Naval Submarine Medical Research Laboratory

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DEVELOPMENT OF A GENERAL HEARING CONSERVATION STANDARD FOR DIVING OPERATIONS: RESEARCH ON HEARING-CONSERVATION FOR EXPOSURE TO NOISE IN DRY HYPERBARIC ENVIRONMENTS: I. BASIC CONSIDERATIONS AND PRELIMINARY EXPERIMENTS

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Development of a General Hearing Conservation Standard for Diving Operations: Research on Hearing-Conservation for Exposure to Noise in Dry Hyperbaric Environments: I. Basic Considerations and Preliminary Experiments

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Report 1204

Naval Medical Research and Development Command
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Summary Page

Objective

To develop means of insuring accurate calibrations of microphones and earphones in hyperbaric environments, to determine the feasibility of measuring valid auditory thresholds in the NSMRL hyperbaric facility, and to obtain preliminary data on the applicability of existing hearing-conservation standards to regulating noise exposure in compressed air.

Findings

Providing care is used in handling them, and calibrations are performed in suitable gas, it should not be necessary to calibrate condenser microphones in diving environments more than once a year. Calibration studies should be undertaken to determine the performance of ceramic microphones that are less expensive and more rugged than condenser microphones for use in compressed air environments.

Careful selection of earphones and pre- and post-experiment calibrations may be relied upon for experiments in compressed air, but instrumentation for in situ calibrations should be developed.

It was demonstrated that with minimal precaution, valid auditory threshold measurements can be obtained in NSMRL hyperbaric chamber #1.

The ear appears to be less sensitive to noise in compressed air at 3 atmospheres than it is in air at 1 atmosphere if sound is measured in terms of sound pressure. Preliminary data indicate that the use of existing hearing-conservation standards for regulating noise exposure in compressed air is inappropriately conservative. The ear may respond to sound intensity or particle velocity rather than sound pressure.

Application

These findings contribute to the establishment of a hearing-conservation standard for Navy divers exposed to intense noise in diving helmets and hyperbaric chambers.

Administrative Information

This research was carried out under Naval Medical Research and Development Command Work Unit 63713N M0099.01C-5050, Development of a general hearing-conservation standard for diving operations. The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of Defense, Department of the Navy, or the U.S. Government. It was approved for publication on 23 April 1997, and designated as NSMRL Report 1204.

Abstract

Condenser microphones were calibrated in compressed air to 10 atmospheres (atm) and the results were highly similar to previous studies. Providing care is used in handling them, and calibrations are performed in suitable gas, it should not be necessary to calibrate condenser microphones in diving environments more than once a year. Calibration studies should be undertaken to determine the performance of ceramic microphones that are less expensive and more rugged than condenser microphones for use in compressed air environments. Several earphones were also calibrated in compressed air but the results were not consistent for most earphones, and instrumentation for *in situ* calibration earphones on each dive should be developed. However, careful selection of earphones and pre-post experiment calibrations may be relied upon for experiments in compressed air. It was demonstrated that with minimal precaution, valid auditory threshold measurements can be obtained in NSMRL hyperbaric chamber #1. The ear appears to be less sensitive to noise in compressed air at 3 atm than it is in air at 1 atm when measurements are made in terms of sound pressure. The ear may respond to sound intensity or particle velocity rather than sound pressure. Present hearing-conservation standards appear to be overly conservative for direct application to noise exposure in compressed air environments.

Development of a general hearing conservation standard for diving operations: Research on hearing-conservation for exposure to noise in dry hyperbaric environments: I. Basic considerations and preliminary experiments

Military and commercial divers, caisson workers, and hyperbaric medical personnel work in closed environments with artificial atmospheres at elevated ambient pressure in which life-support and other equipment may at times produce considerable noise (Summit and Reimers, 1971; Molvaer and Gjestland, 1981; Lakhov, 1982a,b; Smith, 1983; Curley and Downs, 1986; Curley and Knafelc 1987; Russell and Cilento, 1994). However, there are no established procedures for assessing noise exposure in diving environments. Because auditory thresholds have been reported to be reversibly increased under such conditions, it has been suggested that lessened auditory sensitivity at least partially protects divers from the effects of noise exposure (Fluur and Adolfson, 1966; Thomas et al., 1974; Farmer, 1994). A medically conservative approach, therefore, might be to apply existing hearing-conservation standards to control noise exposure in diving operations. Unfortunately, such an application would also severely restrict operating times for some diving systems and diver-operated equipment (Molvaer and Gjestland, 1981; Smith, 1984). What is needed is not a conservative standard but an appropriate one. Accordingly, the Naval Medical Research and Development Command tasked the Naval Submarine Medical Research Laboratory (NSMRL) to develop realistic guidance for noise exposure in dry hyperbaric environments.

Noise in hyperbaric operations can induce significant temporary auditory-threshold shifts (TTS) indicating that noise-induced permanent threshold shifts (PTS) may result from such exposures. Curley and Downs (1986) found A-weighted (dB(A)) noise levels within a prototype diving helmet were as high as 115 dB(A) under some operating conditions although the levels were generally in the vicinity of 104 dB(A). Their subjects incurred mean TTSs at 2000 Hz of 9 to 17 dB (range, 0 to 25 dB) measured six to seven min. following four-hour exposures. Curley and Knafelc (1987) found noise levels in the U.S. Navy MK 12 Surface Supplied Diving System helmet varied from about 90 dB(A) at 1 atmosphere (atA, 1 atm = 101.325 kPa) to about 103 dB(A) at 4 atA in compressed air. Exposures of 120 min. produced TTSs ranging up to 35 dB at 2000, 3000, and 4000 Hz.

In addition to intrinsic noise (primarily gas-flow noise) produced by diving systems, divers may also be exposed to noise generated by noisy underwater tools. Noise levels within a MK 12 diving helmet mounted on a mannequin (no gas-flow noise) were found to vary between 85 and 99 dB(A) when commonly used hand-held tools were being operated nearby (Smith, 1988). Molvaer and Gjestland (1981) found that intrinsic diving system noise (in the standard Siebe-Gorman and the Diving Systems International Superlite 17) could combine with tool noise to induce magnitudes of TTS that suggest that lengthy exposures to such noises might be hazardous to hearing.

Furthermore, there is considerable evidence (Fluur and Adolfson, 1966; Oliver and Demard, 1970; Appaix and Demard, 1972, Thomas et al., 1974; Smith, 1984) that the frequency response of the ear is altered in hyperbaric environments. The ear may be less sensitive to low-frequency noise but more sensitive to high-frequency noise in hyperbaric helium-oxygen than it is in normobaric air environments. Molvaer et al. (1982) questioned the applicability of A-weighted noise levels in atmospheres other than air.

As Molvaer and Lehman (1985) point out, it has been known since the time of Aristotle that barotrauma may injure ears and produce temporary or permanent hearing loss. There is also a question as to whether or not diving activity itself, apart from identifiable episodes of barotrauma, impairs hearing. That question has been studied for over 35 years without resolution (Coles and Knight (1961); Coles, 1963, 1976; Molvaer and Lehman, 1985; Edmonds, 1985; Farmer, 1994). Impaired hearing due to non-noise-related agents (e.g. sub-clinical barotrauma) is not a concern of the present research. In this work, the population of interest consists of healthy young divers with normal ears. They need to be protected from excessive noise, regardless of risks to hearing from non-noise agents.

