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Original Article

Acoustic reflexes are common but not pervasive: evidence from the National Health and Nutrition Examination Survey, 1999–2012

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Abstract

Objective: To determine whether acoustic reflexes are pervasive (i.e. sufficiently prevalent to provide 95% confidence of at least 95% prevalence) and might be invoked in damage-risk criteria (DRC) and health hazard assessments (HHA) for impulsive noise.
Design: Cross-sectional analyses of a nationally-representative study.
Study sample: National Health and Nutrition Examination Survey (NHANES) data collected between 1999 and 2012 were used. Over 60 thousand reflex traces obtained from 15,106 NHANES participants were used in the study, along with demographic, audiometric, health and exposure variables obtained in that study.
Results: Acoustic reflexes were not sufficiently prevalent to be deemed pervasive by any detection method or in any subgroup defined by age or audiometric characteristics. The odds of observing acoustic reflexes were greater for women, young adults, and people with better hearing sensitivity. Abnormally high tympanometric admittance and ''Other'' race/ethnicity (i.e. people who do not self-identify as exclusively Non-Hispanic White, Non-Hispanic Black, Mexican–American, or Hispanic) were associated with lower odds.
Conclusions: Acoustic reflexes are not sufficiently prevalent to be included in DRC and HHA for impulsive noise.

Keywords: Noise, middle ear, demographics/epidemiology, hearing conservation

Introduction

The acoustic reflex is a bilateral contraction of the middle ear muscles in response to a moderate- to high-level elicitor stimulus (Metz, 1952; Moller, 1961; Dallos, 1964; Golding et al, 2007). Contractions of the middle ear muscles alter the impedance of the middle ear system, and can be detected indirectly via changes to a probe signal introduced into the ear canal (Metz, 1952). Conventional probe signals include pure tones and, more recently, transient signals such as chirps and clicks (Allen, 1986; Keefe et al, 1992; Schairer et al, 2013) have been used. A listener's acoustic reflex status has been used diagnostically as an indication of the integrity of the ascending auditory pathway through the lower brainstem and the motor pathways leading to the middle ear muscles (Wilber, 1976; Wiley & Block, 1984).

Acoustic reflexes also play a role in damage-risk criteria (DRC) for impulsive noise. The justification for invoking acoustic reflexes as a protective mechanism derives from studies reporting differences in auditory outcomes associated with stimulus conditions thought to activate the acoustic reflex. For example, the presence of a high-level signal meant to elicit an acoustic reflex has been shown to alter the magnitude of noise-induced temporary threshold shift (Fletcher & Riopelle, 1960; Karlovich, et al, 1972). In addition, significant correlations between acoustic reflex magnitude and the magnitudes of noise-induced temporary threshold shifts have been found (e.g. Gerhardt & Hepler, 1983). However, there have been studies suggesting that attention or distraction can alter the acoustic reflex (Klockhoff, 1961; Robinette & Snyder, 1982), so responses observed under laboratory conditions might not generalise to field operations.

The earliest DRC for impulsive noise was developed by Coles et al (1967). This DRC was modified and adopted by the National Academy of Sciences/National Research Council Committee on Hearing, Bioacoustics and Biomechanics, CHABA (Ward, 1968), and implemented in MIL-STD-1474D (Department of Defense, 1997),

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which is a materiel acquisition standard that has been used as a *de facto* DRC for impulsive noise. The section of MIL-STD-1474 pertaining to impulsive noise has also been used for health hazard assessments (HHA). Among the modifications to the Coles et al (1967), DRC was an accommodation for the acoustic reflex. All persons exposed to impulsive sounds were presumed to have a fully-active acoustic reflex for signals having pressure-envelope (*B*) durations greater than or equal to 200 ms, and these reflexive contractions were expected to eliminate additional accumulation of risk after that time (Ward, 1968, p. 6).

The Auditory Hazard Assessment Algorithm for Humans (AHAAH) (Price & Kalb, 1991; Price, 2007a, 2007b) is a more recent DRC that attempts to model the physiology of the auditory system and derive risk estimates based on estimated displacement of the basilar membrane. In AHAAH, the acoustic reflex is presumed to start 9 ms following impulse onset and follow a step function having a time constant of 11.7 ms. Thus the acoustic reflex is expected to approach its maximum value within 44 ms (i.e. three time-constant intervals plus the initial lag relative to stimulus onset) and remain at maximum magnitude throughout the exposure. The acoustic reflex in AHAAH is presumed to provide an approximate 20-dB reduction in exposure at all frequencies (Murphy et al, 2010) after reaching its maximum. In AHAAH, this reflex timing and magnitude is expected to be present among all exposed listeners, despite experimental evidence indicating that the influence of middle ear muscle contractions is restricted to the low frequencies and varies across individuals (e.g. Reger, 1960; Mendelson, 1963; Rabinowitz, 1977; Gerhardt & Hepler, 1983; Feeney & Keefe, 1999).

A recent evaluation of AHAAH (Zagadou et al, 2016) revealed the need for the correction of several AHAAH parameters and proposed an alternative model endpoint based on integrated cochlear energy (ICE) instead of the maximum frequency-specific integrated squared basilar membrane displacement. Despite these modifications, the ICE model shares many common features of the AHAAH model in that it is also a time-domain electroacoustic model intending to represent human auditory physiology.

A DRC that includes a beneficial role for the acoustic reflex presumes that its implementation of the acoustic reflex represents the effect among all (100%) exposed people. It is logically impossible to establish 100% protection with confidence via population sampling, so a provisional criterion of 95% confidence of a minimum of 95% prevalence has been used in the development of DRC for impulsive noise for quite some time (Ward, 1968). The importance of the lower bound of the 95% confidence interval surrounding the observed percentage has been recognised since 1985 (e.g. Patterson, et al, 1985; Johnson, 1993; Patterson & Ahroon, 2004).

