USAARL REPORT NO. 83-3

HEARING LOSS FROM LOW-FREQUENCY NOISE
(Reprint)

By
Charles K. Burdick

October 1982

U.S. ARMY AEROMEDICAL RESEARCH LABORATORY
FORT RUCKER, ALABAMA 36362

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Reviewed:

Bruce C Leibrecht LT

Bruce C. Leibrecht, Ph.D., MAJ, MSC
Director, Sensory Research Division

Roger W. Wiley

Roger W. Wiley, LTC, MSC
Chairman, Scientific Review Committee

Released for Publication:

Dudley R Price MC

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER USAARL 83-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Hearing Loss from Low-Frequency Noise (Reprint)		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles K. Burdick		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS SGRD-UAS-AS US Army Aeromedical Research Laboratory Fort Rucker, Alabama 36362		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102A 3M161102BS10, CB 282
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Aeromedical Research Laboratory Ft Rucker, Alabama		12. REPORT DATE October 1982 13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This report is a reprint of a presentation made at a symposium sponsored by the National Institute for Occupational Safety and Health, Cazenovia, NY, 15-18 June 1980. It was also published in "New Perspectives on Noise-Induced Hearing Loss" Raven Press, NY, 1982.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

- Noise
- Hearing-loss
- Damage-risk criteria
- Hearing conservation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT:
The auditory damage-risk criteria (DRC) defining exposure to continuous noise specifies the intensity levels of noise in terms of A-weighted levels. A series of studies were undertaken to investigate the suitability of using A-weighted intensity levels in formulating the DRC. Groups of chinchillas were exposed to octave-bands of noise with center frequencies of 31.5-, 63-, 125-, 250-, and 1000-Hz. Bands of noise with center frequencies below 500 Hz produced maximum threshold shifts three to seven octaves above the center frequency of the noise band. This sharply contrasts with the finding that bands of noise with center frequencies of 500 Hz and higher, produce maximum shifts one to one and one-half octaves above the center frequency of the noise band. The general finding was that low-frequency noise produces high-frequency hearing loss.

New Perspectives on Noise-Induced Hearing Loss, edited by R. P. Hamernik, D. Henderson, and R. Salvi. Raven Press, New York © 1982.

Hearing Loss from Low-Frequency Noise

Charles K. Burdick

U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 63632

The current auditory damage-risk criteria for exposure to continuous noise specifies the intensity levels of noise in terms of A-weighted levels. The effect of A-weighting is to de-emphasize the importance of the low frequencies in producing loss; for example, by reducing the measured intensity 0.8 dB at 800 Hz, 26 dB at 63 Hz, and 39 dB at 31.5 Hz (1). The current damage-risk criteria specifies that individuals without hearing protection can be exposed for 8 hr to any noise with an intensity level of 90 dBA or less. Consequently, individuals can be exposed to very intense levels of low-frequency noise. For example, an octave band of noise centered at 1,000 Hz has an intensity level of 90 dBA and an octave band level of 90 dB SPL (SPL = sound pressure level re 20 μPa), however, an octave band of noise centered at 31.5 Hz has an intensity level of 90 dBA and an octave band level of 129 dB SPL. The implicit assumption has been that these two bands of noise are equally hazardous to hearing even though there is a 39-dB difference in the octave band level of the two. Because of the de-emphasis of low-frequency noise by A-weighting, the efficacy of using A-weighted intensity levels in the formulation of the damage-risk criteria has been questioned (e.g., 8). Since nearly all the studies done on noise-induced hearing loss produced by narrow bands of noise concentrated on the frequencies of 500 and 4,000 Hz (e.g., 6,7,9,13–16,18,17), insufficient data existed to evaluate the use of A-weighted intensity levels in the damage-risk criteria. Consequently, a series of studies were undertaken to investigate the suitability of using A-weighted levels in formulating the damage-risk criteria. This chapter summarizes a portion of the data from some of those studies.

