# Voyager flight crew hearing threshold levels resulting from 5- and 9-day continuous in-flight noise exposure

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The flight crew of the Voyager aircraft were continuously exposed to a broadband noise for nearly 5 days during a trial flight, and for over 9 days during their nonstop flight around the world. Evaluation of the threshold shifts resulting from these exposures represents a unique opportunity to study the effect of human exposure to intense continuous noise for long durations. Postflight audiometry demonstrated that the 9-day flight did not result in larger hearing threshold shifts than those following the 5-day flight. Neither crewmember incurred a permanent threshold shift from these exposures.

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## INTRODUCTION

Asymptotic threshold shift (ATS) was an important discovery of studies of long duration noise exposure effects on hearing (Mills *et al.*, 1970; Mosko *et al.*, 1970; Melnick, 1974; Melnick and Maves, 1974; Nixon *et al.*, 1975). This discovery has been an important factor in the development and refinement of hearing damage risk criteria for occupational and nonoccupational exposures that exceed typical 8 h workday durations, often by substantial amounts (Shaw, 1983).

These studies demonstrated that, for humans, the growth in hearing threshold levels (HTLs) reached a plateau or asymptote as exposure durations exceeded 8 to 16 h. The ATS did not increase with continued exposure to the same noise for periods of up to 48 h, the maximum duration of these studies. Recovery from asymptote to preexposure threshold levels was prolonged for the longer exposure durations, reflecting a greater hearing damage risk for the longer durations. The period of time required for recovery was at least as long as the duration of the continuous exposure (Nixon *et al.*, 1977; Stephenson *et al.*, 1982).

It would be highly desirable to empirically verify the relationship between ATS and permanent threshold shift (PTS). It has been assumed by some that exceptionally long duration noise exposures may result in incomplete recovery to preexposure hearing thresholds. Likewise, the recovery process may be delayed and an increased risk of permanent hearing loss incurred when the exposure is severe enough to cause threshold shifts that exceed 45 dB (Miller, 1974; Ward, 1960). Although ATS data are used to estimate the maximum amount of permanent threshold shift from a given exposure condition (Ward, 1975; Mills, 1976; Mills *et al.*, 1979), reasonable ethical considerations would not permit human exposures to the experimental conditions required to verify the relationships between ATS and PTS.

The nonstop flight around the world by Dick Ruttan and Jeanna Yeager in the Voyager aircraft resulted in an exceptionally long noise exposure for both crewmembers. In a trial flight lasting 111 h and 44 min, and in the nonstop flight around the world (216 h, 3 min), both crewmembers received continuous noise exposures that have not been duplicated in a laboratory and would be highly unlikely to be duplicated in any occupational and/or natural environment. Their pre- and postflight audiometric data therefore represent a unique opportunity to evaluate the effect of very long duration noise exposures not measured before on growth and recovery of hearing threshold shifts in humans.

## I. IN-FLIGHT NOISE EXPOSURES

The Voyager aircraft interior noise levels for both the cockpit area and the rest area are shown in Table I. Measurements were made with a Bruel and Kjaer 2204 sound level meter and free-field microphone at octave bands centered at 31.5 Hz to 8 kHz with both engines and a single engine in operation. The overall noise environment ranged between

TABLE I. Voyager aircraft interior sound-pressure levels (dB *re*: 20 $\mu$Pa). Data supplied by Bose Corporation. Overall A-weighted levels: 99.0–103.4 dB(A).

| | Cockpit area | | Rest area | |
|---|---|---|---|---|
| Octave bands | 2 engines | 1 engine | 2 engines | 1 engine |
| 31.5 | 100 | 98 | 95 | 90 |
| 63 | 108 | 103 | 109 | 100 |
| 125 | 107 | 102 | 112 | 101 |
| 250 | 100 | 102 | 109 | 102 |
| 500 | 95 | 100 | 100 | 106 |
| 1000 | 90 | 85 | 92 | 94 |
| 2000 | 85 | 81 | 86 | 82 |
| 4000 | 82 | 72 | 80 | 76 |
| 8000 | 73 | N/A | 68 | 70 |

99.0 and 103.4 dB(A), varying with altitude, engine settings, and the like. It was not feasible to instrument the Voyager for precise in-flight noise measurements because space and weight considerations were profoundly critical and because noise measurements were peripheral to the objectives of this flight.

