

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

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REPORT NUMBER 923

HEARING AND UNDERWATER NOISE EXPOSURE

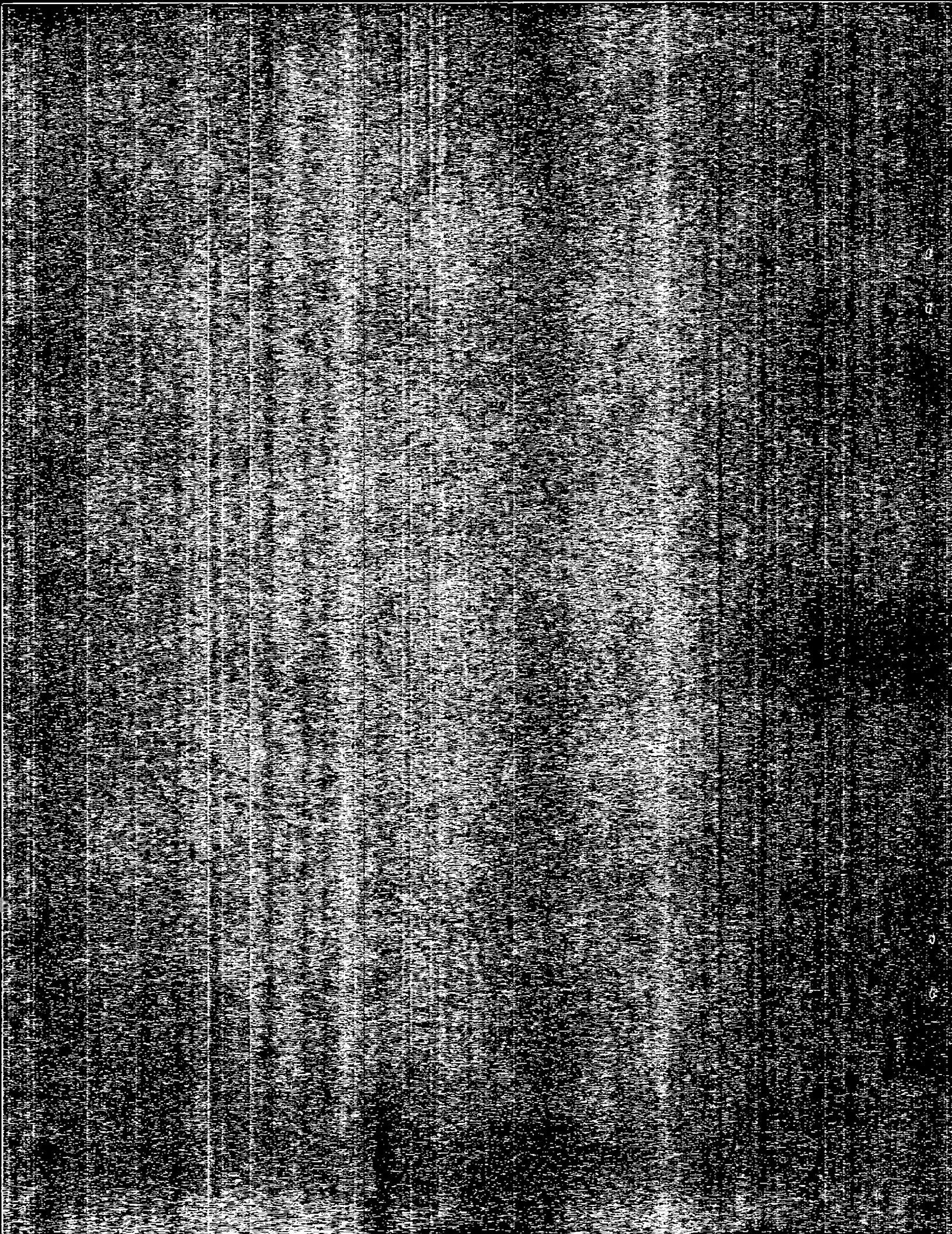
by

Paul F. Smith

Naval Medical Research and Development Command
Research Work Unit M0099, PN-003-3155

Released by:

Claude A. Harvey, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory
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Paul F. Smith

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

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SUMMARY PAGE

THE PROBLEM

To review existing auditory theories and experimental evidence on hearing in water in order to determine whether sufficient information exists to establish a hearing-conservation standard to control exposure of divers to intense noise in water.

FINDINGS

No adequate theoretical basis exists for generalizing hearing conservation standards that govern noise exposure in air to control noise exposure in water. Existing empirical evidence is too scant to predict what levels of underwater noise would be safe for divers except within the 1500 to 3500 Hertz frequency range. Further research is required to establish a general hearing-conservation standard for underwater noise exposure. Such research could follow paradigms used to establish damage risk criteria for exposure to noise in air. However, investigators should be alert to the possibility that other organ systems than the ear may be at risk since sound in water is more readily communicated to them than is the case in air. Furthermore, some interference with the performance of diving tasks may accompany exposure to intense sound in water.

APPLICATIONS

These findings contribute toward the establishment of a general hearing conservation standard governing the exposure of Navy divers to intense sound in water.

