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Success of Custom Hearing-Protection Devices within an Enhanced Hearing-Conservation Program aboard a US Navy Warship

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Abstract

This report presents hearing sensitivity data from naval personnel working aboard a littoral combat ship, the USS FREEDOM (LCS-1,) in a noisy ship environment who participated in an enhanced hearing-conservation program that issued custom-molded earplugs. Over a period of 5 years, 11 cases of significant threshold shifts (STSs) were recorded in the approximately 80 sailors who had been enrolled in the enhanced hearing conservation program. However, the entire crew had rotated off the ship by Year 4, resulting in less onboard noise exposure. The best estimated incidence of STS is 5% per person-year (95% confidence limits: 2 to 9%). However, temporary and false negative shifts indicate that the incidence of permanent threshold shifts is likely below 3% per person-year. Average shifts from single and multiple frequencies were calculated, with no consistent trends found over time. For comparison, a similar analysis of the crew of a destroyer, the USS STERETT (DDG-104), produced a significantly higher estimated STS incidence of 13% per person-year (95% confidence limits: 9 to 19%).

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Table of Contents

Figures and Tables

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Background

Noise-induced hearing loss (NIHL) is an enormous problem for the U.S. military where effective speech communications are crucial. Consider the impact on a combat soldier when unable to separate the two commands: "Attack" and "Fall Back." To a lesser degree but still operationally relevant is the time lost repeating commands to a sailor with impaired hearing, or the mistake made by a sailor missing a hissing gas leak or having to guess at what was said in fast-paced emergency situations. NIHL has a measurable economic cost as well. For a specific machinist mate in a noisy machinery room, the average lifetime cost to the taxpayer (both Navy and VA payments) is around $20,000 (Tufts, Weathersby, & Rodriguez, 2010). The total number of veterans receiving VA disability compensation for hearing loss and tinnitus (persistent ringing or buzzing in the ears) as a result of auditory damage was nearly 1,500,000 in 2015, a 10% increase from the previous year (*Veterans Benefits Administration: Annual Benefits Report FY2015*, 2016).

NIHL has no cure, and it can worsen when combined with progressive age-associated hearing loss and lead to a decrease in quality of life. Many important sounds are distorted, and then missed entirely. Not hearing environmental sounds, not understanding a child asking a question, or being unable to converse in a restaurant can all impact quality of life, both inside and out of an operational context. Hearing aids do not fully restore hearing. Unremitting, non-stop tinnitus can also degrade concentration and sleep.

The military recognizes the need to prevent NIHL, and addresses the need by implementing hearing-conservation programs (HCPs) in an effort to train sailors and soldiers to protect their hearing health. Crewmembers of ships who work in high noise environments are required to enroll in the Navy's HCP. In that program, service members are required to have annual hearing evaluations and to be issued hearing-protection devices (HPDs), such as earplugs and/or earmuffs, as well as to watch PowerPoint or video instructions on proper HPD usage. However, these devices may not be used effectively. Poorly trained and unsupervised individuals will often not achieve adequate attenuation with their HPDs (Royster, 2017). One study found that while using foam earplugs, a third or more of industry workers achieve less attenuation than advertised by the manufacturer, putting them at risk for NIHL (Schulz, 2011). In military personnel aboard an aircraft-carrier flight deck, around 50% of foam earplug users either did not wear the plugs or inserted them incorrectly, likely resulting in inadequate attenuation (Bjorn, Albrert, & McKinley, 2006). Most HPDs purchased by the Navy have noise reduction ratings (NRRs) of 20 to 30 dB, but advertised NRRs are often too high and do not account for "real-world attenuation" (Berger, 1993).

A crew of approximately 80 from the USS FREEDOM (LCS-1) was selected to participate in an enhanced HCP in an effort to explore how traditional HCPs could be improved.

USS FREEDOM (LCS-1) is the first ship of one design class of littoral combat ships. It has a shallow draft and high maneuverability, enabling it to operate effectively near the shore. In order to keep the ship deployed for the maximum time, two crews, "blue" and "gold" were assigned to the ship, and alternated in "ownership." Each crew was deliberately small (approximately 45 individuals), and cross-trained in multiple skills. Data from both crews were included for the purpose of this report. The initial crew was relatively senior at commissioning: mean age of 34 years, median of 32 (range: 24-51), and no crewmembers were below the grade of E-5. The ship was equipped with guns, small craft, helicopters, and powered by water-jet propulsion – all high noise sources. Some living and sleeping spaces were located in close proximity to very noisy sound sources. Additionally, some noisy interior spaces, while officially "unmanned," were frequently inspected. Any exposures to steady or fluctuating noise greater than 85 dBA averaged over an 8-hour day pose risk of hearing damage. The entire crew was considered to be at risk for NIHL, and was enrolled in the Navy's HCP.

An earlier report details the FREEDOM crews' attitudes and some examples of HPD performance (Marshall, Weathersby, McCluskey, & Huebner, 2016). This report presents longitudinal data on significant threshold shift (STS) data from naval personnel working in a noisy ship environment who participated in an enhanced HCP (discussed below).

Approach

Enhanced Hearing Conservation Program

For sailors who work in noisy environments (above 84 dBA), the Navy's standard HCP includes an annual audiogram (hearing screening), annual training (a video or PowerPoint presentation) and HPD issue (often only one type and/or size, and without individual fit-training or measurement of acoustic attenuation) (*Navy Medical Department Hearing Conservation Procedures*, 2008). In an effort to expand and improve standard HCPs, FREEDOM crews were provided with an enhanced HCP, supported by members of the Naval Submarine Medical Research Laboratory (NSMRL).

Custom Hearing Protection. The Navy purchased custom-molded hearing protection for the entire crew, as noise was recognized as a hearing health hazard during ship construction. A suite of earplugs was dispensed to each sailor consisting of a "high performance" protection plug (advertised protection NRR of 30 dB), a lower profile "sleep" plug (NRR 27 dB), and a "stereo access" plug (NRR 30 dB) with a bored hole connecting to a 3.5mm stereo jack. The suite of plugs was intended to accommodate the lives of the sailors, allowing them to have hearing protection during all facets of ship life including sleep and relaxation time, as well as time on duty. The sailors were also given a suite of non-custom earplugs to use as needed including foam, flange devices, and earmuffs.

The custom plugs were manufactured using medical-grade silicone by Westone Laboratories Inc. in Colorado Springs, CO. Ear-canal impressions were obtained via injection-molds by a trained impression taker. Approximately 1% of impressions needed to be remade by the trained impression makers on the FREEDOM, compared to a rate of nearly 14% when custom earplugs were introduced on an aircraft carrier (Yankaskas, 2017). In addition to the extra financial cost of remakes, any sailors requiring remakes are at risk for NIHL until/unless the sailor and impression taker can overcome the scheduling challenges inherent aboard an active warship.

Personalized Training. The crews of the FREEDOM were provided crew-specific hearing-conservation training including a hearing-loss simulation demonstration by members of the NSMRL team before being administered their custom devices. They also were taught how to insert the foam and flange earplugs in case of damage to or loss of the custom devices. When the custom device was dispensed, additional one-on-one training was given to ensure proper fit and comfort. Members of the team ensured that the crew members could properly insert their plugs before departure.

Audiometry. Audiometric measurements were made on all crew members prior to USS FREEDOM commissioning in 2008. The crew of the FREEDOM then received annual audiograms from other providers in compliance with the Navy standard HCP for each year they were aboard the ship, and for any subsequent years they were enrolled in an HCP.

Attenuation Measurements. The function of an HPD is to reduce (or attenuate) the level of noise that is heard by the ear. In several instances, attenuation measurements were made on FREEDOM sailors' earplugs (including custom, foam, and flange) using a Michaels and Associates Model 700 Fit Check device. It records hearing sensitivity at several frequencies with and without earplugs and combines the results in a single number PAR (Personal Attenuation Rating). Due to logistical considerations PAR measurements were not taken annually.

Evaluation and Feedback. During the initial visit to the crew of the FREEDOM in 2008, a questionnaire was administered to assess each crew member's current use of hearing-protection devices. Questions were asked regarding preferred earplug type, daily use, insertion, and other crew earplug usage. An evaluation was received from the crew on the training conducted as a part of the enhanced HCP. Comments from the crew such as, "It was very interesting to learn the proper fit for some of the hearing protection I have used improperly in the past," were received with the intention of improving the program. The crews were also asked to evaluate the helpfulness of the enhanced group training and personal instruction on plug insertion. Fifty-seven percent of respondents rated the training as "Very Helpful," while 95% rated the personal instruction as "Helpful" or "Very Helpful" (L. Marshall, unpublished data, 2009). When the crew was revisited in 2009, after the custom hearing-protection devices had been dispensed, they were given a second survey assessing their preferred custom earplug, comfort and satisfaction with the custom devices, and communication ability with the plugs. This survey was repeated during the next visit in 2010, but no surveys were administered in the following years to those who had left the ship.

