The Journal of International Advanced Otology

J Int Adv Otol 2024; 20(2): 171-174 • DOI: 10.5152/iao.2024.231434

Review

Hearing Loss in Space Flights: A Review of Noise Regulations and Previous Outcomes

Ahmet Uğur Avcı

Department of Aerospace Medicine, Gülhane Training and Research Hospital, Ankara, Turkey

ORCID iDs of the authors: A.U.A. 0000-0001-7776-3717.

Cite this article as: Avcı AU. Hearing loss in space flights: A review of noise regulations and previous outcomes. *J Int Adv Otol.* 2024;20(2):171-174.

Noise is the primary cause of hearing loss during space flight. Throughout every phase of flight, particularly during launch, a significant amount of noise is generated and transferred via the vehicle's structure to the places inhabited by the crew. The results of the previous studies provide insights into space flights that may have significant effects on hearing loss. Certain precautions must be taken to ensure the habitability of the spacecraft and prevent potential hearing loss in astronauts or space flight participants.

KEYWORDS: Aerospace medicine, hearing loss, noise

INTRODUCTION

Noise is a natural by-product of spacecraft systems and has many adverse effects that may jeopardize the mission. It causes physiological symptoms, including headaches, tinnitus, and trouble in sleeping, as well as psychological symptoms, such as irritation, difficulty in focusing, and distraction. Most importantly, noise can lead to temporary or permanent hearing loss.[1]

Throughout every phase of space flight, particularly during launch, a significant amount of noise is generated and transferred via the vehicle's structure to the places inhabited by the crew. Crewmembers are exposed to noise from equipment running continuously or intermittently in a small, confined volume. The International Space Station, for instance, is inhabited by hundreds of noise sources that are in close proximity to the crewmembers to provide life support.[2] Certain precautions must be taken to prevent potential hearing loss and other adverse effects of noise in astronauts or space flight participants. Establishing acoustic requirements is the initial phase. Various factors affect the acoustic requirements, such as the type and duration of the trip, the participants' characteristics, and the required equipment for the spacecraft.[3] The spacecraft's acoustic design must comply with the requirements. Routine inspections are also critical to ensure noise levels do not pose a health risk to the crew, and any problematic components must be addressed and remedied immediately. Previous spaceflight experiences have shown that a habitable acoustic design is essential to ensuring a safe and functional environment for the crew.[3]

Many manned space flights have been accomplished, primarily by the United States of America (Mercury, Gemini, Apollo, Space Shuttle, Skylab, and International Space Station—ISS) and Russia (Vostok, Voskhod, Soyuz, Almaz, Mir, and ISS) over the past 65 years.[4] Experience in noise control has been amassed with these space capsules, vehicles, and orbital stations.

Hearing Loss in Space Flights

Long-term 30-year studies of the Soyuz, Salyut, and Mir space stations have shown that losses, particularly at high frequencies, have long-term effects. Cosmonauts were disqualified from flying after missions to these stations because of noise-induced hearing loss (NIHL). 5 cosmonauts had 50 dB loss at 4-6 kHz, and 12 cosmonauts had 30 dB loss.[5-7]

Based on the data from 33 cosmonauts who flew 7-day, 1-year missions on Salyut-6, Salyut-7, and the Mir space station, it was reported that there was a decrease in low-frequency hearing sensitivity following the flights, which partially recovered after a 30- to 60-day adaptation period. Nefedova reported that alterations in hearing threshold were detected at high frequencies (2 kHz and above) following the flight despite individual variances.[6]

Corresponding author: Ahmet Uğur Avcı, e-mail: ahmetuguravci@gmail.com

Received: December 1, 2023 • **Revision requested:** December 13, 2023 • **Last revision received:** December 13, 2023 • **Accepted:** January 3, 2024 • **Publication Date:** March 27, 2024

Available online at www.advancedotology.org

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The Mir station's sound-level measurement records indicate that Mir was louder than the noise limits (see the paragraph below). The noise environment on Mir caused permanent hearing damage to one-third of the long-term crew.[7,8] It was stated that a temporary threshold shift was observed in the postflight tests of 7 astronauts who went on a NASA mission to the Mir station and did not wear hearing protection, but their follow-ups revealed no permanent loss.[7]

The crewmembers' postflight hearing tests on 3 Skylab missions lasting 28-84 days showed no changes. In all, 20-year controls showed 40-70 dB losses at 6-8 kHz and 30-50 dB losses at 3-4 kHz, but it was noted that the losses were consistent with age-related hearing loss.[7]

