

Acute Acoustic Trauma among Soldiers during an Intense Combat

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Abstract

Background: During military actions, soldiers are constantly exposed to various forms of potentially harmful noises. Acute acoustic trauma (AAT) results from an impact, unexpected intense noise ≥ 140 dB, which generates a high-energy sound wave that can damage the auditory system.

Purpose: We sought to characterize AAT injuries among military personnel during operation “Protective Edge,” to analyze the effectiveness of hearing protection devices (HPDs), and to evaluate the benefit of steroid treatment in early-diagnosed AAT injury.

Research Design: We retrospectively identified affected individuals who presented to military medical facilities with solitary or combined AAT injuries within 4 mo following an intense military operation, which was characterized with an abrupt, intensive noise exposure (July–December 2014).

Study Sample: A total of 186 participants who were referred during and shortly after a military operation with suspected AAT injury.

Interventions: HPDs, oral steroids.

Data Collection and Analysis: Data extracted from charts and audiograms included demographics, AAT severity, worn HPDs, first and last audiograms and treatment (if given). The Student’s independent samples *t* test was used to compare continuous variables. All tests were considered significant if *p* values were ≤ 0.05 .

Results: A total of 186 participants presented with hearing complaints attributed to AAT: 122, 39, and 25 were in duty service, career personnel, and reservists, with a mean age of 21.1, 29.2, and 30.4 yr, respectively. Of them, 92 (49%) participants had confirmed hearing loss in at least one ear. Hearing impairment was significantly more common in unprotected participants, when compared with protected participants: 62% (74/119) versus 45% (30/67), $p < 0.05$. Tinnitus was more common in unprotected participants when compared with protected participants (75% versus 49%, $p = 0.04$), whereas vertigo was an uncommon symptom (5% versus 2.5%, respectively, $p > 0.05$). In the 21 participants who received steroid treatment for early-diagnosed AAT, bone-conduction hearing thresholds significantly improved in the posttreatment audiograms, when compared with untreated participants ($p < 0.01$, for 1–4 kHz).

Conclusions: AAT is a common military injury, and should be diagnosed early to minimize associated morbidity. HPDs were proven to be effective in preventing and minimizing AAT hearing sequelae. Steroid treatment was effective in AAT injury, if initiated within 7 days after noise exposure.

Key Words: acute acoustic trauma, hearing loss, noise-induced hearing loss, steroids

Abbreviations: AAT = acute acoustic trauma; ABG = air–bone gap; HL = hearing loss; HPD = hearing protection device; IDF = Israel Defense Forces; NRR = Noise Reduction Rating; PTA = pure-tone audiometry; PTS = permanent threshold shift; TTS = temporary threshold shift

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INTRODUCTION

The ear is the most vulnerable and typically the first organ to incur injury from a blast (or pressure) wave (Darley and Kellman, 2010; Okpala, 2011). Therefore, blast injury to the ear is common among military personnel. Although various hearing protection devices (HPDs) are available in the combat theater, recent reports indicated that some troops decline to wear them, to avoid reduced operational awareness on the battlefield (Abel, 2008; Patil and Breeze, 2011; Dougherty et al, 2013; Yong and Wang, 2015).

Blast-related ear injuries often present as damage to the sensitive structures of the middle and inner ear, that is, the tympanic membrane, ossicular chain, cochlea, and the vestibular system (Darley and Kellman, 2010; Remenschneider et al, 2014; Shah et al, 2014). Damage to these components may result in tympanic membrane perforation; ossicular discontinuity; conductive, sensorineural, or mixed hearing loss (HL); or vertigo and tinnitus. HL can compromise a warfighter's situational awareness immediately and permanently and hamper a service member's ability to fulfill mission requirements, remain in his military occupational specialty, and maintain his fitness for duty. Therefore, the auditory outcomes of acute acoustic trauma (AAT) injury—commonly categorized as temporary threshold shift (TTS), defined as transient loss of hearing after exposure to sound after impulse or blast wave noise, or permanent threshold shift (PTS), defined as perpetual loss of hearing after exposure to sound after impulse or blast wave noise—are of particular interest to military health-care providers.