GENERAL METHODOLOGY

One goal of the studies was to determine the amount of permanent hearing loss produced by low-frequency bands of noise. Consequently, humans could not be used as subjects and an animal model was selected. The chin-

Dr. Burdick's present address is U.S. Army Medical Research and Development Command, Directorate of Research Programs, Fort Detrick, Frederick, Maryland, 21701.

chilla was used in the present study because they have been used extensively in research on noise-induced hearing loss (10).

Groups of four chinchillas served as subjects in all exposure conditions. Some groups consisted of binaural animals and some consisted of animals rendered monaural via surgical destruction of their left cochlea (12). Comparisons between binaural and monaural animals undergoing similar noise exposures failed to detect any differences in the magnitudes of threshold shifts found. Consequently, no further mention will be made of this factor.

All subjects were trained and tested in a double-walled sound room using a shuttlebox avoidance procedure similar to that used by Miller (e.g., 6,7,12) and by Mills (e.g.,14–16,18,19). The presentation of pure tones, the timing and sequencing of events, and the determination of the subject's responses were controlled by a microprocessor. Audiograms were obtained with pure tone signals, which were pulsed with on-times of 720 msec and off-times of 560 msec. Each tone pulse had an exponential rise and decay function with a time constant (63% of full on) of 14 msec. The duration of a trial was 3.84 sec, during which time three tone pulses were presented. If the animal failed to move from one end of the shuttlebox to the other during the 3.84 sec, a mild AC electric shock at a nominal intensity level of 0.7 to 1.0 mA and an electronic buzzer were presented until the response was made. On the majority of trials during testing, the shock was turned off and the buzzer was presented alone. The buzzer was sufficiently aversive to maintain the avoidance behavior and shock was required only intermittently. Further details and discussion of the procedures are available elsewhere (4).

After determining if hearing was normal from the base-line audiograms, each group was then placed in a diffuse sound field for 3 days. (One exception is a 9-day exposure for the group exposed to the octave band of noise centered at 63 Hz and having an SPL of 110 dB (84 dBA). The data from the 9-day exposure is included because it is believed that this appropriately represents the effect of the noise band at that intensity level on the hearing of the chinchilla.) The spectrum of the noise field was monitored twice daily using a spectrum analyzer to insure the integrity of the exposure field. During the exposures, the subjects were removed for 8 to 15 min to determine their thresholds at one to three frequencies. All subjects were tested during exposure at intervals of 4, 8, 24, 48, and 72 hr, and then at daily intervals, either until hearing had completely recovered or for 30 days.

The octave bands of noise used for the exposures had center frequencies of 31.5, 63, 125, 250, and 1,000 Hz. The frequencies of the noise bands, the intensity levels used for the exposures in terms of both octave band and A-weighted levels, and the A-weighting factors are presented in Table 1. The intensity levels of the 63-, 125-, 250-, and 1,000-Hz exposures were nearly equal in A-weighted level, with values of either 94 or 95 dBA. The intensity levels for the 31.5-, 63-, and 1,000-Hz exposures were 81, 84, and 85 dBA, respectively. The experimental design enabled the direct comparison of the

TABLE 1. *Center frequencies, intensity levels (dB SPL and dBA), and A-weighting factors*

Frequency (Hz)	31.5[a]	63[b]		125[a]	250[a]	1,000[a]	
Octave band level (dB SPL)	120	110	120	110	103	85	95
A-weighted level (dBA)	81	84	94	94	94	85	95
A-weighting factor (dB)	−39	−26		−16	−9	0	

[a] Exposure duration was 3 days.
[b] Exposure duration was 9 days.

magnitudes of hearing loss produced by bands of noise presumed to be equally hazardous, or nearly so, because of their A-weighted intensity levels, while at the same time having rather large differences in octave band levels.

