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Laboratory Evaluation of the Warned Middle-Ear Assumption of the Auditory Hazard Assessment Algorithm for Humans (AHAAH)

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14. ABSTRACT
Currently, the United States Department of Defense acquisition standard (MIL-STD-1474E) mandates that the U.S. Army is required to use the Auditory Hazard Assessment Algorithm for Humans (AHA AH) for calculating impulse noise exposure limits of military systems. However, several concerns have been raised about the model. The current study addresses a major concern raised about the middle-ear muscle contraction (MEMC) associated with the acoustic reflex that is assumed, and implemented, as a protective mechanism for certain instances in which a person is "warned" prior to the impulse. If a MEMC can be "warned" and is engaged during an exposure, it could produce significant attenuation, which would alter the risk prediction. Fifty-nine subjects were consented and verified to show clinically assessable MEMCs prior to testing. Using laser-Doppler vibrometry (LDV), we directly measured the time course and relative magnitude changes of a MEMC on TM velocity.

15. SUBJECT TERMS
Laser-Doppler Vibrometry (LDV), middle ear muscle contraction (MEMC), acoustic reflex

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14. Abstract (continued)

For those subjects with an observable MEMC (n=50), 48 subjects (96%) did not show evidence of a conditioned response after training, whereas only 2 subjects (4%) did show evidence of a “warned” response. These findings reveal that MEMCs are not readily conditioned in a majority of individuals, suggesting that a “warned” MEMC is not prevalent within the general population. Therefore, a “warned” MEMC does not appear to be present in enough people to justify inclusion as a protective mechanism and is not appropriate to include when predicting auditory injury risk.

Summary

Background

Repetitive exposure to high-level acoustic impulses, such as those from small arms fire and blast overpressure, increases the susceptibility for hearing loss. Currently, the United States Department of Defense acquisition standard (MIL-STD-1474E) mandates the U.S. Army use the Auditory Hazard Assessment Algorithm for Humans (AHA AH) for calculating impulse noise exposure limits of military systems. The AHA AH is an electro-acoustic model designed to predict the auditory injury that results from intense pressure changes at the ear caused by acoustic impulsive noise exposures and blast overpressure. The model has been presented as validated against the U.S. Army Blast Overpressure Project (BOP); however, other published studies that used the model to analyze the human exposure data collected during the BOP have raised concerns about the AHA AH validation efforts. Such concerns involve the appropriateness of including this model as a medical standard in an updated Damage Risk Criteria, and thus there is still no such medical standard available in the Department of Defense.

Purpose

The current study addresses a concern raised about the middle-ear muscle contraction (MEMC) associated with the acoustic reflex that is assumed, and implemented, as a protective mechanism for certain instances in which a person is “warned” prior to the impulse by means of classical conditioning. For the purpose of a health hazard assessment, an inappropriate implementation of this assumption would result in an underestimation of auditory hazard and may incorrectly predict that some high-level exposures are safe. The current project aimed to test the assumption that the MEMC can be elicited by a conditioning stimulus prior to sound exposure (i.e., a “warned” response).

Methods

In order to assess the effect of the MEMC on ossicular chain motion in human participants, laser-Doppler vibrometry (LDV) was used to measure the motion of the tympanic membrane (i.e., the ear drum) in response to an acoustic reflex-eliciting impulse. After verifying the presence of the MEMC, we attempted to classically condition the response by pairing a reflex-eliciting acoustic impulses (unconditioned stimulus, UCS) with various preceding stimuli (conditioned stimulus, CS). Comparisons were made between the LDV signals recorded in the pre- and post-training blocks. Changes in the time-course of the MEMC following repeated CS-UCS pairings were considered evidence of MEMC conditioning. Any indication of an MEMC occurring prior to the onset of the acoustic elicitor was considered a “warned” response.

Conclusions

These results indicate that it is not appropriate to assume a “warned” MEMC response when determining auditory injury risk for impulsive noise. Knowledge gained from this study will be used to inform updates to Damage-Risk Criteria that will improve predictions of impulse noise limits. Hearing risk assessment models based on scientific evidence increases the ability of the military to achieve this objective and helps better protect the hearing of Warfighters exposed to high-level acoustic impulses.

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Introduction

Great effort over the past few decades has focused on developing a means for assessing the risk of auditory injury from exposure to single and repetitive high-level acoustic impulses, such as those from blast overpressure and firearms. Due to the brief duration of acoustic impulses, the ability to predict the hearing loss resulting from such exposure is not as straightforward as it is for steady-state noise. Currently, the United States Department of Defense acquisition standard (MIL-STD-1474E) mandates the U.S. Army use the Auditory Hazard Assessment Algorithm for Humans (AHAAH) for calculating exposure limits of military systems. It should be noted that MIL-STD-1474E is a design-criteria standard and not a medical standard for establishing exposure limits to be implemented by the Army Hearing Program.

The AHAAH is an electro-acoustic model designed to predict the auditory injury that results from intense pressure changes at the ear caused by blast overpressure and acoustic impulsive noise exposures (Price & Kalb, 1991; Price & Kalb, 2018). The model has been presented as validated against the U.S. Army Blast Overpressure Project (BOP), commonly referred to as the “Albuquerque Study” (G. R. Price, 2001, 2007). However, significant concerns have been raised, and are summarized in an American Institute of Biological Sciences (Wightman, Flamme, Campanella, & Luz, 2010). Recent studies have focused on investigating specific components of the sound transmission pathway modeled by AHAAH, including responses of the tympanic membrane (Gan et al., 2016; Liang et al., 2016), ossicular chain motion and intracochlear pressures (Greene et al., 2017; Greene et al., 2018), while others have focused on updating model parameters and injury estimates (Zagadou et al., 2016), validating model results against human exposure data (Chan et al., 2001; Patterson et al., 2004), or investigating alternate approaches to auditory injury prediction (De Paolis et al., 2017; Zagadou et al., 2016). These studies have raised issues about the validation efforts of the AHAAH and concerns about the appropriateness of implementing this model as a medical standard in future updated damage-risk criteria (DRC).