Roller and Clark, in their study examining the data of 386 astronauts who participated in 93 space shuttle flights, reported that even a single mission on the space shuttle exposed astronauts to enough trauma to cause hearing loss. It was stated that the primary outcome was temporary threshold shifts, and the significant permanent threshold shifts (PTS) were small (0.83 dB in pure-tone audio for both ears). Nevertheless, PTSs were deemed concerning by the authors since they were detected even after a single, brief mission that lasted an average of 9 days and occurred at frequencies associated with the perception of human speech.[9] Overall, sound pressure levels for the space shuttle were measured to be 118 dB internally and 149 dB externally. Hearing protection devices were used for protection at these short-term exposures.[10,11]

There is a paucity of research regarding the effectiveness of noise limits and whether noise in the ISS alone can result in hearing loss. Participants in a study were exposed to artificial International Space Station noise for 70 hours to ascertain whether noise in the ISS environment could cause hearing loss. The study results demonstrated that 70 hours of exposure to environmental noise on the ISS was not enough to cause hearing loss.[12] However, the absence of additional factors that might affect the hearing function and the study's brief exposure period of 70 hours may have influenced its findings.[13]

Etiology

Noise is the primary cause of hearing loss during space flight. The term NIHL describes hearing losses resulting from continuous or intermittent noise exposure. In the United States, workers exposed to noise have a significantly higher prevalence of hearing loss (23%) compared with workers who are not exposed to noise (7%).[14,15] The cochlear hair cells are the main target of NIHL.[16] Prolonged noise exposure damages the cochlear hair cells, leading to hearing loss. Noise-induced hearing loss is always sensorineural and usually occurs in both ears.[17] The majority of noise exposure standards in the workplace and industry are established based on noise levels encountered throughout an 8-hour workday. While in space, the crewmembers are continuously exposed.[8]

Ototoxic agents (organic solvents, chemical asphyxiants, and ototoxic pharmaceuticals) may make the inner ear more susceptible to the adverse effects of noise.[11,18] Previous studies have shown that simultaneous exposure to noise and carbon monoxide (CO) causes more ototoxicity than separate exposures.[19] With rare exceptions, high CO levels are not expected in the spacecraft's cabin air. Carbon dioxide (CO_2) might be another factor that increases the susceptibility of the inner ear. Although CO_2 is regularly extracted from the cabin air, even low CO_2 levels in the cabin (0.7-1%) can lead to mild, compensated respiratory acidosis.[8]

The most significant impact of space travel on human physiology is microgravity.[20] Intracranial pressure increases in a microgravity environment because of the redistribution of fluids.[21-23] Increased intracranial pressure would be transmitted to the cochlea.[8] Moreover, the gravitational shift might affect the mechanical characteristics of the peripheral auditory system. Kadeem notes in his study that changes in the ear fluid's weight would have an impact on ossicle functionality and mechanosensitive processes.[13]

Vibration is another factor that could contribute to hearing loss. It has been shown that workers exposed to intense hand–arm vibration can develop hearing loss.[24] Furthermore, compared with separate exposures, simultaneous vibration and noise exposure are more harmful to hearing function.[7,25] Vibration exposure may damage hair cells and change cochlear blood flow by causing vasoconstriction.[24]

Noise Limits

Sources that produce sound (fans, compressors, etc.) working for more than 8 hours daily are defined as continuous noise sources. NASA developed the Manned Spacecraft Design Standard in 1972, considering lessons learned from the Apollo space flights. This standard provided acoustic noise criterion (NC) curves for managing continuous noise. The NC curves indicate the acceptable noise levels for each octave band.[26] It is agreed that the flight crew's habitable volume may not exceed the limits of the NC-50 curve specified (Figure 1). The NC-40 curve also provides noise limits for the sleeping area (Figure 1). Additionally, impulse or transient sounds in the sleeping area should not exceed 10 dB above the background noise level to avoid waking the crew from sleep.[10,26]

Intermittent sound sources are those that make noise for less than 8 hours. Intermittent sound sources (such as pressurized gas systems, toilets, or exercise equipment) can be disturbing, depending on the duration and intensity of the noise. The acceptable A-weighted overall sound pressure levels on the International Space Station for intermittent noise are listed in Table 1.