The development and widespread availability of instruments for measuring acoustic reflexes led to much research on the use of this new tool for auditory diagnosis. The focus of much of this work was on the differential diagnosis of cochlear versus retrocochlear disorders and on the use of acoustic reflex thresholds for the prediction of hearing sensitivity. In accordance with these goals, most studies (e.g. Popelka, 1981; Gelfand, et al, 1983; Gelfand & Piper, 1984; Golding, et al, 2007) have evaluated response percentages on the basis of individual ears rather than people, utilised clinical samples, screened samples, produced averaged reflex thresholds across frequency and/or replaced absent reflexes with provisional values to permit calculations.

Although these characteristics of study design are reasonable for diagnostic purposes, they lead to response percentages that do not represent prevalence. For example, the unit of analyses in many of these studies was the ear (e.g. Popelka, 1981; Gelfand, et al, 1983; Gelfand & Piper, 1984) rather than the person. This decision could be reasonable when making decisions about ear-specific determinations, but analyses at the level of the ear do not provide information applicable to DRC, which are applied at the level of the person. Except in cases where the responses across ears are perfectly correlated ($\rho = 1.0$), the joint probability of observing a reflex in both ears will always be lower than the probability of observing a reflex in either ear individually. If observations across ears are independent, the joint probability will be the product of the individual probabilities, and the difference between the ear-level and person-level prevalence will be inversely proportional to the correlation between the probabilities across ears.

It was also common practice to replace absent responses with a reflex threshold level one audiometric step greater than the highest tested level (e.g. 125 dB if 120 dB was the highest tested level) (Gelfand et al, 1983; Gelfand & Piper, 1984; Gates et al, 1990), especially in studies designed to predict hearing threshold (e.g. Popelka, 1981). Although this strategy successfully returns a quantity in cases of absent data, the resultant quantity does not retain information about the numbers or stimulus frequencies at which no acoustic reflexes were observed.

Multiple factors have been shown to influence the acoustic reflex, including the characteristics of the eliciting stimulus (Wilson & McBride, 1978; Wilson et al, 1978; Rossi & Solero, 1983, 1984), hearing sensitivity (Gelfand & Piper, 1984; Gates et al, 1990), middle ear status (Gelfand, 2009), some chemical agents (Robinette & Brey, 1978; Cohill & Greenberg, 1979), recent noise exposure (Gerhardt et al, 1979; Ferraro et al, 1981; Gerhardt & Hepler, 1983), attention (Durrant & Shallop, 1969; Robinette & Snyder, 1982), visual stimulation (Robinette & Snyder, 1982) and vocalisation (Borg & Zakrisson, 1975). For a detailed review of these factors, see Hodges and Ruth (1987) and Gelfand (2009).

There is a qualitative difference between the use of the acoustic reflex for diagnostic purposes and the reliance on it in DRC and HHA. Clinical contexts afford environmental and procedural controls intended to optimise the collection of medical information pursuant to establishing a diagnosis. On the other hand, DRC and HHA are meant to be applied to a broad array of people and situations. Although the clinical context permits the outright control of these factors, DRC must account for the deleterious effect of such factors that might be present in the situations experienced by the exposed population.

The current study was the initial step in a larger project designed to inform decisions about whether acoustic reflexes should be invoked as a protective mechanism for impulsive noise. Specifically, this study involved the examination of acoustic reflex prevalence in the civilian non-institutionalized U.S. population, with particular interest in the population of young adults qualified for unrestricted duty in the U.S. Army. A requirement of 95% certainty that an acoustic reflex is present in 95% of a population was considered sufficient evidence that the acoustic reflex is pervasive within that population.

Two populations were of interest to the current study: military personnel and civilians. Military personnel liable to be exposed to impulsive noises were defined as individuals having adequate hearing sensitivity for unrestricted duty, as defined in the H-1 status defined in Table 7-1 of Army Regulation 40-501 Standards of

Medical Fitness (Department of the Army, 2011) and described below. These standards of medical fitness are similar to those used in other branches of the U.S. Department of Defense.

Defining the civilian population that might be exposed to impulsive noise is more difficult. In the civilian population, impulsive noises can include firearm noise, impact noise from tools or machinery and noise from recreational activities such as fireworks. Exposure to these sounds is not restricted to any particular hearing status. To account for the breadth of civilian subpopulations that could be potentially exposed to impulsive noises, we present acoustic reflex prevalence as a function of selected correlates.

Method

Participants

Data from the National Health and Nutrition Examination Survey (NHANES) were used in this study. The NHANES is a complex multistage survey of the civilian non-institutionalized U.S. population. NHANES data collection is organised in two-year cycles, and the cycles starting in 1999 and completed in 2012 were used in the current analyses. Hearing examinations were conducted on subsamples of participants in each NHANES round, and specific age groups were included in hearing tests within each round.

The NHANES participant records used in this study included 15,106 people over the age of 12. Due to the increased risk of inadvertent identity disclosures for age groups with small sample sizes, all participants age 85 and over were combined into a nominal 85 year age group. Details on the demographic characteristics of the participants are provided in Table 1.

The U.S. Army Standards for Medical Fitness categorise performance into numbered groups, with lower numbers representing better fitness for duty. The H-1 hearing status (AR 40-501, Table 7-1) represents the best hearing sensitivity and is defined as: "*Audiometer average level for each ear not more than 25 dB at 500, 1000, 2000 Hz with no individual level greater then (sic.) 30 dB. Not over 45 dB at 4 kHz*". Warfighters meeting the H-1 status criteria are deemed fit for unrestricted duty in the U.S. Army. DRC and HHA for impulsive noises should be most applicable to warfighters with the H-1 status.

Table 1. Participant characteristics.