Comparison Ship

Though it was not the original goal of the project, another small combatant surface ship was chosen for comparison in an effort to understand if the hearing changes onboard the FREEDOM were typical for small warships. The ship chosen was the USS STERETT (DDG-104), an Arleigh Burke class destroyer commissioned within a year of FREEDOM (to avoid the confounding factors of old equipment and changing sailor demographics). In finding a comparison, it was only possible to match the age of the two ships. Their operating conditions, noise sources, and other important characteristics of NIHL are undoubtedly different; however, there was no way to reconstruct individual sailors' daily noise-exposure history on either ship. Seventy-six sailors onboard the STERETT in the year of commissioning had audiograms available in that year out of the approximately 380 who worked aboard the ship; this likely indicates that approximately 20% of the crew were in areas noisy enough to warrant enrollment in the Navy's standard HCP that requires yearly audiograms. Thus, the size of the noise-exposed sailor population on the two ships was comparable. The initial crew was younger than those of the FREEDOM at commissioning: mean age of 27 years, median of 25 (range: 18-47).

Procedures involving STERETT data followed those of the FREEDOM's as closely as possible. The Defense Manpower Data Center provided the identities of the 2008 commissioning crew. All audiograms of STERETT sailors were obtained from DOEHRS (see below); the ship was never contacted directly. For each sailor, the audiogram taken closest to 2008 was used as the baseline for all calculations.

Accessing Audiograms from DOEHRS

Hearing data for the USS FREEDOM and STERETT were obtained from the Defense Occupational and Environmental Health Resource System (DOEHRS). After each audiometric test in their HCP, the service member's audiogram and demographic information corresponding to form DD2216 entries (see Appendix A) are uploaded to DOEHRS.

Audiograms for FREEDOM crew and veterans taken after their time with the NSMRL team were recovered using the personal information from their initial contact. As the primary records used are those found in the DOEHRS database, it is unknown if the audiometry performed was automated or manual. The majority of the crew had evaluations in the first 2 years, but audiogram availability dropped dramatically in the following years as annual audiograms are not collected for service members not in an HCP and not exposed to hazardous noise, or from those that have separated from the military.

Audiograms pulled from DOEHRS spanned five years from the 2008 commissioning to 2013. A "baseline audiogram" for each person was chosen as the one closest to commissioning date, to approximate the FREEDOM crew's baselines obtained by the NSMRL team. Subsequent audiograms were used to calculate changes from baseline after 1, 2, 3, 4, and 5 years.

Current duty station assignments of the crew of the FREEDOM and STERETT were gleaned from the information available from the DD2216 and then checked with a ship roster, if made available. However, the departure times of most sailors are only known to the year. Some records may be missing from the central DOEHRS repository due to poor compliance, procedural errors, or technical issues.

Assessing Significant Threshold Shifts

Change in hearing sensitivity is manifested as a significant threshold shift (STS,) a defined change ("shift") in hearing sensitivity threshold from a previous “reference” audiogram. The Navy definition of STS requires a 10 dB or more change in threshold averaged across individual frequencies of 2 kHz, 3 kHz, and 4 kHz. In standard Navy HCPs, the reference audiogram is different for each individual based on that sailor’s audiogram history. A positive shift indicates poorer hearing, while a negative shift indicates an apparent hearing improvement from the baseline audiogram (*Navy Medical Department Hearing Conservation Procedures*, 2008). Because ears that have permanently lost sensitivity do not improve, a negative shift is taken as indication of normal test-retest variability or another issue. The Navy’s tracking of its own set of reference audiograms was not used for this report. Instead, all reference audiograms were obtained during a 2008 NSMRL team visit to the shipyard, shortly before commissioning of FREEDOM.

An STS may not necessarily mean permanent damage. It can indicate a temporary threshold shift (TTS), or permanent threshold shift (PTS), or it may be due to normal testing variability or procedural error. To differentiate STS into TTS and PTS, a sailor needs to be re-tested (Navy guidelines state that this must occur after spending 14 hours in a quiet environment). If this follow-up audiogram is within acceptable range of the reference, the prior STS is re-classified as an error. If the shift is still found after the re-test and the hearing threshold level at 2, 3 and 4 kHz exceeds 10 dB when compared to the baseline, it is then classified as a PTS (*Navy Medical Department Hearing Conservation Procedures*, 2008). Very few of the STS cases in this study received a re-test after 14 hours in quiet. This report attempts to separate PTS from TTS by examining audiograms taken after the initial shift, even when they were administered after a period greater than 14 hours.

A shift (PTS, STS, or TTS) may also not necessarily mean that a loss of hearing beyond the range of “normal” hearing has occurred. Normal hearing is in the range of -10-25 dB (*Navy Medical Department Hearing Conservation Procedures*, 2008). By Navy definition, in order for a shift to be considered a meaningful loss outside of the normal range, the audiogram must demonstrate a loss at greater than 25 dB HL. Therefore, if on the baseline audiogram, a sailor could previously hear 4 kHz at 5 dB HL (normal hearing) and then had an STS of +10 dB, the resulting hearing level of 15 dB would still fall within the "normal range." This would not be considered a meaningful hearing loss, even though an STS had occurred. However, even if hearing sensitivity remains within normal limits, STS may be indicative of progressive noise-induced changes that may lead to permanent disability levels of NIHL. This report is limited to discussion of the incidence of PTS and TTS.

Results

USS FREEDOM (LCS-1)

Audiogram Availability

The number of original FREEDOM crewmembers' audiograms is plotted in Figure 1 (solid line) against the nearest anniversary year following their introduction to the enhanced HCP (Year 1 is 2009, etc.) Of the commissioning crew, many left the ship as time progressed (dashed line in Figure 1,) with most leaving the FREEDOM after 3 years. Over half of the starting group (46 sailors) had no audiograms after departing from the FREEDOM. Of the remaining sailors, 10 were relocated to another ship, while the rest were scattered among different commands ashore.

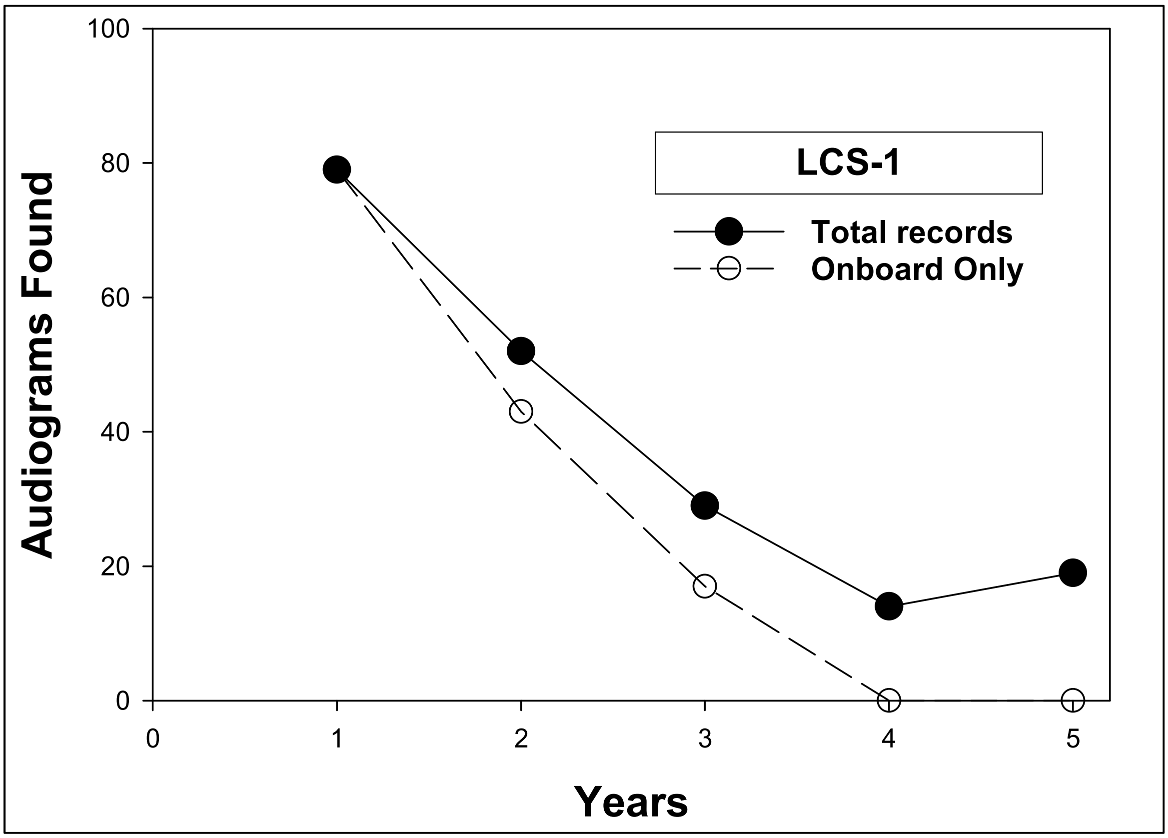

Figure 1. Number of available audiograms in DOEHRS for the crew of the LCS-1 FREEDOM and number of audiograms for crew still onboard yearly. Year 0 is 2008 (ship commissioning). There were 82 audiograms measured in the year of commissioning.