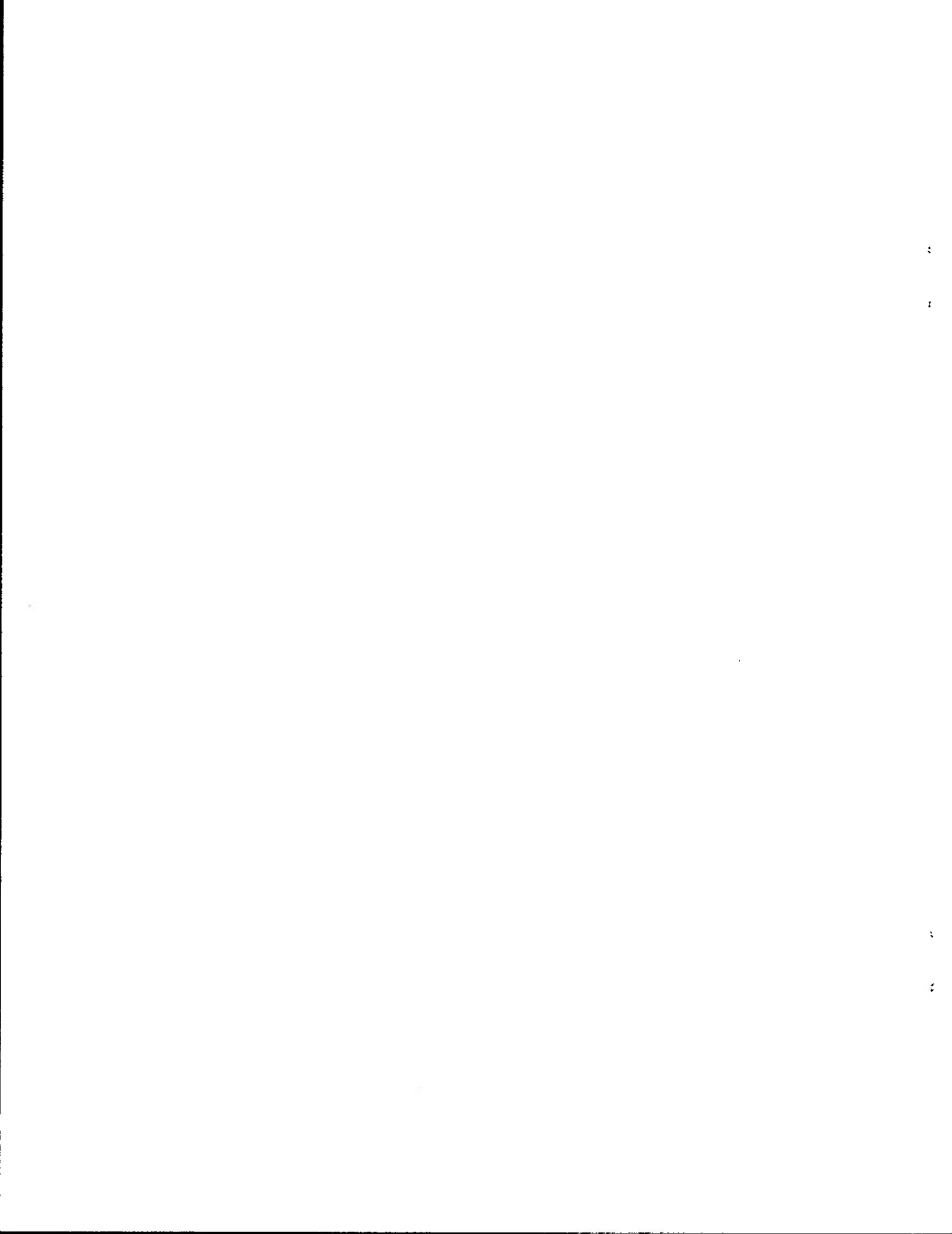
ADMINISTRATIVE INFORMATION

This investigation was conducted as part of Naval Medical Research and Development Command Research Work Unit Number M0099.PN.003-3155 -"The Effects of whole body exposure to underwater sound on the health of Navy divers." The present report was submitted for review on 6 August 1985, approved for publication on 27 August 1985 and designated as NavSubMedRschLab Report Number 923.

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ABSTRACT

Exposure of divers to intense noise in water is increasing, yet no general hearing conservation standard for such exposures exists. This paper reviews three theories of underwater hearing as well as empirical data in order to identify some requirements that an underwater hearing conservation standard must meet. Among the problems considered are hearing sensitivity in water, the frequency and dynamic ranges of the water-immersed ear, and nonauditory effects of underwater sound. It is concluded that: first, no well developed theoretical basis exists for extrapolating hearing conservation standards for airborne noise to the underwater situation; second, the empirical data on underwater hearing suggest that the frequency range covered by an underwater hearing conservation standard must be much broader than is the case in air; third, in order to establish a general hearing conservation standard for underwater noise exposure further research is required on the dynamic range of the ear in water; fourth, underwater noise exposure may involve hazards to other body systems than the ear; and fifth, some noise exposure conditions may interfere with job performance of divers.



INTRODUCTION

Continuing developments in underwater sound technology are converting the "Silent World" to a rather noisy work environment (National Research Council, 1970). Several acoustic devices and noisy tools are used in diving activities while other sound sources, having uses unrelated to diving, are often operated in areas where divers are working. For example, in many installations, Navy divers and swimmers are routinely exposed to sonar transmissions from a variety of large-scale systems undergoing in-port testing. Seismic profilers used in off-shore oil exploration commonly use compressed air guns (Boomers) that have source levels of 200 decibels (dB) above 20 micropascals¹. Furthermore, new underwater power tools such as jet cleaning tools, rock drills, and stud guns are extremely noisy (Molvaer & Gjestland, 1981; Mittleman, 1976). With few exceptions, the potential for noise from such sources to damage hearing has not been assessed.

The development and use of acoustic means of tracking divers has resulted in additional noise exposure. Some tracking systems require divers to wear small but powerful sound transmitters. One such device developed by the U.S. Navy uses a diver-carried "pinger" that produces two to six pulses per second of a 29 to 45 kilohertz (kHz) signal at a sound pressure level (SPL) of 124 dB (measured at 1 yard, Mullen, 1966). More recently, a similar but much more powerful system has been under development (Gill & Gardner, 1978). Called the Portable Acoustic Tracking System (PATS), the latter system would require a diver to carry a transducer that produces a 31.25 kHz signal at a power output of 100 acoustic watts. A request for recommendations concerning the safety of the PATS led to a review of existing research on the effects of intense sound in water on divers (Rooney, 1979; Smith & Hunter, 1979). This report is one additional result of that effort and considers requirements for establishing a general hearing conservation standard for underwater noise exposure.

