NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN

REPORT NO. 1020

DEVELOPMENT OF HEARING CONSERVATION STANDARDS
FOR HAZARDOUS NOISE
ASSOCIATED WITH DIVING OPERATIONS

by

Paul F. Smith

Naval Medical Research and Development Command
Research Work Unit M0096.002-1047

Released by:

W. C. Milroy, CAPT, MC, USN
COMMANDING OFFICER
Naval Submarine Medical Research Laboratory

2 April 1984

DEVELOPMENT OF HEARING CONSERVATION STANDARDS FOR HAZARDOUS NOISE ASSOCIATED WITH DIVING OPERATIONS

Paul F. Smith

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY
Naval Submarine Base, New London
Groton,Ct 06349

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

REPORT NUMBER 1020

Naval Medical Research & Development Command
Research Work Unit M0096.002-1047

Released by:

W. C. Milroy CAPT MC USN
Commanding Officer
Naval Submarine Medical Research Laboratory

2 April 1984

SUMMARY PAGE

THE PROBLEM

To provide information concerning occupational health hearing-conservation standards for divers exposed to intense noise in wet and dry diving environments.

FINDINGS

Existing hearing-conservation standards can not be used to control noise exposure in diving environments because of differences in the frequency response of the ear in surface pressure air and its response in hyperbaric environments. A procedure has been developed for estimating noise hazards in diving environments based on the assumption that noises of equal sensory magnitude are equally hazardous.

APPLICATION

These findings contribute toward the establishment of hearing conservation standards for exposure to noise in diving environments.

ADMINISTRATIVE INFORMATION

This report was submitted in March 1983 and approved for publication in August 1983. It was presented at the IEEE/MTS conference OCEANS '83, August 29 - September 1, 1983. It has been designated as NSMRL Report No 1020.

ABSTRACT

Spectral analyses reveal that wet-suited divers using certain underwater hand-held tools are exposed to intense noise. There is no general hearing-conservation standard (hcs) for noise exposure in wet environments and the existing literature does not provide a theoretical or an empirical basis for developing one. An interim hcs, based on equal sensory magnitudes, is developed and discussed. Temporary auditory threshold shifts resulting from controlled exposure to noise have been used to assess noise hazards. Research in progress at the Naval Submarine Medical Research Laboratory (NSMRL) in which divers are exposed to noise from three classes of hand-held tools is described. There is also a need for an hcs for noise exposure in dry hyperbaric environments, such as in diving chambers, and diving helmets. Since auditory sensitivity is diminished in hyperbaric gas, it is reasonable to assume that the existing hcs for surface pressure can be applied conservatively to dry diving situations. However, recent experience suggests that the surface hcs may be needlessly restrictive for hyperbaric gas environments. New data on this point recently obtained at NSMRL is presented.

DEVELOPMENT OF HEARING CONSERVATION STANDARDS FOR HAZARDOUS NOISE ASSOCIATED WITH DIVING OPERATIONS

Paul F. Smith
Naval Submarine Medical Research Laboratory
Naval Submarine Base, New London
Groton, CT 06349

Divers are exposed to many sources of intense noise in both wet and dry hyperbaric environments. Existing hearing-conservation standards cannot be applied to diving activities because the response of the ear changes from one medium to another. Furthermore, because of differences in the way the ear operates in wet and in dry conditions, separate hearing-conservation standards are required for divers in wet and in dry conditions. Both situations will be discussed.

Wet Divers

Wet-suited divers working in shipyards use a variety of hand-held tools which may be noisy. Our recent analysis of noise recordings provided by the Naval Coastal Systems Center identified two classes of noise produced by the underwater tools in the NCSC sample. One class of noise, broad-band continuous noise, is produced by jet cleaning tools such as the Partek High Pressure Water Cleaner, the Daedalean Concaver Hand Gun, and the Cavijet Underwater Cleaning Tool (models 1-A and 1-B). These tools produce broad-band continuous noise in the 1 to 20 kilohertz (kHz) frequency range at sound pressure levels (SPL) of about 154 decibels (dB). (The reference sound pressure used throughout this paper is 20 micropascals.) The second class of noise called mixed (impulse and continuous) noise is produced by tools such as rock drills, chippers, and impact wrenches. Sampled tools produce noise in the 1 to 20 kHz frequency region at levels between 134 and 144 dB SPL, but they also produce impact or impulse noise at repetition rates and peak SPLs yet to be specified.

