

A Comparison of the Single-sided (Gen II) and Double-sided (Gen I) Combat Arms Earplugs (CAE): Acoustic Properties, Human Performance, and User Acceptance

by Mary Binseel, Kara Cave, Joel Kalb, Tomasz Letowski

ARL-TR-6270

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT The U.S. Army Research Laboratory conducted a multi-factor assessment of the second generation Combat Arms Earplug (Gen II CAE) in order to determine whether it maintained the acoustic properties of the first generation CAE earplug (Gen I CAE) while improving its usability. Both versions of the CAE are dual mode earplugs providing either linear or nonlinear (level-dependent) noise attenuation. The Gen I CAE is a dual-sided earplug, with one side providing linear protection and the other providing nonlinear protection. The Gen II CAE is one-sided earplug, with mode selection accomplished by rotating a cylindrical switch in the body of the earplug. This report documents the results of steady-state and impulse noise attenuation objective and real-ear measurements; localization and speech intelligibility human performance tests; and user-acceptance questionnaires administered to Soldiers deployed in Iraq. The results of acoustic measurements and psychoacoustic assessments of Gen II CAE indicate that it closely matches performance of the Gen I CAE. The deployed Soldiers indicated some problems with the Gen II CAE but in general preferred the Gen II CAE over the Gen I CAE. These data and the qualitative improvements in Gen II CAE design fully justify the acquisition of the earplug by the U.S. Army.				
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1. Introduction

Noise-induced hearing loss in the Army persists as one of the most common injuries experienced by deployed Soldiers. Helfer et al. (2005) reported that of audiology clinic patients, Soldiers returning from deployment had significantly higher rates of tinnitus, noise-induced hearing loss, and H-3 and H-4 profiles* than Soldiers whose visits were non-post-deployment related.

Tinnitus and hearing loss are, respectively, the first- and second-most prevalent service-connected disability for veterans receiving disability payments at the end of fiscal year 2010. Over the last five fiscal years (2006–2010), impairment of auditory acuity (which includes tinnitus, hearing loss, and other conditions, such as chronic otitis media) ranks second only to musculoskeletal system issues as the most prevalent cause for new service-related disability payments, as aggregated by body system. From 2008 to 2009, for new service-related disability payments, the percentage of impairment of the auditory system rose 14.1%, while the overall disability rate increase was 6.9%, and from 2009–2010, impairment of the auditory system rose 17.6%, while the overall rate rose 5.7%. (Department of Veterans Affairs, 2010).

The Army's earplug of choice for protecting Soldiers' hearing is the Combat Arms Earplug (CAE). There are two versions of the CAE. Both versions are dual mode; that is, they provide either linear (fixed) or nonlinear (level-dependent) noise attenuation. The wearer selects the mode based on his or her noise environment. The first generation (Gen I) CAE is dual-sided, with one side providing linear protection and the other providing nonlinear protection. Mode switching is accomplished by removing, reversing, and reinserting the earplug. The Gen I CAE triple-flange tips come in one size. The second generation (Gen II) CAE is one-sided, with mode selection accomplished by rotating a cylindrical switch in the body of the earplug. The objective of redesigning the CAE was to maintain the acoustic properties of the Gen I CAE while improving the fit, comfort, and compatibility with other Soldier equipment. The Gen II CAE has triple-flange tips, which are available in three sizes for better fit, has a lower profile for better equipment compatibility, and is corded for earplug retention.

* H-3 and H-4 are functional capacity assessments for hearing. They are defined in U.S. Army Regulation 40-501 (2007) (Table 7-1) and shown in appendix D in this report. The categories range from H-1 (best hearing) to H-4 (worst hearing). Soldiers with an H-3 or H-4 profile must be assessed by a Medical Evaluation Board physician for retention or assignment limitations.

2. Purpose of the Study

This study was performed to determine if the new Gen II CAE, in particular the nonlinear functionality, was an acceptable alternative to the original dual-mode Gen I CAE. Typically, hearing protection devices (HPDs) are described by their Noise Reduction Rating (NRR) only (40CFR211 subpart B). The calculation of the NRR is a method of combining a hearing protection device's attenuation at many frequencies to one number for easy comparison across devices. However, the NRR is based on measurements of HPD attenuation at only one noise level. Since the attenuation of nonlinear HPDs varies as a function of level, NRR cannot describe the attenuation characteristics of such devices. For nonlinear devices, it is more appropriate to measure attenuation in the two noise environments for which the earplugs were designed: lower-level continuous noise environment (85 dB A and under), where wearing of hearing protection is not required (Department of the Army, 1998) and the CAE should be attenuating at a minimal value in order to allow auditory situation awareness; and in a high-level impulse noise environment, where the CAE nonlinearity should be providing increased attenuation needed to protect the user. Measurements at numerous levels of each of these noise environments should be taken to understand how much attenuation is present, when it begins to increase, the rate of increase, and the noise level at which attenuation reaches its maximum.

In addition, attenuation alone is not a sufficient measure of an earplug's effectiveness. The effect of wear of the earplug on a Soldier's ability to localize sound and to hear and understand speech is also of importance. Finally, the best HPD will not be effective unless it is worn. There must be a level of user acceptance (for example, confidence in the device and sufficient comfort level) for Soldier wear compliance.

This report documents a suite of measurements and studies that address major characteristics of the nonlinear functionality of CAEs: steady-state noise attenuation, real-ear attenuation at threshold (REAT), impulse noise attenuation, speech intelligibility, localization accuracy, and user acceptance. The quantitative measures (attenuation, localization, and speech intelligibility) were performed using the nonlinear mode only, as this is the main mode of CAE wear for dismounted Soldier operations. The linear earplug mode (both Gen I and Gen II CAEs) is not intended to provide auditory situational awareness or speech communication capabilities; therefore, the linear modes of the earplugs were not evaluated in quantitative studies.

2.1 CAE: Dual-sided Version (Gen I)

The dual-sided CAE (Gen I CAE[†]) is shown in figure 1. The earplug is a combination of two separate earplugs (green and yellow) connected back-to-back. Insertion of the green, solid end of the earplug provides noise-level-independent hearing protection (NRR=22 dB) and is intended to be used to reduce steady-state noises, such as noise from vehicles, aircraft, and generators. It provides attenuation of external noises ranging from 32 dB (at 125 Hz) to 44 dB (at 6300 Hz). The yellow end of the earplug provides level-dependent (nonlinear) protection for impulse noise hazards, such as gunshots and blasts. The basic concept and design of the nonlinear CAE was developed by researchers at the French-German Research Institute of Saint-Louis (ISL). The Gen I and Gen II CAEs are manufactured and marketed in the United States by Aearo Technologies, Inc. (acquired by 3M in 2007) (NSN: 6515-01-466-2710) and all the CAE data listed in this section are acquired from the CAE data sheet published by Aearo (Aearo, 2008). The nonlinear mode provides very limited attenuation of noise levels below 110 dBp sound pressure level (SPL) (about 8 dB in 500–1000 Hz range), but its attenuation increases for impulse noise at levels above 110 dBp SPL. This enables the Soldier to hear speech and environmental sounds in relatively quiet environments while still providing protection against impulse noise hazards.

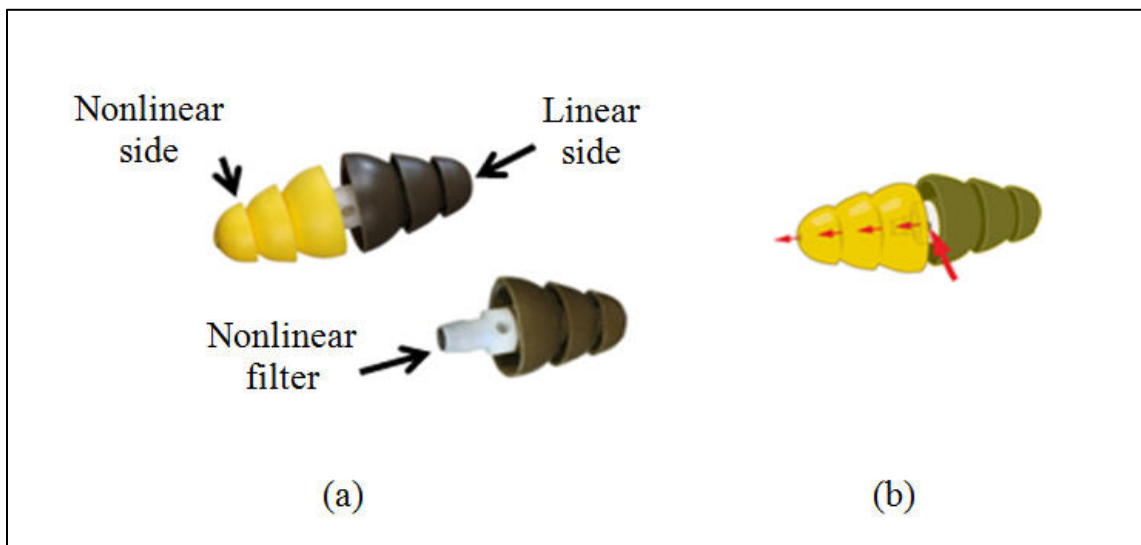


Figure 1. Gen I CAE. (a) Photographs of the complete earplug and earplug with the tip removed. (b) Drawing of the acoustic pathway of the nonlinear mode (courtesy of 3M).

