

Integrating User Voice in Hearing Care With Focus on Off-Duty Warfighter

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ABSTRACT

Introduction:

Noise-Induced Hearing Loss (NIHL) is a growing public health concern in the USA and globally because of the emergence of lifestyle preferences and environmental exposures to sound levels exceeding safe listening limits for extended periods of time. In the military, hearing and communication are important for survival and the Department of Defense's Hearing Center of Excellence highlights the importance of protection from NIHL. Issuance of the World health organization safe audio listening standards along with existing U.S. federal and military standards provides a framework for developing an accessible tool for promoting safe listening.

Methods:

An App is being proposed for an aggregated assessment of a user's daily sound exposure, through personal audio system and ambient sources and providing tools for managing personal sound exposures. The key elements for development of App features were integration of user voice for functionalities, computations based on global standards, including military, for safe listening and alignment with regulatory standards for Apps.

Results:

Features of the App are "Track" for audio and ambient exposures, "Compute" for real-time and cumulative exposures vs. safe listening standards, "Alert" for unsafe exposures using visual and haptic, "Inform" for personal exposures vs. safe dose, associated NIHL risk and education, "Choice" for alternatives that can be relatable to personal lifestyle, and "Share" for informing others as determined by the user. App safety is ensured by privacy and cybersecurity regulatory standards.

Conclusion:

The overall goals of the App are to increase NIHL awareness and to empower users to improve personal listening behaviors that can potentially reduce the risk of NIHL.

INTRODUCTION

There is an increasing concern regarding Noise-Induced Hearing Loss (NIHL) and the resulting auditory and nonauditory adverse health outcomes.¹ The Centers for Disease Control and Prevention (CDC) estimates ~24% of U.S. adults and the World Health Organization (WHO) projects about 1.1 billion young adults worldwide are at risk of NIHL because of routine, prolonged exposures to loud noise mostly because of recreational activities.^{2,3} The CDC estimates indicate 40 million U.S. adults (20-69 years old) have NIHL, where 1 in

2 with NIHL do not have noisy jobs and 1 in 4 U.S. adults who report excellent to good hearing already have hearing damage.⁴

For the military, hearing fitness is a requirement for battle readiness—situational awareness, survival, teamwork, operational planning and execution, response to commands, communication, unit safety, and mission accomplishment.⁵ The Department of Defense Hearing Center of Excellence (DoD HCE) provides clear guidances on the selection and use of hearing protection devices while on duty.⁵ However, the off-duty warfighter, with no hearing protection, could still be at risk for NIHL as a consequence of daily lifestyle needs and recreational activities. Noise-Induced Hearing Loss is painless, progressive, and permanent—but it is preventable.⁶ There is limited availability of tools for real-time, cumulative assessment of daily noise exposure, as a consequence of daily activities and lifestyle choices, with features to facilitate adoption of safe listening practices into one's lifestyle. The proposed Hearing Health App (App) provides real-time assessment of audio and ambient sound exposures vs. U.S. and United Nation (UN) safe standards with user-centered tools to enhance NIHL awareness and to improve listening habits to preserve hearing fitness.

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The App proposed in this article is intended to be sold on the App Store and Google Play stores for iOS and Android versions, respectively.
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METHODS

Three key elements were assessed in the development of the App features and computational aspects as described below.

User Voice: Understanding User Awareness, Needs, and Preferences

An assessment of user awareness of NIHL and preferences for App personalization features was conducted in military and civilian individuals via face-to-face meetings, phone conferences and online questionnaires. The user segments included young adults (age 18–25 years) and adults (age > 25 years), with or without perceived hearing impairment. Queries were related to listening experiences, issues, and awareness. Responses related to problems and preferences were used to guide development of App features. Although there was no Institutional Review Board oversight, all participants were provided with information on scope and objectives of the App and how their feedback would be utilized for App development.