The purpose of this report is to provide some background information on the nature of hearing in hyperbaric environments, to describe the research approach taken to establish a hearing-conservation standard for dry diving environments, and to describe some preliminary experiments that were done. Readers are referred to Sergeant (1975) for a discussion of some of the many problems associated with research on speech and hearing in hyperbaric environments. A number of experiments have been conducted in a variety of diving environments since this report was first drafted. Principles described in the current report have been employed in those experiments. They will be reported subsequently.

II. Psychoacoustics in Hyperbaric Environments:

Stimulus specification

Magnitude. The auditory stimulus is sound, and sound is a time-varying, mechanical/vibratory disturbance propagated through a medium as a sound wave. In a fluid medium the magnitude of that disturbance can be characterized by observing pressure variations (sound pressure, p), the energy in a sound wave (intensity, I), the velocity of particles (particle velocity, u), displacement amplitude of particles (particle displacement, ξ), particle acceleration, a, or a host of other phenomena including heat that are associated with sound. The most convenient means of specifying the auditory stimulus magnitude is to measure sound pressure.

Rettinger (1977, p. 41) provides a table showing the relationships among the four variables listed above. Some of those relationships are:

(1) Intensity (I) $I = p^2/\rho_0 c$

(2) particle velocity (u) $u = p/\rho_0 c$

(3a) particle displacement (ξ)
$\xi = p/2\pi f \rho_0 c$

(3b) $= (1/2\pi f)\,(p/\rho_0 c)$

(4a) particle acceleration (a)
$a = 2\pi f p/\rho_0 c$

(4b) $= (2\pi f)\,(p/\rho_0 c)$

where $\rho_0 c$ is the characteristic impedance (Z) of a sound-transmitting fluid medium and f is the sound frequency. The formulae are shown in non-standard form to emphasize that the ratio $p/\rho_0 c$ appears in all of the equations listed above. It is obvious from equations (1-4b) that as density increases in a given gas undergoing compression, a constant sound pressure will be associated with decreasing intensity, particle velocity, particle displacement, and particle acceleration. Both the density and the velocity of sound vary considerably with diving conditions. Hence, the relationships among sound pressure, intensity, particle velocity, etc. will also vary. Clearly, knowing only the sound pressure in a diving environment is inadequate to specify the acoustics of that environment,

Commonly, the word "intensity" is used to describe any of several measures of magnitude, especially sound pressure, but as shown in equation (1), it has a very specific meaning. Intensity is defined as the average (root mean square) flow of sound power through a unit area parallel to the wave front (i.e., normal to the direction of propagation).

When dealing with noise exposure in diving environments, various disciplines, each with its own set of metric conventions, are encountered. In most applications sound pressure is expressed using a logarithmic "decibel" (dB) scale. Most textbooks in audiology define sound pressure level (SPL) in dB as

$$(5)\ SPL = 20 \log (p_1/p_0)$$

where p_1 is a measured, variable sound pressure and p_0 is a reference pressure. Equation (5) is valid only when the variable and reference pressures are measured in the same acoustical environment. Specifically, the reference pressure p_0 used in any gas is specified as 20 micropascal (μPa) (ANSI S1.8-1989 Reference Quantities for Acoustical Levels). For air, the standard reference atmosphere is 101.3 kilopascal (kPa) at 20° C and 65% relative humidity (ANSI S1.4-1983 Specification for sound level meters). For other gases than air, standard reference conditions have not been established. A more general form of equation (5) is given in the section on impedances below.

In acoustics, the word "level" always refers to the logarithm of the ratio of a variable quantity to a reference quantity. In other areas of acoustics than psychoacoustics and audiology, sound pressure level is usually symbolized as "L_p" rather than "SPL" but the meaning is the same. Because several different aspects of stimulus magnitude will be discussed, not just the magnitude of sound pressure, this report will use the single letter quantity symbol with the subscript denoting the variable of interest. Thus, L_p will denote a sound pressure level, L_i an intensity level, etc.

Frequency and wavelength. Frequency is another important characteristic of sound.

Frequency more-or-less determines the "pitch" of sounds regardless of the medium. Associated with frequency is wavelength (λ = c/f). The wavelength is important in interactions (diffraction, etc.) between a propagating sound and an obstacle such as the human head. For example, diffraction effects alter the sound amplitude at the entrance to the ear canal. Those effects are different in helium-oxygen gas than in air because c is different for those two gases. Frequency is much more easily measured than is wavelength and usually wavelength is calculated from frequency measurements when c is known. Direct computation of c for a particular gas mixture is complicated but suitable approximations may be obtained from diving-gas mix tables such as NAVSHIPS 0994-003-7010 (Battelle, 1971). Frequency/wavelength relationships are also important considerations in calibrating microphones and earphones in hyperbaric gas.

Generally, in psychoacoustics, the auditory stimulus is specified in terms of sound pressure and frequency, but it can as well be specified in other terms such as particle velocity and wavelength. Even in normobaric air, sound pressure does not always completely specify an auditory stimulus magnitude (Zwislocki, p21). As has been just discussed, frequency does not suffice to explain certain effects such as the diffraction of sound about an object. In the present research, auditory stimulus magnitude is sometimes described in terms of sound intensity or particle velocity, and frequency may be expressed in terms of wavelength.

Impedance. An important concept in the acoustics of diving environments is the impedance of a medium (Kinsler et al.,1982, Chap. 6). Two terms that are encountered in the literature are the characteristic impedance and the specific acoustic impedance. The characteristic impedance (Z) is simply a function of the elastic properties of the medium and can be expressed in terms of the density (ρ_0) and velocity of sound (c) in a medium as

$$(6)\ Z = \rho_0 c.$$

Gas density is important acoustically. It has an effect on the vocal tract and on the production of edge tones. Voices take on a nasal quality and it is virtually impossible to whistle in compressed air at pressures greater than about three times normal atmospheric pressure (Bert, 1943, pp. 356-361). The velocity of sound varies greatly with the percentage of helium in a breathing gas, but within any particular gas mixture, velocity is only slightly affected by pressure. Divers breathing helium-rich gas speak with the familiar Donald Duck voice (Sergeant, 1975). Data for computing the characteristic impedances of diving gas mixtures may be obtained from the Diving-gas manual which has tables showing densities and "sonic velocities" for various gas mixtures and pressures (Battelle, 1971).

The specific acoustic impedance (z) is a function of the elastic properties of the medium and the specific type of wave (plane, spherical, etc.) that is being propagated. It can be expressed as the ratio between a sound pressure (p) and a particle velocity (u) as

$$(6a)\ z = p/u.$$

Equations (2) and (6a) indicate that for plane progressive waves in a free field or within a tube, these two impedance terms are interchangeable because under those conditions, Z = z (see Kinsler et al., p 111 and p 231). Discussions in this report are restricted to plane wave conditions.

It was pointed out above that equations (1-4b) indicate that as density increases in a given gas undergoing compression, a constant sound pressure will be associated with decreasing intensity, particle velocity, particle displacement, and particle velocity. Similarly, the impedances of a nitrogen-oxygen gas mixture and a helium-oxygen mixture having the same density will differ because the velocity of sound is greater in the helium-oxygen mixture. Hence, equal sound pressures measured in those two environments will correspond to different sound intensities, etc.