	Unweighted N	*Population %*
Gender		
Female	7583	49
Male	7523	51
Age		
12–19	4371	14
20–29	2077	16
30–39	1869	17
40–49	1799	18
50–59	1633	15
60–69	1728	10
70–79	1008	7
80–85+	621	3
Race/Ethnicity		
Non-Hispanic White	6248	69
Non-Hispanic Black	3621	12
Mexican–American	3040	8
Other Hispanic	1054	6
Other race – including multi-racial	1143	5

The H-2 and H-3 statuses represent poorer hearing sensitivity than the H-1 status. The H-2 status includes average hearing levels for the better-ear in the mid-frequencies between 25 and 35 dB HL, thresholds of up to 55 dB at 4 kHz, and the poorer ear may be non-functional. The H-3 status includes better-ear speech reception thresholds up to 30 dB HL and individuals who have acute or chronic ear disease. The H-4 status includes all cases that do not meet the earlier criteria and was not included in the current study. For the purposes of this study, all cases worse than H-2 are labelled as H-3/4.

Instrumentation and procedures

In NHANES, audiometric testing (e.g. acoustic reflexes, tympanograms, audiometry) was conducted in Mobile Examination Centres (MEC), which travel to each of the sampled regions of the United States. Audiometry and middle ear immittance testing were conducted in sound booths (Acoustic Systems, model Delta 142) that permit testing to 0 dB HL re: ANSI S3.1-1999 (American National Standards Institute, 1999) and audiometers (Interacoustics AD226™) were calibrated in accordance with ANSI S3.6-1996 (American National Standards Institute, 1996). Technicians completing audiometric testing were trained by the study audiologist, who also conducted ongoing monitoring of study data for quality assurance. Audiometry protocols and the details of all other data collection procedures are available on the NHCS websites (e.g. NCHS, 2001, 2011)

Acoustic reflexes and tympanograms were obtained using an Earscan Acoustic Impedance Microprocessor Audiometer with data output (Micro Audiometrics Corp., Murphy, NC), which is a system that uses a handheld probe for both tympanometry and acoustic reflex testing. The probe signal used for tympanometry and reflex detection was a 226 Hz tone. Tympanograms were obtained across a pressure range of −312 to 200 daPa. Reflexes were elicited using 0.5 s tones at 1 and 2 kHz, presented ipsilaterally at a fixed intensity of 105 dB SPL (i.e. 105 and 102 dB HL, respectively). Reflex traces consisting of impedance as a function of time were stored electronically in 17.9 ms increments for a 1.5 s total measurement duration.

Audiometric testing was conducted primarily using an automated procedure similar to the modified Hughson–Westlake procedure (Carhart & Jerger, 1959). The automated procedure implemented in the audiometer differed from the modified Hughson–Westlake procedure because ascending and descending responses were included in the determination of threshold. A recent study of the effect of this difference has revealed no meaningful influence on threshold (McGregor et al, 2016). The primary earphones used were Telephonics TDH-39P earphones, and ER-3A insert earphones were used if ear canal collapse was a concern during testing. In addition to annual exhaustive calibration to ANSI standards, calibration checks were conducted daily with a bioacoustic simulator (Quest model BA-202-27), and detailed calibration checks were conducted before and after MEC transport to the next sampled region.

Data analyses

All data used in this study were downloaded from the National Centre for Health Statistics website (www.cdc.gov/nchs/nhanes/), merged into single datasets per two-year cycle and appended into a single dataset comprising all relevant variables and participant records between 1999 and 2012. Acoustic reflex traces were excised for analyses in MATLAB (Mathworks, Natick, MA) and all other variables were imported for analysis in Stata (StataCorp, College Station, TX).

Acoustic reflexes are detected conventionally by watching for stimulus-linked deflections in the reflex trace that are discernable from background activity or by observing any momentary change in the trace that exceeds a predetermined size (e.g. 0.02 mmho). Visual evaluations of all reflex traces were not done in this study because of practical limitations and concerns about reliable decisions when the deflections were at or near the baseline. The reliance on the peak of the reflex trace was also problematic because acoustic reflexes must follow a physiologically reasonable morphology that cannot be established from peak values alone. In this study, reflexes were detected using two detection approaches help to evaluate the extent to which the results might have been influenced by either approach. All detection approaches were implemented in the MATLAB technical computing environment. Prevalence estimates were also determined for combinations (e.g. *Both* methods simultaneously or *Either* method individually) of results from these detection methods.

The first method relied on a *Frequentist* strategy, which is defined based on a change in the frequency of observations relative to a reference distribution of values. For the current study, reflexes were identified based on a sustained departure of the impedance trace above the baseline impedance for that trace (see upper panel of Figure 1). The minimum departure was at least 1.96 standard deviations above the baseline. The baseline was defined as the mean of the final 0.43 seconds (24 digitised samples) of each reflex trace, and the standard deviation was also defined during this time interval. The baseline interval (i.e. the interval between 1.07 and 1.5 seconds) was chosen because it occurs well past the offset of the elicitor stimulus and any reflexive response observed during manual review of the reflex traces. Our operational definition of a sustained departure was an impedance value greater than the minimum departure for at least 0.05 seconds between 0.09 and 0.6 seconds after elicitor onset.

The second reflex detection method was based on the correlation between the smoothed reflex trace and prototypical reflex traces (see lower panel of Figure 1). Prototypical reflex traces were identified via independent review of reflex traces from over 250 participants (i.e. 1000 reflex traces) by three of the authors (GF, KD, ST). For each trace, each author indicated whether a time-linked change in impedance was present. The morphology of the traces agreed to represent reflexes were examined and three prototypical traces were identified. One prototype had a rapid onset leading to a plateau and decay subsequent to stimulus offset and is similar to the step function in a resistive–capacitive system. The remaining prototypes featured a more gradual growth over the time course of the elicitor, reaching maximum effect in the vicinity of stimulus offset. The last two prototypes were similar to the typical reflex traces identified by Church & Cudahy (1984).