Incidence of Significant Threshold Shifts

Figure 2 contains STS data (Navy definition). The number of new cases is plotted in the nearest calendar year to their first recorded STS. No sailor had a subsequent degradation that would qualify as a second STS in the same ear. One STS case was negative, an apparent "improvement" in hearing in Year 2. As hearing does not improve over time, this result was determined to be a result of test-retest variability. Thus one can conclude that the data contains both false positive and negative classifications when looking at STS.

Eleven sailors of the original FREEDOM crew commissioned in 2008 were found to have an STS. Seven cases happened within the 3 years the sailors were still attached to FREEDOM. One case occurred in Year 4, but the sailor was no longer onboard the FREEDOM. In Year 5, no sailors were still on the FREEDOM, but STSs were still found in three individuals. In that group, one of the sailors was noted to have STS in both ears. Thus, there were 12 ears found with an STS in 11 people. STSs occurred in both junior and senior crewmembers and in crewmembers in their 30's and 40's. Many, but not all, had jobs which took them into noisy engineering spaces. Each STS case is described in detail in Appendix B.

Of note, at least 4 STS cases occurred in sailors who reported not using their custom earplugs in the 2009 survey taken several months after the plugs had been dispensed. Several other STS cases were not surveyed so their custom-earplug usage is unknown. If analysis was restricted to only those crewmembers who reported wearing the custom HPDs, then the incidence of STS would be considerably lower.

Not all of the STS cases were PTS. Of the 4 STS cases with a subsequent record, two cases had a later audiogram within the acceptable range of the baseline (<10 dB shift in the average of results from 2 kHz, 3 kHz, and 4 kHz in each ear). These two cases were declared temporary shifts, not permanent hearing loss (*Navy Medical Department Hearing Conservation Procedures*, 2008). The remaining 2 STS cases had audiograms recorded in all 4 follow-up years. Each had an ear with 3 years of declared STS and 1 year within range of baseline. These cases were deemed to be a permanent shift.

The STS data need to be understood in context of the number of audiograms available (both on and off FREEDOM). For example, in Year 3 two cases of STS were found in 28 individuals with an incidence rate of 7.1%. This 7.1% is very uncertain as records are not available for the whole crew, and because of test-retest variability. If an additional STS case had been recorded, the STS rate would be subject to great change. Although less likely, if two additional STS cases were recovered in Year 3, the STS rate would have doubled from 7.1% to 14.2%. The actual incidence of STS cases aboard FREEDOM in Year 3 could possibly range from 8.8% to 23.5% (using a 95% binomial sampling confidence limit for the proportion 2/28 (Pezzulo, 2015)).

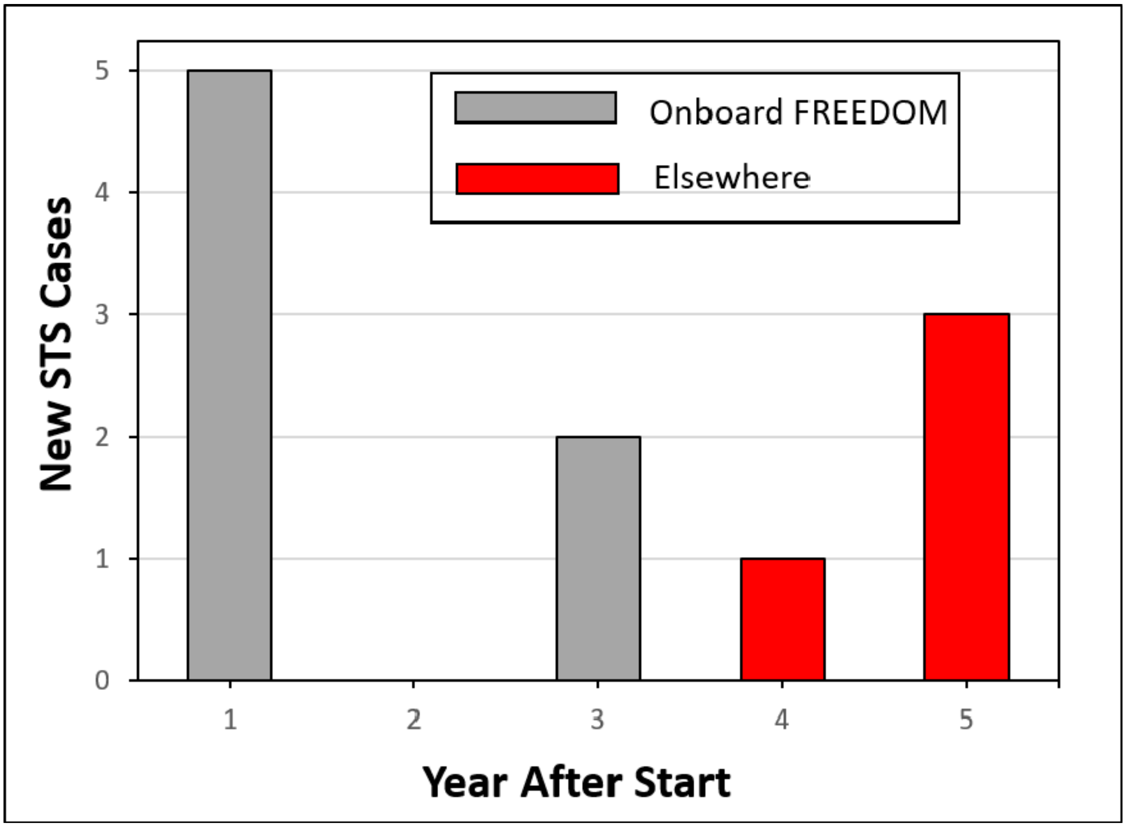

Figure 2. New STS cases by year of first occurrence.

Annual incidence of STS with corresponding 95% confidence limits is plotted in Figure 3. Statistical uncertainty prevents conclusions about changes over time. The best estimate of overall incidence aboard LCS-1 during this time was obtained by combining the data over all years of onboard exposure. In Year 1 there were audiograms found for 79 people and 5 were noted to have an STS. During Year 2, 52 people were still onboard with an audiogram and none had an STS. This process was used for all subsequent years. Cumulatively, there is an annual incidence of 7 STS cases out of 154 person-years of onboard exposure over 5 total years of exposure, or 4.6% per person per year (95% confidence limits of 2-9%). This range is indicated in Figure 3.