RESULTS

A general finding in the investigation of noise-induced hearing loss has been that a narrow band of noise produces its maximum effects one-half to one octave above the center frequency of the noise band (6,7,9,10,13–16,18,19). This already has been qualified for mammalian ears (21) and as a result of the present investigations must be further qualified, at least for the chinchilla, to those noise bands having center frequencies of between 500 and 4,000 Hz. The exposures with center frequencies below 500 Hz have consistently produced their maximum threshold shifts *three to seven octaves above the center frequency*. Figure 1 shows the typical peak threshold shift occurring one-half octave above the noise-band center frequency for the frequencies of 500, 1,000, and 4,000 Hz. The frequencies predicted by extrapolation of the maximum shift for octave bands below 500 Hz are given, as are the actual frequencies of maximum threshold shift found in the present noise exposures for the octave band center frequencies of 31.5, 63, 125, and 250 Hz. The 63-, 125-, and 250-Hz octave band exposures all produced peak threshold shifts at 2,000 Hz, which is, respectively, three, four, and five octaves above the center frequencies. The 31.5-Hz center frequency octave band exposure produced its peak threshold shift at 4,000 Hz, which is seven octaves above the center frequency. This is evidence that the ear of the chinchilla does not respond to noise bands below 500 Hz in the same way that it does to those from 500 to 4,000 Hz.

The threshold shifts immediately following exposure to the 31.5, 63, and 1,000-Hz center frequency exposures at A-weighted intensity levels of 81, 84, and 85 dB, respectively, are shown in Fig. 2. As can be seen, the 31.5-Hz center frequency band produced threshold shifts that were broader and greater in magnitude than those produced by the 63-Hz center frequency band. The 1,000-Hz center frequency band produced a rather classic pattern of threshold shifts, with larger peak shifts than those produced by either of the two low-frequency bands of noise. While half-octave and one-octave

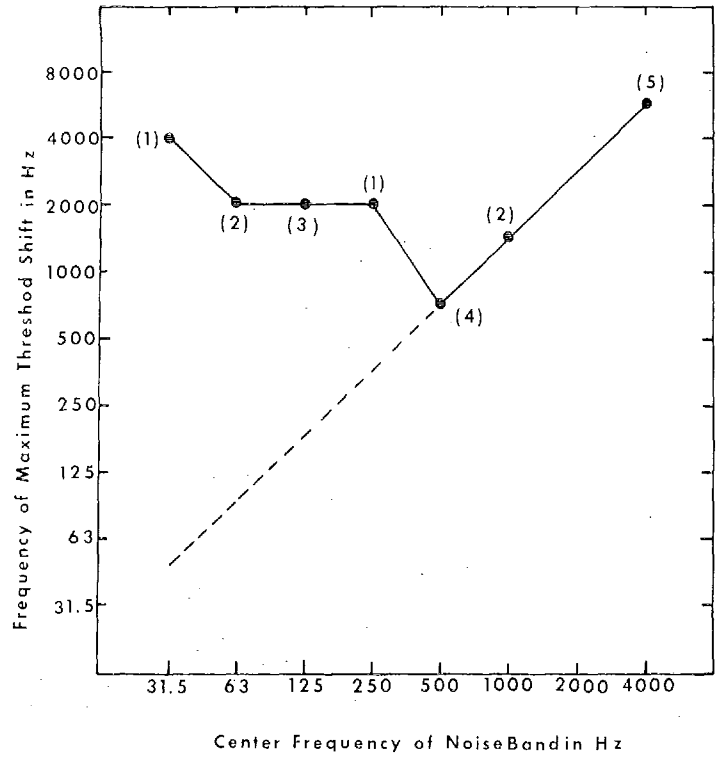

FIG. 1. The actual (*solid line*) and the predicted (*dashed line*) frequencies of maximum threshold shift produced by octave bands of noise with the center frequencies shown. Data points *1*–*3* are from Burdick and co-workers (2–4), data point *4* is from Carder and Miller (7), and data point *5* is from Mills (14).

effects were evident for the 1,000-Hz octave band exposure, none were found for the two low-frequency exposure bands. All three noise bands produced their main effects in the mid to high frequencies.