Reflex traces were smoothed using a Kalman Filter (Kalman, 1960), which is a Bayesian approach for detecting the underlying state of a system in the presence of a noisy signal. Briefly, a Bayesian approach utilises prior observations in a series to predict subsequent observations. The Kalman Filter Package written for MATLAB by Brian Moore (http://www.mathworks.com/matlabcentral/fileexchange/38302-kalman-filter-package, accessed April 26, 2015) was used in this study. Specifically, we used the Standard Kalman Filter function applying an unweighted moving

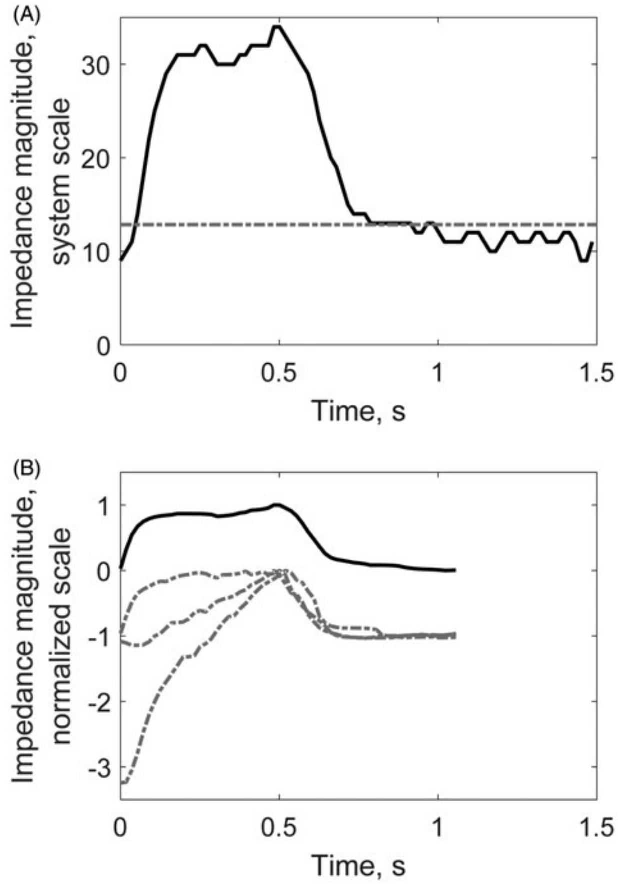

Figure 1. Example of acoustic reflex detection approach. Impedance as a function of time is represented in both panels. The upper panel (A) depicts the raw reflex trace in black. The criterion impedance for this trace (i.e. the impedance magnitude that is 1.96 standard deviations above the mean during the final 0.43 s of the trace) is represented by the grey (dash-dot) line. The lower panel (B) represents the Kalman-filtered reflex trace in black, which is plotted on a normalised amplitude scale. The three prototype reflex traces are shown in grey and have been displaced downward on the plot for clarity.

average window of 0.27 seconds and a look-back window of 0.09 seconds. Time-reversed reflex traces were used to displace filter artifacts (e.g. associated with the moving average and look-back window) to the actual end of the trace and retain interpretable smoothed estimates of reflex onset. Reflex traces were then correlated against the prototypes. For each of the four reflex traces obtained from each person, an acoustic reflex was deemed present if the smoothed reflex trace had a correlation magnitude greater than 0.82 with any prototype. This criterion was determined based on false positive and false negative rates when compared with the authors' judgments of reflex presence on the sample reflex traces as described above. Greater criterion values resulted in unacceptably high false negative rates and lower criterion values resulted in unacceptably high false positive rates.

Variables indicating each participant's reflex status across the four combinations of stimulus and ear were then merged into the larger Stata dataset containing the remaining variables necessary for these analyses. Analyses included cross tabulations and univariable and multivariable binary logistic regression models. All analyses were conducted using the NHANES sample weights, strata and primary sampling units. For more information about the differences between analyses presuming a simple random sample of a population and complex sampling, see Korn & Graubard (1999) and Heeringa et al (2010).

Binary logistic regression was used to examine the relationship between bilateral acoustic reflexes detected by both detection methods and the potential predictors. Each variable was examined first in a univariable (i.e. single-predictor) model, and the variables failing to show at least a weak relationship with acoustic reflexes (e.g. $p > 0.2$) were not evaluated further. All variables not discarded at this stage were entered into a series of multivariable (i.e. multiple-predictor) models and discarded if they failed to show a significant ($p < 0.05$) relationship with acoustic reflexes [see Hosmer & Lemeshow (2000) for a summary of the approach used in model development]. All models were fitted to the population of individuals known to have average or above-average static admittance on the tympanogram.

The primary outcome of interest to this study was the bilateral presence of acoustic reflexes, which were defined as reflexes determined to be present in each ear for at least one (50%) of the two ipsilateral elicitors presented. The distribution of selected prototypical traces was a secondary outcome that was used to determine the prevalence of acoustic reflexes that could be relevant for an impulsive noise.

Results

Descriptive

The prevalence of bilateral acoustic reflexes varied with participant group (Table 2). In no combination of participant group and detection approach was the prevalence of acoustic reflexes greater than 87%, nor was the lower bound on the confidence interval greater than 85%. Prevalence across groups varied as expected, decreasing in groups with older listeners or poorer hearing sensitivity. The confidence intervals surrounding the estimates were generally less than 5%, which is good precision and not surprising due to the large number of observations used in this study.

Table 2. Prevalence of bilateral acoustic reflexes, by participant group and detection approach.

		95% confidence interval limits	
	Prevalence %	*Low*	*High*
All (unweighted $N = 15{,}106$)			
Either	74.6	73.2	75.9
Frequentist	68.3	66.7	69.9
Bayesian/Kalman	58.5	57.1	59.9
Both	52.3	50.7	54.0
Ages 18–30 (unweighted $N = 3280$)			
Either	85.3	82.9	87.4
Frequentist	81.5	78.8	83.9
Bayesian/Kalman	72.2	69.7	74.6
Both	68.4	65.9	70.9
Ages 18–30, H-1 (unweighted $N = 3132$)			
Either	86.9	84.8	88.7
Frequentist	83.4	81.1	85.5
Bayesian/Kalman	73.8	71.6	76.0
Both	70.4	68.0	72.6

An examination of the trends within participant groups suggested that the *Bayesian/Kalman* detection approach was more often confirmed by the *Frequentist* detection approach than vice versa. The difference between the *Bayesian/Kalman* approach and the *Both* detection approach was less than 6%, while the difference between the *Frequentist* approach and the *Both* detection approach was always greater than 16%. The cross-tabulation of *Frequentist* versus *Bayesian/Kalman* outcomes showed that approximately 70% of the disagreements between approaches represented cases where a reflex was identified via the *Frequentist* approach but was not confirmed via the *Bayesian/Kalman* approach (i.e. 1285 of 1846 participant cases; 10,179 of 14,848 reflex traces), which suggests that estimates using the *Frequentist* approach are more likely to contain false positive identifications than the *Bayesian/Kalman* detection approach.