[†] Some authors and developers consider the French-German Research ISL's original one-ended, nonlinear-only earplug to be the first generation CAE, the dual-sided to be the second generation, and the dual-mode one-sided to be the third. We are concerned only with dual-mode variants and will follow the convention as stated in the text.

Both the Gen I CAE triple-flange tips come in one size. Mode switching is accomplished by removing, reversing, and reinserting the earplug. The primary disadvantage of the two-sided earplug is that it must be removed from the ear canal, reversed, and re-inserted for the user to switch attenuation modes. Other usability concerns are that it comes in only one size tip, and its long profile can interfere with other Soldier equipment, such as helmets and communications headsets.

2.2 CAE: Single-sided Version (Gen II)

To address the perceived shortcomings of the Gen I CAE, Aearo redesigned the CAE. The changes to the original design included: (1) a change from a two-sided to a single-sided design in order to allow the user to switch between modes without removing the earplug from the ear canal; (2) addition of a retention cord connecting the left and right earplugs (the cord is designed to break if it gets hung up on anything or it can be removed if the Soldier prefers non-corded plugs); (3) availability of three different ear tip sizes to better fit Soldiers; and (4) decrease of the overall earplug profile for better equipment compatibility. The manufacturer's goal was to maintain the acoustic response of the Gen I CAE but to improve its comfort, fit, equipment compatibility, and functionality in order to increase user acceptance and Soldier compliance. The Gen II CAE is shown in figure 2. The Gen II CAE has triple-flange tips that are available in three sizes for better fit, and has a lower profile for better equipment compatibility. The earplug stem, which houses the nonlinear filter, is also smaller in the Gen I CAE raising questions regarding the objective and subjective performance of the redesigned earplugs.

Olive green, yellow, and red tips inserted on the hard core of the earplug (which contains the nonlinear acoustic filter) are intended to fit small, medium, and large size ear canals, respectively. Mode switching in Gen II CAE is accomplished by rotating a cylindrical switch in the body of the earplug. Note, that the flat shape of the switch makes it very likely that after insertion the two-sided side hole will be aligned horizontally (facing forward and backward).

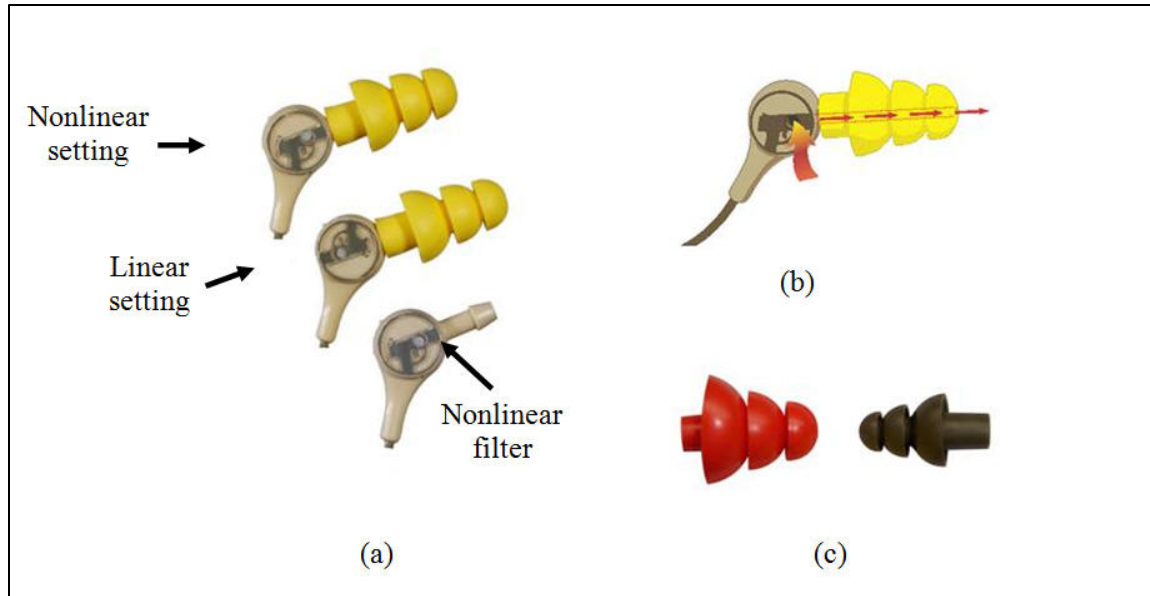


Figure 2. Gen II CAE. (a) Photographs of the complete earplug with each mode selected and with the tip removed to show the nonlinear filter. (b) Drawing of the acoustic pathway of the nonlinear mode (courtesy of 3M). (c) Photographs of the large (red) and small (olive green) tips.

Note: In figure 2 all images are approximately to scale.

3 Steady-state Noise Attenuation

3.1 Method

Steady-state noise attenuation measurements were conducted using the Knowles Electronics Manikin for Acoustic Research (KEMAR). KEMAR was developed for use by the hearing aid community, and is generally not appropriate for use in attenuation measures. However, Berger (1992) established that for earplugs with an intentional acoustic pathway, such as the nonlinear mode of the CAE, KEMAR may be appropriate for insertion loss measures and can produce results in reasonable agreement with data obtained using humans.

The attenuation measurements were made in the U.S. Army Research Laboratory, Human Research and Engineering Directorate (ARL/HRED) reverberant chamber in building 520 at Aberdeen Proving Ground (APG), MD. Pink noise, which has equal energy in all octave bands, was used as an input signal. The noise was played from a CD player connected to a Crown Macrotech 602 amplifier, which fed the signal into three ElectroVoice FX 100 loudspeakers within the reverberant chamber. The loudspeakers were arranged in the orthogonal pattern to create a diffuse field complying with the requirements in American National Standards Institute (ANSI, 2008). Noise levels inside the KEMAR's ear canals were measured using a Symphonie data acquisition and analysis system manufactured by the 01dB company. The right ear of the manikin was occluded with the earplug under test, and the left ear was unoccluded.

Measurements of the noise reduction were made for the following test conditions: no earplug, Gen I CAE (nonlinear mode), and Gen II CAE (nonlinear mode). The noise input level at the unoccluded manikin ear was set at 65 dB A, which is a common conversational speech sound level. The measurements were made in the diffuse field. Background noise level in the test space was below 35 dB A. For each test condition (earplug variant) three measurements were made with earplug re-insertion (for the earplug conditions) between measurements.

3.2 Results and Discussion

Each set of three steady-state measurements was averaged and plotted by frequency. The results are presented in figure 3. The curves shown in figure 3 are the $\frac{1}{3}$ octave insertion loss levels measured in the ear canal for the un-occluded ear and the two occluded ear conditions for the 65 dB A-weighted pink noise input signal measured at the ear.

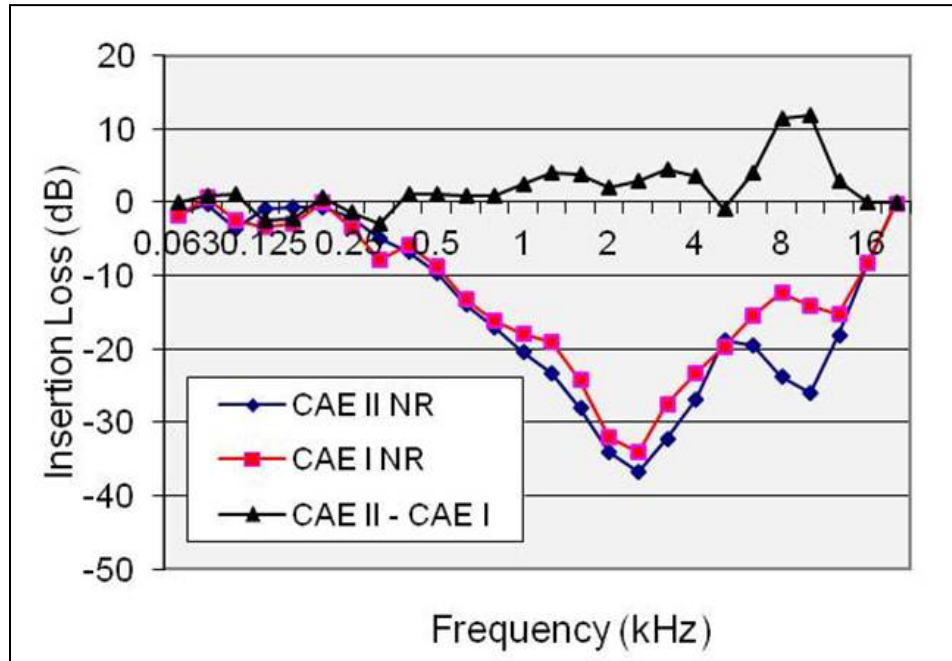


Figure 3. Noise reduction (NR) curves for Gen I CAE (CAE I NR; squares) and Gen II CAE (CAE II NR; rhombs). The bottom curve (CAE I – CAE II; triangles) shows the difference in noise reduction caused by both plugs for 65 dB A-weighted pink noise input signal.