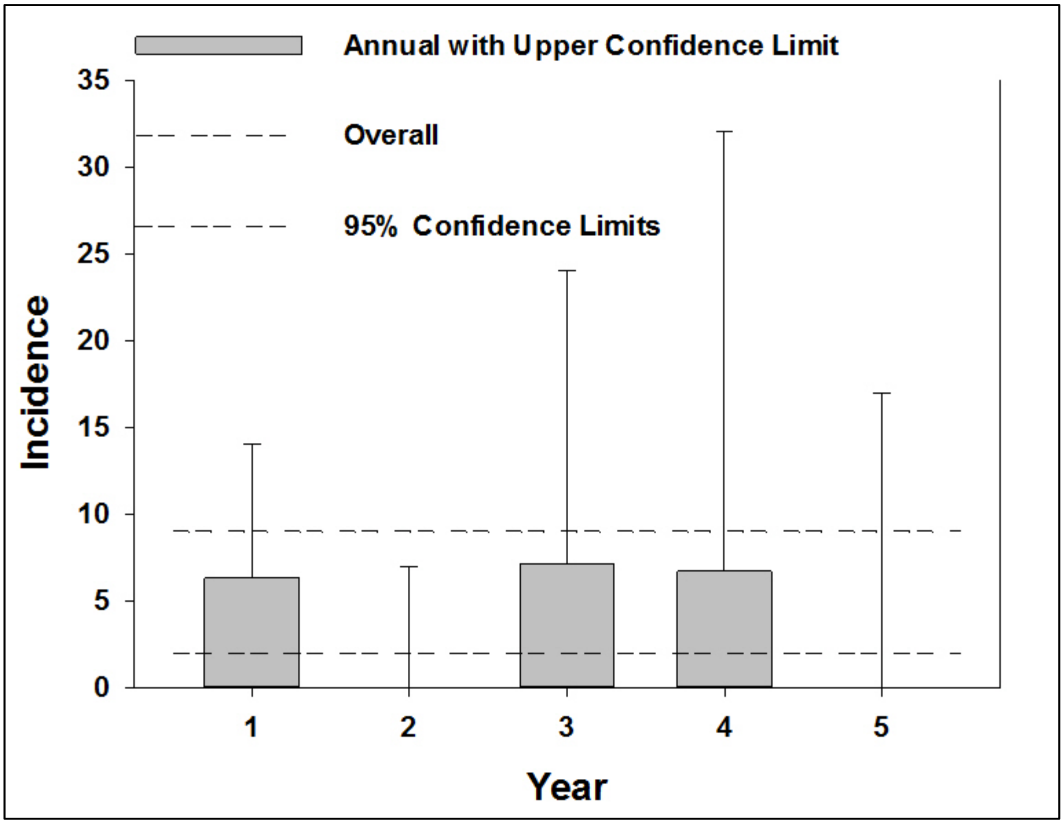

Figure 3. Annual incidence of new STS cases, with error bars showing the upper 95% confidence limit due to random sampling error. The lower 95% confidence limit bars are not shown, but are below 2% in all five years.

The further examination of the STS cases revealed at least 2 temporary shifts, and evidence for a false shift (an apparent increase in hearing sensitivity). Removing these 3 cases from the STS total leaves 2.6% (95% confidence limits of ~1 to 7%) of individuals with permanent decrements while onboard FREEDOM. This number potentially could have been even smaller if more STS cases had a follow-up to determine permanence.

Analysis of individual frequency shift magnitudes

Due to the available sample, raw numbers of STS cases and the population size make trends over time difficult to detect. As the confidence intervals overlap substantially, true year-to-year distinctions are impossible to determine; therefore, additional analysis looking for changes in incidence over time was performed. The statistical power of using binary data (STS or no STS) is quite limited compared to the richer data of multinomial data; e.g., the categories "hot" and "cold" are bimodal, whereas different temperature ranges are multimodal. Change in hearing sensitivity is multimodal, taking on a variety of values (-10, -5, 0, +5, +10, +15, and ±20 dB or more). Appendix C contains graphs and discussion of average shifts from both single frequencies and small groups of frequencies; however, there was no consistent pattern of shifts found, regardless of frequencies and averages observed.

USS STERETT (DDG-104)
Audiogram Availability
Figure 4 shows the audiograms recovered for the STERETT crew over the 5 years. Like the FREEDOM crew, the number of available records decreased each year. Figure 4 (lower trace) shows the number of audiograms recovered from sailors still on the STERETT. These recovery data are similar to those from FREEDOM in (Figure 2) with the exception that a few STERETT sailors were still onboard in Years 4 and 5. Of the original group, 33 sailors no longer had recorded audiograms after leaving STERETT and 41 still had more available audiograms, but were no longer on the ship. Of the latter, 12 were relocated to another ship, 3 were in low noise exposed commands (schools and recruiting) and the remainder moved into commands with both high and low noise environments (e.g., a Naval Base).

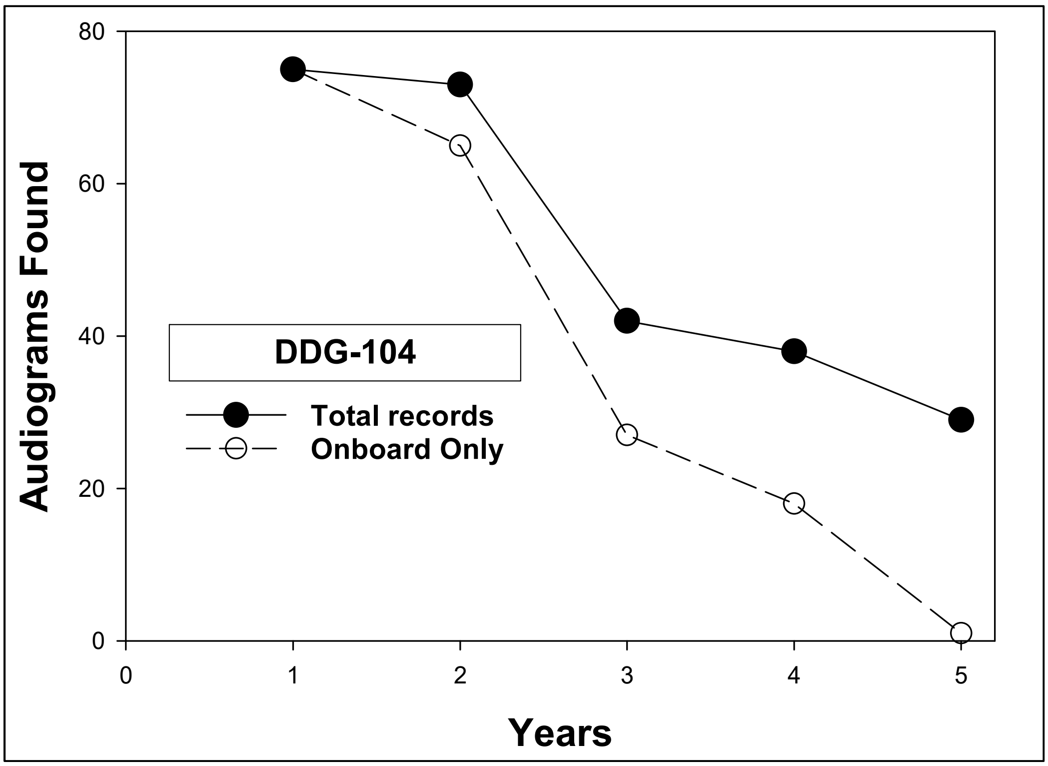

Figure 4. Audiograms recovered from sailors on USS STERETT and initially enrolled in a HCP on a 5-year time period. *Total audiograms of USS STERETT crew over 2008 to 2013, and the number from sailors identified as still being onboard the ship at that time.*

Incidence of Significant Threshold Shifts
In sailors still onboard the STERETT, 25 new STS cases were noted (four more were found in sailors who had departed the ship). The number per year varied from 0 to 10, and 9 cases were negative shifts ("improved hearing"). Plotted in Figure 5 are yearly incidence rates, along with 95% confidence limits based on the number of cases. As with the FREEDOM, the uncertainty in incidence rates is too large to confidently differentiate across different years. Also in line with the FREEDOM data (Figure 3), the STERETT STS cases occurred in sailors still onboard the ship only in the early years. From checking available subsequent year audiograms in 12 of the

STS cases, 8 were found to be a temporary shift. It is possible that more of the STERETT cases were actually temporary due to a lack of re-testing after the shift was recorded.