In animal models, exposure to impulse results in anatomic changes that range from distorted stereocilia of the inner and outer hair cells to complete absence of the organ of Corti and rupture of Reissner's membrane. Generally, no changes are found in the blood vessels, spiral ligament, or limbus. A few minutes after exposure to impulse noise, edema of the stria vascularis appears, and may persist for several days. Histopathologically, the primary site of AAT injury in humans appears to be the rootlets that connect the stereocilia to the top of the hair cell. With loss of stereocilia, hair cells die. Death of the sensory cell can lead to progressive Wallerian degeneration and loss of primary auditory nerve fibers (Oesterle, 2013).

AAT injury is typically observed in 3000–6000 Hz in pure-tone audiometry (PTA), and is often narrowly focused at 4 kHz. The extent of a TTS is usually predictable on the basis of the causative noise's intensity, frequency, content, and temporal pattern of exposure (i.e., intermittent or continuous). In the military setting, avoidance from noise in individuals with AAT practically means the temporary reassignment to a more rear, noncombative position. Also, AAT usually accompanies other com-

bative injuries, but can also present as a solitary injury, and sometimes as a “silent” disability during the battle. Reports on AAT in the military setting have been anecdotal so far, and comprised rather small groups of patients (Breeze et al, 2011; Shah et al, 2014).

Research has focused mainly on prevention of AAT in the military with preexposure administration of antioxidants (Oishi and Schacht, 2011; Rajguru, 2013; Kopke et al, 2015) and magnesium among combatants (Joachims et al, 1993; Attias et al, 1994; Sendowski, 2006) and education to properly use HPDs. Although medical treatment of AAT is aimed at correction of impaired cochlear microcirculation and tissue oxygenation, there is no consensus on the current recommended treatment in AAT injuries. Of note, the protective effect of postexposure steroids in AAT has been demonstrated in animal experiments, but only in few human reports (Le Prell et al, 2007; Meltser and Canlon, 2011; Maeda et al, 2015).

In this article, we sought to describe the burden of confirmed AAT injuries among military personnel during and shortly after an intense combat, and to assess the benefits of HPDs and steroids (if worn or administered) on hearing outcomes in selected cases.

PARTICIPANTS AND METHODS

The work has been approved by the Israel Defense Forces (IDF) Medical Institutional Review Board.

Setting

During the military operation “Protective Edge” (July–August 2014), also known as the 2014 Israel-Gaza conflict (to learn more about it refer to https://en.wikipedia.org/wiki/2014_Israel%E2%80%93Gaza_conflict), soldiers with suspected AAT injuries were referred either to the IDF ambulatory otolaryngology/audiology outpatient clinics or to civilian otolaryngology/audiology outpatient clinics/emergency rooms, depending on the severity of their overall injury (if there were combined injuries), availability of military and civilian health-care facilities, evacuation distance, and transportation resources. In soldiers presenting with multiple trauma injuries, the more serious injury had been addressed before auditory complaints could have been evaluated. In these cases, suspected AAT injuries were investigated only when soldiers recovered enough to be able to undergo a hearing test.

Participants

In this retrospective study, we retrieved outpatient visit summaries and hearing tests from electronic medical files of IDF soldiers complaining of HL or hearing disturbances that were directly or indirectly related to exposure to excessive noise. Soldiers with AAT injuries

were enrolled if history, physical examination, and hearing tests were all consistent with an AAT. Otherwise, referrals that were not directly related to loud noise exposure or other conditions associated with an abrupt hearing impairment, but not related to noise exposure (e.g., idiopathic sudden sensorineural HL), were excluded. Since only records and hearing tests from the IDF clinics were available for our analysis, we do not report on confirmed AAT injuries in soldiers seen, treated, or followed up in civilian facilities.

Study Period

Because AAT injuries have not always been reported immediately after the acute event, as some soldiers presented several weeks later, we decided to include relevant referrals within 3 mo after cease-fire was declared (end of August 2014), to enroll the second-wave soldiers who were not previously referred during the intense fighting. All the hearing tests were performed with an audiometer calibrated according to the ANSI 2004 standards.