Standards: Alignment With U.S. (Federal, Military) and UN Standards for Safe Listening

The DoD HCE along with the U.S. Army Research Lab (ARL) and U.S. Army Public Health Center (APHC) provide safe listening standards and education to mitigate NIHL risk in service personnel.^{7–9} In addition, there are safe listening standards from National Institute for Deafness and Communication Disorders, National Institute for Occupational Safety and Health, and Occupational Safety and Health Administration (OSHA) to limit occupational noise exposures. To address evolving young adult lifestyles where exposure mainly results from recreational listening, the International Telecommunications Union (ITU) H.870 guideline and the WHO-ITU global standard for safe listening devices and systems regulate exposure to loud sounds through personal audio devices/systems.^{10–14} Computation methodologies were based on assessment of real-time and cumulative ambient and audio sound exposures compared with the safe listening standards described above.

Regulations: Alignment with Mobile App Regulatory Guidances

Proactive engagement with U.S. and UN regulatory organizations is important to ensure App alignment with current health standards. Recently, we presented at 2019 ITU Kaleidoscope academic conference describing App features with focus on computation methodologies and safety features such as privacy and cybersecurity.¹⁵

RESULTS

Summary of User Voice Assessment

An assessment of military and civilian awareness (n = 50) of NIHL and preferences for App personalization features was conducted. The feedback received, as summarized below,

indicated that there were commonalities between the military and civilian responders with additional considerations for the military.

Military responses: Young adult, no hearing impairment

- Understand high risk of NIHL, because of instruction from senior personnel
- Do not consistently use hearing protection devices as these adversely impact situational awareness and completion of duties
- Only wear hearing protection devices when operating machinery; oftentimes still exposed to loud sounds, such as artillery, when not operating such machinery
- Continual use of audio devices including wireless earbuds, off-duty
- Unwilling to compromise recreational experiences (e.g., music concerts) where expenditure has been made on tickets to enjoy the experience
- Development of hearing loss anticipated later in life (post-military engagement)
- App could help to assess risk during off-duty hours or post-discharge; should be relatable to military lifestyle; could potentially help in preserving residual hearing

Civilian responses: Young adult, adult, without and with hearing impairment (including tinnitus)

- Limited awareness of NIHL
- General perception that NIHL is not a risk for them
- Use of personal audio devices and wireless earbuds throughout the day even during interactions with others
- Reliable sound measurement standards and computation with a continuum of assessment and alerts that can be incorporated into daily activities
- App could be helpful to assess and potentially mitigate NIHL risk

Computation of Real-time and Cumulative Safe Listening Exposures

Ambient sound data are sampled by the phone microphone, and audio sound data are determined from the phone volume level. The audio exposure level has been validated with Apple, Beats, and Samsung headphones. These data are collected in dBA and stored in secure cloud-based databases following the cybersecurity standards mentioned later in this article. These data are fetched to be used in the calculation of real-time and cumulative exposures as described below.

A summary of U.S. (Army, occupational) and UN (audio) safe listening standards is provided in Table I. The Army and nonmilitary (occupational) standards for limits on daily sound exposures are similar. It is important to note that only relevant Army safe listening standards have been incorporated into the App. Further developments of the App will also incorporate more standards to address Navy and Air Force exposures as

TABLE I. Summary of Ambient and Audio Safe Listening Standards

Exposure type	Safe listening standard
Military	ARL: Limit B—SPL “shall not be” equal to or exceed an 8-hour time weighted average of 85 dBA. APHC: Damage at 85 dBA or more for continuous noise
Occupational	DoD HCE: Limit >80-85 dBA CDC (NIOSH): Recommended Exposure Level (REL): 85 dBA over 8 hours OSHA: Permissible Exposure Limit (PEL): 90 dBA over 9 hours
Recreational (audio device)	NIDCD: ≤70 dBA: Safe, >85 dBA: Damage over time WHO-ITU (H.870) Adults: 80 dBA for 40 hours a week: Children: 75 dBA for 40 hours a week

APHC, U.S. Army Public Health Center; ARL, U.S. Army Research Lab; CDC, Centers for Disease Control and Prevention; DoD HCE, Department of Defense Hearing Center of Excellence; ITU, International Telecommunications Union; NIDCD, National Institute for Deafness and Communication Disorders; NIOSH, National Institute for Occupational Safety and Health; OSHA, Occupational Safety and Health Administration; SPL, Sound Pressure Level; WHO, World Health Organization.