Threshold shifts present after 72 hr of exposure to the octave bands of noise centered at 63, 125, 250, and 1,000 Hz, at intensities of either 94 or 95 dBA, are shown in Fig. 3. All three low-frequency bands were equal in A-weighted level (94 dBA) and the intensity level of the 1,000-Hz band was 1 dBA greater (95 dBA). The predominant effects were in the mid to high frequencies as they were in the lower level exposures. Although all of the exposures were nearly equal in A-weighted intensity level, there was about a 25-dB spread in the magnitude of the maximum threshold shift. Note that the magnitude of threshold shift increased, as a function of exposure center frequency. This occurred in spite of the fact that the octave band level increased substantially (95–120 dB SPL) as exposure frequency decreased. It has been known for the frequencies of 500 to 4,000 Hz that as exposure

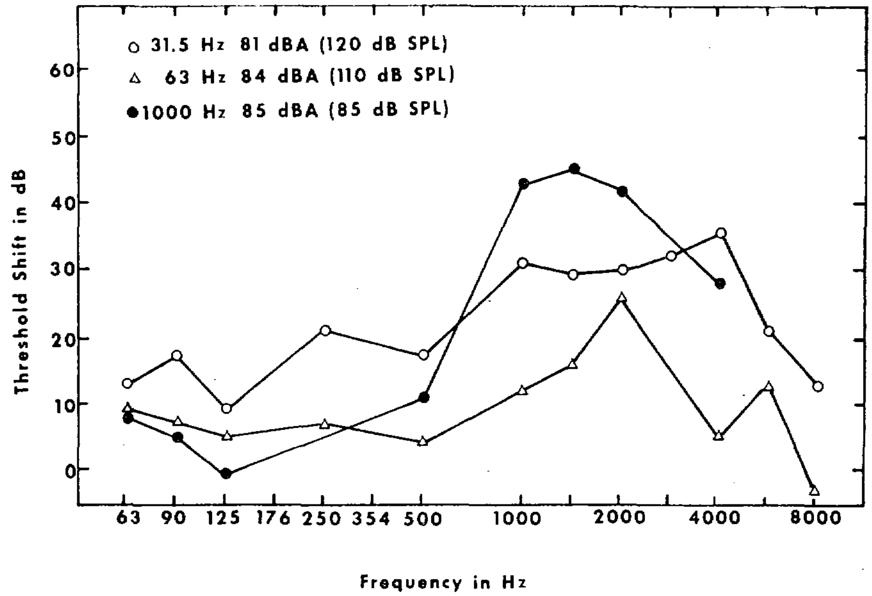

FIG. 2. Threshold shifts in dB across frequency produced by a 3-day exposure to octave bands of noise centered at 31.5 Hz and 1,000 Hz and by a 9-day exposure to an octave band of noise centered at 63 Hz. The intensity level of each exposure condition is given in octave band level (dB SPL) and A-weighted level (dBA).