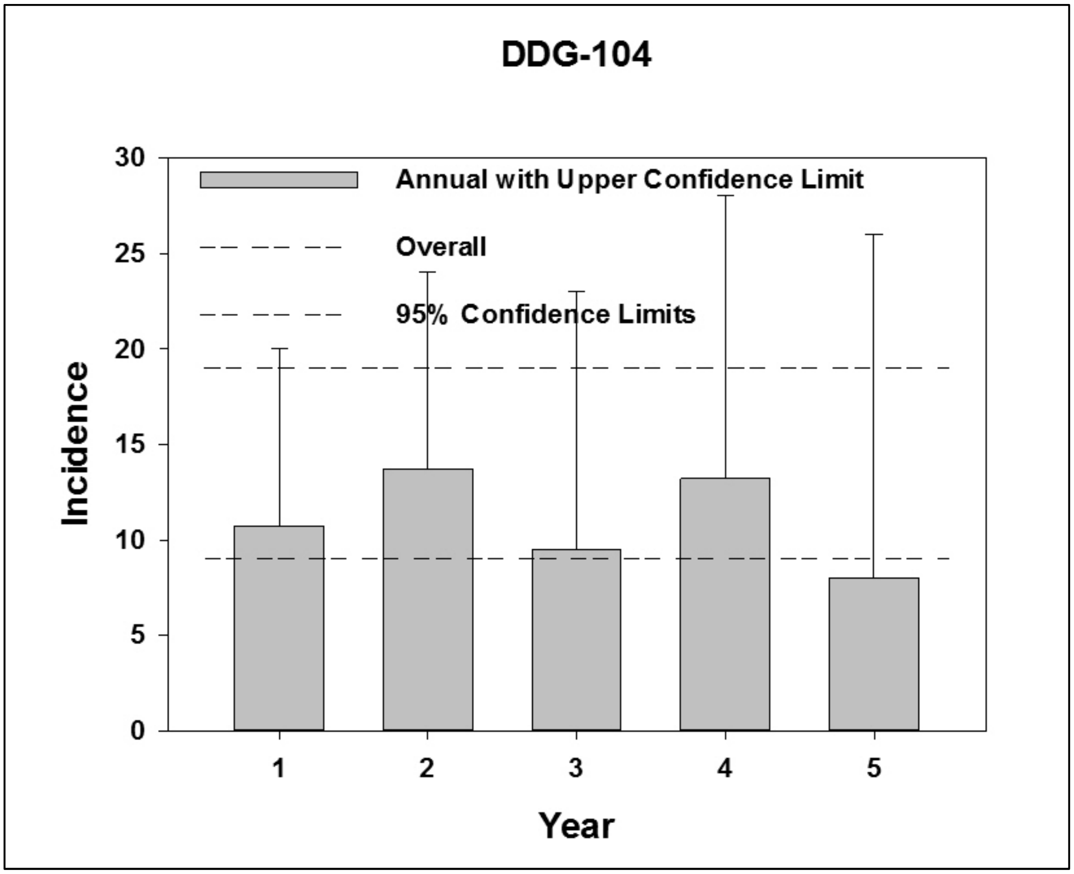

Figure 5. Annual and overall incidence of STS STERETT sailors from 2009-2013 with error bars showing the 95% confidence limits due to random sampling error.

To get the best estimate of STS incidence while still onboard, person-years (cases per year) of crewmembers still assigned to the ship were calculated. Seventy-five sailors were still onboard after Year 1, with 8 cases of STS. The same method used with FREEDOM data was repeated for STERETT. Figure 5 shows both the annual and overall incidence of STS. Cumulative onboard outcome was 25 STS cases in 187 person-years on exposure, or 13.4% annual incidence (95% confidence limits: 9 to 19%). Nine of the 29 cases were an apparent improvement in hearing acuity, indicating a roughly 31% false positive rate in declaring a decrement in hearing.

The STERETT incidence is over double that found with FREEDOM. The 95% confidence limits of the 2 ships narrowly overlap. The difference is likely not due to sampling randomness (p ~ .005 with the Fisher exact test).

Discussion
This 5-year follow-up of the LCS-1 FREEDOM is a rare opportunity to examine longitudinal changes in sailors' hearing. Although the raw rate of STS appeared to vary in different years, the small number of individuals prevented confident conclusions about yearly changes in incidence. The examination of between-subject averages of frequency shifts (both single frequencies and combinations) also failed to discern a statistically significant trend over years, despite using a higher precision measure.

The STS cases reported are not all attributable to a failure in the enhanced HCP or in the custom HPDs. While the goal of the program was to reduce noise-induced hearing loss, the main responsibility for compliance lies with the sailor. Of the eleven cases described in Appendix B, at least four STSs could be attributed to not regularly wearing hearing protection or failing to get the initial custom HPDs. Of the remaining six, three sailors left the ship within the first year, and no information about their compliance with the program was available. Compliance is necessary for any health intervention to succeed. Sailors tend to prioritize completing their duties, often ahead of maintaining health. HPD use can be inconvenient, uncomfortable if not properly selected and fitted well, and interfere with verbal and wired communication. Individual crewmembers need to be motivated to overcome impediments so as to preserve their hearing. Provision of devices that allow communication under hearing protection is very useful. Leadership by example could also make a crucial difference.

Waiting for STS to occur ensures that the HCP program records hearing-conservation failures, after change in hearing threshold has likely become permanent. Different methods are needed to indicate impending hearing loss, while intervention is still possible. Measurements of otoacoustic emissions (OAEs, sounds made in the inner ear and detected in the ear canal) can demonstrate enhanced sensitivity to future noise-induced hearing loss before the audiogram shows an STS (Lapsley-Miller, Marshall, Heller, & Hughes, 2006). Development of hardware and procedures for OAE use in HCPs has been supported by the Navy, and the technology is approaching readiness for large field trials.

To examine the long-term implications of a sustained hearing loss, Table 1 summarizes the results of simple calculations made by the authors showing the career-long prevalence (with any definition of NIHL) of sailors who worked in areas with a 3%, 4%, or 5% annual incidence (by the same definition) of permanent NIHL. Their exposure could have lasted for 3 years (about 1 sea-duty tour), 6 years, 12 years (at the high-end of sea-duty time), or a full 20-year naval career. The chance of incurring NIHL is over 20% for most cases by 6 years, and can reach 50% or more.

Chance of an Individual Incurring Hearing Loss during Naval Career (%)				
Annual NIHL Incidence Rate	**Years of Exposure**			
	3 years	**6 years**	**12 years**	**20 years**
3%	9	17	31	46
4%	12	22	39	56
5%	14	26	46	64

Table 1. Career-long NIHL rates of sailors exposed to different levels of hazardous noise for different lengths of a career. Time not tabulated is assumed to be spent in quiet areas. Hearing loss due to aging was not included.

Other longitudinal studies can help provide incidence rates to determine if rates of hearing loss in FREEDOM crew members are high or low compared to other Navy populations. An examination of 338 crewmembers (chosen for their initial excellent hearing) assigned to an aircraft carrier during a 6-month deployment showed a 4.4% STS rate (confirmed with follow-up test) over that period (Lapsley-Miller et al., 2006). The FREEDOM PTS rate of 2.6% is less than the aircraft carrier outcome, but statistical uncertainty prevents a firm conclusion. Comparison of FREEDOM with STERETT also appears to show less permanent change on FREEDOM.

Less direct comparisons are possible with other previously reported studies. A review of many Navy records shortly before they were merged with DOEHRS indicated an STS prevalence rate of 10 to 40% (Page, Bonhker, Rovig, Betts, & Sack, 2002). Permanent threshold shifts in active duty Air Force personnel varied between 4.6–16.7% between 2005 and 2011 (Soderlund, McKenna, Tastad, & Paul, 2016). A Center for Naval Analysis review of DOEHRS data found that the enlisted rates represented on FREEDOM have a lifetime prevalence of 15-20% — larger than other categories (Shaw & Trost, 2005). Any studies of one-snapshot prevalence are difficult to compare to the study reported here. The snapshot includes sailors with hearing loss just suffered, as well as longstanding cases, and no exposure period is inferred.

Continued or new hearing loss of the sailors' hearing after leaving the FREEDOM and STERETT may be an interesting future direction of study.

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Appendix A. DD2216 - Audiogram report

HEARING CONSERVATION DATA
(This form is subject to the Privacy Act of 1974 - use Blanket PAS - DD Form 2005)

1. ZIP CODE/APO/FPO/PAS

2. DOD COMPONENT
A - ARMY N - NAVY F - AIR FORCE M - MARINE CORPS 1 - OTHER DOD ACTIVITY

3. SERVICE COMPONENT
R - REGULAR V - RESERVE G - NATIONAL GUARD 1 - OTHER

4. SOCIAL SECURITY NUMBER
5. NAME *(Last, First, Middle Initial)*
6. DATE OF BIRTH *(YYYYMMDD)*
7. SEX M - MALE F - FEMALE

8. PAY GRADE, UNIFORMED SERVICES
9. PAY GRADE, CIVILIAN
10. SERVICE DUTY OCCUPATION CODE
11. MAILING ADDRESS OF ASSIGNMENT