An additional concern with the model raised by the AIBS peer review is that the middle-ear muscle contraction (MEMC) associated with the acoustic reflex is assumed to be present, which may not be reasonable (Flamme, Deiters, Tasko, & Ahroon, 2017; McGregor et al., 2018), and implemented as a protective mechanism that may be activated prior to the arrival of the acoustic impulse if the listener is “warned”, presumably by means of classical conditioning (DoD, 2015; Patterson & Ahroon, 2004; G. Price & Kalb, 2018; G. R. Price, 1991, 2001). The acoustic reflex, which is commonly tested by audiologists, activates with a latency that is sufficiently long that the resulting MEMC would not affect sound transmission (i.e., protect) for an impulse noise exposure (Dallos, 1964). The AHAAH model, however, assumes that “if the listener knows that the shot is going off, or if the impulse is one of a series (as in a machine gun), the muscles *might* be contracted at the time the impulse arrives” (G. R. Price, 2010). The model developers suggest the extended experience of the BOP listeners with the countdown given prior to the blast overpressure exposure classically conditioned the acoustic reflex in these listeners to be activated at the time the impulse arrived.

It should be noted that under this assumption, the “warned” option presumes there is a fully engaged MEMC prior to the arrival of the impulse, which provides protection and reduces

the risk factor for auditory injury. Thus, the AHAAH model allows the user to decide whether to evaluate the response to the impulse as though it were “unwarned” (onset of MEMC occurs sometime after the impulse due to the reflex latency) or “warned” (MEMC is engaged prior to the start of the impulse). To date, there is limited evidence of eliciting the acoustic reflex via classical conditioning. In a technical report published by the developers (G. R. Price, 2005), some older studies were cited as demonstrable evidence that the MEMC can be classically conditioned in some animal models (Bates, Loeb, Smith, & Fletcher, 1970; Brainerd & Beasley, 1971; G. Djupesland, 1965; Yonovitz, 1976); however, it is unclear whether MEMCs may be elicited prior to a sound exposure (i.e., the “warned” response) in humans, and the amount of protection afforded in these “warned” situations has not been quantified.

The available evidence for MEMC activation in anticipation of an acoustic exposure thus appears equivocal in the scientific literature. It is imperative that these assumptions be experimentally validated before accurate damage risk criteria can be established. For the purpose of a health hazard assessment, an inappropriate implementation of this assumption would result in an underestimation of the risk of acoustic exposure to the auditory system, and may incorrectly predict that some high-level exposures are safe. The current project aimed to specifically test the assumption that MEMCs may be elicited in anticipation of an acoustic stimulus via classical conditioning that is by pairing an eliciting acoustical stimulus with a conditioning stimulus prior to sound exposure (i.e., a “warned” response).

Methods

Sixty-six volunteers were consented and underwent audiometric screening to determine if they met the inclusion criteria for the study. Subjects underwent an otoscopic examination to ensure the ear canals were unoccluded and that the tympanic membrane (TM) could be visualized, and were dismissed otherwise. Pure-tone air-conduction hearing thresholds were measured and no volunteer was included if they had greater than 20 dB HL at any of the octave-band center frequencies spanning from 125 Hz to 8 kHz. Standard tympanometric measures were conducted using the Interacoustics (Middlefart, Denmark) Titan™ IMP440 impedance measurement system to ensure that middle ear motion and function were within normal limits for both ears. Acoustic reflex thresholds were measured for each volunteer using the Titan™ system prior to testing in order to verify that acoustic reflexes could be elicited by standard audiometric test equipment, and subjects dismissed otherwise.

Out of the initial 66 volunteers, 59 met the inclusion criteria and were enrolled to participate in the study. Following completion of audiometric testing and enrollment, we used a single-axis laser-Doppler vibrometer (LDV) (Polytec GmbH, Waldbronn, Germany) to measure tympanic membrane velocity in response to a continuous, moderate level pure tone stimulus (hereafter referred to as the probe) presented to the same (ipsilateral) ear via a glass-covered speculum adapter (Polytec A-HLV-SPEC). Brief acoustic signals (hereafter referred to as the elicitor) were used to elicit an MEMC and were presented to the ear contralateral to the LDV measurement ear. Changes in the velocity of the TM motion synchronous with the elicitor were used to identify the MEMC response. Note, study recruitment material included inclusion criteria; thus, we can assume subjects self-selected for normal hearing individuals prior to enrollment, biasing recruitment towards individuals likely to show intact acoustic reflexes.

Additionally, the vast majority of individuals assessed in this study had substantial, and recent experience with firearms either recreationally or professionally, as assessed with a pre-experiment survey. All experimental procedures followed the regulations set forth by the Army Human Research Protections Office and were approved by the United States Army Medical Research and Materiel Command (USAMRMC) Human Subjects Institutional Review Board.