As stated above, reflex traces were obtained using a handheld probe. It was plausible that the use of a handheld probe could have influenced the error rates for the detection approaches. A probe movement (e.g. attempting to maintain a hermetic seal) during the time window appropriate for an acoustic reflex might lead to a false positive response. The same probe movement during the period after the reflex time window could increase the variability of the trace, which would lead to a false negative response. It was reasonable to expect that probe movement errors should be less likely to influence the *Bayesian/Kalman* detection approach, which is based on the morphology of the trace.

The potential for false negative responses (e.g. due to movements of the handheld probe) was evaluated by examining the prevalence of acoustic reflexes across deciles of variance for the baseline segment of each reflex trace. The distribution of variances during this segment was used to produce ten groups of equal size (i.e. deciles). Reflex prevalence was essentially constant through the 7th decile and declined thereafter. When evaluated for the subpopulation at the 5th decile and below on all traces (i.e. those participants who fit in the least noisy 50% for each trace), prevalence estimates increased between 1.9% (ages 18–30, *Either* detection method) and 7.5% (all ages, *Both* detection methods). The maximum estimated reflex prevalence among people after excluding the noisy traces was 89% (ages 18–30, *Either* detection method, H-1 hearing status), which remains below the criterion prevalence necessary to declare that acoustic reflexes are pervasive for any of these groups.

In addition to evaluating the sensitivity of the prevalence estimates to variance in the reflex traces, we also examined changes in prevalence when estimates were based only on those participants with normal static admittance on tympanograms for both ears (i.e. excluding the subpopulations with atypically low or atypically high static admittance). The prevalence of acoustic reflexes in this subpopulation increased between 2.3% and 4.6% and the greatest prevalence estimate was 89.2% (ages 18–30, *Either* detection method, H-1 hearing status). For those with normal static admittance in both ears and having the least noisy 50% for all traces, the increases in prevalence ranged between 4% and 12%, and the greatest prevalence estimate among people with normal static admittance and the least noisy 50% of traces was 90.9% (ages 18–30, *Either* detection method, H-1 hearing status).

It is possible for a person to have both an H-1 hearing status that permits unrestricted military duty and a hearing impairment that would be classified clinically as a slight or mild hearing impairment. The prevalence of acoustic reflexes among participants with the best hearing sensitivity and normal static admittance was also estimated. The A11 audiometric configuration was the indicator of the group with the best hearing sensitivity. This audiometric configuration was defined using NHANES data, and it represents the configuration with the best sensitivity. The mean thresholds for the people best described by this configuration were 11 dB HL or better (for further details, see Ciletti & Flamme, 2008). Among people with this audiometric configuration and normal static admittance, prevalence estimates increased between 4.4% and 18.7%, and the greatest prevalence estimate was 91.3% (ages 18–30, *Either* detection method, H-1 hearing status). Following exclusion of people with the noisiest 50% of traces, the greatest prevalence estimate increased only slightly (92.3%) and remained lower than the criterion for pervasiveness.

The acoustic reflex prevalence rates presented above represent the rates of individuals presenting a stimulus-linked change in impedance. However, the morphology of the stimulus-linked change differed across individuals and was more complicated than the first-order approximation following an electroacoustic analogy (Hung & Dallos, 1972) and the simplifications presented in studies involving relatively small numbers of people (Borg, 1982; Church & Cudahy, 1984). The prototype consistent with a protective role for impulsive noises (i.e. the upper prototype in the lower panel of Figure 1), has an onset similar to the step function of a resistive–capacitive system and approaches maximal effect within 100 ms. This prototype is similar to the reflex function implemented in AHAAH, but it was observed in only 48% of traces from individuals classified as having acoustic reflexes via the *Bayesian/Kalman* approach. The remaining reflex traces were more strongly correlated with the other reflex prototypes, which grew slowly throughout the elicitor duration and reached a maximum near the elicitor offset.

As stated in the introduction, the probability of detecting reflexes in both ears is the outcome of the joint distribution of the probability of detecting reflexes in either ear. Across ears, the across-ear correlation between the individual ear probabilities was approximately 0.31 (0.31 for the *Frequentist* detection approach; 0.32 for the *Bayesian/Kalman* approach).

Correlates of acoustic reflexes

A variety of potential correlates of prevalence were examined to identify the subpopulations at reduced odds of exhibiting an acoustic reflex. These variables were divided into demographic (e.g. gender, age and race/ethnicity), auditory (e.g. audiometric configuration and status, tinnitus, cerumen status and tympanometric static admittance), exposure (e.g. firearm use, occupational noise, leisure noise) and general health (e.g. hypertension, diabetes) categories.

Logistic regression models were developed first via three age categories: Under age 20, ages 20–29, and ages 30 and over (results not shown). This age division was used initially because the vast majority of warfighters who are exposed to impulsive noises will be in the 20–29 year age group, while civilians exposed to these sounds either occupationally or during leisure can be of any age. It was important to determine whether age modified the effects of any factors in the model and if a different array of risk factors operated for people who might be exposed as part of military service. The risk factors did not vary across these age groupings, so we present a single model encompassing the available age range (i.e. ages 12 and above).