THEORIES OF UNDERWATER HEARING IN MAN

In this review, three theories of underwater hearing will be discussed. One, called the "tympanic" theory was developed by Bauer (1970). He states that underwater hearing is accomplished in essentially the same way as hearing in air. That is, sound enters the ear canal and vibrates the tympanic membrane with consequent transmission of the sound to the cochlea through the ossicular chain. However, because the human ear is adapted (impedance matched) to function in air, and because the characteristic acoustic impedance of water is much greater than that of air, a large impedance mismatch exists between the water and the immersed ear. Consequently, the human ear is not as sensitive to water-borne sound as to air-borne sound, the loss of sensitivity being frequency dependent. Bauer's model predicts no loss of sensitivity at 100 Hz but an

¹. All sound pressure levels, regardless of medium, are referred to 20 micropascals.

almost linear drop in sensitivity of about 12 dB per octave as frequency increases from 100 Hz to 5000 Hz.

A second theory is the "bone-conduction" theory of Reysenbach de Haan (1956), which states that because the impedance of soft tissue is very close to that of water and because the impedance of the skull is not much greater, sound is readily transmitted from water to the cochlea through these tissues, bypassing the acoustically inefficient tympanic route. That is, the ear canal is acoustically transparent in water, and man's ossicular chain is not effective in water primarily because the ossicles lack sufficient mass. Further, because of cross conduction through the skull, the two cochleae are not independently stimulated underwater as they are in air. Hence, sound localization is not possible for man in water.

The third theory is the "dual-path" theory of Sivian (1947), who theorized that underwater hearing in man is mediated by both tympanic and bone conduction mechanisms that are of approximately equal sensitivity at 1000 hertz (Hz). At other frequencies, one or the other of the two paths may predominate. One implication of the dual-path theory is that given two equally efficient routes by which underwater acoustic energy reaches the cochlea, a deficit in only one route may not result in deficient underwater hearing. Also, in some circumstances, these two mechanisms may interact.

The experimental evidence bearing on these three theories has been reviewed in detail by Smith (1969), Harris (1973), and Adolfson and Berghage (1974) among others. Hence, only a very brief summary is necessary here in order to examine the implications of existing theory and the available supporting evidence for underwater hearing conservation. We shall consider first the means by which the cochlea is stimulated, then, the frequency and dynamic ranges of the water-immersed ear.

MECHANISM OF UNDERWATER HEARING IN MAN

A number of early studies of underwater hearing in man have shown that the water-immersed ear is less sensitive than the ear in air in the 125 to 8000 Hz frequency region; that the greatest difference in sensitivity occurs at those frequencies at which the ear is most sensitive in air; and that the underwater audiometric function is rather flat in comparison to that in air (Reysenbach de Haan, 1956; Hamilton, 1957; Wainwright, 1958; Montague & Strickland, 1961). Consequently, those authors concluded that underwater hearing in man is predominantly bone-conduction hearing. Alternative explanations of those results have also been offered in terms of the "tympanic theory", however. For example, Bauer's model describes the data from some of these studies. Bennett (1962) also supported the tympanic theory when he suggested that, whether in air or in water, the ear responds to particle velocity rather than to sound pressure. In Bennett's view, the middle ear acts as a

mechanical transformer that transforms ear-drum velocity to pressure in the cochlea. He stated that the particle velocity at threshold was the same in air as in water under the conditions of the Montague and Strickland experiment. Bennett suggested that the major apparent change in thresholds measured by Montague and Strickland may be attributed to the use of a velocity sensitive device in media of different impedances. Thus none of these early studies provide unambiguous evidence concerning mechanisms.

The dual-path theory of underwater hearing received partial confirmation in experiments by Smith (1965, 1969) in which it was found that divers with depressed "tympanic" hearing thresholds (conductive losses) but normal bone conduction thresholds at 6 and 8 kHz showed no loss of underwater hearing sensitivity in comparison to divers with normal hearing threshold levels for both pathways. That finding, of course, is also consistent with the bone-conduction theory and has been taken as evidence by other writers (Harris, 1973; Hollien, 1973) that underwater hearing is mediated by a bone-conduction mechanism. Clearly, while the "tympanic" route may or may not play some role in underwater hearing, bone conduction is certainly important at least at the higher frequencies. No theory that fails to include a bone-conduction mode can explain Smith's results.

Nevertheless, it seems improbable that bone conduction is the only mechanism by which energy reaches the cochlea from the water. If the tympanic route were not functional in water, then divers should not be able to detect differences in the direction from which a sound emanates (Reysenbach de Haan, 1956). The view that localization was not possible under water was widely held (Harris, 1973; Hollien 1973; Adolfson & Berghage, 1974), although anthropological material offered by Firth (1966) and others (Parry, 1954; Tham Akow, 1949) seemed to indicate that sound localization by man under water not only is possible, but is quite accurate. The fish-listening juru-selam in Kelantan and Trengganu on the east coast of Malaya were apparently very successful in locating schools of fish by diving beneath the surface and listening. Some juru-selam were reputed to be able to not only detect the location of a school of fish but to be able to estimate the course that the school was following.

Being strongly committed to a bone-conduction theory of underwater hearing, Hollien (1973), despite prior experimental evidence (Ide, 1944; Feinstein, 1966; Andersen & Christensen, 1969; Leggiere et al., 1970) was surprised that his subjects could perform above chance level on an underwater auditory localization task. In subsequent experiments by Hollien's group, Feinstein (1973) demonstrated that the mean minimum audible angle under water is about 7.3 degrees for white-noise sources. Though localization in water is not as precise as in air, the difference in accuracy is largely explained by the difference in the velocity of sound in the two media. This

finding, which has been independently confirmed (Smith, et al., 1974), may not necessarily imply that the tympanic pathway contributes in some way to underwater hearing, but a plausible explanation of how precise auditory localization by bone conduction might be possible has not yet been proposed.

