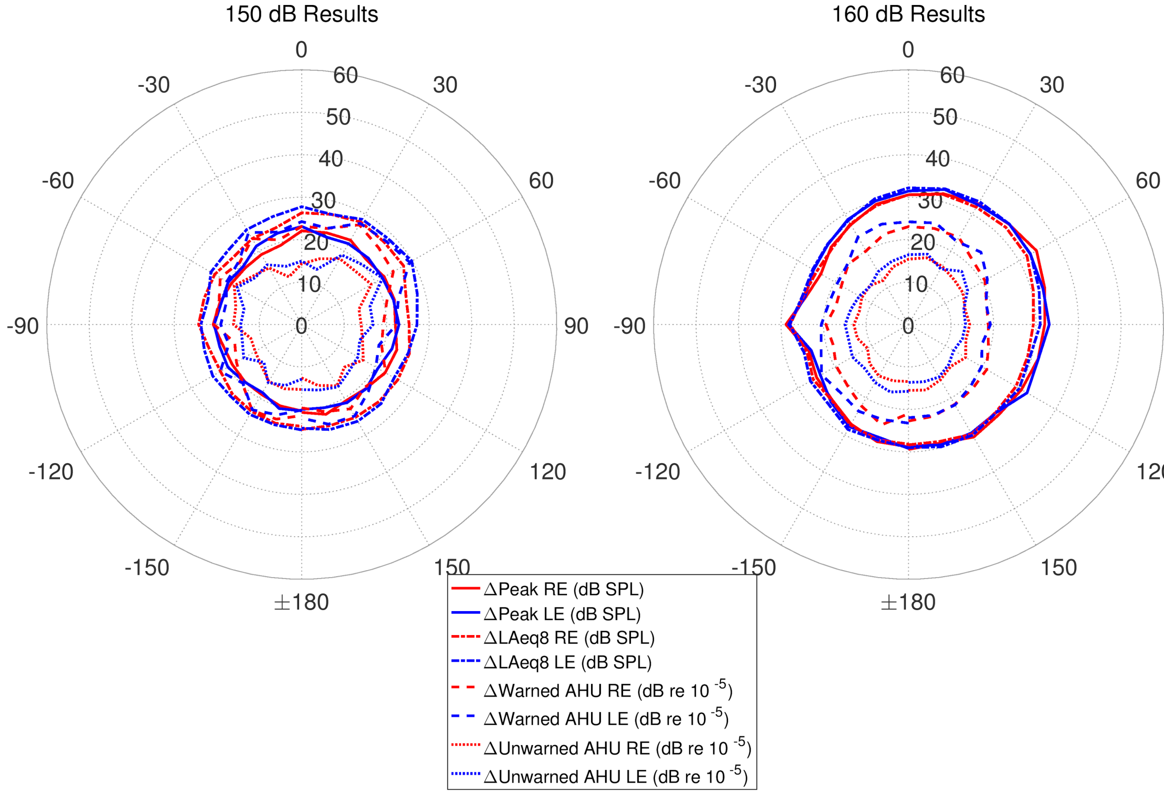

Figure 8: ***The reductions of various metrics for the PELTOR ComTac III earmuff with the electronics turned ON for right and left ears as a function of angle and impulse level. The peak level reductions, $\Delta\bar{L}_{Peak}$, are solid lines. The reductions of L_{Aeq8}, $\Delta\bar{L}_{Aeq8}$, are dashed-dotted lines. The reductions of warned auditory hazard level, $\Delta\bar{L}_{Warned}$, are the dashed lines and the reductions of unwarned auditory hazard level, $\Delta\bar{L}_{Unwarned}$, are dotted lines. The red curves are the right ear and the left ear are in blue.***

reports of the ability to condition the MEMC response and measure its response indicate that conditioning is not widely prevalent as claimed by the AHAAH model developers (Price, 2005; Price, 2007). Thus, one can argue that the use of the warned AHAAH model is suspect for any damage risk criterion. Second one might argue that the unwarned AHAAH model response fails to reflect that known performance of hearing protection devices with regards to how little attenuation or reduction of the risk is observed in these measurements. All of the protectors in the off or closed and properly fit condition are capable of providing 25 to 30 dB of protection and that level of impulse risk reduction was not observed in the AHAAH unwarned data. Finally, we note that the unprotected AHAAH response can be affected by the nonlinearity of the model to reduce the apparent risk when high level impulses are experienced. The 160-dB impulses could be driving the stapes into clipping which may explain why the unwarned reductions are consistently lower than the warned reductions.

The $\Delta\bar{L}_{\text{Peak}}$ reductions proved to be quite similar to the $\Delta\bar{L}_{\text{Aeq8}}$ reductions. When the impulse is filtered by the ATF ear simulator, the waveform spectra is enhances in the 2 to 4 kHz region due to the outer/middle ear transfer function. The 150-dB impulses have a peak at about 125 to 200 Hz and when filtered by the ear canal, there is additional gain. The 160-dB impulses have a more well-formed shock wave and therefore more high frequency content. The open-ear response exhibits greater change as a function of angle for the 160-dB impulse compared to the 150-dB impulses (see Figure 2). Differences between $\Delta\bar{L}_{\text{Peak}}$ and $\Delta\bar{L}_{\text{Aeq8}}$ are expected as the spectral shifts with increased level for the shock tube impulse moves the energy into higher frequencies where the protectors tend to be more effective (Fackler *et al.*, 2017).

We also note that the manner in which $\Delta\bar{L}_{\text{Peak}}$ was computed was not as prescribed by the ANSI S12.42 standard (ANSI-ASA S12.42, 2010). The S12.42 standard uses a limited set of impulses for the open-ear conditions at 132, 150, and 168 dB peak SPL to calculate transfer functions between the field probe microphone and the open ears of the fixture. The transfer functions were not calculated for this paper, rather the open-ear responses were measured and used as the references for each angle. So long as the levels of the impulses are comparable and the fixture and blast probe were not moved during the series of measurements, the results should agree.

Finally, the diffraction effect of the head-shadowed ear at -90° was a surprising result, but easily understood. Hagerman *et al.* (1996) did not evaluate enough angles to identify this effect with real persons' ears. In the Mehrgardt and Mellert (1977) paper, the diffraction is apparent. The continuous tone stimulus may only be circumstantially compared with the impulse data we report. Nevertheless, models that aim to predict the response of protectors should consider how to incorporate the baffle effect of the head, the filtering effects of the outer/middle ear, and a rudimentary calculation of the diffraction effect around the head.

5. CONCLUSION

Fackler *et al.* (2017) showed that impulse spectral insertion loss yields good agreement across impulsive and continuous noise sources. An equivalent A-weighted energy approach is reasonable to describe protector performance yielding similar results as have been reported for IPIL. The auditory hazard units are likely affected by the nonlinearity of the AHAAH model for the open-ear response and inconsistent results are observed between warned and unwarned conditions.

Hearing protector models for the response when worn and used in impulsive noise environments must include the baffle and head-shadow effects. The baffle effect can add between 4 to 6 dB and the head-shadow effect can reduce impulse protection 5 to 10 dB. Diffraction around the head exhibited a greater effect for the unoccluded condition than the occluded condition.

DISCLAIMER

The findings and conclusions presented in this report are those of the authors and do not necessarily represent those of the National Institute for Occupational Safety and Health and the Centers for Disease Control and Prevention. Products mentioned in this report are not endorsed by NIOSH or the CDC.

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