12. LOCATION - PLACE OF WORK
13. MAJOR COMMAND
14. DUTY TELEPHONE *(Include area code)*

15. AUDIOMETRY a. PURPOSE 1 - 90 DAY 2 - ANNUAL 3 - TERMINATION 4 - OTHER

AUDIOMETRIC DATA RE: ANSI S3.6 - 1989	LEFT						RIGHT					
	500	1000	2000	3000	4000	6000	500	1000	2000	3000	4000	6000
b. CURRENT AUDIOGRAM DATE *(YYYYMMDD)*												
c. REFERENCE AUDIOGRAM DATE *(YYYYMMDD)*												
d. SIGNIFICANT THRESHOLD SHIFT (STS) 1 - NO 2 - YES / e. THRESHOLD SHIFT →												

f. REMARKS *(Include exposure data)*

g. TYPE OF PERSONAL HEARING PROTECTION USED
1 - SINGLE FLANGE (VS1R) 2 - TRIPLE FLANGE 3 - HAND FORMED EARPLUGS 4 - EAR CANAL CAPS 5- NOISE MUFFS 6 - OTHER

h. EXAMINER NAME *(Last, First, Middle Initial)*
i. TRAINING CERTIFICATE NO.
j. SERVICE DUTY OCCUPATION CODE
k. OFFICE SYMBOL

l. AUDIOMETER TYPE 1 - MANUAL 2 - SELF-RECORDING *(Automatic)* 3 - MICROPROCESSOR
m. MODEL
n. MANUFACTURER
o. SERIAL NUMBER
p. LAST ELECTROACOUSTIC CALIBRATION DATE *(YYYYMMDD)*

16. FOLLOWUP NO. 1 a. MINIMUM 14 HOURS NOISE FREE SINCE CURRENT AUDIOGRAM *(See item 15.b.)*

AUDIOMETRIC DATA RE: ANSI S3.6 - 1989	LEFT						RIGHT					
	500	1000	2000	3000	4000	6000	500	1000	2000	3000	4000	6000
b. CURRENT AUDIOGRAM DATE *(YYYYMMDD)*												
c. REFERENCE AUDIOGRAM DATE *(YYYYMMDD)*												
d. SIGNIFICANT THRESHOLD SHIFT (STS) 1 - NO 2 - YES / e. THRESHOLD SHIFT →												

f. EXAMINER NAME *(Last, First, Middle Initial)*
g. TRAINING CERTIFICATE NO.
h. SERVICE DUTY OCCUPATION CODE
i. OFFICE SYMBOL

j. AUDIOMETER TYPE 1 - MANUAL 2 - SELF-RECORDING *(Automatic)* 3 - MICROPROCESSOR
k. MODEL
l. MANUFACTURER
m. SERIAL NUMBER
n. LAST ELECTROACOUSTIC CALIBRATION DATE *(YYYYMMDD)*

17. FOLLOWUP NO. 2 a. MINIMUM 14 HOURS NOISE FREE SINCE CURRENT AUDIOGRAM *(See item 15.b.)*

AUDIOMETRIC DATA RE: ANSI S3.6 - 1989	LEFT						RIGHT					
	500	1000	2000	3000	4000	6000	500	1000	2000	3000	4000	6000
b. CURRENT AUDIOGRAM DATE *(YYYYMMDD)*												
c. REFERENCE AUDIOGRAM DATE *(YYYYMMDD)*												
d. SIGNIFICANT THRESHOLD SHIFT (STS) 1 - NO 2 - YES / e. THRESHOLD SHIFT →												

f. EXAMINER NAME *(Last, First, Middle Initial)*
g. TRAINING CERTIFICATE NO.
h. SERVICE DUTY OCCUPATION CODE
i. OFFICE SYMBOL

j. AUDIOMETER TYPE 1 - MANUAL 2 - SELF-RECORDING *(Automatic)* 3 - MICROPROCESSOR
k. MODEL
l. MANUFACTURER
m. SERIAL NUMBER
n. LAST ELECTROACOUSTIC CALIBRATION DATE *(YYYYMMDD)*

DD FORM 2216, JAN 2000 PREVIOUS EDITION MAY BE USED. Reset Adobe Professional 7.0

Appendix B. USS FREEDOM Case Studies

The following descriptions are intentionally vague to protect the exact identities of individual crew members. Gender identification is not provided. The seniority categories used were: Junior (E-3 to E-6, O-1 and O-2;) Senior (E-7 and O-3;) Very Senior (E-8, E-9, O-4 and O-5.) The age categories compared to the prior even decade were: early – from years 0-2; mid – from years 3 to 7; and late – from years 8-9. These categories were assigned to each case at the time of their STS.

Case A: This very senior person in their mid-40s had a right ear shift in less than 1 year. This person reported spending over 12 hours per day in engineering spaces wearing double hearing protection. The custom-molded earplugs were not used on watch at all – only for personal music off-hours. Attenuation was not measured.

Case B: This junior member, in their mid-30's, reported limited use of custom-molded earplugs (customs) after 30 minutes because they were uncomfortable. The customs' measured performance was below the attenuation criterion, and new impressions and customs were provided. However, there was little commitment from the sailor to get fitted for their replacements, so the order went unfulfilled. An STS was reported in Year 5 in the member's right ear, after two years of no record of audiograms.

Case C: This junior member, in their mid-30's, was not seen past the 2009 visit and custom plug distribution. That person reported some discomfort with custom plugs, and could not wear them longer than a few minutes. This sailor worked in the noisy waterborne mission zone frequently. An STS was reported in Year 4 in the right ear, after the sailor left the ship between 2009 and 2010.

Case D: This junior member, in their mid-30's, had an STS in the right ear in Year 3 while still attached to LCS. This person preferred customs over the non-custom options, but did not consistently wear any HPD- custom or non-custom- in noisy environments. Reported living in the berthing area where sound >85dBA when #1 fire pump was turned on. This individual reported that they never wore HPDs, custom or stock.

Case E: Very senior engineering person in their late 40's showed an STS in the left ear in Year 1 after joining the ship. Declined to even be fitted for custom HPDs.

Case F: Very senior engineering member, in their early 40's, had an STS in the right ear in the first year. Hearing conservation team did not see person after 2009 so there is not much information on use of customs. Member was very enthusiastic about the program as stated on the program evaluation in 2009. Attenuation was not measured.

Case G: This junior member, in their mid-30's, had an STS in the right ear in Year 3 while still onboard the LCS. This individual claimed to have used at least one pair (High Performance) everyday, until all three pairs were lost in their bag on a flight in Year 2. New customs were ordered later that year.

Case H: This senior person, in their early 30's, was found to have an STS in the left ear upon initial examination in 2008, which was confirmed on re-test later that month. In Year 1 they had an STS in the opposite ear. This sailor's duties were not in the engineering spaces, but in other high noise environments (waterborne mission zone and anchor windlass).

Case I: This person, in their late 30's, in Year 5 had an STS in the left ear, after three years without an audiogram. This senior crewmember preferred foam because of the ability to discard used pairs instead of cleaning. This individual was not seen past February 2009 by the enhanced hearing conservation team, and there is no further information on the use of customs. Attenuation was not measured.

Case J: This junior crewmember, in their mid-20's, had an STS in the right ear in Year 1. There is no further information on use of customs or person's experience with HPDs on the ship. This person left the Navy in 2010. Attenuation was not measured.

Case K: This junior person, in their mid-30s, had an STS in Year 5 in both ears. This person did not wear HPD for regular work day as they were not in noisy work environment. This person had slight discomfort when removing customs, but could wear them for over 2 hours if needed (i.e., gun qualifications). Attenuation was not measured.

Appendix C. USS FREEDOM Frequency Averages

Basis. A more sensitive measure of change is one with greater precision, i.e., if more categories are available for possible outcomes, the result is more precise. The change in hearing sensitivity has better inherent precision than an STS yes/no, as it takes on a variety of values (-10, -5, 0, +5, +10, +15, and ±20 dB etc.). These values can be averaged across all crewmembers' ears and the average is determined better than any single outcome, even if the test-retest variability is 5 dB or more. For example, in the case of Year 3, the average shift at 4 kHz is 3.1 dB with a standard error of the mean (SEM) of 0.8 dB. Approximate 95% confidence limits are at 2*SEM above and below the mean with a confidence region of 1.5 dB to 4.7 dB. This allows for confident rejection of the possibility of no change (shift of 0 dB), as well as any large shift (5 dB or more) in the average data.

The following shift data was an effort to determine any trend in the frequency averages across the years for the crew of the USS FREEDOM.

Navy shift average. The average hearing threshold shift of the same frequencies used to make a decision about a Navy STS (average of 2kHz, 3kHz, and 4kHz) was examined. Every individual's average shift was recorded in dB, regardless of whether a shift is declared STS or not.

Figure 6 plots this "Navy" average frequency in the gray bars. A smooth degradation trend that could be characterized with more precision than the binomial precision of STS cases was not observed. If the change was a gradual degradation of hearing sensitivity, there should be a visible upward trend in the plotted changes, but is not apparent. All yearly averages are within about 1.5 dB of each other. The lowest is in Year 2.