well as exceptions and/or higher standards based on job categories. However, only the OSHA Permissible Exposure Limit (PEL) and the WHO-ITU provide formulas for computing real-time cumulative A-weighted sound pressure level exposures (in dBA). The App calculates the user’s occupational environmental exposure compared with OSHA PEL exposure using the following formula:

$$D = 100 * \left(\frac{C(1)}{T(1)} + \frac{C(2)}{T(2)} + \dots + \frac{C(n)}{T(n)} \right) \quad (1)$$

where $C(n)$ indicates the total time of exposure at a specific noise level. D represents what percentage of the OSHA standard for daily noise exposure to which the user has already been exposed.

$T(n)$ indicates the reference duration calculated by:

$$T(n) = \frac{8}{2^{(L-90)/5}} \quad (2)$$

where L is the Sound Pressure Level (SPL) of the exposure.

For users whose sound exposure is primarily through audio devices, the App calculates audio exposure via the WHO-ITU Standard. The exposure is calculated by

$$\int_{t_1}^{t_2} (p_a(t))^2 dt \quad (3)$$

where $p_a(t)$ is the SPL in Pa. This exposure is then compared with WHO weekly dose of 1.6 Pa²h for adults and 0.51 Pa²h for sensitive users (i.e., children).

To address military standards of noise dosages over a set amount of time (e.g., an 8-hour time period) the cumulative exposures are calculated using the OSHA formula. To compensate for the different reference exposure volume for the

8-hour period, from different standards, the percent dosage calculation, D , is multiplied by a factor f , where f is the ratio of the recommended 8-hour noise level (85 dBA) of OSHA over the recommended 8-hour noise level of other standards.

Unlike calibrated sound level meters that need calibration for accurate ambient sound exposures to comply with safety standards, our App uses the personal phone microphone to provide estimates of off-duty ambient sound in a quick and accessible manner with real-time computation for safe exposures. Therefore, because the phone microphone is used rather than an external microphone, the assessment of real-time and cumulative exposures is estimates because of possible discrepancies in phone microphone accuracy and phone placement that may affect the sampled ambient exposure. Also, distance between the mic and the user may significantly affect the sampled sound exposure. It is intended to include a disclaimer that the noise levels measured through the mic do not necessarily represent the noise levels experienced at the ear of the user.

Another way phone use, specifically the use of phone processing abilities to compute exposure, affects accuracy concerns the computation between sampling periods. App inactivity is addressed based on the phone operating system. For the Android version, the App periodically starts, runs in the background, and terminates while the user is not actively using the app. In the event of a dramatic change in sound environment, the user is encouraged to resample to increase the accuracy of the estimate. The iOS version has notifications to encourage resampling when a designated period since the previous sampling has been elapsed.

App Features

Learnings from user feedback along with safe listening recommendations from DoD HCE, ARL, and APHC were used to design simple and effective App features. The App’s key