The data presented in figure 3 show that Gen II CAE resulted in slightly greater insertion loss at frequencies above 400 Hz than Gen I CAE. However, the only significant differences ($p < 0.05$) were observed at 8,000 and 10,000 Hz where the Gen II CAE provided greater attenuation by about 8–14 dB. These differences in attenuation are most likely due to resonant vibrations of the solid part of Gen I CAE protruding from the ear.

4. Real Ear Attenuation at Threshold (REAT)

4.1 Method

The attenuation values discussed in the previous section were determined by placing earplugs in the ears of a KEMAR manikin. The use of a manikin is acceptable for measuring relative attenuation of earplugs with intentional acoustic pathways. However, the attenuation values determined this way do not fully represent human performance. A common method to measure attenuation of continuous noise that hearing protectors are likely to provide for the actual users is the REAT method. The REAT method is governed by ANSI standard S12.6 *American National Standard Methods for Measuring the Real-Ear Attenuation of Hearing Protectors* (ANSI, 2008). To determine attenuation of hearing protectors using the REAT method, the standard requires measurement of the hearing thresholds for 20 people with ears open and with ears occluded by hearing protectors, at several standard frequencies. The difference between the occluded and unoccluded hearing thresholds at a given frequency is the REAT attenuation of the earplug at this frequency.

Ten volunteers aged 21 to 35 who had been screened to ensure normal hearing (≤ 20 dB hearing level [HL] at the audiometric frequencies of 125; 250; 500; 1,000; 2,000; 4,000; and 8,000 Hz) participated in the REAT testing of both Gen I CAE and Gen II CAE in nonlinear mode. The REAT tests were conducted in a diffuse sound field according to ANSI (2008) with the exception that the group of listeners was limited to ten volunteers instead of the 20 people required by the standard for testing earplugs. Each threshold was measured twice and the results were averaged for each participant and test condition.

4.2 Results and Discussion

The REAT data averaged across all participants are shown in table 1.

Table 1. Mean (M) and standard deviation (SD) of the REAT data for Gen I CAE and Gen II CAE. M (Gen I–Gen II) is the difference between means.

Earplug	Measure	Frequency (Hz)						
		125	250	500	1,000	2,000	4,000	8,000
Gen I CAE	Mean	3.0	3.3	7.8	13.0	19.8	21.3	18.5
	SD	3.1	3.6	2.5	7.3	5.2	4.6	3.8
Gen II CAE	Mean	2.0	2.3	4.3	11.3	17.8	20.0	22.3
	SD	2.0	3.2	4.4	8.3	7.8	9.1	6.7
M (GenI – GenII)		1.0	1.0	3.5	1.7	2.1	1.3	–3.8

Paired comparison tests for REAT Gen I CAE and Gen II CAE data at each test frequency revealed statistically significant differences ($p < 0.05$) at two frequencies: 500 Hz and 8,000 Hz. Gen I CAE provided significantly greater attenuation at 500 Hz and the Gen II CAE provided significantly greater attenuation at 8,000 Hz. While the result at 500 Hz is not reflected in steady-state attenuation values obtained with the KEMAR manikin, the difference at 8,000 Hz has similar character.

5. Impulse Noise Attenuation

5.1 Method

The impulse attenuation measurements for Gen I CAE and Gen II CAE were conducted at ARL/HRED's M-Range facility at APG, MD. The test fixture used was a manikin developed by the French-German Research ISL specifically for impulse noise measurements. The unique features of the manikin include acoustic isolation of the measurement elements (ear simulators, microphones, and preamplifiers) and mechanical uncoupling of the measurement elements from the manikin head shell (Buck and Parmentier, 1999). The manikin was placed normal to the weapons fire; that is, with the left ear pointing towards the impulse source, in order to get the worst-case scenario of energy arriving at the ear (normal incidence). The recordings were made in the left ear only. The source of impulse noise was an M16 rifle. Measurements were made simultaneously by a microphone located in the left ear canal of the ISL manikin and a free-field microphone located at 0.5 m away from the manikin, in the same plane (same distance from the impulse source). The distance between the ISL manikin ear and the firing weapon was 0.2 m, 0.5 m, 1 m, 2 m, 4 m, 8 m, 16 m, 32 m, and 64 m to make attenuation measurement for different impulse noise levels. There were three shots fired and recorded at each distance. The ISL manikin and the location of the free-field microphone are shown in figure 4 for the 1 m measurements.

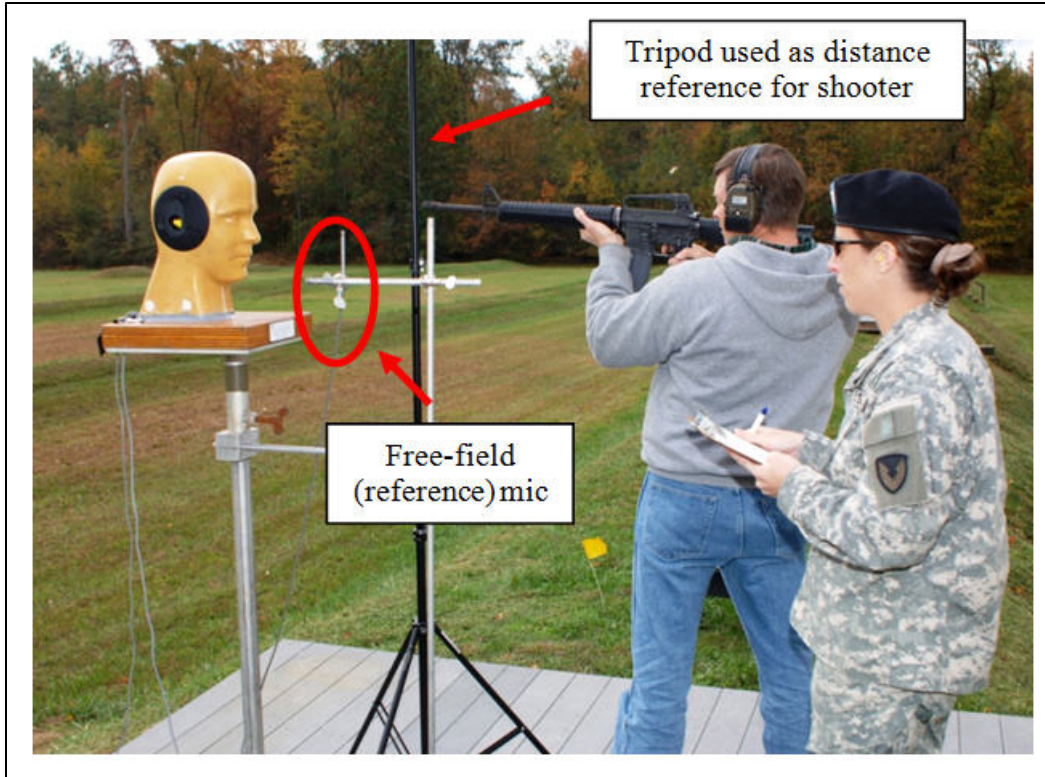


Figure 4. Impulse noise measurements at the M-Range using ISL manikin.

5.2 Results and Discussion

The relationship between peak pressure levels (PPLs) recorded through the ISL manikin and the distance to the noise source (M16 rifle) are shown in figure 5. The shaded squares are the data for the open left ear of the ISL manikin and the shaded triangles are the data for each of the CAE earplugs inserted in this ear. In addition, the levels recorded by the free-field microphone are also shown. The *ISL - Bare Ear PPL* line is located higher than the *Free Field PPL* line because of the pressure gain due to the manikin's ear, similar to what occurs in a human ear.