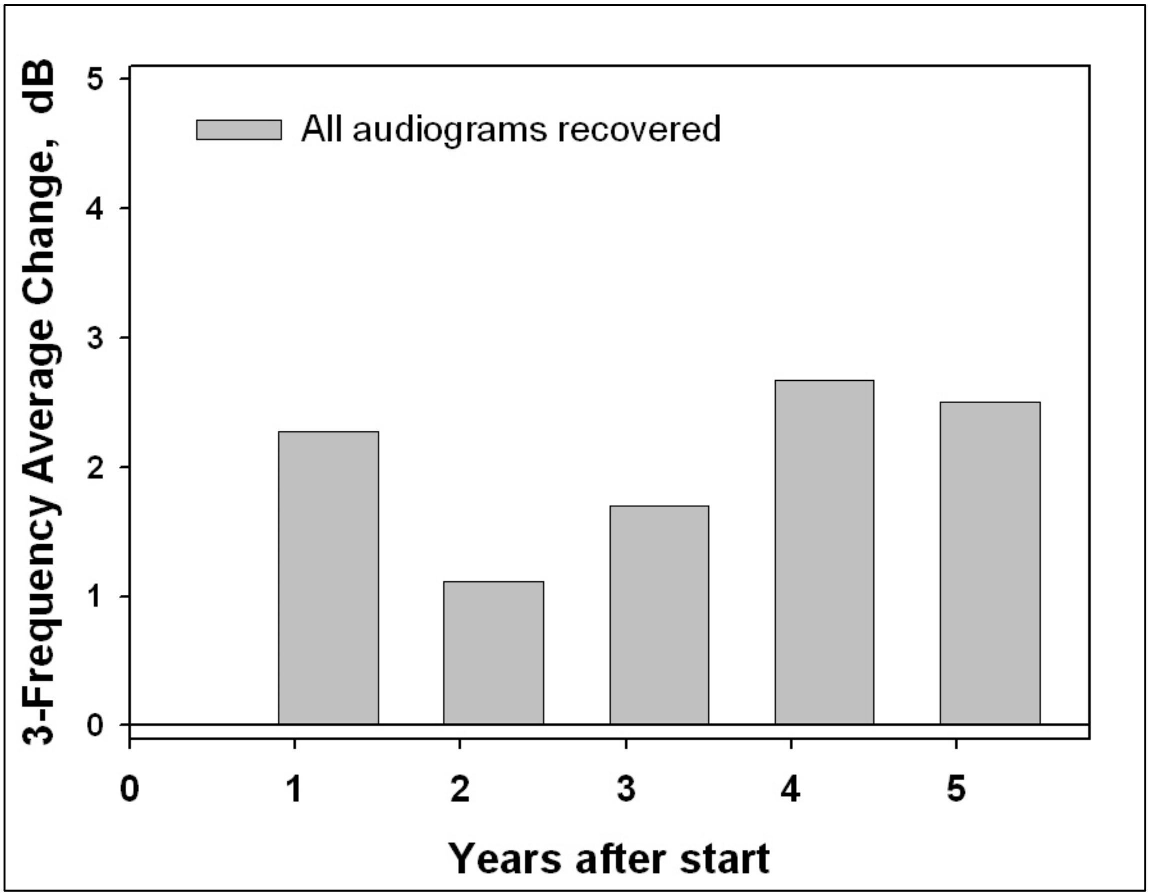

Figure 6. Average change in combined 2, 3, and 4 kHz plotted against time from start of the study. Change is the audiometric shift, indicating decreased hearing sensitivity. Both ears from all audiograms available were used in this calculation. Each year-group average was obtained from a different group of sailors, which was smaller in each subsequent year.

Part of the explanation for the lack of a smooth degradation may lie in an incomplete history of the crew rotation: 3 of the STS cases who contribute heavily to the Year 1 average had no follow-up in later years. Thus their shifts (between 10 and 11.7 dB) are not available for inclusion in the subsequent years' results. Excluding those cases in all years does not produce a smoother trend than seen in Figure 6. In fact, selecting only the crew that had audiograms while assigned to the ship for Years 1, 2, and 3 leaves a cleaner "longitudinal" group (plotted in Figure 7 as yellow bars). Year 4 had too little data to examine. Still there is still no continuous trend. The select longitudinal group had similar ages to the whole cohort with a range 26-38 and an average of 32. The year-to-year dB change are outside the normal variability for this average, as confidence limits on the estimated means are half a decibel or less for the standard error of the mean (SEM) in Years 1-3. The high precision of these means is due to averaging 3 frequencies by 2 ears by 50 people or more. The longitudinal grouping and the precision of the mean average effects are reflected in Figure 7. There is no definitive reason for Year 2 hearing to appear to be better than Year 1, though the difference in means is significant at $p \leq .05$ (before correcting for multiple comparisons).

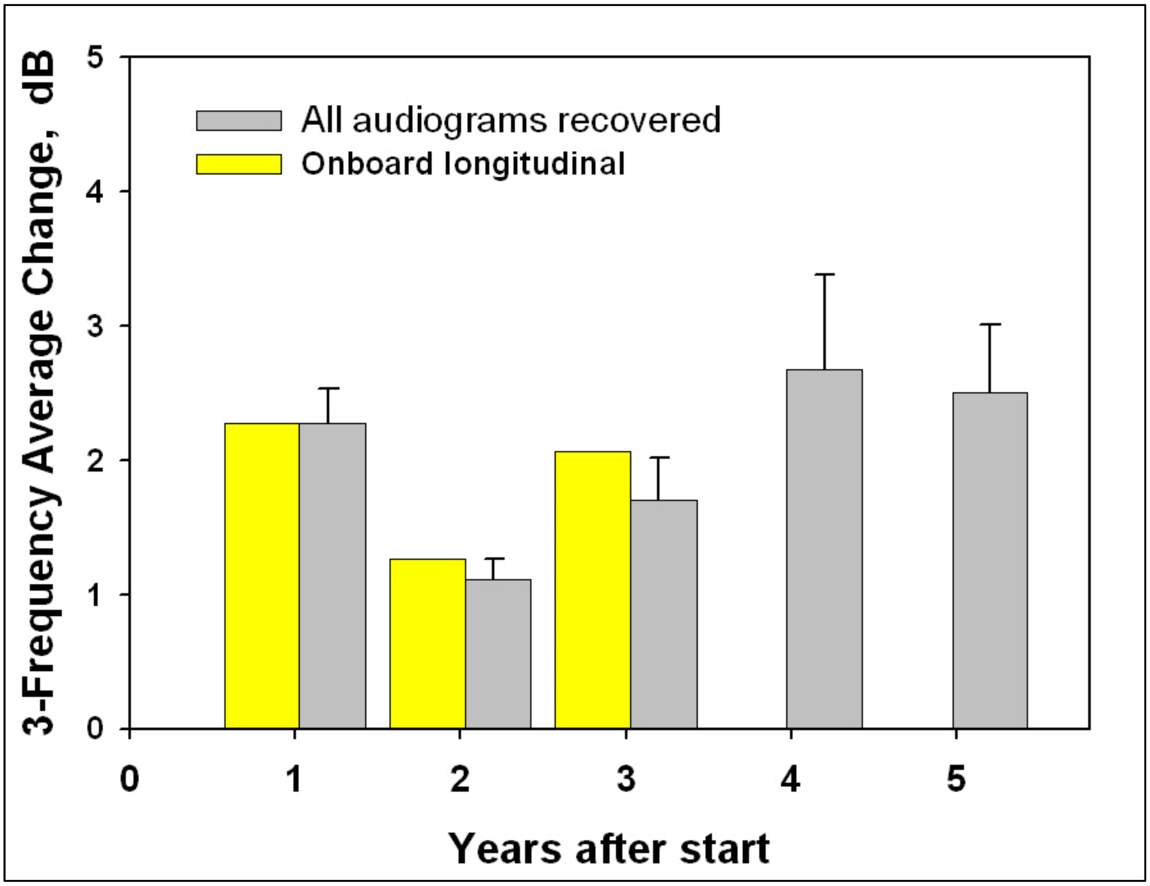

Figure 7. Average shifts from baseline in 3-frequency combination (2, 3, and 4kHz) used to define an STS. Error bars are 1 SEM. Only the yellow bars have identical people in each year's average.