Still other tools of interest are underwater stud guns. These tools fire small explosive charges and produce a third class of noise called impulse noise. Stud guns sometimes produce impulse SPLs and durations that exceed those recommended as safe for exposure of divers to underwater explosions.[1,2] Since the effects on the ear of these three classes of noise are different, they need to be treated separately in a hearing conservation standard.

At present, there is no general hearing conservation standard governing noise exposure while diving. There are several reasons why a simple transformation of existing standards to underwater noise exposure is not valid.

For example, the underwater hearing threshold function is flatter than the threshold function in air.[3] In air, the human ear is rather insensitive to low frequency sound, maximally sensitive in the 500 to 4000 Hz frequency region, and relatively insensitive to frequencies above 4000 Hz.[4] The upper frequency limit for hearing in air for young, healthy persons is in the 20 to 25 kHz region. In water, on the other hand, the human ear is considerably less sensitive at frequencies of 125 to 8000 Hz. At low frequencies there is about a 50 dB reduction in sensitivity from the in-air thresholds, but at higher frequencies the difference is larger: about 65 to 70 dB. From a report by Deatherage et al.[5], and from our own informal observations, the water immersed human ear is responsive to frequencies as high as 120 kHz apparently because at high frequencies the predominant mechanism for underwater hearing is bone conduction rather than the usual mechanism involving the external ear canal and the middle ear.[6] With bone conduction, the ear responds to frequencies as high as 225 kHz at reasonably moderate intensity levels.[7]

In order to meet a pressing need, the U.S. Naval Medical Command (NAVMEDCOM) has established an interim procedure for evaluating underwater noise hazards based upon the concept that noises of equal sensory magnitude are equally hazardous to the ear. The procedure, illustrated in Table I, applies only to the first class of noise described above, that is, broad-band continuous noise. The values in the top line of the table are the center frequencies for the octave bands covered by the NAVMEDCOM ruling. The second line contains octave band sound pressure levels for one of the tools in our sample. Shown in line 3 are the underwater hearing-threshold values reported by Brandt and Hollien.[3] For each octave band of an underwater noise spectrum, a sensory magnitude is estimated by calculating the difference between the octave band level (line 2) and the underwater hearing-threshold at the center of the band (line 3). By adding this sensory magnitude (line 4) to a corresponding in-air hearing-threshold value[4] (line 5), the octave band level for an equivalent noise exposure in air is estimated (line 6). Next, by combining the octave band levels (L_i), an overall equivalent sound pressure level (L) is obtained. This level is then evaluated against an existing hearing-conservation standard for noise exposure in air in order to compute a maximum permissible exposure time (T).

The example given in Table I is for a water jet cleaning tool currently in use by both the Navy and the civilian diving community. It is apparent that the high noise output of this tool seriously limits the amount of time that it may be used in any one working day. Table II gives some results for other tools that have been examined so far. Please note, however, that the noise level produced by any tool varies greatly with operating conditions.

NSMRL is investigating the validity of the NAVMEDCOM procedure by comparing the magnitudes of temporary auditory-threshold shifts (TTS) resulting from controlled exposure to bands of noise in water with those produced by comparable noise exposures in air. TTS magnitude is assumed to be a reliable index of hazard to the ear.

In an earlier study[8] using this experimental method we compared the TTS produced by exposure to intense pure tones in water with TTS produced by a comparable exposure in air. The results indicated that, at an exposure frequency of 3500 Hz, the difference in sound pressure levels which would produce equal magnitudes of TTS in air and underwater is about 68 dB. This is comparable to the difference in threshold sensitivity of the human ear in the two media at 4000 Hz and, therefore, tends to confirm the validity of the NAVMEDCOM

The opinions expressed here are those of the author and do not necessarily represent the official views of the U. S. Navy Department.