AAT Characteristics

Parameters assessed included age, gender, type of service, past medical and surgical history, injury date, worn HPDs, presenting symptoms, concomitant injuries, date(s) and result(s) of initial and follow-up hearing test(s), and treatment given. Past medical and surgical histories were focused on previous hearing complaints, ear diseases, and surgeries, if there were any. Soldiers with abnormal hearing tests were referred to an otolaryngology specialist for physical examination and decision regarding treatment plan. “Immediate” presentation was considered when soldiers were referred within 10 days after an alleged AAT had occurred; “late” presentation was considered as referral on the 11th day or later. We questioned on the immediate action leading to the AAT injury, and general questions regarding the use of HPDs during the operation. Not all the questions were answered by all the participants; hence the number of participants who answered each question varied. For the purpose of this study, we anonymized any identifying personal and military details.

Definition of HL

Since AAT injury was the main interest of our research, we defined “hearing impairment” as HL >20 dB at high-frequencies pure-tone average (at 3, 4, 6, and 8 kHz) at the initial audiometric evaluation. According to the local protocol, 3 kHz is an interoctave frequency that is not always tested, unlike 4, 6, and 8 kHz. Normal hearing was defined when air- and bone-conduction thresholds were ≤ 25 dB at all frequencies; conductive HL, ≥ 2 frequencies demonstrating an air–bone gap (ABG) >10 dB and no

bone-conduction threshold >25 dB; sensorineural HL, presence of any threshold of ≥ 30 dB at any frequency and no more than one frequency with an ABG of ≥ 15 dB; and mixed HL, ≥ 2 frequencies demonstrating an ABG of ≥ 15 dB and ≥ 1 bone-conduction thresholds of ≥ 30 dB. Mild, moderate, severe, and profound HL were defined as hearing level thresholds between 21–39, 40–69, 70–90, and >90 dB in PTA, respectively (Clark, 1981).

Treatment

Treatment was conservative in most AAT injuries. When presented “immediately” after the acute event, soldiers were instructed to avoid any exposure to loud noises for the next 7–10 days, and recommended not to return to the battlefield. At present, there is no consensus on the role of steroids in AAT, due to confounding evidences for and against this treatment. Since there is no such guideline officially published by the IDF Medical Corps, the decision to treat AAT with steroids was up to the treating otolaryngologist. Most authors advocate administration of steroids early in the course of AAT (Moon, 2007; Psillas et al, 2008), yet they are offered even 30 days after noise exposure (Salihoğlu et al, 2015). Therefore, soldiers who presented “immediately” after the acute event were allocated to either observation only or to oral steroid treatment, based only on the otolaryngologist’s experience. When steroids were administered, prednisone at 1 mg/kg/day was administered for 7–10 days (maximal dose 60 mg/day). When there was a “late” presentation, soldiers were evaluated, but no steroid treatment was offered. Subsequently, all confirmed AAT injury soldiers were invited for future follow-up visits.

Statistical Plan

Data were recorded using Microsoft Excel software (Microsoft, Redmond, WA). Contingency table analysis for comparing rates between unmatched samples was performed using the χ^2 test or Fisher’s exact test, as appropriate. The Student’s independent samples *t* test was used to compare continuous variables. All tests were considered significant if *p* values were ≤ 0.05 .

RESULTS

Overall, 186 soldiers participating in the military operation were referred after complaining of HL, tinnitus, or ear discomfort, and comprised our reference population. Of them, 122 were duty soldiers, 39 were career army personnel, and 25 were reservists, with a mean age of 21.1, 29.2, and 30.4 yr, respectively. The majority of the soldiers were males (183, 98%). Sixty-seven (36%) soldiers wore HPDs at scene.

Hearing impairment was recorded in 92 (49%) of these soldiers, and they comprised our study population. Of the 134 ears affected, 83 (62%) had mild HL, 31 (23%) had moderate HL, and 20 (15%) had severe HL. Table 1 summarizes the characteristics of soldiers with hearing impairment, according to the severity of HL. These 92 participants with AAT were exposed during the 51 days of operation to battlefield noise consisting of a wide range of weapons firing; explosions of mortars, missiles, and bombs; noise of armored vehicles and jet planes; and assault helicopters flying overhead.