In general, the noise levels to which participants will be exposed during a flight are limited to 85 dBA (A-weighted decibels), except for the launch and atmospheric entry stages. For exposure to 85 dBA

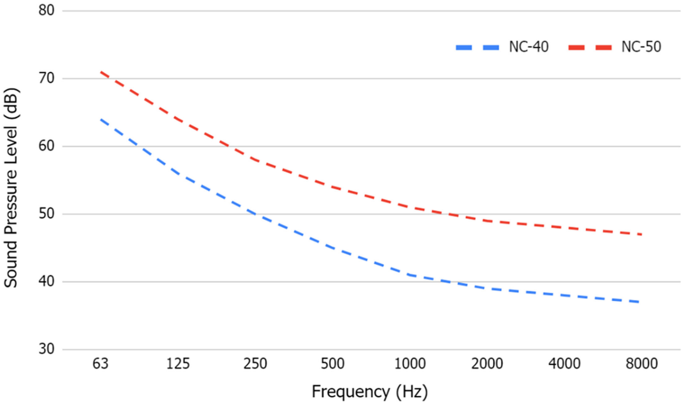

Figure 1. Noise criteria curves.

Table 1. Intermittent Noise A-Weighted Sound Pressure and Corresponding Operational Duration Limits

Maximum Noise Duration (per 24-hours)	8 Hours	7 Hours	6 Hours	5 Hours	4.5 Hours	4 Hours	3.5 Hours	3 Hours	2.5 Hours	2 Hours	1.5 Hours	1 Hour	30 Minutes	15 Minutes	5 Minutes	2 Minutes	1 Minute	Not Allowed
A-weighted overall sound pressure level (dBA)	49	50	51	52	53	54	55	57	58	60	62	65	69	72	76	78	79	80

Note: Adapted from NASA Spaceflight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health | Standards, https://standards.nasa.gov/standard/NASA/NASA-STD-3001-VOL-2.

and higher, hearing protection devices (ear plugs, earmuffs, and helmets) must be worn. The ceiling limit for launch and entry is 105 dBA, except for impulse noise.[3,10] Impulse noise is a sudden and transient burst that surpasses the background noise level by a minimum of 10 dB and lasts no more than 1 second.[3] The peak sound pressure level for impulse noise without hearing protection is limited to 140 dB for all mission phases, except for launch, entry, and abort.[10] Infrasound (sounds at frequencies below 20 Hz) should be limited to 150 dB in the 1-20 Hz frequency range to avoid any potential side effects like nausea and dizziness.[10]

The intelligibility of speech is another essential aspect. About 95% of the sentences should be intelligible (with regular vocal effort when individuals face each other) for effective communication, and 98% intelligibility in sentences can be achieved with a minimum of 75% intelligibility in keywords.[27] According to NASA, for critical messages, keywords should be at least 90% intelligible.[10]

High levels of background noise and reverberations may compromise the audibility of speech. The term reverberation time (T60) refers to the time required for the energy density in the acoustic field to fall 60 dB below the steady-state value when the sound source is turned off. The T60 must be less than 0.6 seconds in the 500-Hz, 1-kHz, and 2-kHz octave ranges for ISS modules or structures with similar volumes.[10]

There is not any conclusive evidence that vibration on space missions leads to hearing loss. Nevertheless, as per NASA standards, vibration levels in the spacecraft (including hand and whole-body vibrations in different phases) are restricted to threshold levels that do not cause any adverse health effects.[10] NASA uses international and American standards to establish vibration limits (ISO 2631-1:1997(E), ANSI/ASA S2.70-2006).

CONCLUSION

The acoustics were a major habitability problem even on the International Space Station (ISS). Many components became NC-50 compatible due to improvements made over time.[2,26] Furthermore, the ISS has noise dosimeters placed across various station parts to measure noise levels regularly, and astronauts are equipped with personally worn audio dosimeters. The noise exposure levels of crewmembers during the work and sleep periods are routinely monitored with these dosimeters. When sound levels rise above 60 dB, it is advised to use hearing protection (if they exceed 72 dB, it is required). Any crew activity that surpasses noise levels of 60 dBA is classified as hazardous to address and minimize the potential dangers associated with noise exposure.[28]

The results of the previous studies, regardless of their heterogeneity, provide insights into spaceflights that may have significant effects on hearing loss. To date, the duration of space missions has varied from a few days to several months. However, given humanity's aspirations for future space exploration, including missions to the Moon and beyond, it seems evident that more long-term missions are undoubtedly forthcoming, and not only space agencies but also many commercial companies like Blue Origin, SpaceX, Space Adventures, etc., are actively working on these missions. Strict compliance with acoustic limits for future long-term missions is essential to achieving these "distant" destinations. For future long-duration missions, equipment needs to be designed to comply with the limits and to be able to troubleshoot potential noise problems quickly. It is obvious that violating noise regulations, whether for commercial, personal, or any other reason, will have detrimental consequences.

Peer-review: Externally peer-reviewed.

Declaration of Interests: The author has no conflict of interest to declare.

Financial Disclosure: The author declared that this study has received no financial support.

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