Equipment

During testing, participants sat in an otolaryngology exam chair (Reliance® Model 980/981) with their head restrained in a sound attenuating booth. The laser-Doppler vibrometer (Polytec OFV-534) is a precision optical transducer used for measuring vibration velocity at a fixed point. The LDV is an interferometer-based technology utilizing the Doppler effect, sensing the frequency shift of back scattered light from a moving surface. Briefly, LDV works by comparing the frequency of the outgoing light with the frequency of reflected light from the moving surface, where the frequency of the reflected light is modulated by the velocity of the reflecting object. All acoustic stimuli during LDV testing were presented to the participants using Etymotic Research ER-3C earphones, and the sound pressure level of the probe tone measured with an ER-7C probe microphone (Etymotic Research Inc., Elk Grove Village, IL). Stimulus presentation and LDV data acquisition were performed using a Tucker-Davis Technology (TDT, Alachua, FL) system controlled by custom-written MATLAB® (MathWorks Inc., Natick, MA) software.

Procedure

The experiments reported here used techniques previously reported in the literature (Svane-Knudsen & Michelsen, 1989) and further developed at USAARL (Jones, Greene, & Ahroon, 2017) for directly measuring the presence and time course of MEMC in awake, behaving human participants (Figure 1). Briefly, LDV was used to measure TM motion in response to an acoustic reflex-eliciting impulse as a proxy for assessing a MEMC in human participants. Subjects sat in the exam chair and a head strap was placed across the forehead (see Figure 1A) to reduce motion. An insert earphone was placed into the left (contralateral) ear of the participant in order to deliver the acoustic reflex-eliciting stimulus (either a 500 ms 1kHz tone at 110 dB SPL or a recorded .22 caliber gunshot at 110 dB peak). In the right ear, an aural speculum (covered with a glass window) was placed into the ear canal and fixed into position so that the participant's TM could be visualized. An earphone was attached to the speculum in order to deliver the probe stimulus (continuous 500 Hz pure tone).

Using a surgical microscope (Zeiss POMI-1), the laser was focused on the light reflex of the umbo (Figure 1B). The LDV laser beam was focused on the light reflex of the TM near the umbo of the right ear (Figure 1B and 1C). The position near the umbo was chosen because the manubrium of the malleus is firmly attached to the TM at this point, is located near the center of the TM, and represents a reliable anatomical landmark across individuals. In addition, this placement is near the point of maximum excursion along the manubrium of the malleus and is generally sufficiently reflective, thus providing a high signal-to-noise ratio signal (Beyea, Rohani, Ladak, & Agrawal, 2013; Röösl, Chhan, Halpin, & Rosowski, 2012; Whittemore, Merchant, Poon, & Rosowski, 2004).

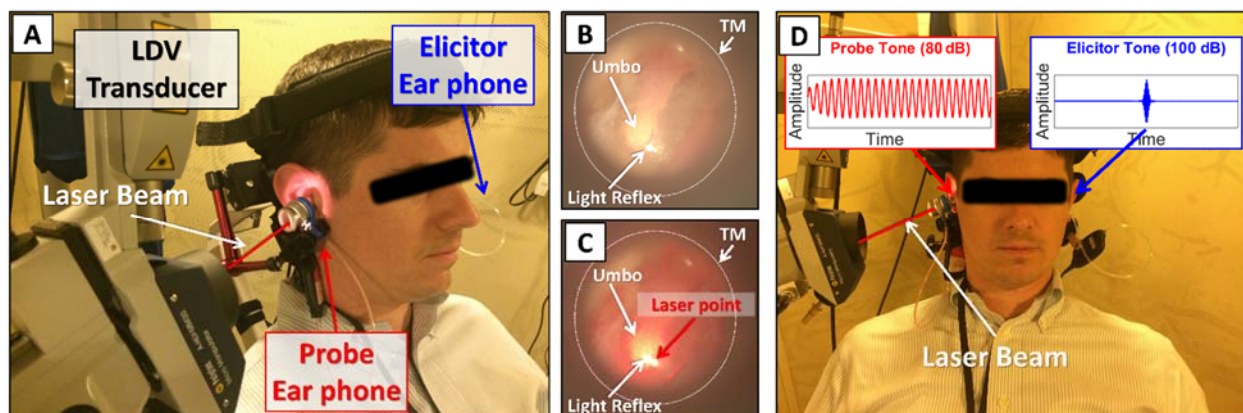


Figure 1. Experimental Setup. A) The LDV was mounted on a surgical microscope and the laser beam was focused into the ear through an aural speculum. B) The light reflex of the TM near the umbo. C) The laser point placed onto the light reflex. D) Visualization of stimulus presentation and experimental paradigm. A continuous probe tone was presented to the ear being measured by the LDV system. The elicitor was presented to the opposite ear in order to elicit a contralateral acoustic reflex.

In order to detect and quantify the MEMC, the LDV measures of tympanic membrane motion before and after elicitor tone presentation were compared. The TM of the participant was set into motion with a probe tone in the same ear as the LDV measurement (Figure 1D, red signal), and the MEMC was elicited by presenting the elicitor tone in the opposite (Figure 1D, blue signal) ear. The probe tone was played continuously throughout testing, while the elicitor and presentations were separated by randomly assigned intervals of 10 ± 2 second. Note: the elicitor presentation occurs at a fixed probe stimulus phase for all repetitions of each condition in order to allow averaging across repetitions.

The motion of the TM (in response to the probe tone) during the elicitor presentation was compared to the TM motion immediately prior to the elicitor onset. Figure 2 plots the two acoustic signals (red and blue traces) and the median of the LDV signal (green trace) recorded during five presentations of the elicitor obtained from one subject. For the stimulus condition shown in Figure 2 (probe: 500 Hz at 90 dB; elicitor: 1000 Hz at 100 dB), the MEMC is observed as a decrease in the LDV recorded signal that begins at ~ 60 ms after the elicitor presentation. Note that in Figure 2 the ordinate of the LDV recording has been adjusted to highlight the signal decrease and does not show the full scale of the LDV signal. For ease of presentation in subsequent figures, the envelope of the median LDV signal (Figure 2B, black trace) was

extracted using the Hilbert transform and then normalized to the average of the signal in the 500 ms window prior to elicitor presentation (normalized ordinate is indicated on the right of plot).