Among the 36 participants whose AAT was attributed to noise exposure from engagement in active fighting according to their report, 5 (14%) reported that operating their own weapon resulted in their hearing impairment, while 31 (86%) reported that nonself fire (enemy fire or own forces fire) was the cause for their HL. Non-use of HPDs during the direct course of action, seconds or minutes before what led to sensation of hearing impairment, was reported by 38/45 (84%) participants. Among the 38 not using HPDs, 26 (68%) were startled by friendly fire or enemy fire, 3 (8%) were engaged in active fighting, and 9 (24%) were in a military base or compound during letup or during temporary truce. The reasons for not using HPDs included lack of mandated use, forgetfulness, improper use of HPD, removal of protection for communication, and local command not to use protection.

Thirty-six percent (14/39) of soldiers reporting on hearing impairment were either radio operators or operators of heavy machine guns, shoulder missiles, and mortars.

Among the 97 soldiers who used HPDs, 27 (28%) had confirmed HL. In contrast, of the remaining 89 soldiers who did not use hearing protection, 65 (73%) had a confirmed HL. Therefore, soldiers who used HPDs were significantly less likely to have HL, when compared with soldiers who did not use them (p for $\chi^2 < 0.0001$).

Of the 92 soldiers with HL, 56 (61%) showed up at 1-mo follow-up visit, and hearing tests were repeated. Figure 1 shows mean bone- and air-conduction levels

for soldiers who presented with AAT-related hearing complaints, at initial presentation and at the last audiogram performed.

Of the 92 soldiers with confirmed AAT-related HL, 71 (77%) were not treated, while 21 (23%) were treated with oral steroids for 7.8 days in average (range: 7–10). All the patients tolerated well the steroids, and there were no significant side effects with this treatment. Figure 2 shows mean bone-conduction levels for soldiers treated with steroids versus soldiers for whom follow-up audiometry was available but were not treated. In the steroid-treated group, a significantly greater improvement in mean air and bone conduction has been demonstrated at follow-up audiogram at all frequencies when compared to untreated soldiers ($p < 0.01$). The mean bone-conduction improvements from the first to the last hearing test in the steroid-treated group was 3.3, 3.9, 6.3, 7.3, and 7.8 dB at 0.5, 1, 2, 3, and 4 kHz, respectively, which were significantly higher than the mean reciprocal improvements in the nonsteroid group: -0.1, 0.1, 1.3, 1.7, and 3.6 dB at 0.5, 1, 2, 3, and 4 kHz, respectively ($p = 0.01$ for 0.5–4 kHz).

DISCUSSION

Best- and noise-related ear injuries are a concern during deployment because they can compromise a soldier's situational awareness and adversely affect operational readiness. The ability to hear and recognize combat-relevant sounds is a vital component to situational understanding and provides a tactical advantage. Noise-induced HL is a tactical risk and threatens both individual and unit combat effectiveness. This work demonstrated that the hearing impairment in the described combat setting was prevalent, HPDs were effective in preventing HL associated with AAT, and early-administered steroids improved the hearing in affected participants.

From the beginning of combat, the Medical Corps headquarters instructed field medical staff to stress the importance of using HPDs 24/7. The most common

Table 1. Characteristics of Participants with Hearing Impairment, According to Severity

	Ears (n = 134)					
	Participants (n = 92)			High-Frequency PTA (4.0–8.0 kHz)		
	Bilateral	Unilateral	Total	Mild HL	Moderate HL	Severe HL
N	42 (46%)	50 (54%)	92	83	31	20
Age (mean \pm SD)	25 \pm 6.7	24.3 \pm 5.4	24.6 \pm 5.1	24.2 \pm 6.5	24.6 \pm 4.6	27.2 \pm 6.8
Type of service						
Duty service	26	28	54 (59%)	56	18	7
Career personnel	8	14	22 (24%)	17	9	4
Reservist	8	8	16 (17%)	10	4	9
Worn protective device, n (%)	11 (26)	16 (32)	27 (29)	26 (31)	11 (36)	1 (5)
Immediate presentation, n (%)	20 (48)	21 (42)	41 (45)	15 (18)	10 (32)	16 (80)
Steroid treatment, n (%)	9 (21)	12 (24)	21 (23)	12 (15)	9 (29)	8 (40)

Notes: Of the 92 participants who presented with HL, 42 experienced bilateral HL, while 50 experienced unilateral HL. SD = standard deviation.