Smith (1984) has shown that sounds measured in terms of L_p can be compared across environments by converting L_{ph} measured in a diving environment to a "surface equivalent" intensity level L_i using

$$(7)\ L_i = L_{ph} + 10 \log (Z_a/Z_h)$$

where the subscript (a) refers to normobaric air and (h) to a medium such as compressed air or helium-oxygen mixtures. Smith (1984) called the last term in equation (7) the "correction for impedance" (C_z). That is,

$$(7a)\ C_z = 10 \log (Z_a/Z_h)$$

The unit of C_z is the decibel.

As has been previously stated, for progressive plane waves, particle velocity (u), sound pressure, and the characteristic impedance of a medium are related as

$$(2)\ u = p/\rho c.$$

Equation (2) shows that if density or sound velocity is increased, a constant sound pressure will be associated with a decreasing particle velocity. It can also be shown that stimuli can be compared across environments in terms of particle velocity (u) or a particle velocity level (L_u) by

$$(8)\ L_u = L_{ph} + 20 \log (Z_a/Z_h) = L_{ph} + 2\,C_z.$$

Of the various properties of sound (pressure, intensity, particle velocity) sound pressure is by far the easiest to measure in all environments and is usually the only property measured or considered. It is not necessarily the property to which the ear responds.

Auditory function in hyperbaric gas.

Some of the physical and physiological factors that are important to research in diving environments have been summarized by Smith (1984). Fluur and Adolfson (1966) and Thomas et al. (1974) found that bone-conduction thresholds (Sensory Acuity Level) are not affected by ambient pressures of up to 31 atm. Adolfson and Fluur (1967) concluded that the degraded speech discrimination that they observed in divers in compressed air was due to the cognitive disorders associated with oxygen intoxication, not to altered auditory sensitivity. Auditory thresholds for water-immersed ears do not vary between depths of 12 to 105 feet (Brandt and Hollien, 1967, 1969) at least for frequencies at which the bone-conduction pathway is predominant (Smith, 1969). Also, speech reception is unaffected by water immersion provided the speech signal is sufficiently intense and delivered through a communication system of adequate fidelity (Brandt and Hollien, 1968) These findings suggest that cochlear and central auditory processes are unaffected by water-immersion or hyperbaric pressure. Thus, only alterations in the auditory system distal to the cochlea need to be considered to explain altered auditory function in diving environments.

The ear is widely regarded as a pressure sensitive device (Bekesy, 1960, p 95) and analytic models of the ear are worked out in terms of sound pressure transformations. A crude first approximation to the ear canal is a tube open at one end and terminated by a rigid plug. At the plug, no air movement is possible (particle velocity is always zero) and sound pressure is doubled. It is well known that sound pressure is greater near the tympanic membrane than it is at the entrance to the external auditory meatus (Shaw, 1974) and that finding naturally reinforces the notion that the sound pressure at the tympanic membrane is the auditory stimulus.

A more realistic model of the ear however, is a tube terminated by a mobile membrane behind which is a gas-filled cavity (Shaw, 1974; Rabbit, 1989). In such a model non-zero particle displacements are inevitable at the membrane. The behavior of the tympanic membrane in response to sound is exceedingly complex (Khanna and Tonndorf, 1972), and the role of the middle ear cavity in controlling the tympanic membrane is not fully understood (Rabbitt, 1989). It seems presumptuous then, in the absence of appropriate analyses, to assert that the ear is a pressure sensitive device. It has long been known that direct mechanical vibratory displacement of the tympanic membrane is an effective auditory stimulus (Wilska, 1935).

The implication of the foregoing is direct: if one observes elevated threshold L_ps in a diving environment, that result does not necessarily imply that the ear is "less sensitive" or has incurred a "reversible hearing loss" as Farmer (1994) concluded. It could mean that the ear does not respond to sound pressure (as it is generally assumed to do) but to some other aspect of the stimulus (energy or power, particle velocity or displacement, etc.).

III. Calibrations of Microphones and Earphones.

Calibration artifacts. It is also necessary to consider the effects of altered acoustics on calibrations. In helium- or hydrogen-rich environments wavelength-dependent phenomena (diffraction, resonance, etc.) that contribute to auditory sensitivity differ from those of normobaric air. It is shown below that such wavelength-dependent factors can appear to alter the response of the ear in diving environments when auditory thresholds are compared only in terms of sound pressure measured in an earphone coupler when, in fact, no change had occurred in the functioning of the ear (see also Smith, 1984).

Telephonics TDH-39, -49, and -50 earphones are commonly used in audiometry (ANSI S3.6-1989) and have also been used for experiments on hearing in hyperbaric environments. The earphones are typically calibrated in a National Bureau of Standards coupler (NBS 9-A) or a similar device that couples the earphone to a calibrated microphone. However, the behavior of earphones on couplers and on ears can greatly affect calibration results. For routine clinical purposes (such as calibrating an audiometer) careful attention to detail is sufficient to obtain reproducible and meaningful standardization. If, in an experiment on hearing in hyperbaric gas, coupler measurements are made with the hope of specifying the auditory stimulus in terms of sound pressure at the eardrum, misleading results can be obtained unless the behavior of the earphone in the coupler and on the ear are taken into account.

For example, Cox (1986) developed a transfer characteristic to convert sound pressures produced by a TDH-39 earphone in an earphone/microphone coupler to sound pressures at the eardrum. Cox's transfer characteristic is shown in Figure 1a in which negative values indicate that the L_p at the eardrum is lower than the L_p measured in the coupler. The over-estimation by the coupler of sound pressure at the eardrum below 0.4 kHz is due to wavelength related acoustic leaks that are in turn due to imperfect sealing of the earphone to the subject's head (Burkhard and Corliss, 1954). In the 1.00 to 4.00 kHz region the underestimation of eardrum sound pressures is due to wavelength dependent resonance within the ear canal (Weiner and Ross, 1946; Shaw, 1974). Cox's transfer characteristic may be valid in compressed air environments because the velocity of sound is the same in compressed air and normobaric air hence the frequency-to-wavelength relationship is not altered.

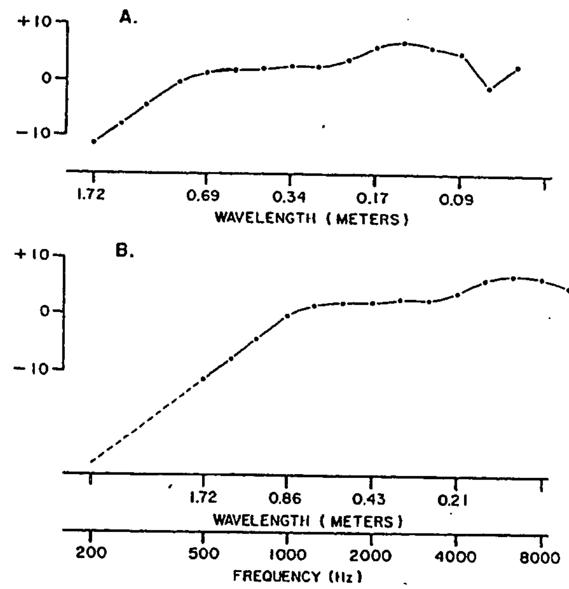

Figure 1. A comparison of expected coupler-to-eardrum transformations in air at 1 atm and in a gas mixture of 95% helium, 5% oxygen. Data in panel a. redrawn from Cox (1986).