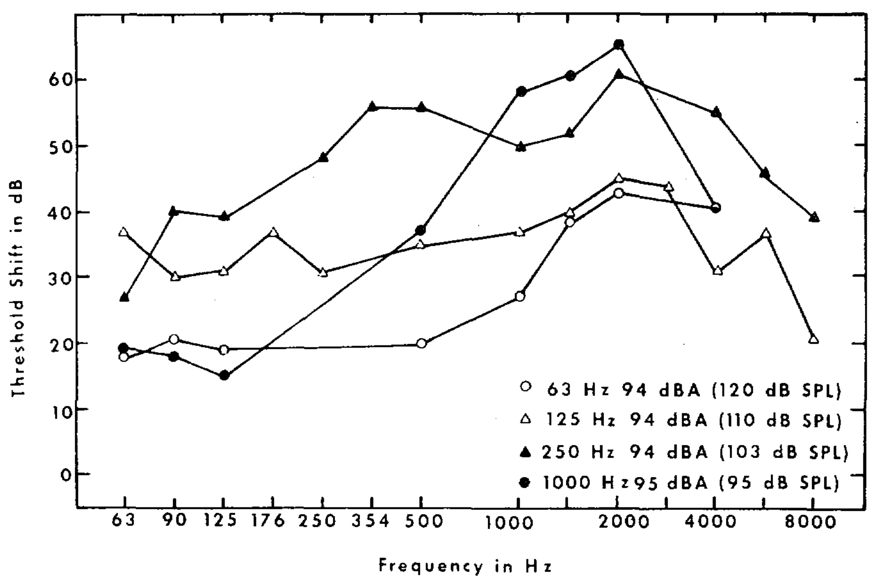

FIG. 3. Threshold shifts in dB across frequency produced by a 3-day exposure to octave bands of noise centered at 63, 125, 250, and 1,000 Hz. Exposure levels are expressed both in terms of octave band level (dB SPL) and A-weighted level (dBA).

frequency is decreased, intensity level must be increased to produce a constant level of threshold shift (cf., 6,7,10,17). The present results appear to extend this relationship to the low frequencies as well.

Examination of the threshold shifts at the half-octave frequencies shown in Fig. 3 is also interesting. For the exposure centered at 63 Hz, there was a small peak in threshold shift at 90 Hz relative to adjacent frequencies; for the exposure centered at 125 Hz, there was a slight peak in threshold shift at 176 Hz relative to its adjacent frequencies; and for the exposure centered at 250 Hz, there was a large peak in threshold shift at 354 Hz relative to its adjacent frequencies. In fact, the exposure centered at 250 Hz produced a bimodal pattern of threshold shift, with the first peak at the half- to full-octave frequency region and the second, slightly larger peak at 2,000 Hz.

The octave band of noise centered at 250 Hz appears to be near the pivotal frequency in terms of differences in the response of the chinchilla's ear to low- and high-frequency noise. As Mills et al. (17) have pointed out, for frequencies of 500 to 4,000 Hz, the maximum threshold shift is produced one-half to one octave above the center frequency of the noise band, and a second peak of lesser magnitude occurs higher in frequency than the first peak. The present studies indicate that for frequencies of 31.5 to 125 Hz, the reverse occurs; that is, the maximum threshold shift occurs at a frequency several octaves above the center frequency and a second peak of lesser magnitude occurs at the half-octave frequency.

The permanent threshold shifts as measured 30 days post-exposure are shown in Fig. 4. The shifts produced by the low-level exposures (81–85 dBA) are depicted in the lower panel and the shifts produced by the higher level exposures (94 and 95 dBA) are depicted in the upper panel. The data in both panels reflect variations in the patterns of the permanent threshold shifts but little difference with regard to the magnitudes of the shifts. It appears, therefore, that these bands of noise of nearly the same A-weighted intensity produce similar amounts of permanent hearing loss. The predominant permanent losses occurred in the same mid to high frequencies that showed the largest temporary threshold shifts.

RELATIONSHIP TO MAN

The high-frequency loss induced by low-frequency noise is not unique to the chinchilla. First, Jerger et al. (11) found that humans exposed to tones ranging in frequency from 2 to 22 Hz at intensity levels of 119 to 144 dB SPL developed threshold shifts in the frequencies from 3,000 to 8,000 Hz. Second, in a pilot study (20) in which humans were exposed to the octave band of noise centered at 63 Hz and at intensity levels of 110 and 120 dB SPL (84 and 94 dBA), it was found that the peak threshold shifts occurred between 1,000 and 3,000 Hz. Consequently, the evidence to date suggests that the human ear and the chinchilla ear may respond similarly to low-frequency noise. In summary, these studies show that low-frequency noise produces