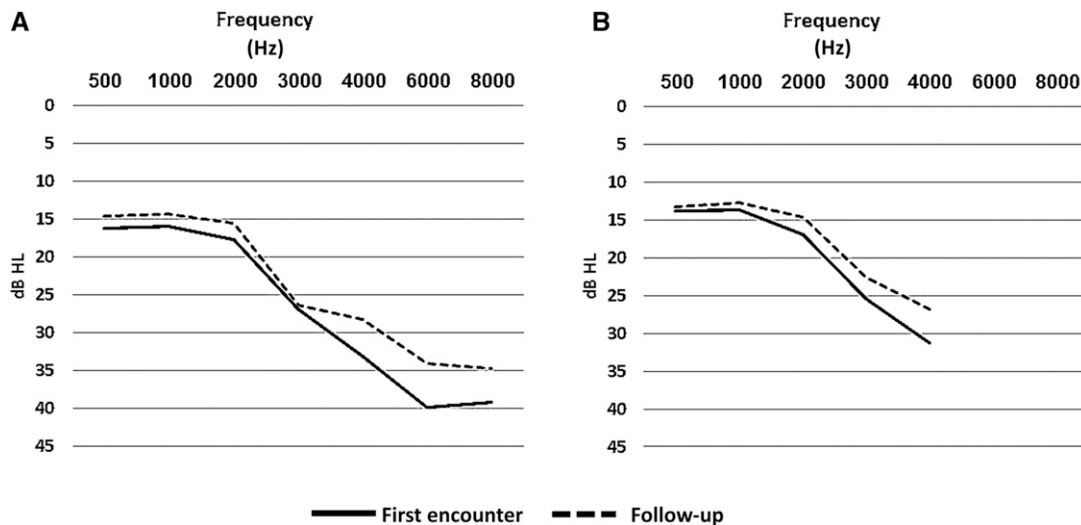


Figure 1. Mean (A) air- and (B) bone-conduction levels in 186 soldiers presenting with hearing complaints. Solid line, at initial presentation; dashed line, at the last audiogram performed.

HPDs distributed to the battalions are shown in Figure 3. The effectiveness of HPDs to decrease sound exposure within a given working environment is measured in units of Noise Reduction Rating (NRR) (in dB). The higher the NRR value associated with a hearing protector, the greater the potential for noise reduction. As shown, the three major ear plugs used by IDF's combatants are 3Ms: (a) E-A-R™ classic™ foam ear plug, NRR = 31 dB; (b) E-A-R™ Ultrafit™, NRR = 25 dB; and (c) Single-Ended Combat Arms™ earplugs, NRR = 7 dB in open mode and 23 dB in closed mode. The E-A-R classic™, with the highest NRR, requires training and experience in fitting in the ear canal, mostly because of its foam composition and ability to expand back to its original dimensions.

Special attention was focused on the importance of correct insertion of the various HPDs. Combatants using armor helmets for protection and communication were instructed to tightly fasten the chin strap. This is due to the effect of the negative pressure wave, which, when exceeds the force of the headband, causes the ear cups to be lifted from the head (Le Prell et al, 2007). Medical staff was instructed on the importance of quick evacuation of soldiers with suspicious AAT injuries. In addition, a new generation of HPDs designed for the military setting is currently under way.

Loud sounds, electrical stimulation, puffs of air, stimulation of the face, and so on, are all capable of eliciting the stapedial muscle response. It is not just an auditory reflex, but is part of a set of facial reflexes. In the case of intense gunfire, there are a number of unconditioned stimuli (facial stimuli) that can accompany the sound, each of which could elicit this response (Maeda et al, 2015). Yet, there are no definitive data regarding whether the middle ear muscles are conditioned in people firing weapons; that is, whether the middle ear mus-

cles contract in advance of an impending impulse (Foss et al, 1989; Job et al, 2016). In this study, the majority of AAT injuries were not in the combatant's control (e.g., unexpected enemy encounters, enemy and friendly forces fire). These may give support to the notion that awareness to impulse noise may lead to middle ear muscle contractions, which may lower the risk for hearing damage.