The crewmembers' noise exposures were influenced by the sound attenuation provided by the hearing protection worn during each of the flights. Crewmembers wore a commercially available radio communication headset during the 5-day trial flight; during the nonstop flight around the world, crewmembers wore a radio communication headset that was custom modified by Bose Corporation to include active noise reduction circuitry. In addition, during both flights, crewmembers wore a commercially available foam earplug. Unfortunately, a minor technical difficulty inhibited the in-flight use of the active noise reduction circuitry. Consequently, the crewmembers' at-the-ear noise exposures are a function of headset and earplug passive attenuation. Field studies of the foam earplugs (Berger, 1989) report an average overall attenuation value of about 13 dB (mean minus one standard deviation). Field studies of a variety of earmuffs (Berger, 1983) report generally homogeneous overall attenuation values in the range of about 10 dB (mean minus one standard deviation). It is likely that earplugs were the principal contributor to the crewmembers' hearing protection and that the two flights resulted in similar at the ear noise exposures.

## II. AUDIOMETRIC MEASUREMENTS

Audiometry calibration and testing procedures complied with respective ANSI standards. All baseline and postflight audiograms were obtained using identical manual audiometric test procedures. Baseline data for crewmembers' hearing threshold levels were the average of the audiometric data collected during routine preflight physical examinations conducted in 1984, 1985 and 1986 (Table II). Subject JY has normal HTLs, and subject DR has a mild to moderate, bilateral, sensorineural hearing loss in the high frequencies.

Postflight audiograms were conducted at the Mojave desert location in a mobile audiometric van supplied by the Audiology Center of Redlands, California. Sound fields within the IAC booth of the mobile van met or exceeded the criteria for permissible levels of ambient noise (ANSI S3.1-1977), from 500 Hz to 8 kHz. The temporary threshold shifts (TTS) for each crewmember collapsed across both ears are contained in Table III. It is apparent from the postflight audiograms that both crewmembers sustained considerable threshold shifts. The magnitude of these shifts is greater than would have been expected based on laboratory estimates (i.e., real ear attenuation at threshold method) of headset hearing protection levels and more in keeping with what would be expected using estimates of hearing protection obtained during field use. For example, for the octave band centered at 500 Hz, crewmembers would have experienced real world attenuation of 11 dB (mean minus one standard deviation) (Berger, 1988). Noise levels at the crewmembers' ears would have ranged between 84 and 95 dB for the octave band centered at 500 Hz. Based on data reported by Mills *et al.* (1979, Table II), this would result in TTS of 14 to 32 dB at 1000 Hz. This is in general correspondence with the TTS values reported in the present study.

TABLE II. Baseline hearing threshold levels.

| | DR | | JY | |
|---|---|---|---|---|
| Frequency (Hz) | Left ear | Right ear | Left ear | Right ear |
| 500 | 2 | 2 | 0 | 0 |
| 1000 | 0 | 0 | 0 | 3 |
| 2000 | 5 | 5 | 0 | 2 |
| 3000 | 13 | 33 | 2 | 2 |
| 4000 | 40 | 38 | 2 | 2 |
| 6000 | 38 | 38 | 12 | 13 |
| 8000 | 48 | 35 | 5 | 8 |

## III. DISCUSSION

The greater levels of TTS observed in the lower frequencies correspond to the spectral dominance of these frequencies in the overall noise exposure. The TTS observed in the higher frequencies reflects the ability of low-frequency noise to affect more basal regions of the cochlea (Mills *et al.*, 1979). Since the noise exposure was not confined to a single octave band, there was no single second peak, as reported by Miller *et al.* (1963) and Mills *et al.* (1979). Instead, the higher frequencies showed generally elevated thresholds. The intersubject differences observed between the amount of shift seen in the high frequencies are probably related to differences in their audiometric baseline sensitivity at those frequencies. For example, DR was not expected to have demonstrated as much high-frequency TTS as JY since his high-frequency baseline thresholds were already elevated.