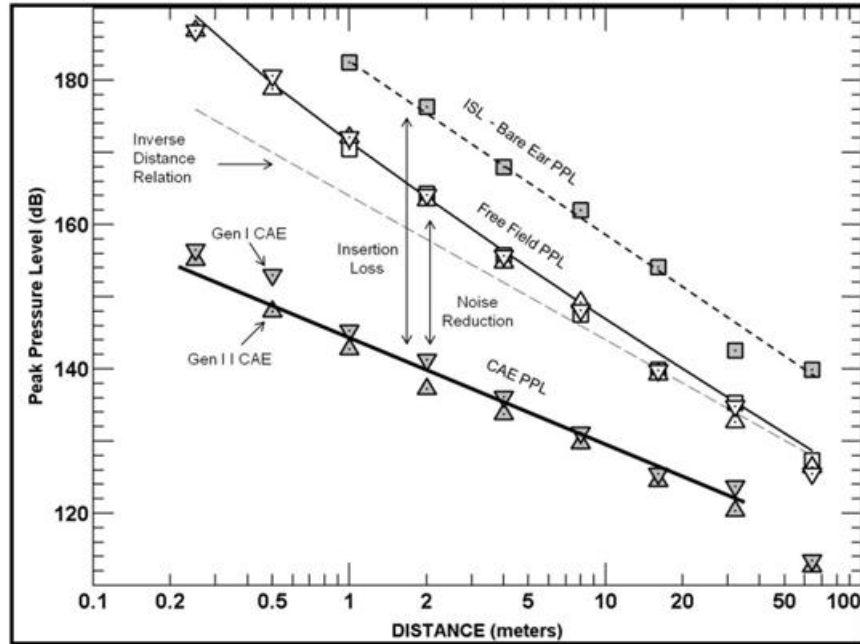


Figure 5. Impulse noise peak pressure measurements data.

Note: Description of data from figure 5 is included in the text.

The attenuation of peak pressures was clearly equivalent for the two versions of the CAE (bottom line in figure 5). The graphs also show the nonlinear character of both plugs across the range of tested sound pressure levels; i.e., the attenuation of the free field peak pressure varies from about 12 dB for the shots at 64 m distance (the lowest stimulus peak pressure) to about 32 dB for the shots at a distance of 0.2 m (the highest stimulus peak pressure). However, there are other factors that can affect the hearing hazard of an impulse, such as the shape of the waveform experienced by the eardrum. In order to verify that both nonlinear CAEs attenuate the impulse noise in similar ways, the impulse waveforms recorded at the manikin's microphone under the CAEs were compared directly. In all cases the two waveforms were very similar, confirming previous findings. Two examples of waveform comparison are shown in figure 6.

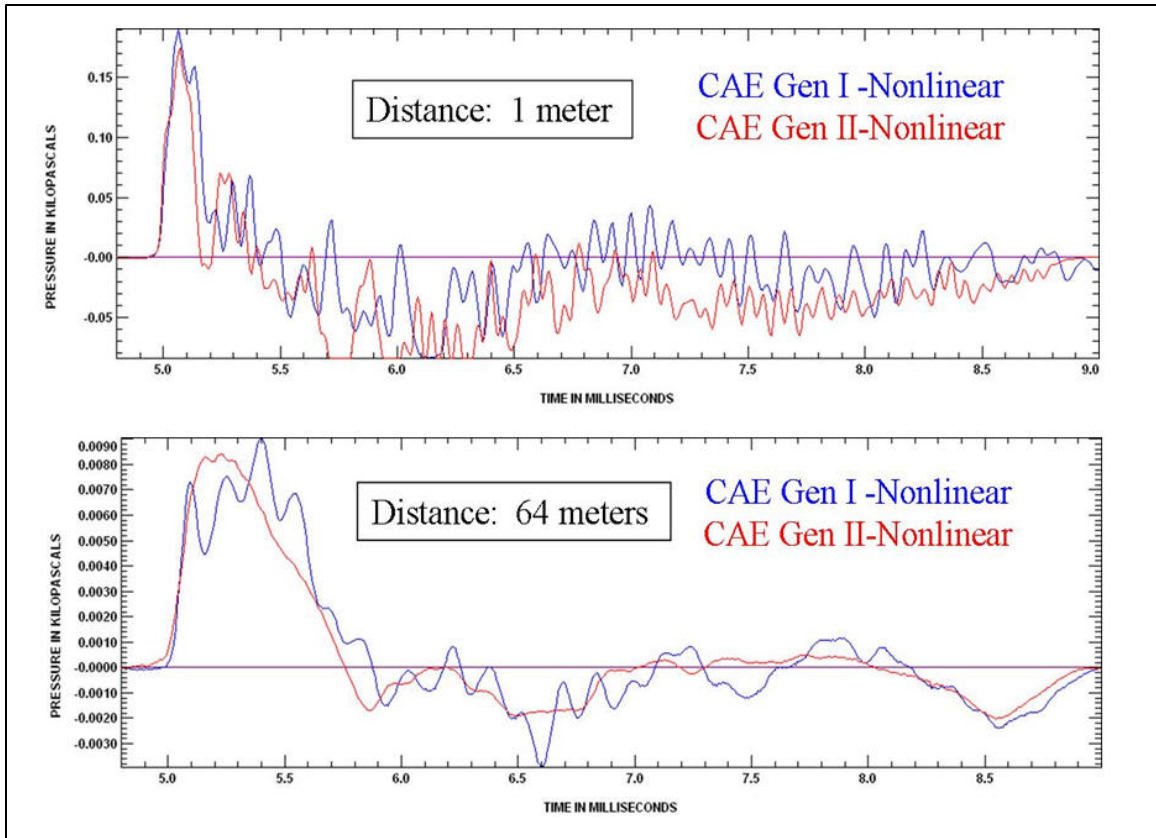


Figure 6. Comparison of M16 rifle waveforms under Gen I CAE and Gen II CAEs. The M16 rifle was fired at 1 m (upper panel) and 64 m (lower panel) distances.

While both waveforms under the earplugs in figure 6 are similar in overall shape, they do vary in a way that might be important to hearing protection. When waveforms from equivalent exposures (e.g., a 2 m firing distance exposure) were analyzed using the Auditory Hazard Analysis Algorithm for Humans (AHAH) (Price, 2007), the impulses produced less hearing hazard under the Gen II CAE than under the Gen I plug. We hypothesize that this is due to the fact that there are fewer waveform axis crossings (i.e., positive-to-negative or negative-to-positive pressure changes crossing the ambient pressure axis) with the Gen II CAE. It is quite possible that this is due to greater CAE Gen II attenuation at high frequencies.

NR and insertion loss (IL) caused by both earplugs are frequency dependent as shown in figure 3 for continuous noise. Examples of similar functions calculated for impulse noise (M16; 2 m) are shown in figure 7. Again, the curves for both earplugs are quite similar with the Gen II CAE showing somewhat greater attenuation at high frequencies. The differences in level and shape of IL functions in figures 7 and 3 indicate the nonlinear character of both earplugs across wide frequency ranges.

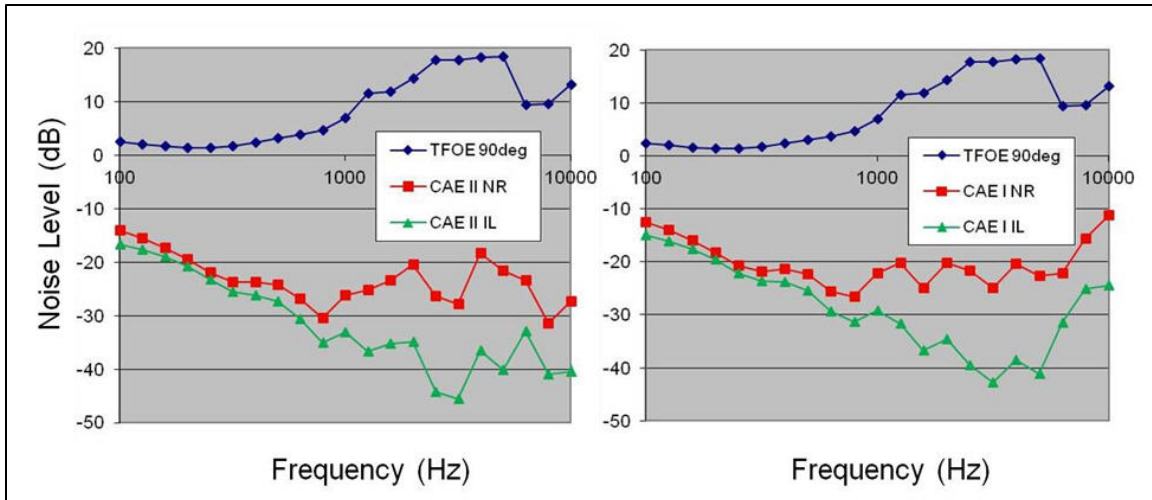


Figure 7. IL (triangles) and NR (squares) frequency functions of Gen I CAE (right panel) and Gen II CAE (left panel). The top line (rhombs) represents transfer-function-of-ear (TFOE) that is earplug independent.

6. Speech Intelligibility

6.1 Method

Speech intelligibility testing was conducted at the Hostile Environment Simulator (HES) at APG, MD, using a Scantek P012 dodecahedron loudspeaker and Scantek AP600 multi-channel power amplifier for signal presentation. The test material was a short version (CAT-36) of the Callsign Acquisition Test (CAT) speech intelligibility test developed specifically for military applications (Rao and Letowski, 2006; Rao et al., 2006; Blue et al., 2010). Two signal-to-noise ratios (SNRs) were employed to present just discernible (SNR = -8 dB) and easily to discriminate (SNR = -2 dB) speech stimuli in the background of a 63 dB A-weighted Baghdad street noise.