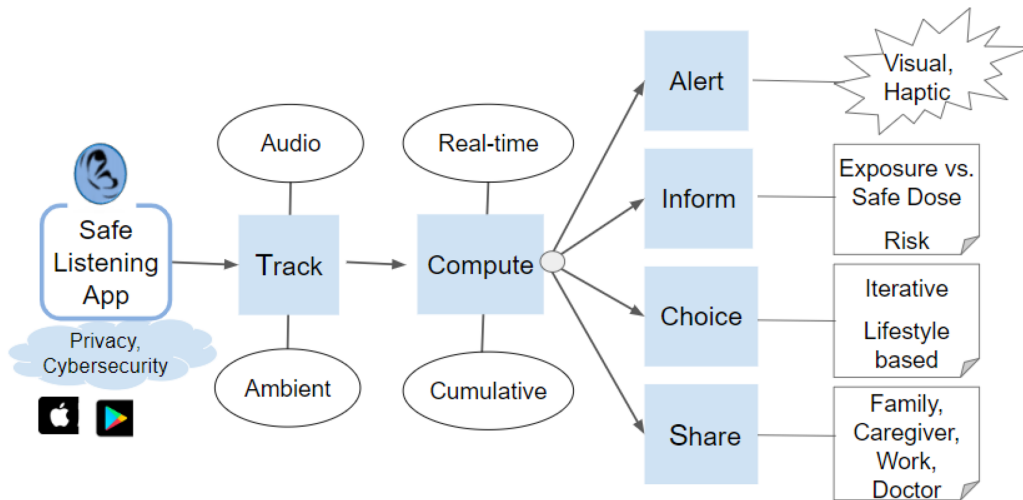


FIGURE 1. Safe listening App features.

objective is to empower the user to improve personal listening habits by providing:

- Awareness: NIHL risk not readily sensed by warfighter
- Accessibility: iOS and Android, easy to use
- Active and Customizable Monitoring: User defined settings for measuring and receiving notifications
- Personalized Feedback: Choices using DoD HCE EARS²U (Education, Adjusting volume and duration of use, Recognizing personal sound exposures, Selecting appropriate lifestyle activities, Seeking annual hearing checkups, Understanding NIHL consequences) hearing loss prevention strategy, personal metrics to manage personal healthcare¹⁶
- Safety: Privacy and Cybersecurity measures meeting regulatory standards^{17,18}

Figure 1 presents the following App features.

“Track” includes

- Ambient + Audio sound exposures using phone microphone,
- Daily and weekly noise dosage, and
- Adjustable user sampling preferences.

“Compute” includes

- Real-time dBA assessments,
- For ambient exposure: calculation using OSHA standard to meet DoD criterion of 85 dBA for 8 hours/day with 3 dB per doubling exchange rate,
- For exposure from audio: calculation using WHO-ITU standard of 80 dB for 40 hours/week,
- Calculation of cumulative exposure via summation of ambient and audio exposures, and
- Real-time comparison of cumulative exposure to safe listening standards.

“Alert” includes

- Visual and Haptic signals when nearing and exceeding safe daily exposure,
- Timer for remaining duration in current exposure environment before being at potential NIHL risk, and
- Additional notification options based on user preference.

“Inform” includes

- Daily and weekly exposures vs. safe dose,
- Personal reports on listening profile, improvements and management of NIHL risk, and
- Educational modules on criticality of hearing for job performance, safety, quality of life. It is structured according to EARS²U hearing loss prevention strategy as well as the APHC Hearing Health Education and the HCE Comprehensive Hearing Health Program information.^{9,19} In addition, relevant DoD resources (as listed previously), regulatory resources (e.g., FDA hearing aids, WHO Make Listening Safe initiatives) and options for personal hearing health monitoring (such as hearWHO App).^{20–22}

“Choice” includes

- Lifestyle-based personal action cues: Volume-duration-distance changes, alternative listening options, use of hearing protection,
- Iterative, with sequential choices being provided to engage the user in changing listening pattern if a previous cue did not result in exposure change, and
- “Sound Library” of activities and their respective exposure levels (in dBA) based on federal and military publications and categorized into lifestyle activities;

source for selection of alternative activities to allow for recovery.

“Share” includes

- Personal exposure reports at the discretion of user; could be used to support hearing screening.

Over the course of a day, the phone samples, either automatically or manually when the user launches the App, ambient and audio exposures as inputs to the features above. During that time, the user interacts with app through initiating manual sampling, receiving alerts, analyzing and understanding his exposure in daily reports and educational modules, and receiving and implementing suggestions for changing his listening pattern.