However, had the Cox derivation been made for an environment having a sound velocity 2.5 times that of normobaric air (approximately the velocity of sound in a 95% He, 5% O2 mixture) the resulting transfer characteristic would be similar to the curve in Figure 1b. The entire transfer characteristic is shifted upward in frequency because of the altered correspondence between frequency and wavelength. Thus, knowing the sound pressure produced in a coupler by an earphone in hyperbaric helium-oxygen is essential but insufficient. From Fig. 1b it can be seen that if one measured thresholds at 500 Hz in a helium-oxygen environment, the estimate of eardrum sound pressure could be about 12 dB too high if the normobaric coupler-to-eardrum transfer characteristics in Fig. 1a were used to estimate eardrum L_ps. That is, even if no actual change in threshold occurred at 500 Hz for divers in a 95% He, 5% O2 environment one might conclude, on the basis on coupler measurements, that a threshold elevation of 12 dB had occurred.

Unfortunately, there are no empirical data on coupler-to-eardrum transfer characteristics taken in environments other than normobaric air that are comparable to the curve in Fig. 1. It will be shown below that the behavior of TDH-39 earphones is radically altered in compressed air. Throughout the current research stimulus levels are generally specified in terms of coupler sound pressure levels. Unless differences in the earphone/coupler behavior and the acoustics of various gases are taken into account however, erroneous conclusions concerning the behavior of the ear in those gases may result.

Calibration methods, microphones. A Bruel & Kjaer (B&K) type 4144 condenser microphone was calibrated using procedures similar to those described by Thomas et al. (1972) but using swept-frequency stimuli rather than discrete, fixed frequencies. The data handling techniques for the preliminary calibrations are described by Russotti et al. (1985). Briefly, the microphone was mounted on a B&K type 4151 artificial ear and then a piston-phone (B&K type 4220) was used to determine the pressure response of the microphone at 250 Hz at normal atmospheric pressure. Next, a B&K type UA 0023 electrostatic actuator was used to determine the frequency response of the microphone from 40 to 14,000 Hz. The signal was generated by a B&K type 1022 signal generator, then passed to a B&K type 4142 microphone calibration apparatus which in turn drove the electrostatic actuator. The microphone response as a function of frequency was digitized (Digital Equipment Company LPS 11) and stored in a Digital Equipment Company PDP 11/34 computer. Next, the microphone with the electrostatic actuator still mounted on it was subjected to various hyperbaric pressures (air) from 1 to 10 atm in a Bethlehem model 615 IP table-top hyperbaric chamber. At several pressures the frequency response of the microphone was again taken with the voltages applied to the actuator being the same as at 1 atm. The microphone response at each pressure was also digitized and the PDP 11/34 then computed and stored the frequency response of the microphone for each pressure. The difference between the response of the microphone at any pressure and the response at 1 atm is a measure of the loss of sound pressure sensitivity of the microphone due to ambient pressure (Mullen, 1972).

Upon completion of the microphone calibrations the apparatus was returned to normal atmospheric pressure, the electrostatic actuator was removed, and the artificial ear configured for earphone calibrations (6 cm3 coupler, B&K DB 0909). Two dozen TDH-39 300-ohm earphones mounted in MX/41-AR cushions were calibrated at ambient pressures of 1 to 10 atm. The frequency and the microphone output were digitized and input to the PDP 11/34. The appropriate, previously stored microphone correction curve was subtracted to yield the true pressure frequency response of the earphone under test.

Other tests run on a small number of B&K 4144 microphones are described below.

Results and discussion of calibrations.

Microphones. The results of the preliminary condenser microphone calibrations were similar to those reported elsewhere for compressed air (Harris, 1980; Thomas et al., 1972). The condenser microphones exhibited a smooth, pressure-related loss of sensitivity during compression and regained sensitivity during decompression. Murry and Sergeant (1971) found that a condenser microphone may require several hours to regain its sensitivity after compression. Consequently, several tests were made of the stability of condenser microphones during and following compression and decompression. In general, if the rate of compression was very high (about 0.5 atm/sec or greater) to some pressure, the microphone response would slowly vary over a period of twenty to thirty minutes but eventually stabilize. When the rate of compression was comparable to that used on manned dives, however, the microphone stabilized within a minute or two of reaching a steady hyperbaric pressure. Consequently, we have adopted the convention of compressing and decompressing microphones at rates of about 2 atm/min. for calibration studies. While this rate is much slower than that permitted by the manufacturer, the results are better. Calibration results during many compression and decompression cycles (to 10 atm) at that rate while using an electrostatic actuator in both compressed air and helium-oxygen produced results that differed by not more than 0.5 dB at any frequency from trial to trial.

The performance of condenser microphones in compressed air, nitrogen-oxygen, and helium-oxygen were compared in another series of calibration studies at pressures up to 10 atm. Although the gas densities differed, the performance of condenser microphones in hyperbaric nitrogen-oxygen and compressed air is generally indistinguishable at pressures at least up to 10 atm.

The frequency response of a condenser microphone in helium-oxygen does vary from its response in compressed air (Thomas et al., 1972). Our results did not differ significantly from their Figures 2 and 5. In any particular gas mixture however, condenser microphones are quite stable and compression-to-compression results are highly repeatable.

Construction techniques can alter the behavior of microphones considerably. Using compressed air, Smith et al. (1990) found that while the behavior of a ceramic microphone was similar to that of a condenser microphone in that both types lose sensitivity under hyperbaric pressure, important differences were found. The condenser microphones used by Thomas et al. (1972) and Smith et al. (1990) exhibited resonance at 4 kHz in compressed air but the ceramic microphone used by Smith et al. (1990) showed a resonance peak at 2 kHz. The differences in the responses of a condenser and a ceramic microphone in compressed air are shown in Figure 2.

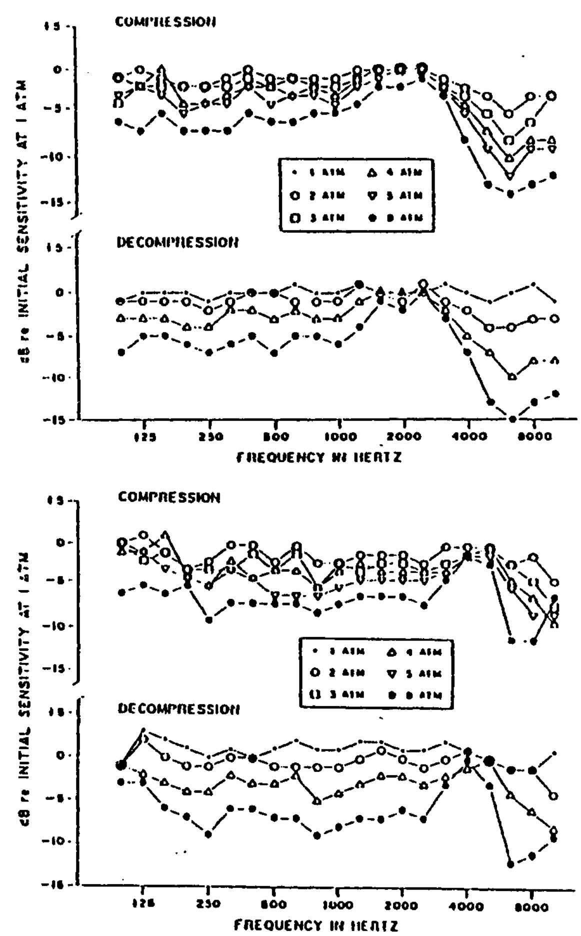

Figure 2: Frequency responses of a condenser microphone (upper panel) and a ceramic microphone (lower panel) relative to their responses at 1 atmosphere absolute before and during compression to, and decompression from 8 atmospheres absolute. From Smith et al. (1990).