Andersen and Christensen doubt that inertial or compressional bone-conduction mechanisms could explain their underwater sound-localization data, but they state that the osseotympanic route might play a role. (See Naunton, 1967, for a discussion of these bone-conduction mechanisms and Harris (1973) for a discussion of how such mechanisms may relate to hearing in water). Hollien restates the bone-conduction theory in terms of "force and amplitude relationships" and denies that the external auditory mechanisms can play an effective role in underwater hearing. He speculates on various bone-conduction mechanisms that might account for underwater localization but he is unable to make a definitive statement. Also, Harris, citing other theoretical and experimental research on hearing by bone conduction, argues that when the skull is ensonified in water, sufficient time and intensity disparities may exist at the two cochleae to permit auditory localization by bone-conduction mechanisms. His argument is tenuous, however, and as he states, the data have outstripped theory.

The earliest experimental evidence that the tympanic path does play some role in underwater hearing was provided by Ide (1944). On the assumption that Sivian's dual-path hypothesis was correct, Ide reasoned that, "Sound received through areas midway between the ears, particularly the top and back of the head, can have no directional character but does contribute to the overall loudness." Thus, the sound reaching the inner ear by the tympanic route is to some extent masked by the sound arriving via the bone-conduction route. Ide found that the divers' binaural sensation was enhanced when they wore a four-inch wide strip of half-inch thick sponge rubber running mid-sagittally over the top of the head from the forehead to the base of the skull. Without the use of such a device, all underwater sounds initially appeared to Ide's subjects to originate directly overhead. Remarkably, Ide found that many of his divers could localize under water without the use of the rubber strip after only brief training with it. Ide concluded that the sponge rubber reduced the masking effect of the bone-conducted sound permitting the interaural disparity in the tympanic pathways to be utilized by the divers. Norman et al. (1971) have reported that neoprene patches over the ears of otherwise bare-headed divers reduced the accuracy of underwater auditory localization from that obtained for bare-headed divers, although these same patches had little effect on hearing sensitivity. One diver with a single patch over his right ear reported that the stimuli had all appeared to come from his left side. This finding complements Ide's and lends further support to the dual-path hypothesis of Sivian.

Apparently, therefore, a dual path theory is required to explain all of the underwater hearing data. Unfortunately, since the dual path theory is not well developed, and since the tympanic and bone conduction theories are clearly inadequate, no acceptable theoretical basis exists for transposing present hearing-conservation standards to the underwater situation. In any case, the partial theories of underwater hearing that have been offered are restricted to predicting hearing threshold levels in the 125 to 8000 Hz frequency range. They do not deal with such matters as the overall frequency and dynamic ranges of the water-immersed ear.

Thus, additional empirical evidence must be considered in order to determine in what important respects hearing in water differs from hearing in air. From a hearing conservation point of view, two important factors need to be considered. Hearing in water and air may differ in the range of frequencies to which the ear is sensitive and secondly, in the range of intensities that the ear can process at a given frequency (the dynamic range of the ear). These are treated separately below.

FREQUENCY RANGE OF THE EAR IN WATER

A number of experiments on underwater hearing sensitivity are summarized in the earlier cited reviews. In general, agreement among the experiments is very poor. The Hollien group's results, however, have been repeatedly reproduced (Brandt & Hollien, 1967; Brandt, 1967; Hollien & Brandt, 1969) and may be taken as representative of normative hearing threshold levels for the frequencies tested. Brandt and Hollien found that, for their subjects, the differences between water-conduction and air-conduction threshold sound pressure levels ranged from 18 dB at 125 Hz to 56 dB at 8000 Hz.

Comparisons of auditory-threshold levels in air and water in terms of SPL, though common in the literature, are misleading since the characteristic acoustic impedances of the media are ignored. The impedances are taken into account by converting sound pressure measurements to intensity. The data shown in Figure 1 are from Brandt and Hollien (1967) and Smith (1969) plotted to yield differences in auditory-threshold intensity levels in water and in air as a function of frequency. Since neither study reports thresholds in air for the experimental subjects in terms of minimum-audible-field (MAF), the underwater MAF data are compared with binaural MAF-air values given in Licklider's (1951) figure 5. Comparisons could as well have been made with ISO standard R226 (International Organization for Standardization, 1961). However, the ISO data have been questioned by Berger (1981) especially for low frequencies. Either comparison leads to similar conclusions, however.

Although Smith's data for 31 and 62 Hz must be regarded as merely suggestive (the transducer output was somewhat distorted), Figure 1 shows that at 125 Hz, auditory-threshold