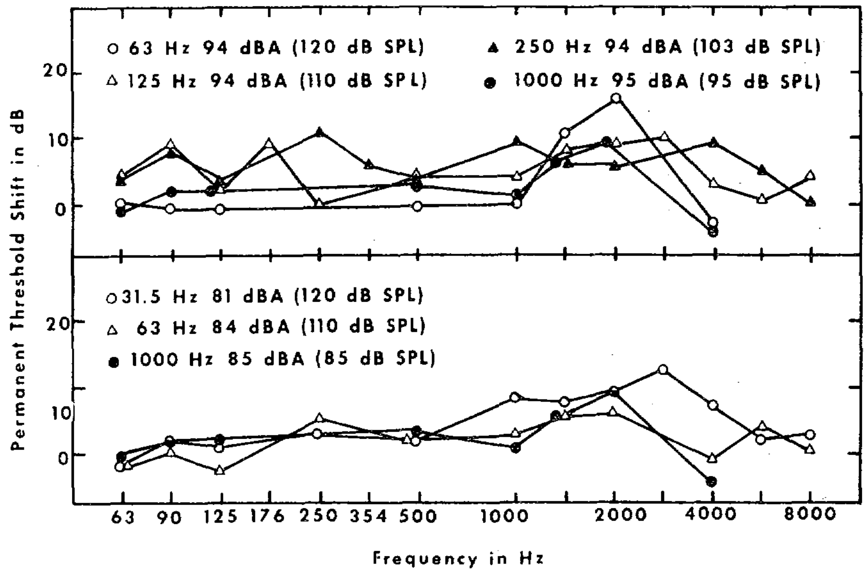

FIG. 4. Permanent threshold shift in dB across frequency as determined 30 days post-exposure. **(Top)** The permanent shifts produced by 3-day exposures to octave bands of noise centered at 63, 125, 250, and 1,000 Hz. **(Bottom)** The permanent shifts produced by 3-day exposures to octave bands of noise centered at 31.5 and 1,000 Hz and by a 9-day exposure to an octave band of noise centered at 63 Hz. Exposure levels are expressed both in terms of octave band level (dB SPL) and A-weighted level (dBA).

high-frequency hearing loss and may explain why noise-induced, low-frequency hearing losses are rarely, if ever, seen.

ACKNOWLEDGMENTS

I would like to gratefully acknowledge the invaluable assistance of the following individuals: R. T. Camp, Jr., C. E. Hargett, Jr., I. Lomba-Gautier, R. Morrow, B. T. Mozo, and J. H. Patterson. The views of the author do not purport to reflect the positions of the Department of the Army or the Department of Defense (Para 4-3, AR 360-5). In conducting the research described in this report, the investigator adhered to the "Guide for the Care and Use of Laboratory Animals," as promulgated by the Committee on Revision of the Guide for Laboratory Animal Facilities and Care of the Institute of Laboratory Animal Resources, National Research Council.

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DISCUSSION

B. Bohne: Since this is group data, do you have any measure of variability? Do the cochleograms show a bimodal cochlear lesion?

C. Burdick: We have variability like everyone else. The variability is primarily one of magnitude; the cochlear lesion occurs in the same location. In answer to the second part of your question, we do find hair cell loss in the apex accompanied by some hearing loss. We do have a problem at 2 kHz. Here we see a small 10- to 15-dB hearing loss; however, the cochleae appear essentially normal in this region.

D. Johnson: The A-weighting may not be appropriate when we are talking about the high levels of noise exposure; at lower levels, the A-weighting seems to make some sense with respect to the potential trauma associated with the noise.

J. Zwislocki: With the very low frequency that you are using, you may get wave reflection from the helicotrema and actually set up a standing wave pattern in the cochlea. It would be interesting to do a finer analysis of the audiogram of these animals, because if you are having any wave reflection, you could find maxima and minima in the pattern of hearing loss that are not harmonically related.

C. Burdick: In some of our work that we are doing with Don Teas, we are looking at cochlear microphonic distributions using these low-frequency signals. Using 63 Hz, we see harmonic components around 3,000 cycles that may be related to the standing wave patterns that you are suggesting.

C. Trahiotis: With very low-frequency signals and at high intensity, it is possible that there is spread of masking. Have you looked at any of these effects in your animals?

C. Burdick: No, we've considered this but have not looked at it.