A group of 10 listeners, age 21 to 35, participated in the study. Each listener had normal hearing as determined; by a hearing screening test passed at 20 dB HL at the audiometric frequencies of 125; 250; 500; 1,000; 2,000; 4,000; and 8,000 Hz. Groups of from one to four listeners were seated at 2 m from the loudspeaker, and all sound level measurements were made at the listener's location with the listener absent. Listeners responded to the stimuli by writing down the perceived CAT signal. The tests were conducted for open ear, Gen I CAE, and Gen II CAE conditions. Only the non-linear mode of each earplug was evaluated. A view of the data collection scenario is shown in figure 8.



Figure 8. Speech intelligibility testing of Gen I CAE and Gen II CAE.

6.2 Results and Discussion

Speech intelligibility data obtained in this study were converted into rationalized arcsine units (rau) (Studebaker, 1985) and subjected to repeated measure analysis of variance (ANOVA-R). The conversion from percent correct scores into rau units is a nonlinear conversion intended to correct for the non-constant variance of scores resulting from a limited range of speech intelligibility scores. Average scores close to 0% or 100% will have smaller variance than those near 50%. The average speech intelligibility scores expressed in percent correct are shown in figure 9. As can be seen from presented data, the listeners performed much better in the bare ear (unoccluded) condition than with ears occluded with either of the earplugs.

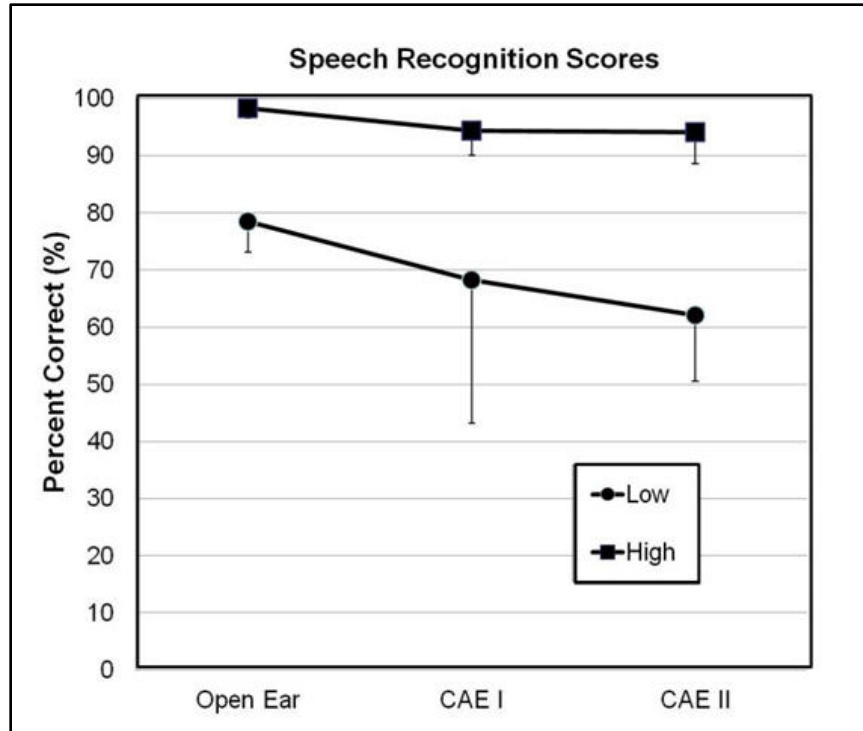


Figure 9. Speech intelligibility scores expressed in percent correct for the three conditions compared in the study. Labels low and high correspond to low (–8 dB) and high (–2 dB) SNRs used in the study.

The analysis of variance (ANOVA) test revealed a statistically significant effect of the listening condition factor [$F(2, 22) = 5.62, p = 0.011$]. A post-hoc Tukey test revealed significant differences between open ear condition and both earplug conditions; however, no significant differences were found between both versions of the CAEs. The scores for Gen I CAE and Gen II CAE in the low SNR conditions look different but both data sets were very incongruent resulting in large standard deviations and insignificant statistical effect of the type of plug. Large standard deviations at the low SNR reflect listeners' difficulty in using the earplugs; difficulties that were more pronounced for the Gen I CAE that has only one size. As expected, scores for open ear condition were much higher than scores with the earplugs.

7. Localization Precision

7.1 Method

To assess the effects of the Gen I CAE and Gen II CAEs on spatial orientation of the wearer, a sound localization study was conducted using a loudspeaker array consisting of twelve loudspeakers equally distributed ($0^\circ, \pm 30^\circ \pm 60^\circ \pm 90^\circ \pm 120^\circ \pm 150^\circ, 180^\circ$) along a horizontal circle ($r = 3$ m) surrounding the listener. The loudspeaker array is shown in figure 10.

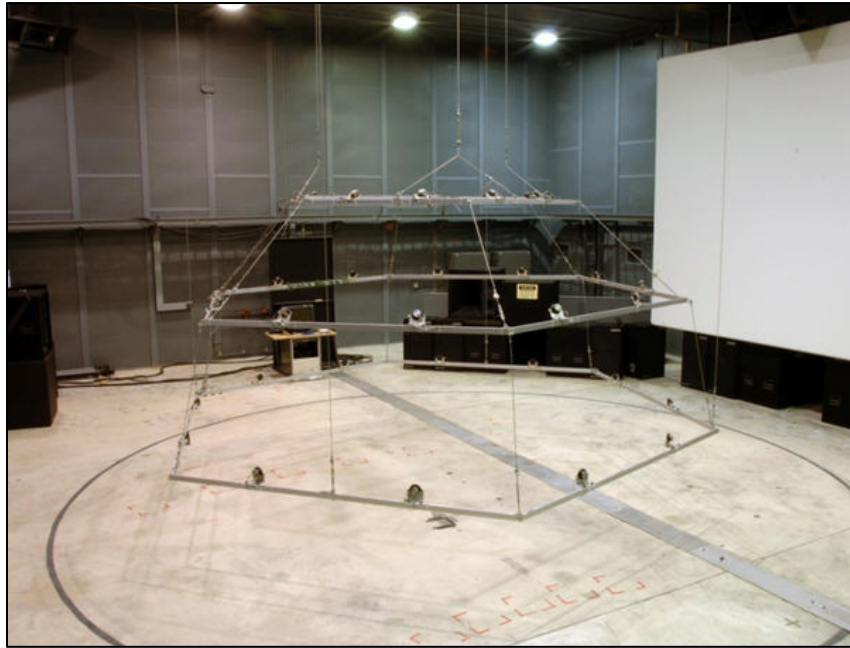


Figure 10. Loudspeaker array used in the sound localization study. Twelve loudspeakers at 30° intervals located in the lowest ring of the array were used.

The same group of listeners participating in the speech intelligibility study participated in the localization study. The study was conducted in the HES facility at APG, MD. The target sounds were recordings of the word “medic” and an AK 47 rifle shot. The target sounds were presented in the background of pink noise presented at about 53 dB A. The SNR levels of the target sounds were +10 dB and 0 dB for the word “medic” and +7 dB and -3 dB for the AK 47 rifle shot. The above levels were representing easily discernible and just noticeable levels, respectively, for both target sounds determined in a pilot study.

During the study the listener sat in a rotating chair at the center of the loudspeaker array on a raised platform that placed their ears level with the 0° elevation loudspeaker ring. The chair was free to rotate $\pm 180^\circ$ azimuthally (yaw). It was equipped with a laser pointer mounted in the center of a horizontal bar attached to the chair in front of the participant and a digital compass to register the position of the laser pointer. The laser bar is shown in figure 11.



Figure 11. Laser bar mounted on the rotating chair used in the localization study. The cubic-looking elements on both sides of laser pointer contain a digital compass and response buttons.

In response to presentation of a target sound the participant rotated the chair to point the laser in the direction from which they believed a stimulus came, and then pushed a button to register the compass reading of the position of the laser pointer. In order to prevent visual detection of the loudspeakers, black acoustically-transparent cloth was hung inside the loudspeaker array. This way, locations of the individual loudspeakers were obscured from the listener's view. The hanging cloth also provided a surface to reflect the light from the laser pointer providing feedback to the participant regarding the actual direction of the laser beam. A computer recorded the response based on the output of a digital compass attached to the bar. Corrections were made for the difference between the location of the participant's head and the location of the digital compass.

7.2 Results and Discussion

The localization errors are of two types: constant errors and random errors (Letowski and Letowski, 2012). Constant error, called sometimes the signed error, and random error, expressed usually as SD of the signed error, can be combined geometrically together in a form of global root mean square (RMS) error capturing both precision and accuracy of the listeners' judgments. The mean localization errors calculated in this study were the unsigned errors that are a form of global errors with decreased contribution of the random error (Letowski and Letowski, 2012). This type of error is frequently reported in comparative localization studies and has been calculated here for an easy comparison of the collected data with other published studies.