Following the nine-day Voyager around the world flight, DR exhibited TTS levels similar to those experienced from the 5-day trial flight; JY exhibited somewhat less TTS. One probable source for this variability is the substantial intrasubject variability in an individual's TTS with repeated laboratory exposures (Stephenson *et al.*, 1981). However, extreme fatigue following each flight may have contributed to this variability (Ruttan, 1988). Also, it was not possible to control the time between the flight termination and the initiation of the "immediate" postexposure tests. Nevertheless, both crewmembers sustained considerable TTS from the 9-day flight, and it is apparent that this exposure did not result in larger threshold shifts than those following the 5-day flight. The lack of an increased level of TTS between the 5- and 9-day exposures is consistent with results from animals exposed to moderate noise levels for equivalent or greater durations (Mills, 1973, 1976; Bohne and Clark, 1982).

Audiograms were obtained for each crewmember 24 h postflight for both the 5- and 9-day flights. Since monitoring audiometry was of peripheral concern, it was not possible to schedule multiple postflight audiometric tests in order to closely monitor TTS recovery patterns. Twenty-four hours following the 5-day flight, both crewmembers had experienced improved hearing sensitivity at all frequencies. One is

TABLE III. Temporary threshold shift following 5- and 9-day noise exposures.

TTS following 5-day (10–15 July 1986) Voyager trial flight[a]

| Subject D R | Frequency (Hz) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Immed. post (7/15/86) | 32 | 29 | 20 | 15 | 11 | 10 | 19 |
| 24 h post (7/16/86) | 26 | 23 | 17 | 12 | 9 | 11 | 8 |
| 5 months post (12/13/86) | 8 | 14 | 9 | 7 | 6 | 5 | 11 |

| Subject J Y | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Immed. post (7/15/86) | 37 | 28 | 23 | 27 | 15 | 17 | 31 |
| 24 h post (7/16/86) | 21 | 15 | 9 | 7 | 6 | 6 | 7 |
| 5 months post (12/31/86) | 5 | −2 | −1 | −3 | −3 | 6 | 6 |

TTS following 9-day (14–23 December 1986) Voyager around the world flight

| Subject: D R | Frequency (Hz) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Immed. post (12/23/86) | 29 | 26 | 24 | 2 | 17 | 13 | 10 |
| 1 day post (12/24/86) | 23 | 17 | 14 | 7 | 8 | 19 | 10 |
| 7 days post (12/30/86) | 2 | 5 | 3 | 0 | 1 | 7 | 14 |
| 2 months post (2/15/87) | 1 | 5 | 5 | −6 | 4 | 5 | 6 |

| Subject: J Y | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 500 | 1000 | 2000 | 3000 | 4000 | 6000 | 8000 |
| Immed. post (12/23/86) | 14 | 19 | 12 | 11 | 2 | 16 | 12 |
| 1 day post (12/24/86) | 20 | 17 | 10 | 4 | −2 | 12 | 12 |
| 7 days post (12/30/86) | −3 | 0 | 0 | −2 | 3 | 0 | 1 |
| 2 months post (2/15/87) | −3 | −7 | −4 | −8 | −8 | 0 | 3 |

[a] All TTS are based on the mean of control audiometric data obtained on 4 March 1984, 24 June 1985, and 8 June 1986 during preflight physical examinations.

tempted to speculate that the HTLs measured 24 h following the 9-day flight show less recovery than 24 h following the 5-day flight. This would be consistent with laboratory data demonstrating 48-h noise exposures produce longer recovery periods than 24-h noise exposures. (Stephenson *et al.*, 1982). However, there simply are not enough data to substantiate this speculation. The apparent slower recovery for JY may reflect an artifact in the *immediate* 9-day data. It is equally probable that this reflects normal variance in the small database.