In another test, the output of a condenser microphone was monitored during compression in air from 1 to 10 atm while the electrostatic actuator was driving the microphone continuously. For a constant actuator driving voltage, the output of the microphone dropped smoothly with compression. When the actuator drives the microphone during decompression, however, the microphone response may become erratic especially with relatively fast decompression rates. This apparently occurs because, as the pressure within the hyperbaric chamber decreases, the humidity increases and vapor accumulates between the electrostatic actuator and the face of the microphone. Blue arcing between the actuator and the microphone was sometimes observed under those conditions, and it is reasonable to suppose that similar arcing may occur between the diaphragm and the highly-charged back-plate of any condenser microphone. When the microphone is de-energized during decompression and the humidity is permitted to subside, the response of a condenser microphone is very close to its response during compression.

During several experiments over an eight-year period, calibrations have been repeatedly performed in compressed air to 5 atm and in helium-oxygen to 10 atm on the same microphones with remarkable consistency. While the most frequently used microphone shows some signs of aging, the change in its sensitivity at 1 atm has been less than 1 dB at any frequency up to 8000 Hz over a five-year period.

Calibration methods, earphones. While the behavior of condenser microphones was found to be predictable from compression to compression if they are not abused, the behavior of the TDH-39 earphones mounted in MX-41/AR supra-aural cushions bordered on chaotic. Each earphone appeared to have its own peculiar response to changes in ambient pressure and, for many earphones, the frequency response at any given pressure could not be duplicated during subsequent compressions. The frequency response also varied markedly between compressions and decompressions for many phones. Thomas et al. (1974) reported similar erratic behavior for TDH-39 earphones both between earphones and within the same earphone during different pressurization. Whether this variability is due to the earphone, the cushion, or both was not determined.

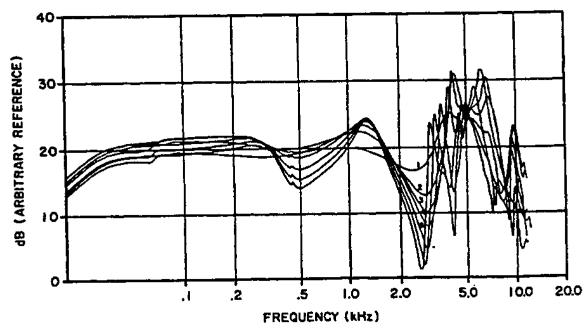

Figure 3. Frequency response of a TDH-39 earphone at several ambient pressures in compressed air. Parameter is pressure in atmospheres absolute.

Continuous, swept-frequency stimuli were used in preliminary earphone calibration experiments. Results for one earphone are shown in Figure 3 for ambient pressures of 1, 2, 3, 4, 6, 8 and 10 atm. As that figure shows, above 2000 Hz a TDH-39 shows resonance peaks and troughs in a coupler at 1 atm (normal atmospheric pressure). In compressed air the resonance peaks and troughs become more pronounced and begin to occur at 350 to 400 Hz. Below the resonance region, earphones produced somewhat greater sound pressures for a constant driving voltage as ambient pressure increased. The overall results indicated that unless precise frequency control is maintained from trial to trial while performing experiments at (supposedly) fixed discrete frequencies (the procedure apparently used by Thomas et al., 1974) the resonances could partially explain the inability to replicate calibrations at 2000 Hz and above.

Occasionally an earphone's coupler response was observed to vary continuously at a fixed ambient pressure. Small vents were drilled into the back case of two TDH-39s but the problem was not solved. As expected, the vent holes reduced the low frequency output of the earphones but did not improve frequency response or stability. The variations of coupler response over time may have been due to gas being slowly absorbed by the MX-41/AR cushion. Changing the cushion usually corrected the problem but new cushions were sometimes more variable than old ones with a history of successful compression/ decompression. Also, new cushions were sometimes observed to distort under pressurization, preventing an adequate cushion to coupler seal. Shrinkage of the cushion diameter also has been observed. All of those factors can affect the performance of an earphone in a coupler or on an ear.

No effort was made to determine the cause of such behavior but it is probably related to the materials and methods used in manufacture of the muffs. While all MX-41/AR cushions are built to a uniform standard and are required to "withstand an oxygen bomb test at a pressure of 300 psi..." there is considerable latitude in material specifications and construction technique (ANSI S3.6-1989) and those can lead to significant performance differences among cushions (Michael and Bienvenue, (1980).

It was obvious that the safest procedure to follow would be to calibrate earphones in situ. In the TTS experiment described below and in several subsequent experiments in compressed air, that was not possible because condenser microphones (the only type available for the experiment) and their preamplifiers are considered to be fire hazard in compressed air environments and usually can not be used on manned hyperbaric operations in this laboratory unless the partial pressure of oxygen is below that capable of sustaining combustion. Instead, the selected earphones were calibrated in a small table-top hyperbaric chamber (Bethlehem, 615 IP) immediately prior to and immediately following an experiment. If there were no significant differences between those two calibrations the experimental results were accepted. Otherwise, the results were discarded.

Four (out of 24) earphones were identified that behaved consistently from trial to trial during discrete frequency calibrations. The output of those earphones varied less that 0.5 dB for a ten percent change in frequency at any half octave from 250 to 8000 Hz in compressed air and, at any frequency, the response from trial to trial (compression to decompression and subsequent compression cycles) varied less than 1.5 dB. Those earphones were used in the TTS experiment described below. As a further precaution, discrete-frequency calibrations were performed with the earphones being driven by the same instrumentation that is used during an experiment to control circuit impedances and because certain instruments, such as clinical audiometers, produce frequencies that may vary considerably from nominal settings.

When using variable oscillators as signal sources, frequencies are controlled to within 1 Hz by using calibrated frequency counters.

IV. An Experiment on Temporary Threshold Shift:

Purpose of preliminary studies. The purpose of the work reported below was to refine measurement procedures to be used in subsequent research. Specific goals were to develop means of insuring accurate calibrations of microphones and earphones in hyperbaric environments, to determine the feasibility of measuring valid auditory thresholds in the NSMRL hyperbaric facility, and to obtain preliminary data bearing on the role of the acoustic impedance of the diving medium in noise exposure.

Research approach. The studies reviewed in the introduction demonstrate that a noise hazard of some magnitude exists in dry diving operations, but the magnitude of the hazard is not quantified. Because the relationship between TTS and permanent threshold shift (PTS) is uncertain, one can not assert that the TTS following a noise exposure predicts how much PTS will occur with routine exposure to that noise. There is no universally agreed upon magnitude of TTS that defines the border between "safe" and hazardous exposures. Furthermore, noise exposures producing no measurable TTS can produce other disturbing effects on the ear (Champlin, 1987).