One specific reason that the global error is more appropriate in this study than the constant error itself is the fact that the sound inlet in both earplugs is located on the side of the plug and the user has very limited control over the direction the inlet is facing. In the case of a cylindrical form of the Gen I CAE, a random insertion of earplug results in random direction of the inlet in the sagittal plane. In the case of Gen II CAE, which has a flat rotary switch, there are two inlets on both sides of the switch and they will face front-back directions with much greater probability than any other direction when the plug is normally inserted. Such difference in probabilities of sound inlet facing specific direction between both CAEs may differently affect localization repeatability (precision) of both earplugs, which can be captured by calculating unsigned localization errors caused by both earplugs.

The localization data averaged across both test sounds, both SNRs, and all projection angles are presented in figure 12. The overall data showed no significant differences (ANOVA-R) between the Gen I CAE, Gen II CAE, and open ear conditions in the localization precision of the target sounds sources. This indicates that the difference between both earplugs in probability with which the inlet faces different directions during repeated insertions does not differentiate the earplugs in terms of localization precision and most likely do not affect localization precision of the earplugs at all. The same data but presented separately for both signals used in the study are shown in figure 13.

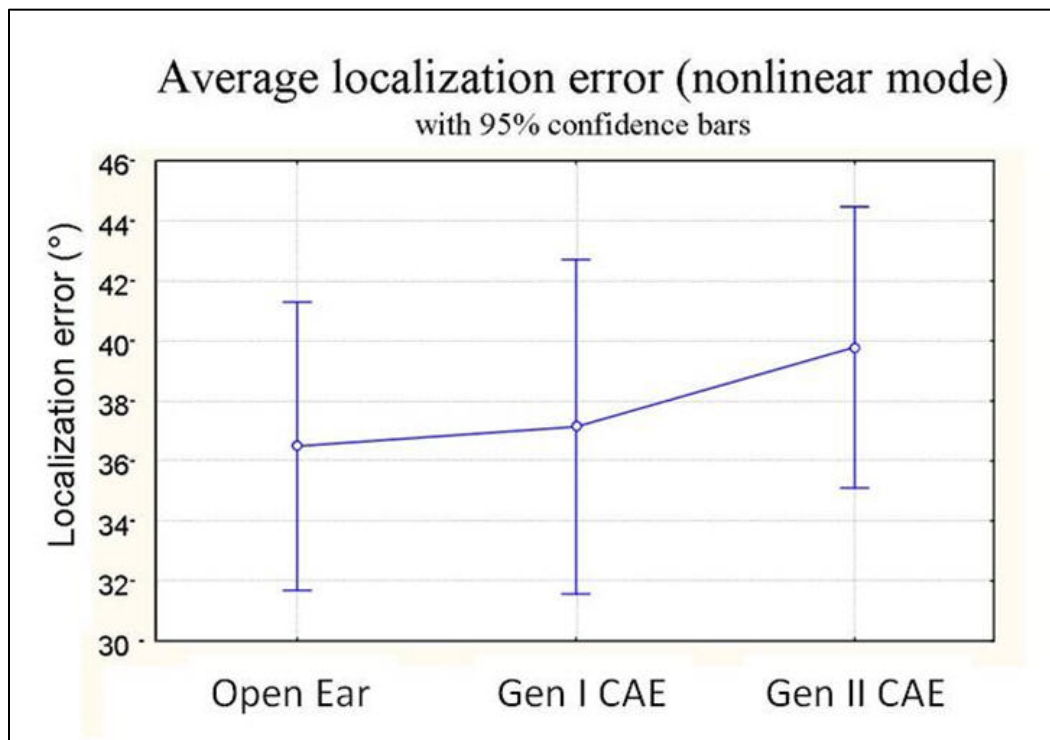


Figure 12. Overall unsigned localization error averaged across the signals, signal levels, and projection angles.

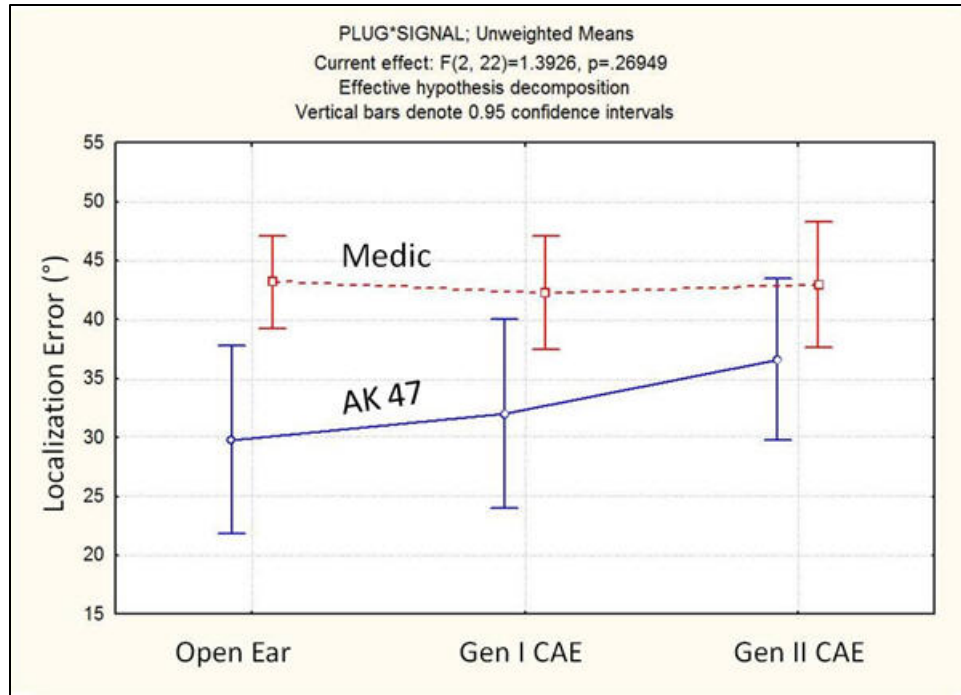


Figure 13. Unsigned localization errors made by the listeners for *Medic* and *AK 47* sounds.

The large size of all errors shown in figures 12 and 13 is due to a large number of front-back (FB) and back-front (BF) confusions of the listeners, which are natural in difficult listening conditions. A tendency of Gen II CAE to produce slightly larger localization errors than the Gen I CAE is likely related to greater attenuation of high frequencies by the former earplug and may be to some degree direction dependent. The directional distribution of errors in both cases and for open ear is shown in figure 14.

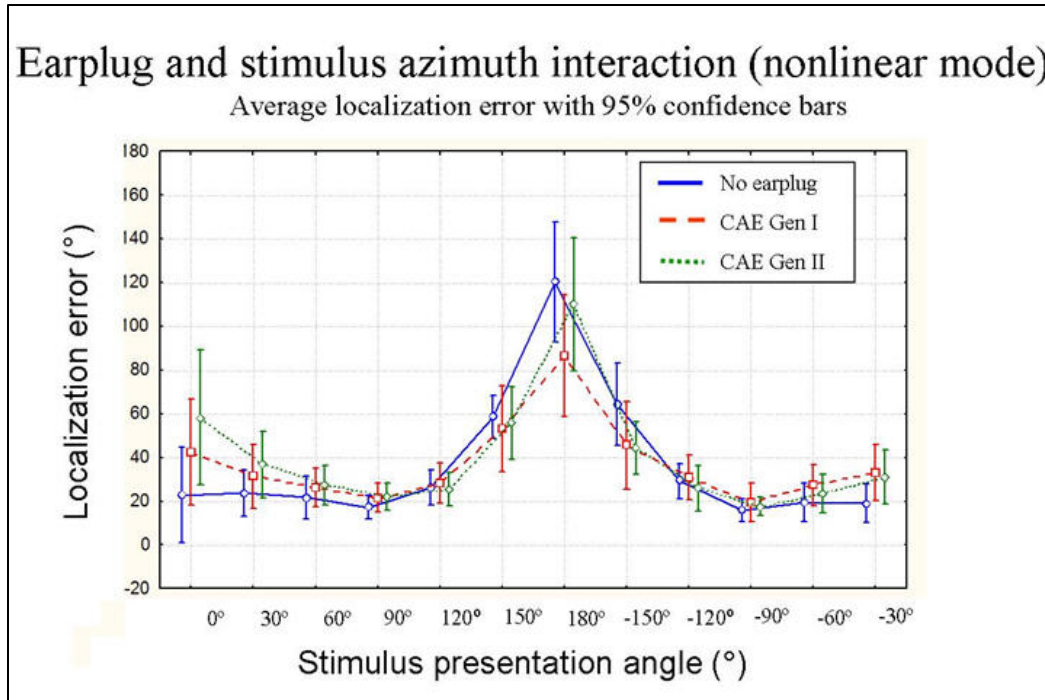


Figure 14. The size of unsigned localization errors as a function of direction for all three listening conditions investigated in the study. The listener was facing 0° direction.