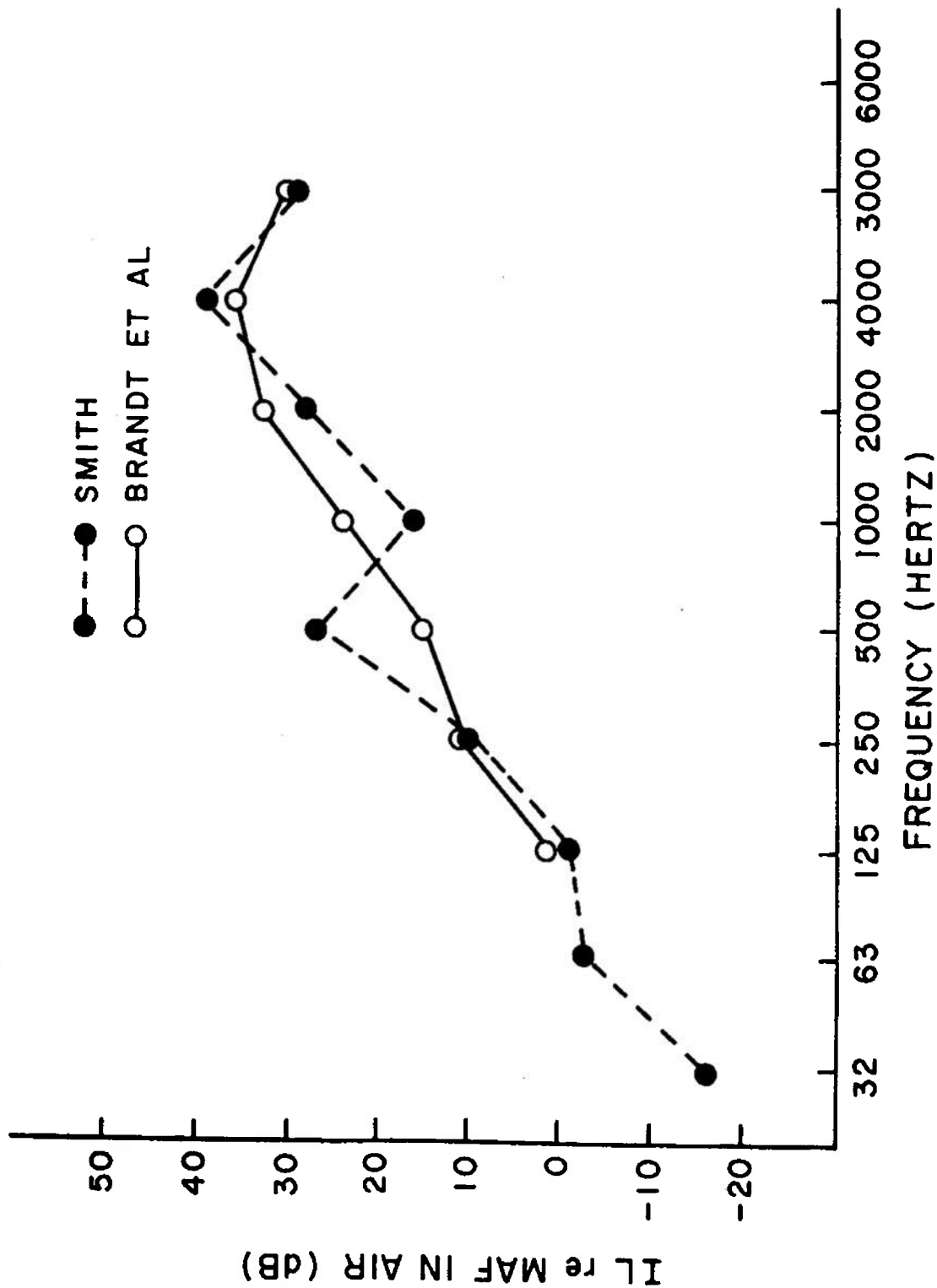


Figure 1. Differences in auditory-threshold intensity levels as a function of frequency. The reference levels at each frequency are taken from the minimum audible field curve (6) in Licklider's figure 5 (1951).

intensity levels are essentially equivalent in air and in water, and at frequencies below 125 Hz man may be more sensitive to sound in water than in air (in agreement with Bauer). From 125 Hz to 4 kHz the difference in threshold sensitivity increases at a rate of about 7 to 8 dB per octave which is less than the 12 dB slope predicted by Bauer. Beyond 4 kHz the threshold difference becomes smaller (here contrary to Bauer's prediction). Comparison of threshold intensity levels in Figure 1 shows that the difference in sensitivity of the ear in the two media is not as large as the 50 to 70 dB usually referred to in the literature (Adolfson & Berghage, 1974).

That "ultrasonic" frequencies are audible in water has also been demonstrated. In 1953 G.L. Bishop (1953) of the Naval Underwater Systems Center found that divers could clearly hear a 30 kHz signal at 137 dB. They did not reliably hear the signal at 32 kHz at 132 dB. Deatherage, Jeffress and Blodgett (1954) reported hearing a 50 kHz signal when any part of the skull was immersed in a bucket of water containing a sound projector. They reported that the threshold for a totally immersed swimmer exposed to 50 kHz to be about 140 dB SPL. During informal (unpublished) tests at the Naval Submarine Medical Research Laboratory using a set-up similar to that of Deatherage et al., it was found that observers in air could hear up to 128 kHz (system limit), but signal levels were not measured. Also, the underwater hearing threshold of one diver at a depth of 12 feet was found to be about 134 dB SPL at 48 kHz.

The Deatherage et al. note and the observations of Bishop and those at the Naval Submarine Medical Research Laboratory demonstrated that hearing in water at "ultrasonic" frequencies does occur and is mediated by a bone-conduction mechanism. Viet (1979) reviewed the work of several investigators who reported on high-frequency hearing by bone conduction in air. For example, Haeff and Knox (1963) reported that a water-coupled crystal (listener in air) could be heard up to 108 kHz with mastoid placement. Their observers reported that the pitch of the signal, regardless of its frequency, corresponded to the pitch of an 8-9 kHz signal. A similar effect was noted by Deatherage et al. who believed that the perception of ultrasound was the result of stimulation of the basal end of the cochlea. Sagalovich and Melkumova (1966) demonstrated bone-conduction hearing sensitivity up to 225 kHz.

Corso (1963) and Corso and Levine (1965a, 1965b) conducted systematic psychoacoustic studies of bone-conduction hearing in air at frequencies up to 95 kHz. Corso and Levine (1965b) also found that pitch discrimination breaks down in the ultrasonic region. No comparable systematic psychoacoustic data for underwater hearing at frequencies above 16 kHz are available. Nevertheless, given sufficient amplitude, underwater sound can be perceived by divers over a much wider frequency range than is the case for air-conduction hearing in air. That Corso's results would be duplicated for immersed listeners is a

reasonable hypothesis.