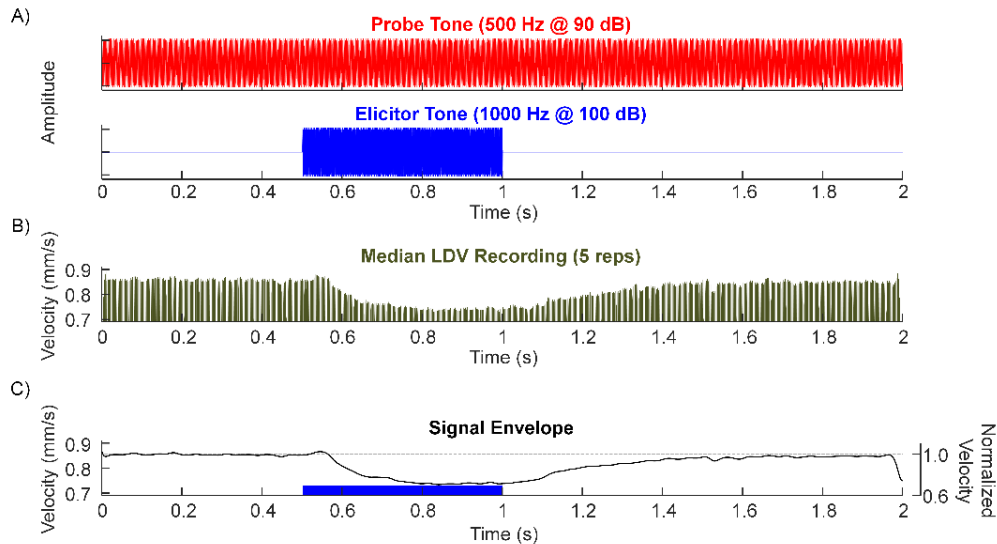


Figure 2. Example of stimulus presentation paradigm and data analysis. A) The probe tone (red) and elicitor (blue) presented to the subject. B) The median filtered LDV recording (green) of 5 elicitor presentations. C) The envelope of the median LDV signal for plotting and visualization purposes. The grey dashed line indicates the average of the signal (500 ms) window prior to elicitor presentation and the blue bar indicates timing of the elicitor tone presentation.

After verifying the presence of an MEMC in response to an acoustic elicitor (for example, see Figure 2B and 2C), we attempted to classically condition the response by pairing the reflex-eliciting acoustic impulse (unconditioned stimulus, UCS) with various preceding stimuli (conditioned stimulus, CS). Changes in the time-course of the MEMC following repeated UCS-CS pairings would be considered evidence of MEMC conditioning. In order to test whether the MEMC could be “warned”, a training paradigm consisting of UCS-CS stimuli pairings were presented to the subjects [5 repetitions (pre-training), 25 repetitions (training) and 5 repetitions (post-training)] for three different preceding stimulus conditions (i.e., Light Flash, Countdown and Button Press). The number of training repetitions was chosen to match previous work that reported an anticipatory MEMC was elicited in 80% of the subjects tested using 30 pairings of a mild electrocutaneous stimulus with a 1 kHz pure tone (Yonovitz, 1976). For the current study, subjects would be presented with 30 pairings prior to the post-training recording.

These preceding stimuli were chosen to encompass a visual stimulus, an acoustic stimulus, and an engagement stimulus, in which the subject was responsible for initiating the upcoming acoustic elicitor. LDV recordings were made during the pre-training and post-training presentations, and the timing of the MEMC onsets in these two conditions was compared. Light flash and button press conditions had an LDV recording length of 3 seconds, the Countdown condition had a 5 second recording duration. Changes in the time-course of the MEMC following repeated UCS-CS pairings were considered evidence of MEMC conditioning; the magnitude of the change in velocity was assessed as a supplementary measure of MEMC

activation, but was less consistent due to variability resulting from LDV measurement location and angle, and was not considered a reliable measure of the change in cochlear input impedance (Feeney et al., 2001).

The Light Flash (LF) stimulus was generated using a TDT Flashlamp System which consists of a Flash Lamp Driver, a LS1130 Flashlamp and a F01 Liquid Light guide (Tucker

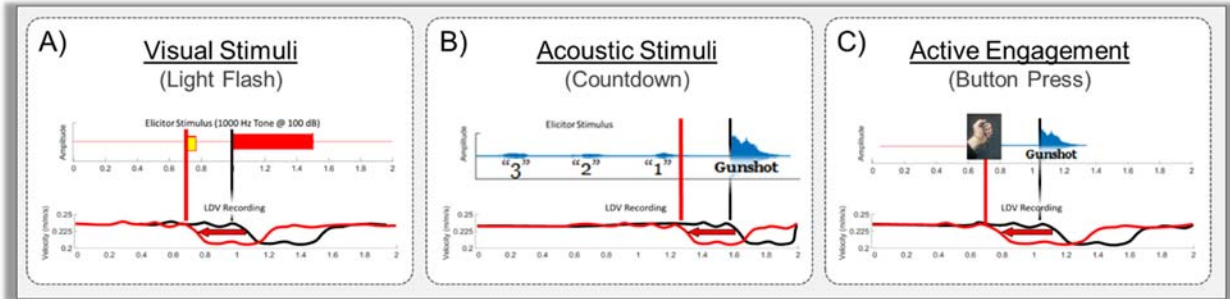


Figure 3. Visualization of experimental approach. A-C) Each of the preceding stimulus conditions are represented. The black trace at the bottom of each figure represents the normal activation of an MEMC in response to the acoustic elicitor. Following repeated pairings with the preceding conditioning stimulus, there would be a shift (indicated by the red arrow) in the timing of MEMC and indicate an anticipatory response (red traces).