All tested variables were found to be statistically significant in the univariable context (Table 3), but many of these variables lost statistical significance upon entry in the multivariable model. For example, participants with systemic health conditions (e.g. hypertension or diabetes) had odds ratios (OR) of approximately 0.5, indicating that people having either condition would be at one-half the odds of showing an acoustic reflex, but these relationships indicated essentially equal odds after other factors (e.g. age, gender) were included in the model. The final model included all demographic variables (i.e. gender, age, race/ethnicity), auditory variables pertaining to hearing sensitivity (i.e. audiometric configuration and Army hearing status) and high static admittance on the tympanogram.

After adjusting for the other factors in the model, people with better hearing sensitivity, women, and younger adults had greater odds of showing acoustic reflexes. Age effects show that, relative to 12–19 year olds, there is a slight increase in the odds of detecting bilateral acoustic reflexes among those between 20 and 39 years. This difference corresponds to an increase in marginal prevalence from 61% to 70% and 64% for 20–29 and 30–39 year olds, respectively. Although the hearing sensitivity, gender and age effects are easy to interpret, the race–ethnicity difference is impossible to interpret because sub-categories were not available. People in the *Other* race/ethnicity category (i.e. people who did not self-identify as Non-Hispanic White, Non-Hispanic Black, Mexican–American, or other Hispanic race/ethnicity) had poorer odds of exhibiting acoustic reflexes. No additional race/ethnicity categories were found to be significantly different from one another during post-hoc analyses using the Wald test ($p > 0.05$).

In general, the auditory variables pertaining to hearing sensitivity suggested that reductions in hearing sensitivity, even at frequencies remote from the elicitor frequencies, reduced the odds of detecting an acoustic reflex. In addition, abnormally high static admittance on the tympanogram (e.g. with tympanograms having high peaks) was associated with reduced odds of detecting an acoustic reflex.

Military

This study was conducted to inform DRC and HHA for impulsive noises, with special interest in military service members whose hearing sensitivity is categorised using hearing statuses defined in AR 40-501.

People with hearing sensitivity worse than the H-1 hearing status have significantly lower odds of exhibiting acoustic reflexes. This relationship was observed in both the univariable context (H-2 OR: 0.40 [0.32–0.50]; H-3/4 OR: 0.29 [0.25–0.34]) and following adjustment for other factors in the multivariable model (H-2 OR: 0.62 [0.46–0.83]; H-3/4 OR: 0.58 [0.44–0.77]).

People with hearing sensitivity within the H-1 hearing status were not, however, at equal odds of exhibiting acoustic reflexes. For example, people with the A19 or A22 audiometric configurations, which fit well within the bounds of the H-1 hearing status, were at approximately one-half to two-thirds the odds of exhibiting an acoustic reflex in univariable and multivariable models, respectively, relative to people with the best hearing sensitivity (i.e. the A11 audiometric configuration). Thus, people meeting the H-1 status are not a homogeneous group with respect to the acoustic reflexes.

Discussion

The present study was conducted to inform decisions about how – indeed whether – to invoke a role for acoustic reflexes in DRC and

Table 3. Logistic regression results. Unadjusted OR were obtained via univariable binary logistic regression. Adjusted OR were obtained via a single multivariable binary logistic regression model. Terms marked ''n/a'' represent predictors that were not significant ($p > 0.05$) in the final multivariable model.

	Bilateral acoustic reflex	
	OR (95% CI) Unadjusted	*OR (95% CI) Adjusted for all variables remaining in model*
Demographic variables		
Age, years		
12–19	1.0	1.0
20–29	1.36 (1.13–1.64)	1.50 (1.25–1.82)
30–39	0.98 (0.82–1.17)	1.13 (0.95–1.35)
40–49	0.68 (0.57–0.79)	0.86 (0.71–1.04)
50–59	0.48 (0.39–0.57)	0.69 (0.55–0.86)
60–69	0.32 (0.27–0.38)	0.52 (0.42–0.64)
70–79	0.22 (0.18–0.27)	0.38 (0.30–0.49)
80 and over	0.32 (0.27–0.38)	0.18 (0.11–0.28)
Gender		
Male	1.0	1.0
Female	1.11 (1.01–1.23)	1.19 (1.01–1.39)
Race/ethnicity		
Non-Hispanic White	0.80 (0.70–0.91)	1.05 (0.91–1.21)
Non-Hispanic Black	0.93 (0.82–1.06)	1.02 (0.87–1.20)
Mexican–American	1.0	1.0
Other Hispanic	0.87 (0.61–1.2)	0.93 (0.64–1.35)
Other race/ethnicity	0.63 (0.50–0.78)	0.65 (0.51–0.81)
Audiometric variables		
Army hearing status		
H-1	1.0	1.0
H-2	0.40 (0.32–0.50)	0.57 (0.41–0.80)
H-3/4	0.29 (0.25–0.34)	0.67 (0.47–0.96)
Audiometric configuration		
A11	1.0	1.0
A19	0.52 (0.44–0.61)	0.64 (0.82–0.79)
A22	0.52 (0.44–0.61)	0.61 (0.50–0.75)
A33	0.69 (0.52–0.92)	1.07 (0.77–1.50)
A47	0.47 (0.33–0.66)	1.09 (0.70–1.70)
A48	0.31 (0.24–0.39)	0.56 (0.43–0.74)
A59	0.31 (0.23–0.42)	0.81 (0.54–1.20)
B26	0.35 (0.26–0.47)	0.61 (0.43–0.86)
B29	0.30 (0.24–0.38)	0.53 (0.40–0.71)
B74	0.28 (0.19–0.40)	1.12 (0.70–1.95)
B82	0.29 (0.19–0.43)	0.90 (0.49–1.66)
B91	0.16 (0.09–0.29)	0.74 (0.36–1.53)
C55	0.20 (0.10–0.39)	0.68 (0.32–1.48)
D78	0.10 (0.06–0.19)	0.54 (0.25–1.19)
A45:A35	0.37 (0.28–0.50)	0.66 (0.46–0.95)
High static admittance		
Left ear	0.24 (0.18–0.32)	0.36 (0.26–0.48)
Right ear	0.23 (0.17–0.33)	0.32 (0.22–0.46)
Excessive cerumen		
Left ear	0.74 (0.64–0.86)	n/a
Right ear	0.72 (0.62–0.84)	n/a
Impacted cerumen[a]		
Left ear	0.68 (0.52–0.90)	n/a
Right ear	0.74 (0.56–0.96)	n/a
Abnormal otoscopy		
Left ear	0.69 (0.62–0.78)	n/a
Right ear	0.70 (0.62–0.79)	n/a
Tinnitus		
No	1.0	n/a
Yes	0.82 (0.75–0.90)	n/a
Health and exposure variables		
Firearm use		
No	1.0	n/a
Yes	0.75 (0.67–0.85)	n/a
Occupational noise exposure		
No	1.0	n/a
Yes	0.89 (0.80–1.00)	n/a
Leisure noise exposure		
No	1.0	n/a
Yes	0.86 (0.78–0.96)	n/a
Hypertension		
No	1.0	n/a
Yes	0.57 (0.51–0.64)	n/a
Diabetes		
No	1.0	n/a
Yes	0.50 (0.42–0.59)	n/a