Since man's hearing is more sensitive in water than in air at frequencies below 125 Hz and is clearly more sensitive in water than in air at frequencies above 16 kHz, then hearing conservation standards for divers ought to encompass a much wider frequency range than do such standards for usual industrial situations. While intense low frequency sound sources are probably not common, some seismic exploration devices that are sometimes tested in port use sound sources that produce impulses with low-frequency components of very large amplitude (the so-called boomers, National Research Council, 1970). Low-frequency machinery noise radiated through the hulls of moored vessels can also be very intense. Devices that produce intense sound in the frequency range above 16 kHz are quite common and may also present a hearing hazard (National Research Council, 1970; Rooney, 1979; Smith & Hunter, 1979).

DYNAMIC RANGE OF THE EAR IN WATER

In general, in the frequency range of 250 to 8000 Hz, man's sensitivity to sound is reduced upon submersion in water. Montague and Strickland have shown that, at 1500 Hz, reduced sensitivity is accompanied by an increased tolerance to intense sound. Their divers would briefly tolerate SPLs as high as 165 to 175 dB. Montague and Strickland measured temporary auditory-threshold shifts (TTS) beginning some five minutes after each exposure and reported average TTSs of 7 and 6 dB at 3000 and 4000 Hz, respectively. Because of the procedures used, exposure levels and durations varied across divers making interpretation of the threshold shifts difficult. But, the results leave no doubt that prolonged exposure to conditions similar to those used by Montague and Strickland would produce greater amounts of TTS. Assuming that noise exposures that produce TTS, if routinely experienced, will produce some permanent hearing damage, then routine exposure of divers to such conditions is hazardous to their hearing.

Smith et al. (1970) exposed six men to 3500 Hz pure tones of 1.25 second duration repeated every 2.5 seconds for a period of 15 minutes at SPLs of 168 and 178 dB. TTS was measured at 2 minutes post-exposure (TTS_2) and compared to TTS_2 induced by similar exposures at lower levels in air. The results indicated that the SPL of 3500 Hz tones in water must be about 68 dB higher than the SPL of tones in air in order to induce comparable magnitudes of TTS. This corresponds to an intensity difference of about 33 dB, which compares well with the differences in auditory-threshold intensities in air and in water at 3000 to 4000 Hz shown in Figure 1.

Corso and Levine (1965a) plotted equal loudness contours for bone-conduction hearing at frequencies as high as 95 kHz. They found that equal loudness contours appear to converge at about 85 kHz. This is an important result since it indicates

that the high-frequency content of broad-band noise, and especially impulse noise, may be of greater importance in water than in air. The cochlea is partially protected from intense high frequencies in air by the filtering action of the external auditory canal and the middle-ear system. This protection is not afforded in underwater exposure to noise. Deatherage et al. warned that strong bone-conduction stimulation at ultrasonic frequencies, while seldom producing aural pain, will produce tinnitus of several days duration. During informal tests at the Naval Submarine Medical Research Laboratory, unpleasant sensations including dizziness were reported by some observers while listening to 50 to 108 kHz signals, but only one, with repeated and relatively prolonged exposures, experienced long-lasting tinnitus (unpublished).

Thus, while the dynamic range of the ear may be similar in water and in air in the 1500 Hz to 3500 Hz frequency range, it may become quite small at very high frequencies. No data exist on the dynamic range of the immersed ear at frequencies below 1500 Hz.

Little information is available concerning the effects of broad-band underwater noise - especially impulse noise - on divers' hearing. A number of tasks performed by divers such as cleaning structures with high-pressure water jets or rock drilling may produce hazardous levels of broad-band and impulse noise (Mittleman, 1976; Molvaer & Gjestland, 1981). Mittleman found that three diver-operated underwater stud guns produce impulse SPLs as high as 195.3 dB at the diver's head and chest but, more usually, SPLs were within 3 dB of 185 dB. Divers exposed to that noise did not report any discomfort or "noticeable effects on ears..." although the impulse (measured in pounds per square inch integrated over time (PSI msec)) produced by stud guns often exceeded the 2 PSI msec recommended by Christian and Gaspin (1974) as the maximum safe impulse for exposure of divers to underwater explosions. No TTS data were taken by Mittleman.

Paul F. Gould and David Wyman of the Naval Coastal Systems Center have made extensive noise measurements on a variety of hand-held underwater tools. Very graciously, they have made their data available to this laboratory. The Gould and Wyman data show that divers using water-jet cleaning tools, rock drills, impact wrenches, and chipping tools are exposed to broad-band noise in the 1 to 32 kHz region at sound pressure levels ranging up to 160 dB and occasionally higher. Many divers are exposed to underwater explosives, yet no experimental studies have been done on the effects of such exposures on hearing.

Thus, the empirical data available for formulating a general underwater hearing-conservation standard are very scanty. Hearing-conservation standards for noise exposure could be established by comparing the intensities in air and water

that produce comparable amounts of auditory TTS provided, of course, that such studies are not arbitrarily restricted to the usual audiometric frequencies. However, TTS studies may not reveal deleterious effects associated with very high frequency exposures such as were reported by Deatherage et al.

Furthermore, a research approach to the problem of noise exposure in water that focused on hearing studies alone would not insure that the general health of divers would be adequately protected or that noise-exposed divers could perform assigned tasks efficiently. Some extra-auditory effects of sound on divers also need to be considered.