Davis Technologies, Alachau, FL). The Flashlamp was located outside of the sound booth to minimize the level of the audible click associated with the activation of the bulb (which was further masked by the ipsilateral probe tone and bilateral insert earphones, thus rendering the click inaudible). The liquid light guide was used to direct the light flash stimulus into the sound booth and onto a photography softbox (Interfit, Atlanta, Georgia). The softbox was placed approximately 60-100 cm in front of the subject such that the light flash was clearly in the field of view, and 20-30 cm in diameter. Note, the room light was switched off during this task, thus the light flash was clearly visible but not uncomfortably bright. The light flash was 100 ms in duration and was presented 250 ms prior to the elicitor. Thus, there was 150 ms between the end of the light flash and the elicitor onset. Subjects were instructed to quietly listen to the stimuli, with their eyes open, throughout the duration of the stimulus presentation.

The Countdown (CD) stimulus consisted of a male talker saying, “3...2...1...” followed by a recorded .22 caliber gunshot. The voice recording was played back at ~65 dB SPL in order to be audible, but not elicit an MEMC itself. There was a 490 ms period of silence between the final spoken number at the end of the countdown and the gunshot recording. For this condition, subjects were instructed to quietly listen to the stimuli.

The Button Press (BP) condition consisted of the subject pressing a button-switch wired to trigger playback of the same recorded .22 caliber gunshot. The gunshot was presented 150 ms following the button press to reduce the potential effect of movement artifact without producing an audible delay. Subjects were instructed to wait 5-10 sec between each of their button presses and to vary the duration in between each press to reduce any potential cues that could arise from a consistently repetitive timing.

Presentation order of the three stimulus conditions were pseudorandomized for each

subject. Comparisons were made between the LDV signals recorded in the pre- and post-training blocks. The experimental approach and predicted effect of MEMC conditioning are demonstrated in Figure 3. The vertical black and red line in each figure indicates the timing of the elicitor and preceding conditioning stimulus, respectively. Any indication of an MEMC occurring prior to the onset of the acoustic elicitor (i.e., represented by the red trace occurring before the black line in Figure 3A-C) would be considered a “warned” response.

Results

Out of the 59 subjects tested, MEMCs were not visible in LDV measurements in 9 subjects (15%) despite all subjects having detectable acoustic reflexes using clinical tools prior to testing. This variability may be either due to lack of a measurable MEMC or due to an LDV technique unsuitable to measuring the MEMC, but demonstrates that MEMCs are highly variable across individuals and highlights the difficulty in measuring the time course of these responses for brief duration stimuli. Of the 50 subjects (81%) showing an MEMC, we attempted to classically condition the response via a training paradigm that paired reflex-eliciting acoustic signals with three different test conditions. Both non-conditioned and conditioned (i.e., unwarned and warned, respectively) responses were observed.

Figure 4 shows data collected for two subjects for the countdown condition. The purpose of this figure is to show the steady baseline in the LDV recording during the countdown, which

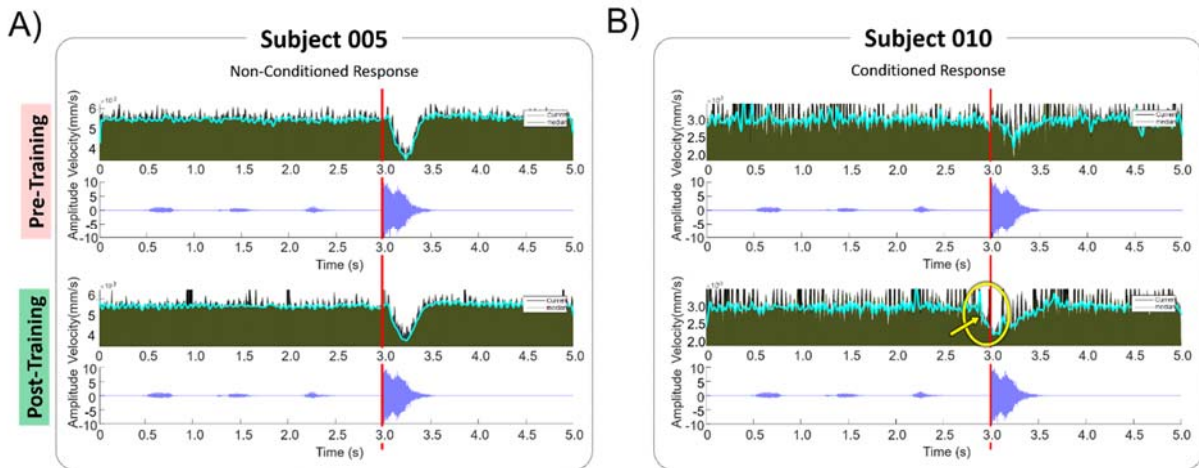


Figure 4. Individual data collected for two subjects before and after training paradigm. The red line in each figure indicates the timing of the elicitor presentation. A) Example of a non-conditioned MEMC response. B) Example of a potential conditioned MEMC response. The MEMC begins prior to the elicitor indicated by the yellow arrow.

indicates the sound level of the countdown itself did not elicit a MEMC response. In addition, the variability of the LDV signal quality between subjects, where some recordings were noisier than others. In Figure 4A, there was no difference in the timing of the MEMC response, i.e., the decrease in velocity still occurs after the elicitor presentation in the post-training recording. This means experience with the countdown did not “warn” the MEMC to contract in anticipation of the subsequent acoustic impulse.