Under some circumstances TTS can be used as a relative measure of noise hazard, however. If the frequency spectrum and intensity of two noises to which the same group of subjects are exposed are exactly the same, the conditions under which ears incur more (or less) TTS can be taken as the more (or less) hazardous condition without making any assumptions about "absolute" hazards. As a trivial example, if an exposure to a particular noise for ten minutes produces greater TTS than does exposure to that noise for five minutes, one may reasonably conclude that the ten minute exposure is more hazardous than the five minute exposure. Similarly, if workers exposed to a tone or narrow band noise while wearing ear protectors incur less TTS than they do when exposed to the same stimulus under the same conditions but not wearing ear protectors it is reasonable to conclude that the "ear protected" condition is the less hazardous condition. By extension, if a ten minute exposure to a narrow band noise while wearing ear protectors produces the same amount of TTS as a five minute exposure to the same stimulus without muffs, those two exposure conditions may be considered (with caution) as equivalently hazardous.

That basic rationale underlies the work reported here; that is, TTSs induced by brief noise exposures in diving environments are compared to the TTSs induced by comparable stimuli in normal atmospheric (normobaric) conditions. A range of intensities (at least two) is applied in at least one environment with the aim of being able to interpolate equivalence of noise hazard. Once equivalence is established, existing hearing-conservation guidance may be translated to regulate noise exposure in diving environments (Smith et al., 1970). In the present research, brief exposures that are close to the maximum permissible daily noise dose at 1 atm (OPNAVINST 5100.23B, Chapter 18) were used as the standard against which TTS induced by comparable exposures in diving environments will be assessed.

Method

Subjects. The subjects in this experiment were six experienced Navy divers who had volunteered for a saturation diving experiment. One subject had a hearing level (HL) of 10 dB at 3 kHz and 20 to 25 dB at 4.0 kHz in the ear used (one only) in this experiment. The other subjects had HLs not in excess of 5 dB at 3 and 4 kHz in the ears used in this experiment. One subject, who had normal hearing in one ear but a severe impairment in the other, declined to participate in the TTS experiment but he did serve as a sham subject. That is, during the exposure period no fatiguer was delivered to the earphone.

Choice of stimuli. Comparisons of the effects of "real-world" noises on the ears would be difficult to make in the present research because the spectra of noises such as are produced by gas-flow or tools are generally complex and may vary with environmental conditions. Also, the frequency response of the ear may be altered in diving environments, and the ear's response may differ in different media (compressed air vs helium-oxygen, for example, Adolfson and Berghage, 1974; Molvaer et al., 1982; Smith, 1984). It is essential that stimulus conditions be used that are directly comparable across environments.

Appropriate comparisons can be made if the stimuli are as simple as possible. Thus, in this research the exposure stimuli are pure tones which may be precisely controlled in both frequency and amplitude.

A pure tone at 80 to 110 dB L_p re 20 μPa in normobaric air produces maximum TTS at a frequency one-half octave above the frequency of the fatiguing tone (Hirsch and Bilger, 1955). By observing TTS resulting from the separate application of fatiguing tones at several frequencies throughout the auditory frequency range, one may discover, for each frequency and diving environment, equally noxious exposure conditions. Those results may be then be combined to generate frequency-weighted curves (damage risk criteria) that may be used to assess broad-band noise hazards in each diving environment (Smith et al., 1970).

Apparatus. The fatiguing tone (2.828 kHz) was generated by a Hewlett-Packard model 204C oscillator. The level of the fatiguer was controlled by a Daven Type H-693-R attenuator network with a 0.1 dB resolution. The auditory test-tone (4.0 kHz) was taken from a GenRad 1309-A oscillator, and was turned on and off by a Grason-Stadler 829E electronic switch (50% duty cycle, 500 millisecond period, 10 msec rise/fall time) and passed through a Grason-Stadler E 3262A recording attenuator. Either the fatiguing-tone or the test-tone could be selected by switch for delivery to a TDH-39 earphone mounted in an MX-41/AR cushion and an Amplivox Audiocup circumaural muff. A Ballantine Model 643 Vacuum Tube Voltmeter and a Hewlett-Packard 5512A Electronic counter were used to measure stimulus voltages and frequencies.

The headset and the recording attenuator response button were located in the hyperbaric chamber and were connected to the apparatus though a shielded cable pass-through. All exposures were administered in the inner lock of a double-lock hyperbaric chamber (NSMRL Chamber #1. See Fig. 4 in Sergeant, 1975). Audiograms were taken in a certified audiometric booth using a Tracoustics RA-410-N audiometer.

Procedure. The subjects were run in two, three-man groups on two separate saturation dives at a simulated depth of 65 feet of sea water (nominally, 3 atm). During the first two days of each dive the chamber remained pressurized at 3 atm. TTS data were taken on the second day.

Audiograms were taken in a standard clinical setting one day prior to the beginning of the experiment. On that day also, subjects were instructed on the procedure and given brief training in threshold tracing with a recording attenuator. Audiograms were also taken on two separate days following the dive.

TTS was measured for four exposure conditions. Before the simulated dive the first condition (100 dB re 20 μPa) was run in the hyperbaric chamber with the hatch closed but at normal atmospheric pressure (1 atm). Pre-exposure thresholds at 4 kHz were measured for five minutes. This duration provided the subjects with further training on tracing thresholds at a single frequency over an extended time period and gave the experimenter the opportunity to intervene should any subject appear to need re-instruction on the threshold tracing task (one did). Then, the fatiguing tone (2.828 kHz at 100 dB re 20 μPa) was turned on for five minutes following which threshold at 4 kHz was again measured for five minutes. Following five minutes in silence, threshold testing resumed for an additional five minutes. In subsequent experimental sessions pre-noise-exposure thresholds were measured for one minute or any longer duration required to assure that a stable baseline had been established. The post-exposure quiet period following the initial post-exposure threshold measurement and subsequent threshold

Table I. Comparison of threshold sound pressure levels (L_p) measured in a clinical setting and within the hyperbaric chamber. Hearing levels (HL) measured with the RA-410N audiometer were measured in 5 dB increments and were converted to L_p by comparing HLs with the L_ps determined during audiometer calibrations. Threshold L_ps determined in the hyperbaric chamber are based upon calibrations of that system and are rounded to the nearest 1 dB. Both sets of thresholds are based upon the mean of three tests for each subject within each setting. The first "Change" column is the difference between thresholds measured in the clinical setting using the RA-410N and those measured within the hyperbaric chamber a 1 atm using the experimental apparatus. Only one threshold determination was made at 3 atm for each subject. The last column shows the differences between threshold L_ps in the hyperbaric chamber at 3 atm and those at 1 atm. All entries are rounded to the nearest 1 dB. All L_ps are re 20 μPa.

Subject	RA-410N HL	RA-410N L_p	Chamber L_p 1 atm	Change dB	Chamber L_p 3 atm	Change dB
1	22	32	27	5	31	4
2	0	10	9	1	16	7
3	3	13	14	-1	25	11
4	8	18	13	5	33	20
5	3	13	10	3	21	11
6	10	20	20	0	23	3
Means s.d	7.6	17.6 7.92	15.5 6.83	2.2	24.8 6.34	9.3

measurements were eliminated for the third and fourth experimental conditions.