Despite the controversies regarding the contraction of middle ear muscles, during the development of the Auditory Hazard Assessment Algorithm for Humans: Hazard Evaluation of Intense Sounds (Moon, 2007), the preponderance of the evidence was held to be that such a response exists for the human ear. The Auditory Hazard Assessment Algorithm for Humans model is used by militaries to assess the type of HPD to be used when firing a weapon, and the number of daily exposures allowed when the combatant is aware or not aware to the impulse noise generated when operating a weapon.

Based on this study, we recommend that the combatant's ears must be protected at all times when in combat zone or when in position to be surprised by enemy or forces fire. Two military professionals attracted our attention for their high incidence. The first is the tactical radio operator who carries a portable very high frequency radio transmitter and uses an ear set with a hollow insert placed in one ear and connected to the radio transmitter to enable hearing radio communication. Unfortunately, the passive ear insert is not designed to attenuate noise. As a consequence, only the contralateral ear is protected with a conforming-to-the-standard HPD. The second is the infantry combatant who specializes in operating weapons with a caliber larger than small arms, such as heavy machine guns, shoulder missiles, sniper rifles, and mortars. All of these are characterized by peak sound pressures that can reach

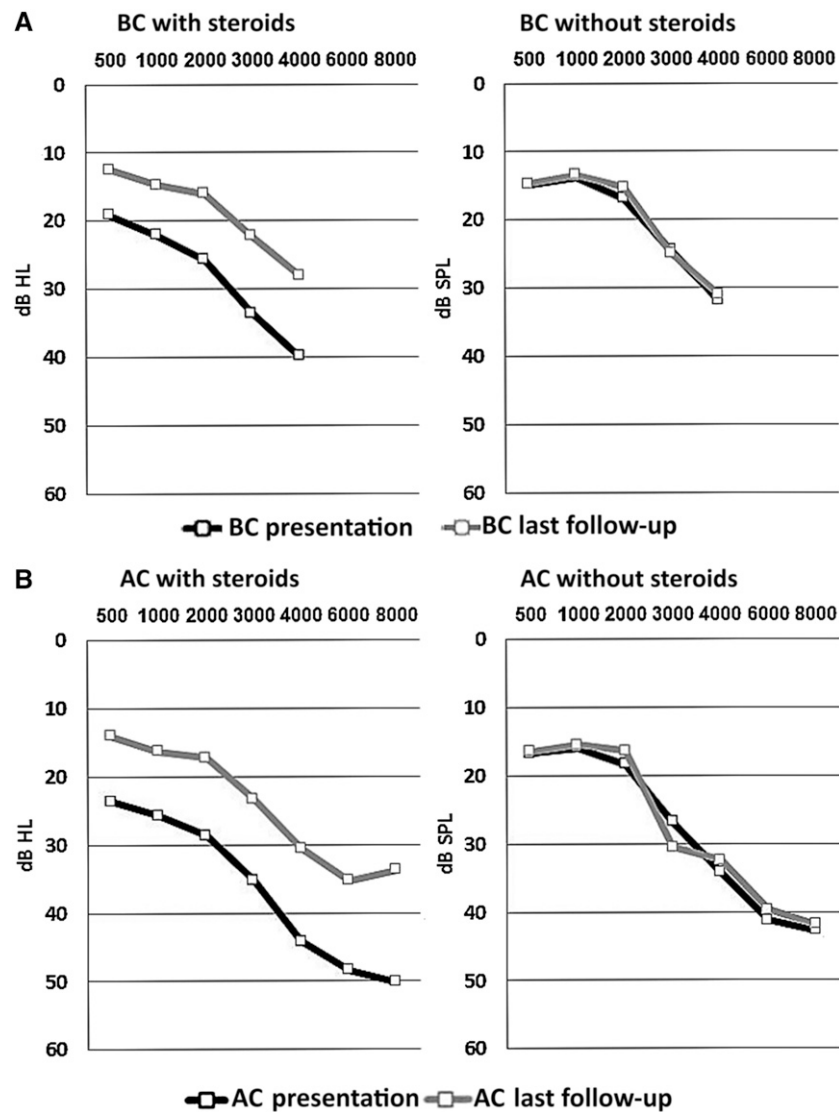


Figure 2. Mean (A) bone- and (B) air-conduction levels in 29 ears (21 soldiers) with HL who were treated with steroids versus 55 ears (35 soldiers) with HL who were observed only. Black line, at initial presentation; gray line, at the last audiogram performed. AC = air conduction; BC = bone conduction.