A summary of the data collected in this study is shown in Figure 5. Columns correspond to the three stimulus conditions (indicated at the top of the column). The acoustic waveform used as the elicitor is plotted on the top row (blue trace), and the timing of the acoustic elicitor (vertical red line) and conditioning stimulus (vertical black line) are depicted in each of the subsequent plots. Each trace in the subsequent plots represents the normalized, average TM velocity from one subject. As described in Figure 3, the decrease in velocity following the acoustic elicitor (red line) indicates a reflexive MEMC (light red traces) and a decrease in TM velocity prior to the elicitor presentation (green traces) indicates an anticipatory MEMC.

In order to plot all of the data on the same y-axis, all of the traces were normalized to the root-mean squared (RMS) amplitude of the LDV signal during the baseline period (i.e., the 500

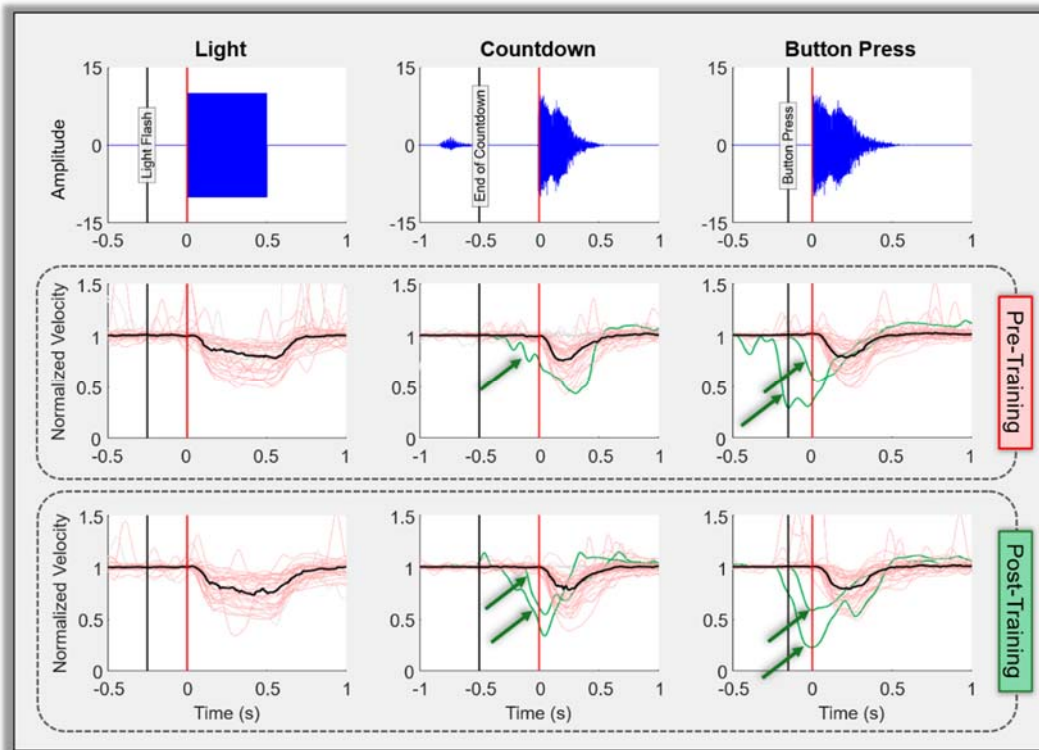


Figure 5. LDV measurements before and after training paradigm. The top row depicts the waveform of the acoustic elicitor. The black line represents when the preceding stimulus was presented and the red line corresponds to the elicitor presentation. Two subjects (out of 50) showed an anticipatory MEMC (green traces indicated by the green arrows).

ms prior to the preceding stimulus presentation). The MEMC response averaged across subjects is indicated by the thick black trace in each of the subplots in Figure 5. Note that if the majority of subjects showed an anticipatory MEMC response, the average response would have shifted to the left in time and occurred prior to the elicitor (vertical red line); however, the vast majority of subjects show purely reflexive MEMC, thus the mean remains to the right of the red line in each of the conditions tested here. Additionally, it appears the duration of the MEMC closely follows the duration of the acoustic elicitor. Here, an MEMC response at or below 75% of the normalized velocity at the time of elicitor onset was considered a “pre-contracted” or “warned” response and was plotted in green.

For those subjects showing an MEMC, 48 subjects (96%) did not show evidence of a conditioned response after training, whereas only 2 subjects (4%) did show evidence of a “warned” response (see Figure 5, green arrows). All anticipatory responses observed were for the gunshot conditions (i.e., countdown and button press), whereas no anticipatory responses were seen for the light flash condition. Both subjects showing an anticipatory MEMC response did so for the button press condition prior to training indicating that some individuals may have the ability to contract their middle-ear muscles when actively engaged and responsible for causing the acoustic impulse to be delivered. It should be noted that the pseudo-random assignment ordering of conditions for both of these subjects had each listen to the Countdown condition first, so prior experience with the gunshot stimuli may have contributed to anticipatory MEMC responses observed in the Button Press condition.

Indeed, one of these two subjects reported volitional control over their middle-ear muscles, and intentional contraction during these tasks. No other subjects reported a similar ability or activity. There are some subtle indications that this is in fact happening. For instance, this particular subject exhibited an anticipatory MEMC response for both pre- and post-training in the countdown and button press conditions. While it is promising that the possibility of actively controlling the middle-ear muscles exist, this was only the case for one, at most, two out of the 50 subjects tested here and should not be relied upon as a protective mechanism in hearing health risk assessments. This ability appears to be uncommon in the general population, and overall these results suggest that MEMC rarely contract in anticipation of an acoustic elicitor.