NONAUDITORY EFFECTS OF SOUND IN WATER

Physical effects:

On several occasions during various (unpublished) experiments using high-intensity sound that were done at the Naval Submarine Medical Research Laboratory, divers have reported that depth gauges became erratic, breathing regulators would free-flow, water carried in a face mask tended to jiggle or ripple, and sometimes fogging occurred within the face mask at SPLs well in excess of 174 dB. Such effects were not reliably observed at SPLs lower than about 174 dB. Divers have reported that these phenomena are somewhat annoying, but would not seriously interfere with job performance since the effects only occur while the sound is present. Such reports assume, of course, that the noise would be intermittent and uncorrelated with divers' activities.

Vestibular disturbances:

It has long been known that peculiar effects occur when divers are subjected to intense sound fields. Montague and Strickland (1961) reported that, at sound pressure levels of 165 dB or more all of their divers experienced a visual effect that most of them described as a rotational movement of the visual field. The effect occurred at the onset of a 1500 Hz signal and was maintained until the tone was stopped. Montague and Strickland called this an oculo-gyral effect. With prolonged or continuous signals and with increased intensity above 165 dB, the oculo-gyral effect was more marked. One diver reported some dizziness when exposed to an intense, continuous tone. Smith et al. (1970) found only one diver who reported an oculo-gyral effect. But, in other (unpublished) experiments at the Naval Submarine Medical Research Laboratory some divers have reported such visual effects under conditions similar to those reported by Montague and Strickland. A suspected physiological basis for the oculo-gyral effect has not been clearly demonstrated but Montague and Strickland did find that wet-suit hoods provided about 10 dB protection from the oculo-gyral effect. Thus, the vestibular system may be stimulated either directly or through the cochlea by intense sound in water. Visual field

displacements are known to occur in humans exposed to certain intense acoustic signals in air (the "Tullio" phenomenon, Parker, et al., 1978).

Other physiological effects:

Duykers and Percy (1979 and as reported by Smith & Hunter, 1979) found that, with very intense underwater exposure levels, large experimental animals incurred some lung damage. Rooney (1979) showed that significant biological effects have been observed at levels as low as $.1 \text{ W/cm}^2$. He calculated that at 31 kHz, sound intensities in water as low as $.1 \text{ mW/cm}^2$ may produce biological effects in divers that could have long term health consequences. This intensity corresponds to an SPL in water of about 154 dB, which may be within 10-15 dB of the threshold of audibility at 31 kHz (Bishop, 1953). Thus, there is reason to suspect that intense sound in water is hazardous to divers. Smith and Hunter found insufficient experimental evidence to conclude that there is no biological hazard to divers who are currently exposed to intense sound in water. A diver undergoing decompression may be particularly at risk (MacKay, 1963. See also Mackay's comments in Smith & Hunter).

Against such concerns must be weighed the fact that for years many divers have been exposed to underwater sound at intensities ranging up to those levels investigated by Montague and Strickland (1961), Smith et al. (1970), Molvaer and Gjestland (1981), and Mittleman (1976). Such exposures have produced no evidence that, apart from the auditory system, the health of divers is affected in any way. Rooney cautions that other effects may not have been observed because no one is looking for them. Indeed, many long-term health hazards (such as white finger syndrome (Raynaud's disease) or noise-induced hearing loss) are insidious in that they produce minimal effects over short periods of time or their effects are masked or misinterpreted.

Because of the relative insensitivity of the ear to sound in water in the 250 to 8000 Hz frequency range, and the very similar acoustic characteristics of sea water and human tissue, underwater noise exposure is not at all comparable to noise exposure in air (Smith & Hunter). The development of hearing-conservation standards for divers must proceed with due regard for other health hazards associated with underwater noise exposure.

NOISE EXPOSURE IN DRY HYPERBARIC CHAMBERS

This review has focused on exposure of wet-suited divers and swimmers to noise in water and has not, therefore, discussed the most common situation in which divers are exposed to intense noise, namely dry-helmet diving and dry diving in hyperbaric chambers. A few comments on that problem seem in order.

The characteristic impedance (Z) of a sound-transmitting medium is the product of the density of the medium and the velocity of sound in the medium. As air is compressed, density increases, but the velocity of sound changes very little. Thus, for compressed air, the ratio of the impedance of surface pressure air to the impedance the hyperbaric medium (Z_s/Z_d) is well estimated by the simple ratio of the respective pressures. For example, at the surface the characteristic impedance of air (Z_s) is 415 acoustic ohms but at 10 atmospheres the impedance of compressed air (Z_d) is about 4150 ohms or 10 times as great as the impedance of surface-pressure air. For a 95% helium - 5% air mixture at 30 atmospheres Z_d is about 6758 ohms. These differences in impedance can be expressed in decibels as:

$$10 \log Z_s/Z_d.$$

The human ear has evolved to have an impedance that is matched to the characteristic impedance of surface-pressure air. As the pressure changes in a helmet or chamber dive, the resulting change in the impedance of the the medium results in a progressively less efficient transfer of energy from the medium to the cochlea through the external and middle ear, assuming no change occurs in the ear itself. Hearing thresholds measured at 30 atmospheres in a 95% helium-5% oxygen/nitrogen mixture would appear to be reduced with respect to thresholds in surface-pressure air due to the impedance mis-match. The greatest change in impedances occurs near the surface, and for each doubling of ambient pressure, a 3 dB change in impedance would occur for a given medium. At 30 atmospheres in a helium-oxygen mixture the impedance mismatch would amount to

$$10 \log 415/6758 = -12 \text{ dB.}$$

However, as the middle ear cavity is filled with the breathing medium the impedance of the ear will change. In fact, the compliance of the middle ear cavity will decrease substantially as the ambient pressure increases. While on first thought this effect may seem to impair hearing, the increased stiffness of the middle ear is exactly in the direction required to maintain an impedance match between the hyperbaric environment and the ear. In compressed air, therefore, there may be no change in auditory sensitivity. But, in helium-oxygen environments, in which the velocity of sound is greater than for air, an upward shift in the resonance frequency of the external auditory meatus alters the frequency response of the ear. Auditory sensitivity may be expected to be reduced at low frequencies but not at high frequencies. The validity of this brief analysis tends to be confirmed by the data of Farmer et al. (1971) and Thomas et al. (1974). The changes in auditory thresholds with changes in depth that they observed are largely explained by changes in the acoustic characteristics of the medium. But by no means are all of their data explained simply by changes in the impedance of the medium. Anomalies in the Thomas et al. data are baffling. Also, Fluor and Adolfsen

(1966) reported that hearing is impaired in compressed-air environments but their results are suspect because of the very great stress (11 atmospheres, air) that their divers were under.