The second exposure (100 dB re 20 μPa, 3 atm) was administered on the second day following compression to 3 atm. Immediately upon return to 1 atm (several days later) the subjects were taken for complete audiograms on both ears and calibration checks were run on the earphone. The third exposure (100 dB re 20 μPa at 1 atm) was done about eighteen hours after the subjects returned to normobaric conditions. The fourth and final exposure (95 dB re 20 dB re 20 μPa at 1 atm) was administered a few days later. Finally, all divers were again examined administered audiograms prior to release from the laboratory.

During the experiments persons not involved in the tests or in operating the hyperbaric chamber were excluded from the chamber control room. Chamber lights were turned off because blowers used for cooling the lights make noise. After establishing acceptable environmental conditions within the chamber the life-support system was secured. Noise levels were sampled at several points outside of the chamber throughout the experiment.

Results and Discussion. Comparisons of post-dive with pre-dive audiograms revealed that no audiometric changes greater than 5 dB HL occurred for any ear at any frequency that could be attributable to the simulated saturation dive or to this experiment. One diver exhibited an apparent 20 dB loss at 4 kHz in his right ear. He complained of hearing voices from outside the test booth during his third clinical test but declined to be re-tested. That subject's left ear had been used in the TTS experiment.

The mean of three HLs at 4 kHz measured with the RA-410-N for each of the six divers' test ears (both groups) are shown in the first column of table I (RA-410-N, HL). The next column gives the clinical results expressed in L_p. Pre-noise-exposure threshold L_ps (mean of three) at 4 kHz measured in the hyperbaric chamber at 1 atm are given in the column under "Chamber L_p, 1 atm" in Table I. Those data indicate that at least for the 1 atm conditions, valid threshold measurements were obtained in the hyperbaric chamber.

Table I also presents the pre-exposure thresholds measured at 3 atm (column labeled "Chamber L_p, 3 atm"). The differences between those data and the mean of the three threshold measurements in the chamber at 1 atm is statistically significant (mean difference, 9.3 dB, $t = 3.67$, $p. < 0.02$, two-tailed test). That "loss" of sound pressure sensitivity corresponds to depth related changes in audiometric thresholds measured at 4 atm by Fluur and Adolfson (1966). Thus, it appears that the TTSs observed in this experiment at 1 atm certainly, and probably also at 3 atm, were not contaminated by the presence of masking noise.

Inadvertently, the calibration data used to establish the exposure level for the first three subjects (subject 1, 2, and 3; group 1) for both the 1 atm and 3 atm conditions, were taken from results that were not corrected for microphone frequency response. The result of that error was that the exposure L_ps re 20 μPa at 1 atm were 101.5 dB for exposures 1 and 3, and 96.5 dB for exposure 4. The exposure L_p re 20 μPa at 3 atm was 98.3 dB for exposure 2. The correct calibration curves were used to compute the thresholds L_ps in Table I.

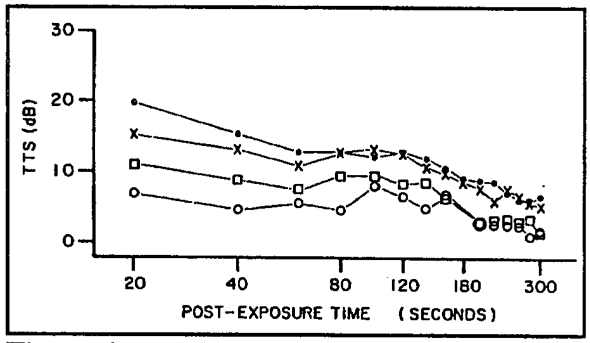

Figure 4 : Mean (n=3) Temporary auditory-threshold shift at 20 second intervals following five-minute exposures to a 2.828 kHz fatiguing tone. Dots: pre-dive exposure, 1 atm, 101.5 dB; X's: post-dive exposure, 1 atm, 101.5 dB; Squares: post-dive exposure, 1 atm, 96.5 dB; Circles: exposure in compressed air, 2.96 atm, 92.3 dB. All sound pressure levels are reference 20 μPa. n=3.

TTS (at 20 sec. intervals) was computed by subtracting pre-exposure thresholds from post-exposure thresholds. The mean threshold shifts are plotted in Fig. 4. Results for all three divers within group 1 were consistent with the mean TTS for all conditions.

The differences shown in Fig. 4 between the two 101.5 dB, 1 atm conditions at 20 and 40 seconds post-exposure are perhaps due to learning. That is, subjects may have learned to more quickly achieve threshold. However, from 60 seconds post-exposure onward those two curves do not differ from each other significantly. The mean TTS at two minutes post exposure (TTS_2) was 12.5 dB for both 101.5 dB exposures. The 96.5 dB exposure at 1 atm produced a TTS_2 of 9.5 dB. The exposure at 3 atm (98.3 dB) produced

Table II. Results of the second temporary auditory-threshold shift experiment. Table entries are the temporary auditory-threshold shifts at 4000 hertz existing two minutes after exposure to pure tones at 2828 hertz. All L_ps are re 20 μPa.

Pressure L_p	Before dive 1 atm 100 dB	After dive 1 atm 100 dB	After dive 1 atm 95 dB	During dive 2.96 atm 100 dB
Subject				
4	14	13	10	7
5	15	15	12	15
Means	14.5	14.0	11.0	11.0

consistently less TTS than the 96.5 dB exposure at 1 atm until 160 seconds after the exposure. Beyond that post-exposure duration both recovery curves are essentially identical and close to full recovery. All three subjects incurred less TTS at 3 atm (mean TTS_2 was about 8.0 dB) than for the either exposure level at 1 atm.

The second group of three divers (subjects 4, 5, and 6) were run under the same conditions but using the correct calibration data. Since only two subjects provided TTS data, the results are shown in tabular form in Table II. Recovery trends for those two subjects were highly similar to those for Group 1.

Subject 6, the sham subject, exhibited no TTS under any condition. As did the three subjects in Group 1, Subject 4 suffered less TTS from exposure to 100 dB at 3 atm than he did from the 95 dB exposure at 1 atm. Subject 5 however, incurred the same TTS at 3 atm as he did at 1 atm for the 100 dB exposure.

V. General Discussion and Conclusions.

The specific goals of these preliminary studies were to develop means of insuring accurate calibrations of microphones and earphones in hyperbaric environments, to determine the feasibility of measuring valid auditory thresholds in the NSMRL hyperbaric facility, and to obtain preliminary data bearing on the role of the acoustic impedance of the diving medium in noise exposure (Smith, 1984). Each of these topics will be discussed further.

1. Calibrations of microphones and earphones in hyperbaric environments:

The results of the microphone calibrations were not different from those reported by many other investigators and the electrostatic calibration procedure is simple and reliable. The results over several studies are so consistent (Harris, 1980, Mullen, 1972; Thomas et al., 1972), that one may safely use a microphone that has been recently calibrated during a prior compression. Subsequent experience over a five-year period showed no important change in microphone performance that could not be detected in routine re-calibrations. It is concluded that, providing care is used in handling them, and calibrations are performed in suitable gas (their frequency response is not the same in compressed air as in helium-oxygen), it should not be necessary to fully calibrate condenser microphones in diving environments more than once a year provided pre- and post-dive piston-phone calibrations show no change.