>170 dBA. In comparison to the 160 dBA of an M-16, the impact of a 170 dBA peak of a mortar can cause TTS or PTS if the ears are not properly protected by double protection (ear plug and ear muff) (Abel, 2008).

The potential auditory risk cannot solely be assessed from the peak noise level. Multiple essential parameters must be measured, which include peak overpressure, rise time, time duration, impulse noise spectrum, and impulse noise energy (Hamernik et al, 2003). By default, we advocate that all combatants wear double hearing protection, but this is not realistic, because it lowers speech recognition and intelligibility to a substantial extent. Correlating between TTS and PTS is difficult to evaluate in humans, because of the difficulty of conducting controlled studies in the workplace and the ethical problem of studying the formation

of PTS (Attias and Pratt, 1985). In a unique military research, Munjal studied the effect of impulse noise and the evolution of TTS and PTS among 100 infantry soldiers (at different ages) who fired different types of weapons (Munjal, 1997). Results demonstrated that the firing produced PTS mainly in the older age group, and in those individuals who were susceptible to impulse trauma. In the younger age groups, the isolated cases of TTS were attributed to individual susceptibility.

We showed efficacy with steroid treatment in AAT injuries, when given within 7 days after the insult. To our knowledge, this report describes one of the largest series of AAT injury in the military setting, and compares well with previous reports. The exact mechanism of steroids on the cochlea in AAT is not well understood. The



Figure 3. Common protection devices delivered to combatants (left to right): 3M Ultrafit™, Ear Classic™, and Combat Arms™ earplugs.

clinical experience of steroids in AAT in the military setting was favorable. Psillas et al (2008) evaluated the role of oral steroids and vasodilators in 52 soldiers who were exposed to intense gunfire noise, and demonstrated better effectiveness with immediate treatment (<24 hr). Branica et al (2008) reported on 166 patients with blast-related inner ear injuries, who were treated with steroids, and showed improvement of 11.3 dB than before therapy. Harada et al (2001) reported on 52 soldiers who were treated with steroids after the sound exposure, and showed that full recovery was associated with early initiation of treatment. However, reports of steroid use in civilian blast trauma settings are less convincing, in regard to the benefits from steroid use. In the 8/100 patients who presented after the Boston Marathon explosion with blast injury and were treated with oral steroids, improvement in bone-conduction hearing at 2 and 4 kHz was documented, although changes did not reach statistical significance (Remenschneider et al, 2014). Even the early-onset administration (within 3 days after loud noise exposure) of transtympanic steroids combined with oral steroids failed to be superior to oral steroids alone in AAT patients (Zhou et al, 2013).

We acknowledge selection bias to our treatment group. In the absence of a treatment protocol and uniformity, the decisions to treat certain soldiers and withhold others were influenced by many factors as described above. As a result, soldiers with more severe AAT were more likely to receive steroids in the absence of contraindications, which was shown to be effective in decreasing bone-conduction hearing thresholds in these participants, but we could not control the diversity of the different injury mechanisms, different dosage and duration, and the variable time elapsed from injury to treatment. The lack of a balanced control group may minimize our findings. Yet, in the absence of clear protocol(s) for AAT management worldwide, this selection bias will continue in real-life clinical settings, where there are no other treatment options available for post-AAT exposure. In addition, the two groups of

patients (with and without steroids) did not have equivalent initial HL thresholds, which made our analysis more complicated. Because of the retrospective nature of this study, matching or pairing of groups could not be performed. Finally, we used a short course of steroids >7 days, and were able to demonstrate significant improvements in soldiers' posttreatment bone-conduction thresholds, unlike patients who presented in the immediate postblast period during the 2013 Boston bombing and received a 14-day course of 60 mg/day prednisone, followed by a 5-day taper-off, but did not have statistically significant changes in their posttreatment audiograms (Remenschneider et al, 2014).

We conclude that about half of the soldiers with alleged AAT injury eventually had a confirmed HL, HPDs were proven to be effective and allow functioning in the military setting at the same time, and steroids were effective for AAT injury if given early.

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