One interpretation of the empirical evidence from several hyperbaric-chamber experiments is that air-conduction hearing acuity is generally reduced (Fluur & Adolfson, 1966; Farmer et al., 1971; Thomas et al., 1974); hence, existing hearing-conservation standards could be applied conservatively to hyperbaric conditions. In an experiment on the chinchilla, Thomas, Farmer, and Kaufmann (1980) found that a sixty-minute exposure to a 300 to 600 Hz band of noise at 105 dB produced less TTS (at 715 Hz) in compressed air at a simulated depth of 66 feet of sea water (FSW) than at surface pressure. When the exposure was administered in a helium-oxygen environment also at 66 FSW no TTS was observed.

Nevertheless, prolonged exposure to hyperbaric pressure may potentiate the effects of noise, thereby eliminating any apparent short-term protection the diver receives from reduced acuity. Molvaer (1980) reported that during a deep saturation dive, divers who were exposed continuously to noise levels below accepted risk limits for hearing damage nevertheless incurred temporary threshold shifts that required more than two days to normalize.

An additional complication is that the frequency response of the ear changes in diving environments. The Thomas et al. (1974) data for humans in helium-oxygen environments show that the reduction in sensitivity to sound pressure is not the same at all frequencies. In particular, they found that, at depth, little or no change occurred in sensitivity at 2000 Hz, and sensitivity increased at 6000 Hz. Fluur and Adolfson (1966) found that the frequency response of the ear is also altered in compressed-air environments. These results prompted Molvaer et al. (1982) to comment that the usual method for evaluating noise using the A weighting on sound level meters is not valid for hyperbaric environments.

Unfortunately, few data on noise-induced TTS are available for saturation dives. Thomas et al. (1974) and Farmer et al. (1971) show that no systematic changes occur in the hearing threshold levels of saturated divers over at least a 200 hour period at simulated depths as great as 1000 FSW. While reassuring, this finding does not inform us as to the ability of the ears of saturated divers to recover from noise exposure.

Thus, little justification exists for assuming that the application of existing hearing-conservation standards to dry diving environments is warranted. Since dry-diving operations are so noisy that divers frequently accumulate maximum allowable daily noise exposures within 20 to 60 minutes (Summit & Reimers, 1971), this problem deserves more systematic attention than it has received.

OTHER VARIABLES AFFECTING HEARING IN WATER

In formulating hearing-conservation standards for wet diving, several additional variables must be taken into account, such as the effects of depth and breathing mixture. On these points only limited data are available. Neither Smith (1969) nor Brandt found any great change in underwater threshold sensitivity as a function of depth (12 to 105 ft). Hollien and Brandt (1969) also found no significant differences in underwater thresholds whether or not the ear canal is filled with air or water, but Bauer (1970) argues on theoretical grounds that underwater hearing ought to be more sensitive with a bubble present in the ear canal. Helium breathing mixtures do not appear to affect underwater hearing thresholds (Brandt, 1967; Waterman & Smith, 1970). Clearly, however, since much underwater noise exposure occurs while divers are breathing mixed gasses, possible effects of such variables on noise-induced threshold shifts must be considered in the development of an underwater hearing-conservation standard.

Divers' dress is another factor to be considered. Wet suit hoods are fairly effective underwater hearing protectors (Montague & Strickland, 1961; Smith, 1969; Norman, et al., 1971). However, the amount of protection provided by hoods seems to vary greatly with fit. Ide (1944) and Montague and Strickland showed that merely exposing additional small parts of the skull greatly reduces if not altogether eliminates the noise-protective effects of hoods. Thus, the same cautions that apply to the use of ear defenders in air should be applied to hoods as underwater ear protectors.

CONCLUSIONS

No well developed theory of underwater hearing exists which would enable a generalization of existing hearing-conservation standards to underwater noise exposure. However, some form of a dual path theory can account for known underwater hearing phenomena. The tympanic route may predominate at low frequencies (perhaps up to 250 or 500 Hz), while bone conduction predominates at frequencies above 4000 Hz. At the intermediate frequencies the two pathways may be approximately of equal sensitivity. At 1500 and 3500 Hz the dynamic range of the water-immersed ear may be similar to the ear's dynamic range in air, but one can not conclude that that is the case at other frequencies. The water-immersed ear is also sensitive to "ultrasonic" frequencies and the dynamic range of the ear in water is small at those frequencies. Thus, hearing-conservation standards for divers must take exposures to high-frequency sound into account. Furthermore, noise levels to which divers are currently being exposed at times exceed levels at which potentially adverse effects on tissues have been demonstrated, and certain effects capable of disrupting job performance have been noted with intense noise exposures. All of these factors,

then, must be considered in establishing a hearing-conservation standard for underwater noise exposure.

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noise to the underwater situation; second, the empirical data on underwater hearing suggest that the frequency range covered by an underwater hearing conservation standard must be much broader than is the case in air; third, in order to establish a general hearing conservation standard for underwater noise exposure further research is required on the dynamic range of the ear in water; fourth, underwater noise exposure may involve hazards to other body systems than the ear; and fifth, some exposure conditions may interfere with job performance of divers.

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