The data displayed in figure 14 show that in all three listening cases the listeners made many more large localization errors for sound sources located in the rear (back) than in the front of them. This indicates a prevalence of BF errors over FB errors when both directions are equally probable. It is noteworthy that the prevalence of BF over FB errors was the greatest for the open ear condition and this may indicate the presence of room reflections in median axis confounding the directional data.

8. User Input: The Questionnaire

8.1 Method

In order to assess user-friendliness and earplug preference, an in-theater evaluation was conducted by Soldiers deployed in Iraq. Ninety pairs of Gen II CAEs were sent to the 28th Combat Support Hospital (CSH) in Iraq. The earplugs were distributed to the Soldiers of the 10th Mountain Division for a two-week trial period of wear. All the Soldiers participating in this study had previously been issued the Gen I CAE. At the beginning of the study an audiologist stationed at the CSH provided a briefing on the purpose and proper insertion and usage of the Gen II CAE, all participants were otoscopically examined, and then each ear was individually fitted by the audiologist. A wallet-sized card describing the earplug and the fitting procedure was also dispensed along with the hearing protection. The card is shown in figure 15.

Gen II Combat Arms Earplug

How to Adjust for Sound Environment

To adjust, grasp the body of the earplug and rotate it:

- For **steady-state noise** (aircraft, watercraft, generators, & vehicles), turn the pistol symbol **away from the ear**. This will soften all sounds. → 
- For **weapons firing**, turn the pistol symbol **toward the ear** (it will “lock” in place). This will protect against short loud sounds but will not greatly soften speech. **Even though weapons fire may sound louder in this position, your hearing is still protected!** → 

Gen II Combat Arms Earplug

Fit and Care

- Select comfortable tip size (green=small, yellow=medium, red=large) and attach it to the earplug body
- Insert the earplug while **gently pulling up and out** on the top of your ear.
- Check for proper fit by **gently tugging** on your plugs - they should not come out with a gentle tug.
- **Yanking** hard on the cord (to remove your plugs) **can cause injury**.
- Keep your plugs **clean with soap and water**, and keep all of the holes free of ear wax and other debris.
- **Dry** your earplugs and return them to your carrying case for ready-to-use access.

Figure 15. A wallet-size card issued with Gen II CAEs.

At the end of the trial period the Soldiers were asked to fill out a questionnaire. The questionnaire is shown in appendix A and it elicited the Soldiers' responses regarding user preference (Gen II versus Gen I), overall satisfaction, comfort, compatibility with communication systems, duration of the Gen II CAE use, cord preference, and reasons for wear non-compliance, if any. Participants were instructed to carry their previously issued hearing protection as back-up for the duration of participation in the study.

8.2 Results and Discussion

Of the 84 participants who received the earplugs, 64 (78%) participants responded to the questionnaire. The Military Occupational Specialty (MOS—enlisted categories) or Area of Concentration (AOC—officer categories) of each respondent was elicited. More than half of the respondents were in a Combat Arms field. The most common were 11B (Infantryman, Infantry Branch), 21B (Combat Engineer, Corps of Engineers), 11A (Infantry Officer, Infantry Branch), 13F (Fire Support Specialist, Field Artillery Branch), and 91W (Metal Worker, Ordnance Branch). The complete breakout of MOS/AOC is shown in figure 16. A list of the MOSs/AOCs is in appendix B and summary of answers in appendix C.

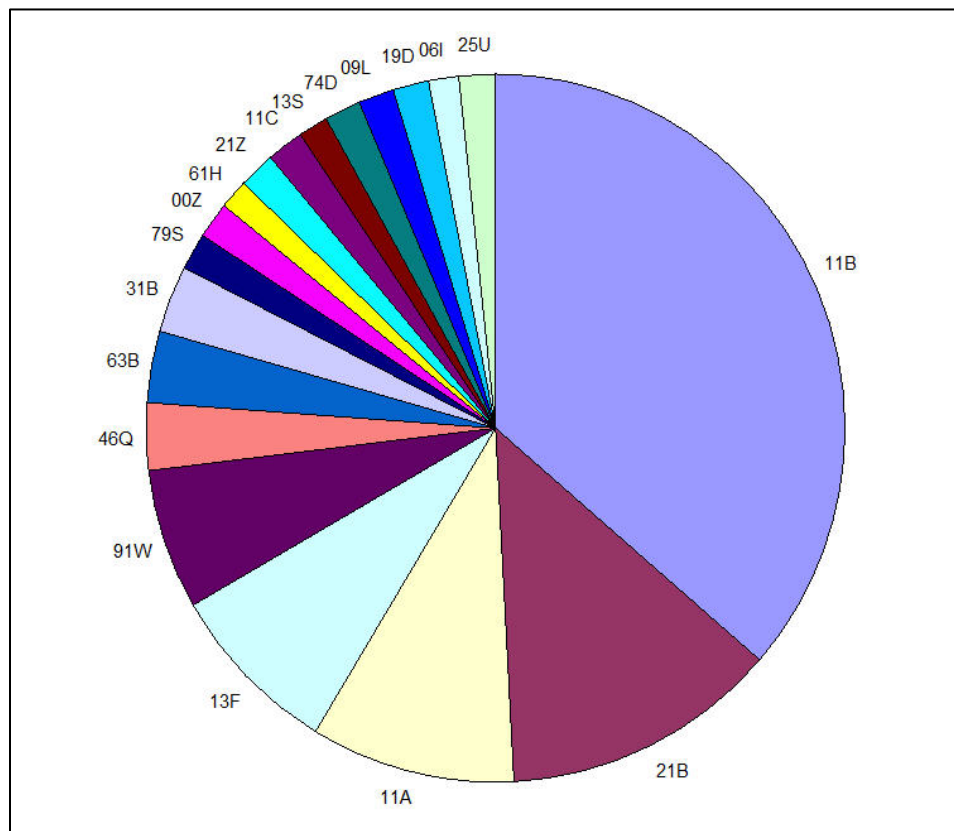


Figure 16. Respondent military occupational specialty or area of concentration.

The question regarding the mode of Gen I CAE regularly used prior to the Gen II CAE trial indicated that the Soldiers responding to the questionnaire had enough experience with the Gen I CAE to provide qualified comparison (Question 4). Participant responses indicated that 49% of participants used the Gen I CAE in both modes, 43% used the non-linear mode only, and 8% used the linear side only (Question 3). Although having the CAE prior to deployment did not ensure its use, the participants' responses indicated that they had at least some experience with the earplug to form a basis of comparison.

Even though the trial period lasted two weeks, the opportunity to wear the Gen II CAE during some of this time may have differed according to the Soldier's mission. Results of the questionnaire showed that the median usage was 6.5 days for 6 hours per day (Questions 5 and 6). Of the 41% (N=26) of responding participants who reported not wearing the new earplug around noise hazards during the trial period, the reasons for non-compliance are listed in table 2. More than one reason was possible per participant. However, all the participants indicated experimenting with the earplug in quiet.

Table 2. Participant reasons for not wearing the Gen II CAE around noise hazards.

Reason	N	
Forgot	12	44%
Uncomfortable	9	33%
Other	6	22%
Felt I couldn't perform my job	5	19%
Too difficult to use	1	4%

To assess the level of pain associated with wear of the earplug, the participants were asked to rate their pain using a visual analog scale in appendix A. A rating of "0" indicated no pain and "10" indicated the worst level of pain; the mean value was 1.9, indicating mild pain that can be ignored. No significant correlation existed between the total hours of wear and pain rating.

One of the major changes in the Gen II CAE design was a one-sided design; however, 68% responded that they still needed to remove the earplug to switch between modes. The addition of the new cord was also a feature change, and 77% reported that they found the cord useful. The wallet card was not well received, with 51% reporting they did not find the card useful.

Questions 11, 12, 13, and 15 dealt with insertion of, use of, and overall satisfaction with the Gen II CAEs, using a 5-point Likert scale for response. For these questions, one-sample t-tests were used to determine if the mean score differed significantly from a rating of "3," meaning "neutral." Overall, participants rated the Gen II CAE easier to insert than "neutral," $t(63) = 7.28$, $p < 0.01$, more difficult than "neutral" to switch between modes with the earplug in their ears, $t(61) = -4.56$, $p < 0.01$, and easier than "neutral" to remember which direction to turn the dial, $t(63) = 3.98$, $p < 0.01$.

A 7-point Likert scale, used to provide a greater precision of responses than the typical in military and industrial questionnaires 5-point scale, was provided to the participants to rate the Gen II CAE in comparison to the Gen I CAE earplug (question 14). On average, participants liked the Gen II CAE slightly better than the Gen I CAE.