At several frequencies, crewmembers' TTS exceeded 25 dB. Despite the magnitude of the shifts (and the exposure durations), both crewmembers' hearing threshold levels recovered to their preflight baseline values. One week following the final flight (the 9-day flight) both crewmembers' thresholds had recovered to their preflight values. A 2-month postflight follow-up further confirmed recovery to preflight HTL. There can be little doubt that neither crewmember incurred a PTS from their exposures.

That the thresholds did recover should be interpreted cautiously with respect to the potential hearing damage risk following exposures of similar durations. Several studies (with various animal species) have demonstrated permanent anatomical and physiological changes following long duration noise exposures, even in the absence of measurable changes in behavioral hearing threshold levels (Carder and Miller, 1972; Bohne and Clark, 1982; Lonsbury-Martin *et al.*, 1987; Bohne, 1988). The conjectured slower recovery for the 9-day flight may reflect a greater hearing damage risk associated with the longer flight.

## IV. CONCLUSIONS

Audiometric data were presented for two persons exposed for 5- and 9-days to in-flight broadband noise with a predominantly low-frequency emphasis. Although the noise exposure levels could not be precisely quantified, levels were clearly adequate to induce substantial shifts in hearing threshold levels. The present data demonstrated that the hearing threshold shift following the 9-day exposure was no greater than that following the 5-day exposure. Hearing levels returned to preexposure values, signifying no measurable permanent threshold shift.


Berger, E. H. (**1983**). "Using the NRR to estimate the real world performance of hearing protectors," Sound Vib. **17** (1), 12–18.

Berger, E. H. (**1988**). "Can real-world hearing protector attenuation be estimated using laboratory data?," Sound Vib. 26–31.

Berger, E. H. (**1989**). Personal communication.

Bohne, B. A. (**1988**). Personal communication.

Bohne, B. A., and Clark, W. W. (**1982**). "Growth of hearing loss and lesion with increasing duration of noise exposure," in *New Perspectives on*