Discussion

The goal of the current technical report is to disseminate the preliminary findings obtained from laboratory experiments that tested the ‘warned’ middle-ear assumption of the Auditory Hazard Assessment algorithm for Humans (AHAH). In this study, we sought to specifically examine whether the MEMC associated with the acoustic reflex could be conditioned to activate prior to the arrival of an acoustic impulse. Using a three-pronged approach, we paired either a visual stimulus (i.e., a light flash), an auditory stimulus (i.e., a verbal countdown) or an active engagement by the subjects (i.e., a button press) with a subsequent acoustic reflex eliciting impulse. Following repetitive presentations of the paired stimuli, the current study tested whether an MEMC could occur prior to the acoustic elicitor. These preliminary findings help provide empirical evidence about the potential state of the middle-ear system during a given impulse noise exposure, which could be used to better estimate the risk of auditory injury.

During the development of the AHAH, it was reasoned that some assumptions needed to be made in the model to account for the effects of the acoustic reflex due to the fact that middle ear muscle response to gunfire-level stimuli was, and still remains, essentially undocumented (G. Price & Kalb, 2018). The associated MEMC is a normal function of the mammalian ear and potentially reduces sound transmission from the middle to the inner ear. Indeed, previous research has shown the MEMC produces time-varying and frequency-dependent reduction in middle ear admittance (Feeney & Keefe, 1999) capable of reducing sound transmission by ~15-20 decibels at low frequencies (below 1000 Hz) and progressively

less at higher frequencies (Andersen, Hansen, & Neergaard, 1962; Zakrisson, 1978). Accounting for any reduction in damaging energy entering the cochlea is significantly important, especially when calculating the risk of auditory injury from intense sound exposures.

Given this, the AHAAH was developed to give users the option to run the model with a MEMC elicited in response to an impulse exposure (i.e., “unwarned”), or a MEMC elicited in anticipation of an impulse (i.e., “warned”), if the user felt the middle-ear muscles were pre-contracted for that particular situation and exposure. Prior to the AHAAH, no other hearing risk assessment tools for impulse noise gave an option to account for any potential effects of pre-contracted middle-ear muscles on sound transmission. However, several concerns about the inclusion of the middle-ear muscle activity in the AHAAH were raised by the AIBS during a panel review of impulse noise injury models available at the time (Wightman et al., 2010). Particularly for the current study, the panel reported that human data regarding the consequences of middle-ear reflex were lacking and evidence for anticipatory MEMC across various studies in the literature were unclear. The panel ultimately “questioned whether anyone understands the protective role of the middle ear reflex in sufficient detail to ascertain when an ear is warned or unwarned”. Indeed, a careful look at previous work on whether the acoustic reflex could be conditioned to activate in anticipation of a known coming sound exposure does not provide any definitive conclusions, especially when considering the implementation of such an occurrence into a health hazard assessment for hearing risk.

Anticipatory MEMC prevalence in literature

Recently, Price & Kalb (2018) reported on the philosophy and theoretical bases for the AHAAH. In this report, it was mentioned that previous research has demonstrated that human MEMC can be conditioned and several studies are cited to support this case (Brasher, Coles, Elwood, & Ferres, 1969; Gisle Djupesland, 1964; G. Djupesland, 1965; Marshall, Brandt, & Marston, 1975; Yonovitz, 1976). However, closer review of these reports reveals equivocal findings in regards to anticipatory MEMCs and their effect on noise exposure. For instance, while Brasher et al. (1969) did report measuring anticipatory MEMCs in a subset of 16 subjects, there were also no significant correlations found between any of the middle-ear muscle responses (reflex or anticipatory) and noise-induced temporary threshold shift (TTS). This led the authors to conclude that middle-ear muscle activity may have a trivial impact on an individual’s susceptibility to noise-induced TTS (Brasher et al., 1969). Additionally, the potential for an MEMC to provide protection for subsequent gunshots in rapid succession, that is, an impulse arriving at a time when the MEMC would still be contracted from the previous impulse, was left as a speculative consideration. Another study demonstrated a conditioned MEMC in 8 out of 10 subjects, but it required pairings of a mild electrocutaneous stimulus with a 750 ms, 1 kilohertz (kHz) pure tone (Yonovitz, 1976). In the present study, the subjects were presented with 30 pairings (i.e., 5 pre-training and 25 training presentations), but only small percentage of subjects (4%) exhibited a conditioned MEMC. This may suggest that the preceding stimuli used in the current study were not as robust in invoking an anticipatory response as an electrical stimulus.

Djupesland (1964) reported that contractions of the tympanic muscles were measured in subjects expecting a strong noise; however, this was studied by direct observation of the tendon of the tympanic muscle. In another study, Djupesland (1965) recorded middle-ear muscle activity using electromyography and observed increased activity of both the stapedius and tympanic

muscles upon the sight of a toy pistol pointed at the non-operated ear. The author suggested that the resulting contractions were in expectation of the loud and unpleasant sound the patients were told came from the pistol. However, if the patient did not expect a sound from the pistol, no response was evident. It should be noted the researcher also recorded the activity of the orbicularis oculi muscle, which is responsible for closing the eyelids. From the data presented in that study (Djupesland 1965, see Fig.6), the eye appears to be closed immediately following the presentation of the pistol to the patient and prior to the MEMC activity. Since each of the muscles recorded are innervated by branches of the facial (CN VII) nerve (Mukerji, Windsor, & Lee, 2010), there is no way to discern from these data whether it was the thought of the toy pistol making an unpleasant sound or broad activation of the facial nerve stemming from an eye closure or perhaps a “winching” at having a toy pistol pointed at them.