(continued)

Table 3. Continued

[a]As judged by audiometric technician via otoscopy.

HHA for impulsive noises. Inclusion of a role for acoustic reflexes in DRC and HHA for impulsive noise would be justified if it is determined that acoustic reflexes are pervasive (i.e. it is known with 95% certainty that 95% of the exposed population exhibits acoustic reflexes). We examined whether it is reasonable to presume that acoustic reflexes are pervasive among people who might be exposed to impulsive noises, with special emphasis on military personnel. The reflex elicitors used were ipsilateral 1 and 2 kHz tones presented at 105 dB SPL for approximately 500 ms.

Prevalence

Acoustic reflexes are common, but they are not pervasive, even for young people with hearing characteristics that would make them eligible for unrestricted military duty. The lower bounds of the 95% confidence intervals for prevalence by any detection algorithm were more than 10% lower than the limit for considering acoustic reflexes pervasive among young people meeting the H-1 hearing criteria (Table 2). This means that the proportion of people whose exposure is underestimated by assuming the presence of an absent reflex would increase from 5 to 15%, which is unacceptably high.

Few studies have provided sufficient data for comparison with the population prevalences in the current study. Many studies designed to inform the use of acoustic reflexes for diagnostic purposes were conducted with screened samples, averaged reflex thresholds across ears, replaced missing values with artificial reflex thresholds just above the limits of the instrument, or used the individual ear as the unit of analysis (e.g. Popelka, 1981; Gelfand, et al, 1983; Gelfand & Piper, 1984). Golding et al (2007) found, in a highly screened elderly population, a 4% ear-level rate of absent reflexes. However, it must be noted that the screening criteria for participants in the tympanometry and acoustic reflex study were required to meet stringent criteria that resulted in the exclusion of 47% of the available sample. Nonetheless, the between-ear correlation observed in the current study suggests that the bilateral prevalence would be less than 94% even after the screening protocol was applied. Gates et al (1990) showed a 12.5% rate of absent contralateral acoustic reflexes at the person level. These authors also report that ipsilateral acoustic reflexes were observed in 970 of 973 participants (99.7%). It seems at first glance that these results stand in stark contrast to the results of the current study, but in Gates et al (1990), ipsilateral reflex testing was conducted only on the subgroup of participants screened for evidence of middle ear disease, ear surgery, asymmetric hearing thresholds and normal contralateral acoustic reflex thresholds. Thus, the high rate of ipsilateral reflexes observed in Gates et al (1990) indicates only that it is rare to have absent ipsilateral reflexes in the presence of normal contralateral reflex thresholds.

The assumption of pervasive acoustic reflexes in other populations is even less tenable than for young people eligible for unrestricted military duty, including people who are exposed to occupational impulsive noises (e.g. firing range instructors, law enforcement officers, armed guards, natural resource officers, construction workers) or people exposed to these types of sounds during leisure time (e.g. recreational hunters and shooters). Reductions in prevalence with age further complicate the implementation of any assumption of acoustic reflexes in DRC and HHA for impulsive noises. It is important to avoid adopting broadly DRC and HHA that were developed for a warfighter population that will be young and healthy and applying those criteria to the general unscreened population.

Most of the positive acoustic reflex traces observed in this study had a morphology that was inconsistent with a protective role for impulsive noises. The upper prototype in the lower panel of Figure 1 has a rapid onset and approaches maximum effect within 100 ms of stimulus onset. Although this duration is quite long compared with impulsive noise durations (e.g. the durations of individual gunshots are typically less than 15 ms in an open space), the upper prototype is the only one that could plausibly provide significant attenuation. This prototype was observed in slightly less than one-half of the cases in which a reflex was identified. The remaining prototypes suggested an acoustic reflex time course that is too sluggish for meaningful attenuation for impulsive noises.

The implementation of the acoustic reflex in AHAAH is not consistent with the results of this study. The results of the current study indicate that the prevalence of acoustic reflexes is too low to justify inclusion of an acoustic reflex component in a DRC. The further assumption that the time course of all acoustic reflexes are the same and produce a rapid onset and rise to maximum effect also finds no support in these data.

Correlates

A large number of factors were significantly related to the odds of detecting acoustic reflexes, but many of these factors failed to show a significant relationship in multivariable models (Table 3), which suggests that many of these factors are proxies for other factors that retained their significance.

The final multivariable model included terms representing hearing sensitivity, age, gender, race/ethnicity and high static admittance on the tympanogram. In general, the greatest odds of detecting acoustic reflexes are found among women between the ages of 18 and 30 with all hearing thresholds (0.5 through 8 kHz) better than 15 dB HL, moderate static admittance bilaterally on the tympanogram. The finding of lower odds of acoustic reflexes among 12–19 year olds is consistent with earlier literature on age differences in acoustic reflexes (e.g. Hodges & Ruth, 1987), but the magnitude of decline with increasing age is greater.