However, condenser microphones often can not be used in compressed air and there is no simple method for calibrating ceramic microphones in compressed air. Smith et al. (1990) compared the performance of a condenser microphone and a ceramic microphone with that of a miniature hydrophone in a diffuse sound field in compressed air. They found that the two microphones perform similarly (but with important differences in detail) in a diffuse sound field in compressed air. It is likely that they would exhibit similar performance in an earphone coupler.

There is no reason to suppose that ceramic microphones would be any less reliable than condenser microphones. In fact, quality ceramic microphones are usually more rugged than condenser microphones. Sergeant and Murry (1971) reported them to be more reliable than either condenser or pressure-gradient microphones. Since ceramic microphones are relatively inexpensive, their use for routine noise measurements in all hyperbaric environments should be investigated. Studies should be undertaken to determine the performance of ceramic microphones in compressed air environments and to develop reliable transfer calibration techniques for them.

By examining the performance of a large selection of earphones it was possible to identify a small number (4 of 24 phones) that behaved well from compression to compression. Because calibrations after the experiment reproduced those before the experiment we have some confidence that the exposure levels during the TTS experiment were as shown in Figure 1 despite the paper error that occurred. However, with in situ calibrations one need be less concerned that the earphone's response has changed. The use of Telephonics type 51 ear phone cushions in place of the MX-41 ought to reduce the variability of earphone response under hyperbaric conditions. At the cost of possibly losing data for an entire experiment if pre- and post- experiment calibrations fail to agree, the procedure used here (careful selection and calibration of earphones) may be relied upon until more satisfactory instrumentation can be arranged.

2. Determine the feasibility of measuring valid auditory thresholds in the NSMRL hyperbaric facility:

Because noise levels within the chamber at 3 atm could not be measured directly it is impossible to argue rigorously that the apparent elevation of thresholds shown in Table I and the reduction in TTS at 3 atm. shown in Fig. 2 did not result from increased masking. Noise levels were measured in the control room outside the chamber. The largest contributor to noise levels outside the chamber was the mechanism of the recording attenuator. That noise was audible to the divers within the chamber both at 1 atm and at 3 atm. But the major sources of noise that the subjects may experience during a simulated dive may be within the chamber (the subjects themselves). Again, ascertaining ambient noise levels can only be done by installing calibrated microphones within the chamber and monitoring noise levels at the time data are being taken. Also, noise producing apparatus such as the recording attenuator should be eliminated from the vicinity of the hyperbaric chamber.

The ambient noise within the chamber at 1 atm was lower at 4 kHz (octave band level of 28 dB re 20 μPa) than is permitted in clinical audiometric booths (42 dB, ANSI S3.1-1977), but at lower frequencies the ANSI levels were exceeded. It was demonstrated that with minimal precaution, valid auditory threshold measurements can be obtained in the NSMRL hyperbaric chamber at 4 kHz at 1 atm. Stringent measures have been instituted to achieve lower ambient noise levels for future experiments.

3. To obtain preliminary data bearing on the role of the acoustic impedance of the diving medium in noise exposure:

A potentially important result of the first TTS experiment (Group 1) was that the fatiguing stimulus at 3 atm (2.828 kHz at 98.3 dB L_p for five minutes) produced consistently smaller amounts of TTS than did a fatiguer at 96.5 dB L_p at 1 atm for all three divers. Thus, it might be concluded that the ear is less sensitive to noise in compressed air than it is in normobaric air. But first, let's consider other aspects of the auditory stimulus related to the characteristic impedances involved.

The velocity of sound does not vary much in compressed air, so Z_h can be expressed directly in terms of ambient pressure with little error. Thus, in the experiments in compressed air at 3 atm, equation (7a) yields

$$C_z = 10 \log 1/3 = -4.8 \text{ dB}.$$

That is, for a given L_p at 3 atm, the L_i is 4.8 dB lower than the intensity of that same L_p measured at 1 atm. If the ear responds to intensity rather than sound pressure then the results in Fig. 4 simply reflect differences in fatiguer intensities. For Group 2, the exposure to 100 dB L_p at 3 atm had approximately the same intensity (L_i = 100 - 4.8 dB) as the exposure to 95 dB L_p at 1 atm. but as has been seen, those results are contradictory. One diver behaved liked the Group 1 divers but one didn't.

For the small changes in TTS that can be expected over a range of fatiguing intensities such as used here, it is obvious that large groups of subjects, run under identical experimental conditions, are required. Also, the amount of TTS produced at 3 atm was quite small suggesting that higher exposure levels should be used in future experiments. For future experiments, therefore, stimulus levels will be equated in terms of L_i. It is concluded, tentatively, the noise exposure in compressed air should be evaluated in terms of L_i rather than L_p.

The thresholds shown in Table I are interesting in that the mean (n = 6) elevation in threshold L_p at 3 atm was about 9.3 dB. If -4.8 dB (the correction for impedance, 10 log (Z_a/Z_h)) is added to that result, a difference in mean threshold L_i of about 4-5 dB remains to be explained. But if the thresholds are expressed in terms of equation (8), mean L_u = mean L_h - 9.6 dB, and the difference between mean L_u at 1 atm and at 3 atm is practically zero. That is, mean threshold particle velocity level is not affected by immersion of the ear in compressed air. It remains to be seen if this result, which has implications for auditory theory, will be replicated in future experiments at other frequencies and in other diving environments. However, it is tempting to conclude that the performance of the ear at 4 kHz is not degraded in compressed air at 3 atm. The ear responds to particle velocity (or particle displacement) just as is does in normobaric conditions.

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The Navy needs to control noise exposure in hyperbaric chambers and diving helmets but the applicability of existing hearing-conservation standards to those environments is uncertain. Consequently, a program of research has been undertaken to develop suitable control measures. The specific goals of the research described in this report were to develop means of insuring accurate calibrations of microphones and earphones in hyperbaric environments, to determine the feasibility of measuring valid auditory thresholds in the NSMRL hyperbaric facility, and to obtain preliminary data bearing on the effects of noise in compressed air on the ear. Condenser microphones were calibrated in compressed air to 10 atmospheres and the results were highly similar to previous studies. Providing care is used in handling them, and calibration are preformed in suitable gas it should not be necessary to calibrate condenser microphones in diving environments more than once a year for routine noise measurement (sound survey) purposes. Calibration studies should be undertaken to determine the

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performance of ceramic microphones that are less expensive and more rugged than condenser microphones for use in compressed air environments. Several earphones were also calibrated in compressed air but the results were not consistent for most earphones and instrumentation for in situ calibration of earphones on each dive should be developed. However, careful selection of earphones and pre- and post experiment calibrations may be relied upon for experiments in compressed air. It was demonstrated that with minimal precaution, valid auditory threshold measurements can be obtained in the NSMRL hyperbaric chamber. The ear appears to be less sensitive to noise in compressed air at 3 atm than it is in air at 1 atm if sound is measured in terms of sound pressure. However, the results suggest that the ear does not respond to sound pressure as is commonly thought, but to other properties of sound such as particle displacement or particle velocity. Present hearing-conservation regulations appear to be overly conservative for direct application of noise exposure in compressed air environments.