Marshall et al. (1975) showed that just thinking about handling a noisy toy is sufficient to trigger the MEMC in one subject and found anticipatory MEMC activity was a common occurrence among the 14 subjects tested in that study. However, in that study the subjects were instructed to watch the meter of the impedance bridge and try to contract their middle-ear muscles or “do anything to make the needle move to the right.” Additionally, the authors report that many anticipatory MEMCs occurred when the SPL of the toy was clearly below that necessary to elicit a normal reflex (Marshall et al., 1975). This finding suggest that the anticipatory events being measured may have not have been generated in expectation of the sound sources themselves. Upon careful review of the reported findings, the literature is ambiguous concerning whether the MEMC can be classically conditioned. As Price & Kalb (2018) recently pointed out, research on this issue would still be valuable, and information about whether or not the human middle ear muscle response is conditionable would be useful. Findings from the current study directly addressed the issue of conditioning an anticipatory MEMC to be elicited.

Implications for damage-risk criteria and health hazard assessments

Since the implementation of the earliest DRC for impulsive noise developed (Coles, Garinther, Hodge, & Rice, 1967) into MIL-STD-1474D (Ward, 1968), the DoD design criteria standard for noise limits has been used as the definitive DRC for impulsive noise (DoD, 1997). Due to the lack of a medical standard, the DRC in MIL-STD-1474D pertaining to impulsive noise has also been used for HHA over the past several decades. It is important to note that while closely-related, the DRC and HHA serve different purposes. In regards to noise, the DRC specifies the maximum permissible limit of exposure; whereas the HHA describe the amount of acceptable noise exposure produced by systems relative to the associated DRC. With the adoption of MIL-STD-1474E, the inclusion of the AHAAH as a DRC may lead to the use of this model as a HHA. In conjunction with the ongoing research into the various components of the AHAAH (Chan, Ho, Kan, Stuhmiller, & Mayorga, 2001; De Paolis et al., 2017; Gan, Nakmali, Ji, Leckness, & Yokell, 2016; Nathaniel T Greene et al., 2018; Nathaniel T. Greene, Jenkins, Tollin, & Easter, 2017; Liang et al., 2016; Patterson & Ahroon, 2004; Zagadou, Chan, Ho, & Shelley, 2016), the findings reported here indicate that the AHAAH model needs several updates

and modifications before it should be balloted for consideration as a medical standard HAA. Specifically, the current study suggests that concerns with the “warned” option of the model are warranted.

Additionally, the use of the acoustic reflex and the associated MEMC time constants in current and future models need to be revisited. The first DRC for impulsive noise developed by Coles et al. (1967) was later modified to presume that the acoustic reflex eliminated the additional accumulation of risk for signals having pressure-envelopes greater than or equal to 200ms (Ward, 1968). Currently, the MEMC in the AHAAH turns on 9 ms after the impulse onset and follows a step function with a time constant of 11.7 ms, and then reaches its maximum value within 44 ms. In the current study, the across-group average MEMC onset for the “unwarned” presentations (i.e., prior to training) indicated that the MEMC contraction started ~72-73 ms after elicitor onset for the CD and BP conditions. While it should be noted that a conservative estimate of the onset timing was taken (i.e., time value of the fit functions at 0.8), the most beneficial role of the MEMC in terms of providing protection would occur at the peak activation (i.e., maximum engagement) which reached roughly ~165-189 ms for the level of gunshot elicitor used in this study. However, the time to peak activation may be shorter for peak levels greater than those tested here as latency changes with stimulus frequency (Møller, 1958).

This study found that although anticipatory MEMC were observable in some individuals, they were certainly not prevalent among the population of the subjects tested. This means that the “warned” option is not appropriate to use when calculating auditory injury risk. In addition, the acoustic reflexes reported here did not exhibit the rapid onset and activation slope implemented in the AHAAH for attenuating the later arriving secondary features associated with an impulse noise. The MEMC also appears to recover quickly and does not remain engaged for much longer after the eliciting stimulus has ended. The findings reported here indicate that DRC or HHA includes the MEMC as a protective at the time of acoustic impulse arrival, they run the risk of underestimating the hazard and may indicate an exposure is safe, when it is not.

Conclusions

To review, the goal of this study was to test the “warned” middle-ear assumption of the AHAAH.

In general, our preliminary assessment indicates that the MEMC can be conditioned to be “pre-contracted”, but only in a small percentage (~4% of the subjects tested here) of the population. Although anticipatory MEMCs were observable in some individuals, they were certainly not prevalent among the population of the subject tested. These findings suggest that a “warned” MEMC likely is not present in enough people to justify inclusion for being considered protective. Thus, the “warned” option of the AHAAH model may not be appropriate to use when calculating auditory injury risk.

Additionally, the acoustic reflexes reported here did not exhibit the rapid onset and activation slope implemented in the AHAAH for attenuating the later arriving secondary features associated with an impulse noise. The MEMC also appears to recover quickly and does not remained engaged for much longer after the eliciting stimulus has ended. The findings reported

here indicate that DRC or HHA which include the MEMC as a protective at the time of acoustic impulse arrival run the risk of underestimating the hazard and may indicate an exposure is safe, when it is not. Knowledge gained from this study indicates the need for updates to hearing health hazard assessments and will inform updates to Damage-Risk Criteria to better protect the hearing of Soldiers and civilians exposed to high-level impulsive noises

Recommendations

Any future updates to hearing risk assessment models intended to calculate the damage resulting from acoustic impulse should not consider MEMC as a protective agent. We recommend the exclusion of the “warned” option from the AHAAH. There does not seem to be enough evidence in the literature or this study to recommend its inclusion when assessing hearing risks associated with impulse noise.

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