*Noise-Induced Hearing loss*, edited by R. P. Hamernik, D. Henderson, and R. J. Salvi (Raven, New York), pp. 283–302.
Carder, H. and Miller, J. (**1972**). "Temporary threshold shifts from prolonged exposure to noise," J. Speech Hear. Res. **15**, 603–623.
Lonsbury-Martin, B. L., Martin, G. K., and Bohne, B. A. (**1987**). "Repeated TTS exposures in monkeys: Alterations in hearing, cochlear structure, and single-unit thresholds," J. Acoust. Soc. Am. **81**, 1507–1518.
Melnick, W., (**1974**). "Human threshold shift from 16-hour noise exposures," Arch. Otolaryngol. **100**, 180–189.
Melnick, W. and Maves M. (**1974**). "Asymptotic threshold shift (ATS) in man from 24-hours exposure to continuous noise," Ann. Oto. Rhinol. Laryngol. **83**, 820–829.
Miller, J. D. (**1974**). "Effects of noise on people," J. Acoust. Soc. Am. **56**, 729–764.
Miller, J. D. Watson, C. S., and Covell, W. (**1963**). "Deafening effects of noise on the cat," Acta-Oto-Laryngol. Suppl. **176**, 1–99.
Mills, J. H. (**1973**). "Temporary and permanent threshold shifts produced by 9-day exposure to noise," J. Speech Hear. Res. **16**, 426–438.
Mills, J. H. (**1976**). "Threshold shifts produced by a 90-day exposure to noise," in *Effects of Noise on Hearing*, edited by D. Henderson, R. Hamernik, D. Dosanj, and J. Mills (Raven, New York), pp. 265–275.
Mills, J. H., Gengel, R. W., Watson, C. S., and Miller, J. D. (**1970**). "Temporary changes to the auditory system due to exposure to noise for one or two days," J. Acoust. Soc. Am. **48**, 524–530.
Mills, J. H., Gilbert, R. M., and Adkins, W. Y. (**1979**). "Temporary threshold shifts in humans exposed to octave bands of noise for 16 to 24 hours," J. Acoust. Soc. Am. **65**, 1238–1248.
Mosko, J., Fletcher, J. L., and Luz, G. (**1970**). "Growth and recovery of temporary threshold shifts following extended exposure to high level, continuous noise," U.S. Army Med. Res. Lab., Fort Knox, KY, Rep. 911.
Nixon, C. W., Krantz, D. W., and Johnson, D. L. (**1974**). "Human temporary threshold shift and recovery from 24-hour acoustic exposure," Aerospace Med. Res. Lab. Tech. Rep. 74–101, Wright–Patterson AFB OH.
Nixon, C. W., Johnson, D. L., and Stephenson, M. R. (**1977**). "Asymptotic behavior of human temporary threshold shift and recovery from 24–48 hour noise exposures," Av. Space Envir. Med. **48** (April).
Ruttan, D., (**1988**). Personal communication.
Shaw, E. A. G. (**1983**). "On the growth and decay of asymptotic threshold shift in human subjects," Proceedings of the Fourth International Congress on Noise as a Public Health Problem, Torino, Italy.
Stephenson, M. R., Johnson, D. L., and Nixon, C. W. (**1981**). "Summary and tabulation of raw data from research on the effects of long duration noise exposure on the human auditory system," Air Force Aerospace Med. Res. Lab. Tech. Rep. 80–57, Wright–Patterson AFB OH.
Stephenson, M. R., Nixon, C. W., and Johnson, D. L. (**1982**). "Long duration (24–48 hour) exposure to continuous and intermittent noise," Air Force Aerospace Med. Res. Lab. Tech. Rep. 82–92, Wright–Patterson AFB OH.
Ward, W. D. (**1960**). "Recovery from high values of temporary threshold shift," J. Acoust. Soc. Am. **31**, 497–500.
Ward, W. D. (**1975**). "Studies of asymptotic TTS," Proc. Aerospace Med. Specialists' Meeting, AGARD, NATO (Toronto) CP-171, C4-1.

# A comment on "Conical bores. Part I: Reflection functions associated with discontinuities" [J. Acoust. Soc. Am. 84, 1613–1619 (1988)] and "Alternatives to the impulse response *h*(*t*) to describe the acoustical behavior of conical ducts" [J. Acoust. Soc. Am. 84, 1606–1612 (1988)]

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According to J. Martínez and J. Agulló [J. Acoust. Soc. Am. **84**, 1613–1619 (1988)] and Agulló *et al.* [J. Acoust. Soc. Am. **84**, 1606–1612 (1988)], reflection functions and modified impulse responses can always be obtained from the corresponding frequency-domain functions through a Fourier transform. The following letter is a revision of that conclusion.

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Reflection functions given in Martínez and Agulló (1988) and modified impulse responses given in Agulló *et al.* (1988) can always be obtained from the corresponding transfer functions through a Laplace transform. Whenever time-domain results do not contain growing exponentials, they can also be calculated from the corresponding frequency-domain functions through a Fourier transform.

Results containing growing exponentials presented in both papers have been correctly obtained although their calculation is incorrectly explained as a Fourier transform.

Moreover, the same results can be obtained directly in time domain (as shown in Sec. IV of Ref. 1).

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Martínez, J., and Agulló, J. (**1988**). "Conical bores. Part I: Reflection functions associated with discontinuities," J. Acoust. Soc. Am. **84**, 1613–1619.
Agulló, J., Barjau, A., and Martínez, J. (**1988**). "Alternatives to the impulse response $h(t)$ to describe the acoustical behavior of conical ducts," J. Acoust. Soc. Am. **84**, 1606–1612.