Reprinted from PROCEEDINGS OF OCEANS, August 29-Sept. 1, 1983

TABLE I.

DETERMINATION OF PERMISSIBLE TIMES FOR EXPOSURE TO NOISE IN WATER

1.	Frequency (Hz)	125	250	500	1000	2000	4000	8000
2.	Tool noise Octave Band Level	156	161	148	137	131	115	0
3.	Underwater Hearing Threshold	70	65	58	60	66	67	74
4.	Sensory Magnitude (Line 2 - Line 3)	86	96	90	77	65	48	-74
5.	In-air Hearing Threshold	21	11	6	4	1	-3	10
6.	Equivalent Octave Band Level, L_i (Line 4 + Line 5)	107	107	96	81	66	45	-64
7.	Overall Equivalent SPL, (L) $L=10 \log (\Sigma 10^{L_i/10})$			110				
8.	Permissible Exposure Time (minutes) $T=16/2^{(L-80)/4}$				5			

The units for lines 2. through 7. are decibels.

procedure at least for pure tones or narrow bands of noise in the vicinity of 4000 Hz.

Preparations are now being made to extend this work to other frequencies and to broad-band noise.

Dry Divers

A hearing-conservation standard is also required for noise exposure in dry hyperbaric environments, such as in hyperbaric chambers and diving helmets.

TABLE II.

NOISE LEVELS AND PERMISSIBLE EXPOSURE DURATIONS FOR THE USE OF SELECTED TOOLS BY WET-SUITED DIVERS

TOOL	EQUIVALENT SOUND PRESSURE LEVEL (dB)	PERMISSIBLE EXPOSURE TIME (minutes)
Stanley Impact Wrench (Model IW-20)	90	170
Stanley Rock Drill (Model HD-45)	86	339
Stanley Rock Drill (Model SK-58)	96	60
Stanley Rock Drill (Model HD-20)	85	404
Partek High Pressure Water Cleaning Tool	93	101
Cavijet High Pressure Water Cleaning Tool (Model 1-A)	101	25
Cavijet High Pressure Water Cleaning Tool (Model 1-B)	82	480
Flow Industries High Pressure Water Jet Tool	96	60
Daedalean Concaver Hand Gun	78	480

Because of the high gas-flow rates inherent in helmets and chambers, dry diving environments are frequently noisy. Summitt and Reimer found that noise levels in diving helmets and hyperbaric chambers are so intense that divers may occasionally receive the maximum permissible daily noise dose within twenty minutes or less.[9] As with the wet diver, the dry-helmeted diver may incur additional noise exposure from noisy underwater tools.[10] Molvaer and Gjestland[11] have measured TTS in two divers who were exposed to the noises in two models of helmets. They found (for one diver) that a one hour exposure to Siebe-Gorman helmet noise produced a maximum TTS of 15 dB (measured three to five minutes or more after the cessation of the noise) in the higher frequencies. The Siebe-Gorman helmet noise combined with underwater rock drilling noise produced its maximum TTS of 35 dB at frequencies of 250 to 1000 Hz. A second diver incurred no TTS from a quieter Superlite-17 helmet but did suffer a 15 dB TTS from noise produced by a water-jet tool. The authors concluded that these results indicate that lengthy exposures to such noises might be hazardous to divers' hearing.

Since no hearing-conservation standard for noise exposure in hyperbaric gas environments exists, the U. S. Naval Medical Command has ruled that existing hearing-conservation standards for normobaric environments be applied, without modification, to dry hyperbaric gas environments.

Noise measurements for some of the tools shown in Table II have also been made inside a Mark-12 diving helmet mounted on a manikin head while a diver was operating one of various hand-held tools nearby. The sound levels obtained are shown in the second column of Table III. Again, it must be noted that the noise output of these tools varies considerably from sample to sample. The third column gives the maximum permissible exposure durations for these particular noise levels. As can be seen, these tools may only be used for a severely restricted amount of time in any one day. Divers wearing Mark-12 helmets while using either the Partek or Cavijet underwater cleaning tools or the Stanley IW-20 impact wrench will receive the maximum daily noise dose within 15 minutes or less.

TABLE III.