Smartphone Visual Interfaces

As depicted in Fig. 2, the visual interfaces show the following:

A: Login page with privacy and cybersecurity notifications

B: Main page with the four main tabs: Profile (qualitative information on user’s listening preferences and trends), Essentials (educational modules, sound library), Decibels (presentation of user’s real-time exposure and cumulative exposure over the course of the day), and History (presentation of user’s cumulative exposure for previous days and weeks)

C: Graphic showing the user’s real-time exposure in dBA

D: Graph showing the user’s cumulative exposure for the day (bottom) as well as a bar indicating the percentage of the daily reference to which the user has been exposed

E: Pop-up alert showing the percentage of daily exposure used, the volume (in dBA) of the current environment, and the timer for remaining duration

F: In-app alert for detected high “ambient” exposure; provides volume-duration-distance cues, EARS²U safe listening framework and cues to alternatives to high-risk activities (sound library resource) to promote recovery

G: In-app alert for detected high personal “audio” exposure; provides with volume-duration cues as well as choices to modify music listening behavior (e.g. different music genre) while still enjoying music

Validation of Computation and Appropriateness of App Features

The App’s intended use, features and military application of the App in off-duty personnel was presented at the 2019 Military Health System research Symposium and the integration of U.S. and UN standards (civilian, military) for ambient and audio sound exposures was presented at the 2019 ITU conference.¹⁵

Safety Features Related to Privacy and Cybersecurity

In accordance with CMS and FDA guidance, the following measures are being implemented.^{17,18}

Privacy:

- No personal identifiers accessed, stored or shared
- Only collects amplitudes of sound in decibels and stores in secure cloud for personal exposure reports
- Sharing of personal reports decided by user

Cybersecurity:

- Conforming to NIST (National Institute for Standard and Technology)
- Prevent unauthorized use, promote trusted content, data confidentiality, vigilance

DISCUSSION

NIHL awareness and improving listening habits to reduce the hearing loss risk are the important considerations for the military as hearing impairment may be a disqualification from service. The proposed App is a software application that can be executed on a mobile platform (Android and iOS) with appropriate privacy and cybersecurity features. The App is intended to be used by the off-duty young adult warfighter for awareness of personal sound exposure with features to support improvement in listening habits that could potentially reduce risk for hearing impairment. Reliability of App functioning, including sound dosimetry calculations, and safety features are based on global standards including the military. Military relevance of App features is addressed by integration of military user voice and military hearing healthcare recommendations. The overall objectives of the App are to empower the user in personal management of hearing health and to encourage use as a companion for hearing health support whenever needed. This app is not meant to diagnose or treat hearing impairment. The App, when on the market, will include a “How To” guide when the user first uses the App.

Of note, there are other apps with different aims in addressing NIHL exposure for civilians and/or warfighters. These apps include the NIOSH Sound Level Meter App for monitoring occupational noise and helping workers make informed decisions, the WHHIP App for informational tool to help warfighters to take charge of their hearing health, and functions of Apple’s Health App for monitoring audio levels from headphones and sound levels from the environment. The proposed App serves as an additional tool that uniquely computes both ambient and audio cumulative sound exposures vs. daily safe dose standards that encourages choices to help reduce exposures potentially harmful noise levels and durations.

The App next steps include user testing and finalization of features. Future plans include new features specific to the needs of veterans with mild-to-moderate hearing impairment to complement over the counter hearing aids (post-FDA over



FIGURE 2. Smartphone visuals for the App.

the counter rule in 2020), personnel with tinnitus, and personnel with auditory processing disorders because of traumatic brain injury.²⁰