High frequency average. Noise-induced hearing loss does not occur uniformly across all hearing frequencies: It preferentially affects the higher frequencies in an audiogram (McBride & Williams, 2001). The average frequency shift of all crew each year was examined, using the averages of 4 kHz and 6 kHz, the two highest frequencies measured in the Navy HCP. Those data are presented in Figure 8. The final 4 years show a smooth trend upward, as expected with noise-related hearing loss. However, Year 1 is surprisingly high. Years 1 to 3 in the onboard longitudinal group do not show a consistent trend.

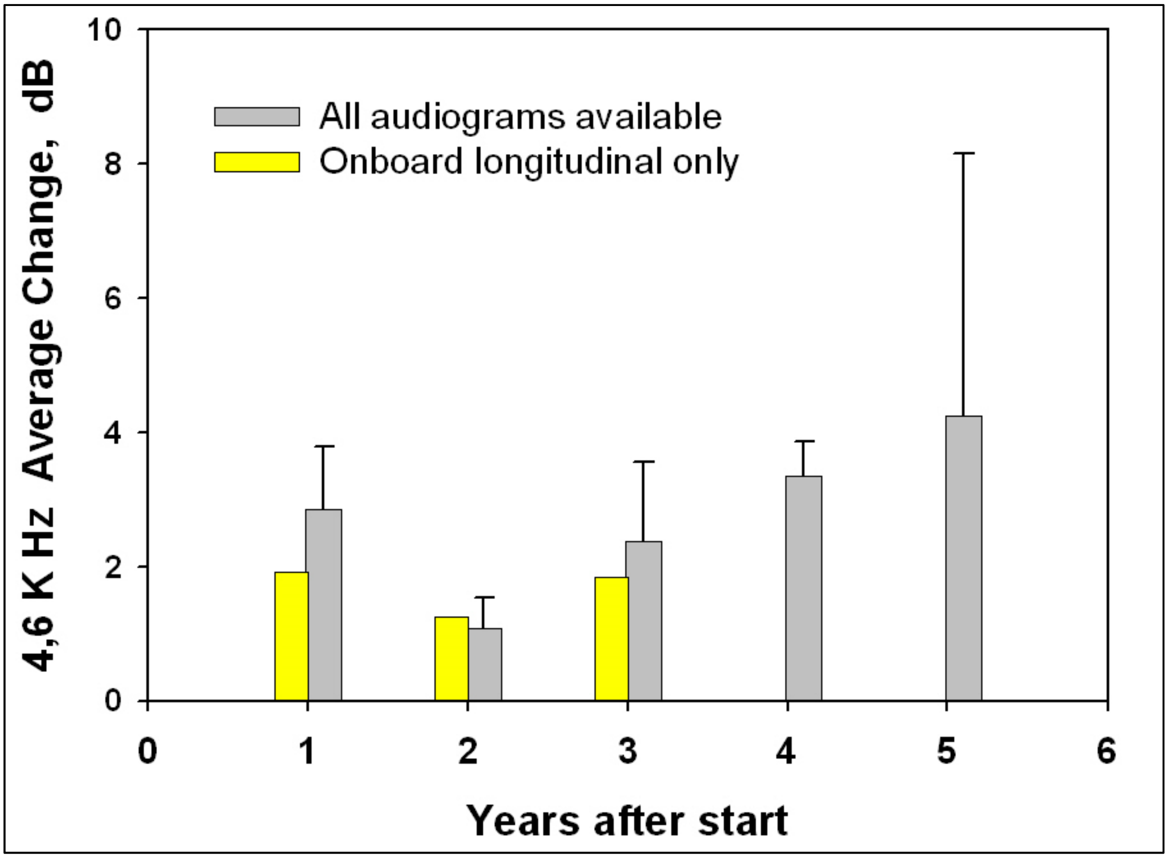

Figure 8. Average change in combined 4 and 6 kHz. Error bars are 1 SEM. Only the grey bars have identical people in each year's average

Single frequency shifts. Single frequency shifts were also explored in order to seek a more sensitive indicator of hearing change. The 4 kHz results are plotted in Figure 9. No convincing trend is seen in total crew results, but the onboard longitudinal group increases by about the amount of the measurement uncertainty.

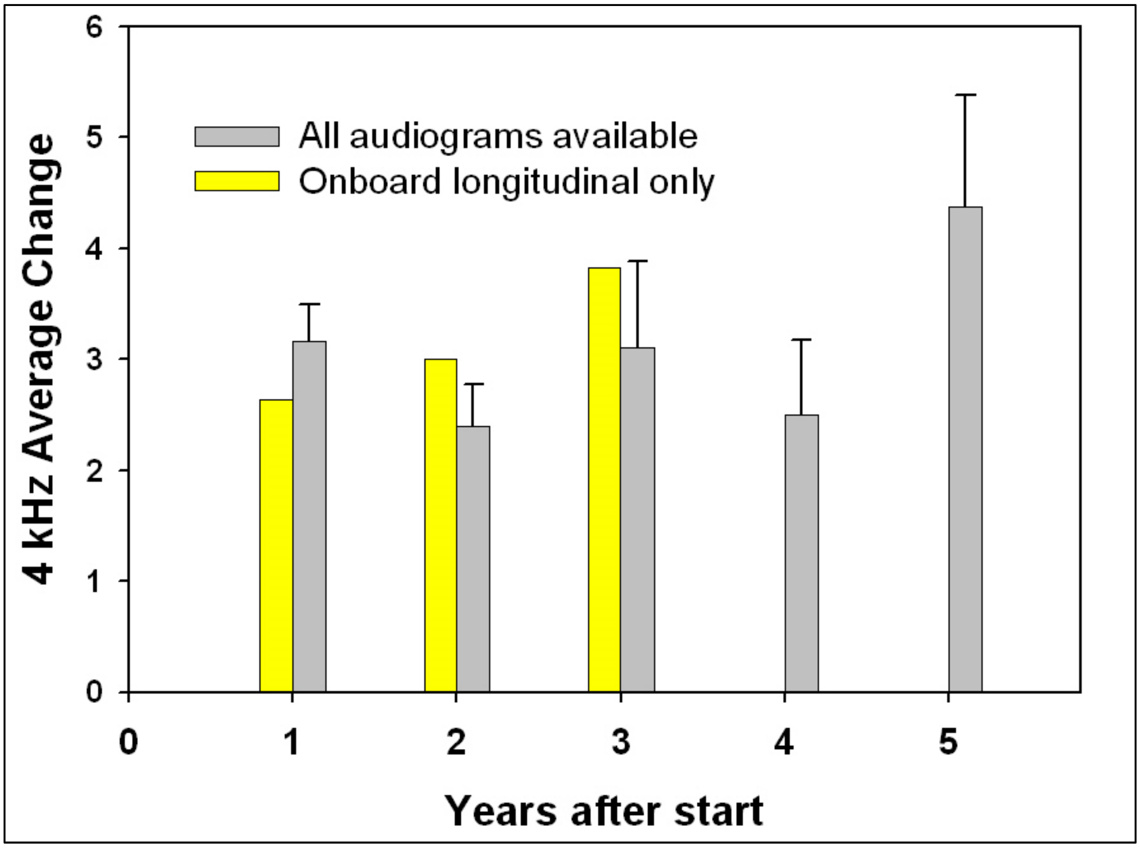

Figure 9. Average change in 4 kHz. Error bars are 1 SEM. Only the grey bars have identical people in each year's average

Trends in the 6 kHz single frequency were also examined (not plotted). No trend was evident. Furthermore, the averages had more uncertainty than the previous plots, probably due to known unreliability of usual audiometric earphones at higher frequencies.

Notch shift. The occurrence of NIHL has been found to produce a characteristic drop in the audiogram at 4 kHz, or 6 kHz (McBride & Williams, 2001). The degree of "noise notch" is calculated from the hearing level of the notch frequency(s) minus the average hearing level of adjacent frequencies. The available Navy audiogram only included results for 2, 3 and 4 kHz, so an adapted method was used (average of entries at 4 and 6 kHz, minus the entry at two times 3 kHz) (*Navy Medical Department Hearing Conservation Procedures*, 2008). The "notch" calculation (not shown) did not show increase with time of exposure, until Years 4 and 5.

Summary. Overall, exploring averages across individuals for one, or a few, frequencies has not shown a consistent trend in hearing loss. Without referring to more complex modeling, a trend would be apparent if a 3 or more year sequence of points increased by more than 2-3 SEM. Since the various frequency averages had estimated SEMs below 1.5 dB in early years, a trend of less than 5 dB might have been discernible. Instead year-to-year changes that often bounced over a 5 or more dB range were observed. If a consistent trend had been observed, further conclusions could have been drawn.