NOISE LEVELS AND PERMISSIBLE EXPOSURE DURATIONS FOR THE USE OF SELECTED TOOLS BY MARK-12 DIVERS

TOOL	NOISE LEVEL (dB(A))	PERMISSIBLE EXPOSURE TIME (minutes)
Stanley Impact Wrench IW-20	105	13
Stanley Rock Drill HS-45	90	170
Stanley Rock Drill SK-58	90	170
Stanley Rock Drill HD-20	91	143
Partek High Pressure Cleaning Tool	104	15
Cavijet High Pressure Water Cleaning Tool Model 1-B	105	13
same	109	6
same	106	11

The literature suggests that the NAVMEDCOM ruling may be too conservative. Fluur and Adolpfson[12] and Thomas et al.[13] found that auditory sensitivity is reduced considerably under dry hyperbaric conditions. The observed reduction in auditory sensitivity is usually attributed to changes in the impedance of the external ear canal and/or the middle ear cavity. However, it is more likely due to the altered acoustic impedance of the atmosphere. The physical relation between sound pressure and intensity in a medium dictates that, for a noise of given sound pressure, the intensity of that noise is lowered as depth increases. This implies that noises of equivalent SPL at the surface and at depth would not be equally harmful to the ear. Thus, if existing hearing-conservation standards are applied to hyperbaric noise exposures the result will be excessively conservative. Indeed, theory and some preliminary evidence to be discussed shortly, suggest that the present NAVMEDCOM guidance could be relaxed at least to the extent of correcting sound pressure levels for the impedance of the medium.

However, the outline for a hearing-conservation standard for dry diving conditions is far from clear. In the usual industrial setting, broad-band noise is typically measured using "A" weighting which discriminates against low-frequency and high-frequency sound. In accordance with the NAVMEDCOM ruling the noise levels in Table III are "A" weighted sound levels. Molvaer et al. point out, as one example of the uncertainty that exists, that "the sensitivity curve of the human ear changes in alien atmospheres and under pressure..." (that is, the changes in sensitivity are not the same at all frequencies) "...so the A-weighting applied to linear noise curves at the surface...is not applicable at pressure.[10] Note that one of Molvaer's divers incurred significant TTS at frequencies below 1000 Hz, an uncommon occurrence with exposure to industrial noise in air at surface pressure.

If the direct application of surface standards to hyperbaric environments is inappropriate, we are left with the question of what an appropriate standard should be. It would be unwise to regulate noise exposure in hyperbaric environments merely on the basis of apparent changes in auditory-threshold sensitivity or on the presumption that intensity rather than sound pressure is the relevant metric for noise exposure. There is no assurance that hyperbaric conditions do not affect cochlear function in ways that could make the ear more or less susceptible to damage from noise at depth than at surface pressures. It is advisable, rather, to base hearing-conservation standards for divers on a series of carefully controlled experiments on noise-induced TTS under a wide range of hyperbaric conditions.

Few studies exist where noise-induced TTS was measured under dry hyperbaric conditions. The few data available[9,10,11] do not provide sufficient information on the response of the ear under controlled acoustic conditions in the variety of hyperbaric conditions necessary for the establishment of an appropriate hearing-conservation standard.

Smith and Haskell[14] have obtained TTS data on five divers during shallow air-saturation dives conducted at NSMRL. The subjects were exposed to intense 2.828 kHz pure tones for five minutes at ambient pressures of 1 and 3 atmospheres absolute (101 and 303 kilopascals). An important result of the experiment is that fatiguing tones of 98 dB SPL produce generally smaller amounts of TTS at a simulated depth of 65 feet than do 96 dB SPL tones at the surface. If this result is repeated in more extensive research now being planned, then a firm basis will have been established for applying more relaxed hearing-conservation standards to hyperbaric-exposure conditions.

References

1. Mittleman, J. 1976. Stud gun sound pressure level study: experimental and theoretical work. Naval Coastal Systems Laboratory Report NCLS-297-76.

2. Christian, E.A. and Gaspin, J.B. 1974. Swimmer safe standoffs from underwater explosions. Naval Ordnance Laboratory, White Oak report NOLX 80.