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REFERENCES

- Eichwald J, Scinicariello F, Telfer JL, Carroll YI: Use of personal hearing protection devices at loud athletic or entertainment events among adults — United States, 2018. Available at <https://pubmed.ncbi.nlm.nih.gov/30335738>; MMWR Morb Mortal Wkly Rep 2018; 67: 1151-5.
- U.S. adults aged 20 to 69 years show signs of noise-induced hearing loss. National Institute on Deafness and other Communication Disorders, 2017. Available at <https://www.nidcd.nih.gov/news/2017/us-adults-aged-20-69-years-show-signs-noise-induced-hearing-loss>; accessed January 7, 2020.
- World Health Organization: Deafness and hearing loss, 2020. Available at <https://www.who.int/deafness/en/>; accessed January 7, 2020.
- Centers for Disease Control and Prevention: Too Loud! For Too Long!: Loud noises damage hearing, 2017. Available at <https://www.cdc.gov/vitalsigns/pdf/2017-02-vitalsigns.pdf>; accessed January 7, 2020.
- Department of Defense: It's a noisy world, protect your hearing. Available at <https://hearing.health.mil/>; accessed January 7, 2020.
- U.S. Army Public Health Command: Hearing loss and noise. Available at https://phc.amedd.army.mil/PHC%20Resource%20Library/HEARING_LOSS_AND_NOISE.pdf; accessed January 7, 2020.
- Department of Defense: Design criteria standard noise limits, 2015. Available at <https://www.arl.army.mil/wp-content/uploads/2019/12/ahaah-MIL-STD-1474E-Final-15Apr2015.pdf>; accessed January 31, 2020.
- Department of Defense: Hearing Center of Excellence. Available at <https://hearing.health.mil/Prevention/Preventing-Noise-Induced-Hearing-Loss/How-Loud-is-Too-Loud>; accessed January 7, 2020.
- Army Public Health Center: Hearing health education, 2019. Available at <https://phc.amedd.army.mil/topics/workplacehealth/hrc/Pages/HearingHealthEducation.aspx>; accessed January 7, 2020.
- National Institute on Deafness and other Communication Disorder: Keep listening to the beat, 2019. Available at <https://www.noisyplanet.nidcd.nih.gov/kids-preteens/keep-listening-to-the-beat>; accessed January 7, 2020.
- U.S. Department of Health and Human Services and the Centers for Disease Control and Prevention: Occupational noise exposure, revised criteria 1998, 1998. Available at <https://www.cdc.gov/niosh/docs/98-126/pdfs/98-126.pdf?id=10.26616/NIOSH-PUB98126>; accessed January 7, 2020.
- U.S. Department of Labor: OSHA standard 1910.95, occupational noise exposure. Available at <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95>; accessed January 7, 2020.
- International Telecommunications Union: International Telecommunications Union-Telecommunications Standardization Sector (ITU-T): Series H, Audiovisual and multimedia systems. H.870. Guidelines for safe listening devices/systems, 2018. Available at <https://www.itu.int/rec/T-REC-H.870-201808-I/>; accessed January 7, 2020.
- World Health Organization: World Health Organization and International Telecommunication Union (WHO-ITU) standard: safe listening devices and systems, 2019. Available at <https://www.who.int/publications-detail/safe-listening-devices-and-systems-a-who-itu-standard>; accessed January 31, 2020.
- Gupta S, Xu X, Liu H, Zhang J, Bas JN, Kelly SK: Development of hearing technology with personalized safe listening features. Proc ITU Kaleidoscope 2019. Available at <https://ieeexplore.ieee.org/document/8996137>; S2.2: 39-46.
- Department of Defense: Hearing center of excellence: hearing loss prevention. Available at <https://hearing.health.mil/Resources/Training/Hearing-Loss-Prevention>; accessed January 7, 2020.
- US Department of Health and Human Services: HIPAA guidance materials, 2020. Available at <https://www.hhs.gov/hipaa/for-professionals/privacy/guidance/index.html>; accessed January 7, 2020.
- Food and Drug Administration: Guidance for industry and food and drug administration staff: content of premarket submissions for management of cybersecurity in medical devices, 2018. Available at <https://www.fda.gov/media/119933/download>; accessed January 31, 2020.
- Hearing Center of Excellence: Comprehensive hearing health program (CHHP) info and materials. Available at <https://hearing.health.mil/Prevention/Comprehensive-Hearing-Health-Program-CHHP>; accessed January 7, 2020.
- Food and Drug Administration: Hearing aids, 2019. Available at <https://www.fda.gov/medical-devices/consumer-products/hearing-aids>; accessed January 7, 2020.
- World Health Organization: Make listening safe, 2019. Available at <https://www.who.int/activities/making-listening-safe>; accessed January 7, 2020.
- World Health Organization: WHO launches the hearWHO app for mobile devices to help detect hearing loss, 2018. Available at <https://www.who.int/news-room/detail/01-03-2018-who-launches-the-hearwho-app-for-mobile-devices-to-help-detect-hearing-loss>; accessed January 7, 2020.