The causal pathways for these relationships cannot be determined because NHANES is a cross-sectional study. So although the relationship between hearing sensitivity and acoustic reflex prevalence is clear, it is unclear whether (a) risk factors leading to reduced hearing sensitivity also lead to reduced odds of acoustic reflexes, (b) people without acoustic reflexes are at greater risk of acquiring hearing impairment because they lack a potential protective mechanism or (c) activation of the acoustic reflex system is compromised by abnormal hearing sensitivity (e.g. Silman & Gelfand, 1981). All causal pathways could be represented in the general population.

Implications for damage-risk criteria and health hazard assessments

DRC and HHA are closely-related tools that serve different purposes. DRC describe the maximum acceptable limit of exposure to potentially harmful agents. HHA describe the amount of exposure produced by harmful agents relative to the associated DRC.

DRC and HHA apply to an exposed population as a whole. In the case of military service members, the population is defined as those people who are deemed qualified for unrestricted duty. At present, the qualification relevant to the DRC and HHA for impulsive noises is the H-1 hearing status, which is essentially represented as a pure tone average (0.5–2 kHz) better than 25 dB HL, hearing thresholds no worse than 40 dB HL at 4 kHz, and no significant threshold asymmetry.

The current study shows clearly that acoustic reflexes are not pervasive among the population having the H-1 hearing status (Table 2) and who would not be disqualified from unrestricted duty on the basis of hearing status. In the current study, we also explored alternate combinations of hearing status and demographic characteristics with the goal of finding a population in which acoustic reflexes were pervasive. No such population could be found. Thus, if the DRC to be used in HHAs include acoustic reflexes as a protective mechanism, the population to be exposed to the impulsive noises should be screened individually for the presence of acoustic reflexes.

Civilians exposed to impulsive noises span a larger range of ages than can be seen among active duty members of the military. Given the decline in the prevalence of acoustic reflexes with age, it would be especially imprudent to include a protective role for acoustic reflexes in DRC and HHA applied to individuals who have not been determined to have acoustic reflexes.

Biases and limitations

As noted in the introduction, clinical protocols are designed to optimise the probability of an interpretable response, which means minimising the influence of mediating factors such as attention, recent noise exposure and visual stimulation. One cannot find a better example of this contrast than the realm of impulsive noise. Workers exposed to impulsive noise must attend to their work which either includes management of the impulsive noise source or an awareness of the impulsive noise source operated by co-workers nearby. Hunters and shooters must remain vigilant for game and perhaps other hunters nearby, and the communication, physical and cognitive demands on the warfighter during impulsive noise exposure scenarios bear no resemblance to the clinical environment. So although clinical measures can provide some information about performance, they may overestimate the likelihood and/or strength of responses found outside the clinical settings.

The handheld impedance probe used in this study might have produced noisier reflex traces than would be found with a probe held in place via friction at the rubber tip. This could have biased downward the prevalence somewhat (between 4% and 12%, leading to a maximum prevalence of 89% using the current results). Studies of prevalence using a diagnostic clinical device should be used to further examine the effect of this difference.

These results represent prevalence estimates for long-duration elicitors at stimulus frequencies chosen to maximise the probability of a response. It is not certain that all individuals for whom acoustic reflexes are observed using clinical stimulus parameters will also exhibit acoustic reflexes for impulsive noises. These stimulus parameters are typical for acoustic reflex screening devices, but the durations were over one hundred times longer and less intense than the typical gunshot. Furthermore, the cognitive load, array of visual distractions and the other features of settings that include impulsive noises suggest that the results presented here represent an upper limit on acoustic reflex prevalence. The increased levels of impulsive noises relative to those used in this study would suggest that the current results are an underestimate of the prevalence seen for impulsive noises. However, the other differences (i.e. shorter duration, increased cognitive load, presence of visual distractions) would suggest the opposite. Acoustic reflexes should not be included in DRC or HHA for impulsive noise exposures until empirical studies have demonstrated that acoustic reflexes provide meaningful protection to at least 95% of people under field conditions.

These analyses were conducted using multiple detection approaches to determine if the major findings were sensitive to a particular approach, and subgroup analyses were conducted to determine whether any subgroup exhibited pervasive acoustic reflexes. Although we consider the *Bayesian/Kalman* approach the most robust, slightly different results could be obtained via algorithms not used in this study. Furthermore, it is possible that testing at higher levels or at additional elicitor frequencies might have returned a slight increase in prevalence among people with hearing impairment and among older people. The presentation levels used in the current study were well into the upper tail of the distribution of acoustic reflex thresholds (e.g. Gelfand & Piper, 1984), so the increase associated with higher presentation levels can be expected to be small. Acoustic reflex information for broadband noise elicitors would be welcome for the purpose of generalising to impulsive noises, which are also broadband. However, the presentation of a larger array of elicitor stimuli would bring the complication of adjusting for cumulative probabilities of false positive responses across stimuli.

As a cross-sectional study, NHANES is unable to support statements regarding causal relationships. Longitudinal studies of the U.S. population would provide tremendous benefit in this and the other health domains sampled by NHANES.

Conclusion

This study found that although acoustic reflexes are common, especially among young people with good hearing sensitivity, they do not meet the criteria required to be declared pervasive. To the extent that acoustic reflexes provide effective attenuation for impulsive noises, DRC or HHA for impulsive noise are at risk of underestimating the hazard for people who do not exhibit acoustic reflexes. It is also noteworthy that in the majority of cases where acoustic reflexes were observed, the reflex traces did not exhibit the rapid onset required for effective attenuation of an impulsive noise.

Perhaps the most poignant insight drawn from this study is the contrast between candidate DRC features that might commonly apply to a population, and those features that are known to apply to all (or nearly all) persons in a population. Even a small degradation in prevalence can lead to the rejection of a candidate DRC feature. This conservative perspective is central to the establishment of safety criteria. The exposures of persons lacking acoustic reflexes should not be informed by DRC and HHA that invoke acoustic reflexes because they would be at an unknown (but increased) risk of harm. On the other hand, exposed persons who have acoustic reflexes will not be put at greater risk of harm by DRC and HHA that do not assume the presence of an acoustic reflex.

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