3. Brandt, J.F. and Hollien, H. 1967. Underwater hearing thresholds in man. J. Acoust. Soc. Amer. 42: 966-971.

4. International Organization for Standardization 1961. Normal equal-loudness contours for pure tones and normal threshold of hearing under free field listening conditions. Standard R226-1961.

5. Deatherage, B.H., Jeffress, L.A., and Blodgett, H.C. 1954. A note on the audibility of intense ultrasonic sound. J. Acoust. Soc. Amer. 26: 582.

6. Smith, P.F. 1969. Underwater hearing in man: I. Sensitivity. NAVSUBMEDRSCHLAB Report 569.

7. Sagalovich, B.M. and Melkomova, G.G. 1966. Range of ultrasonic frequencies perceived by the human ear. Biofizik 11: 156-163.

8. Smith, P.F., Howard, R., Harris, M., and Waterman, D. 1970. Underwater hearing in man: II. A comparison of temporary threshold shifts induced by 3500 Hertz tones in air and underwater. NAVSUBMEDRSCHLAB Report 608.

9. Summitt, J.K., and Reimers, S.D. 1971. Noise. A hazard to divers and hyperbaric chamber personnel. Aerosp. Med. 42: 1173-1177.

10. Molvaer, O.I., and Gjestland, T., Oftedal, T., and Hatlestad, S. 1979. Hearing damage risk due to noise

from jet tool operated under water, Norwegian Underwater Institute Report No. 24.

11. Molvaer, O.I., and Gjestland, T. 1981. Hearing damage risk to divers operating noisy tools under water, Scand. J. Work Environ Health, 7: 263-270.

12. Fluur, E. and Adolpfson, J. 1966. Hearing in hyperbaric air. Aerosp. Med. 37: 783-785.

13. Thomas, W.G., Summitt, J., and Farmer, J.C. 1973. Human auditory thresholds during deep saturation helium-oxygen dives, J. Acoust. Soc. Amer. 53: 347.

14. Smith, P.F., and Haskell, G.B., 1983. A comparison of the temporary auditory threshold shifts induced by an intense pure tone at ambient air pressures of 1 ATA and 3 ATA, NAVSUBMEDRSCHLAB Memorandum Report (in preparation).

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSMRL Report No. 1020	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF HEARING CONSERVATION STANDARDS FOR HAZARDOUS NOISE ASSOCIATED WITH DIVING OPERATIONS		5. TYPE OF REPORT & PERIOD COVERED Interim report 6. PERFORMING ORG. REPORT NUMBER NSMRL Report No. 1020
7. AUTHOR(s) Paul F. SMITH		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Submarine Medical Research Laboratory Box 900 Naval Submarine Base New London Groton, Connecticut 06349		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS M0096.002-1047
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Medical Research and Development Command Naval Medical Command, National Capital Region Bethesda, Maryland 20814		12. REPORT DATE 2 April 1984 13. NUMBER OF PAGES 4
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 released; distribution unlimited

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

18. SUPPLEMENTARY NOTES

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

noise exposure; auditory damage; environmental hazards; diving; diving medicine

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

Spectral analyses reveal that wet-suited divers using certain underwater hand-held tools are exposed to intense noise. There is no general hearing-conservation standard (hcs) for noise exposure in wet environments and the existing literature does not provide a theoretical or an empirical basis for developing one. An interim hcs, based on equal sensory magnitudes, is developed and discussed. Temporary auditory threshold shifts resulting from controlled exposure to noise have been used to assess noise hazards. Research in progress at the Naval Submarine Medical Research

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601 |

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) item 20--continued

Laboratory (NSMRL) in which divers are exposed to noise from three classes of hand-held tools is described. There is also a need for an hcs for noise exposure in dry hyperbaric environments, such as in diving chambers, and diving helmets. Since auditory sensitivity is diminished in hyperbaric gas, it is reasonable to assume that the existing hcs for surface pressure can be applied conservatively to dry diving situations. However, recent experience suggests that the surface hcs may be needlessly restrictive for hyperbaric gas environments. New data on this point recently obtained at NSMRL is presented.