9. Summary and Conclusions

Results of the attenuation measures are that both types of nonlinear earplugs provide very similar linear (low level continuous noise) as well as nonlinear (impulse noise) attenuation characteristics, although the Gen II CAE attenuates steady-state noise about 2–3 dB more than the Gen I CAE at frequencies above 1,000 Hz. The high-frequency ringing that was found to exist for the Gen I CAE is not present with the Gen II CAE.

During perceptual assessment both types of CAE similarly affected speech intelligibility and localization accuracy indicating that if perceptual differences between both earplugs exist they are practically negligible. More importantly the Soldiers of the 10th Mountain Division deployed in Iraq were generally preferred the Gen II CAE in comparison to the Gen I CAE. Given the apparent performance equality of the earplugs, user acceptance/preference should be a key factor in any decision to field the Gen II earplugs. In summary, reported acoustic and psychoacoustic measurements as well as field evaluation by Soldiers in Iraq indicate that the Gen II CAE is closely matched in performance to the Gen I CAE, and qualitative improvements in its design justify the acquisition of the Gen II CAE.

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Appendix A. Questionnaire

Combat Arms Earplug (Gen II) Questionnaire

Volunteer number (assigned by Audiologist): _____

* * * * *

1. What is your current MOS/AOC? _____
2. Which communication systems do you use regularly? (SINGARS, CVC, other-please be descriptive). _____
3. Which mode of the CAE did you use with your communication system?
_____ non-linear (the side that softens sounds less)
_____ linear (the side that softens sounds more)
_____ both
4. Before you deployed, were you issued the Combat Arms Earplug (pictured below)?

_____ yes



_____ no

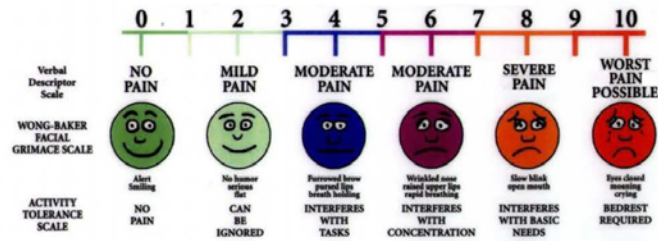
5. How many days did you wear the **new** earplugs (pictured below)? _____



6. When you wore the **new** earplugs, how many hours per day did you wear them? _____
7. If you did not wear the **new** earplugs around noise hazards, what were your reasons for not wearing them? (check all that apply)

____ forgot to wear them ____ too difficult to use ____ felt they didn't protect my hearing
____ uncomfortable ____ felt I couldn't perform my job ____ other
8. Please indicate how comfortable you found the **new** earplugs by circling the number that best corresponds with its description.

This appendix is presented in its original form without editorial change.



9. If you did switch between modes, did you have to remove the earplug from your ear canal to do so?
 _____ yes _____ no

To what extent would you agree with the following statements? Circle one.

10. The **new** earplug was easy to properly insert into my ear canal.

_____ 1 _____ 2 _____ 3 _____ 4 _____ 5 _____
 Strongly Disagree Disagree Neutral Agree Strongly Agree

11. It was easy to switch between the two modes while the earplug was in my ear.

_____ 1 _____ 2 _____ 3 _____ 4 _____ 5 _____
 Strongly Disagree Disagree Neutral Agree Strongly Agree

12. The two main types of noise are impulse noise (i.e. weapon firing & blasts) and steady-state noise (i.e. vehicles, generators, and aircraft). One mode of the earplug protects against impulse and the other protects against impulse and steady-state. It was easy to remember which position to turn the dial for different sources of noise

_____ 1 _____ 2 _____ 3 _____ 4 _____ 5 _____
 Strongly Disagree Disagree Neutral Agree Strongly Agree

13. I think that the **new** earplug is _____ (circle below) than the old Combat Arms earplug.

_____ 1 _____ 2 _____ 3 _____ 4 _____ 5 _____ 6 _____ 7 _____
 Significantly Moderately Slightly Same Slightly Moderately Significantly
 Worse worse worse better better better

14. Overall, how did you like the **new** earplug?

_____ 1 _____ 2 _____ 3 _____ 4 _____ 5 _____
 Strongly Disliked Disliked Neutral Liked Really Liked

Why? _____

15. Did you find the cord on the earplug useful? ____yes ____no

If not, then why? _____

16. Describe what you would like to see improved on the **new** earplug

17.. Did you find the wallet card helpful? ____yes ____no

What would you improve on the card? _____

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Appendix B. Questionnaire Data

1. See figure 15 in this report.
2. Singars: 32 ASIPS: 11 CVC: 8 Other: 10
3. Both: 49% Linear: 8% Nonlinear: 42% None: 0%
4. Yes: 63 No: 1
5. 6.5 days
6. 6.0 hours
7. See table 2 in the text. All respondents experimented with Gen II CAE in quiet.
8. Scale 1 (no pain) – 10 (worst pain): 1.89
9. Yes: 38 No: 19
10. Scale 1 (strongly disagree) – 5 (strongly agree): 3.80
11. Scale 1 (strongly disagree) – 5 (strongly agree): 2.50
12. Scale 1 (strongly disagree) – 5 (strongly agree): 3.47
13. Scale 1 (significantly worse) – 7 (significantly better): 4.38
14. Scale 1 (strongly disliked) – 5 (really liked): 3.30
15. Yes: 47 No: 14
16. Comments:
17. Yes: 31 No: 30

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Appendix C. MOS/AOC List with Series Title and Branch

Note: Refer to figure 6 in this report.

00Z – CSM (branch immaterial)

06I – unknown

09L – Interpreter/Translator (branch immaterial)

11A – Infantry Officer (Infantry)

11B – Infantryman (Infantry)

11C – Indirect Fire Infantryman (Infantry)

13F – Fire Support Specialist (Field Artillery)

13S – Field Artillery Surveyor (now 13T) (Field Artillery)

19D – Cavalry Scout (Armor)

21B – Combat Engineer (now 12B) (Corps of Engineers)

21Z – Combat Engineering Senior Sergeant (now 12Z) (Corps of Engineers)

25U – Signal Support Systems Specialist (Signal Corps)

31B – Military Police (Military Police)

46Q – Public Affairs Specialist (Adjutant General)

61H – Family Medicine (Officer) (Medical Corps)

63B – Light-Wheel Vehicle Mechanic/Heavy Wheel Vehicle Mechanic/Wheel Vehicle Repairer
(now 91B) (Ordnance)

74D – Chemical Operations Specialist (Chemical)

79S – Career Counselor (Chemical)

91W – Metal Worker (Ordnance)

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Appendix D. U.S. Army Hearing Level Criteria

Physical Profile Functional Capacity Guide for Hearing
[adapted from Table 7-1, AR 40-501, 14 December 2007/
Rapid Army Revision (RAR) Issue Date 23 August 2010]

Level	Standard
H1	Audiometer average level for each ear not more than 25 dB for the average of the 500; 1,000; and 2,000 Hz threshold levels; no individual level greater than 30 dB at these frequencies. Threshold level not over 45 dB at 4,000 Hz.
H2	Audiometer average level for each ear not more than 30 dB for the average of the 500; 1,000; and 2,000 Hz levels; no individual level greater than 35 dB at these frequencies. Threshold level not over 55 dB at 4,000 Hz. OR Audiometer level in better ear not more than 30 dB at 500 Hz, 25 dB at 1,000 and 2,000 Hz, and 35 dB at 4,000 Hz. Poorer ear may be deaf.
H3	Speech reception threshold in best ear not greater than 30 dB HL, measured with or without hearing aid; or acute or chronic ear disease.
H4	Functional level below H3.

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List of Symbols, Abbreviations, and Acronyms

AHAAH	Auditory Hazard Analysis Algorithm for Humans
ANOVA	analysis of variance
ANOVA-R	repeated measure analysis of variance
ANSI	American National Standards Institute
AOC	Area of Concentration
APG	Aberdeen Proving Ground
ARL/HRED	U.S. Army Research Laboratory, Human Research and Engineering Directorate
BF	back-front
CAE	Combat Arms Earplug
CAT	Callsign Acquisition Test
CSH	Combat Support Hospital
FB	front-back
Gen I	first generation
Gen II	second generation
HES	Hostile Environment Simulator
HL	hearing level
HPD	hearing protection device
IL	insertion loss
ISL	Institute of Saint-Louis
KEMAR	Knowles Electronics Manikin for Acoustic Research
M	mean
MOS	Military Occupational Specialty
NR	noise reduction
NRR	Noise Reduction Rating

PPL	peak pressure level
RAR	Rapid Army Revision
rau	rationalized arcsine units
REAT	real-ear attenuation at threshold
RMS	root mean square
SD	standard deviation
SNR	signal-to-noise-ratios
SPL	sound pressure level
TFOE	transfer-function-of-ear

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