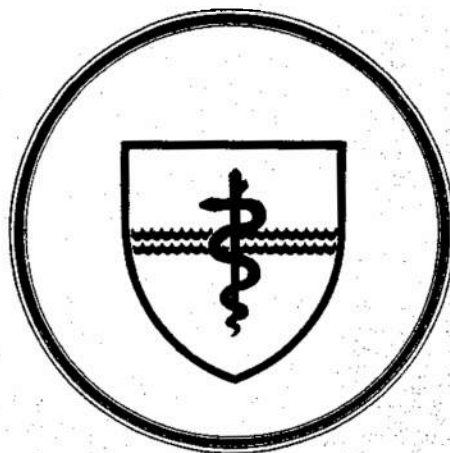


NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.



REPORT NUMBER 1120

EFFECTS OF EXPOSURE TO INTENSE TONES IN WATER
WHILE WEARING WET-SUIT HOODS

by

Paul F. SMITH

Naval Medical Research and Development Command
Research Work Unit M0099.01C-5013

Released by:

C. A. HARVEY, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

22 August 1988

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SUMMARY PAGE

THE PROBLEM

To develop a data base upon which to establish standards for hearing conservation and safety for Navy divers exposed to intense noise in water.

THE FINDINGS

Wet-suited and hooded divers can work for useful periods of time while subjected to tone pulses at sound pressure levels up to 191 dB above 20 micropascal. Non-auditory effects that accompany exposure to very high sound levels in water were found to be annoying but not immediately harmful to divers.

APPLICATION

The findings contribute to the establishment of hearing-conservation and safety standards for Navy divers exposed to intense noise in water.

ADMINISTRATIVE INFORMATION

This research was carried out under Naval Medical Research and Development Command Work Unit No. 63173N M0099.01C-5013 "Development of a hearing-conservation standard for exposure to noise in dry hyperbaric environments." It was submitted for review on 6 July 1988, cleared for publication on 22 August 1988, and designated as NSMRL Report No. 1120.

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ABSTRACT

Wet-suited and hooded divers were exposed to 3500 hertz tone pulses (25% and 50% duty cycles) at sound pressure levels up to 192 dB above 20 micropascal for durations of up to one hour. Temporary auditory-threshold shifts were measured. An exposure of sixty minutes at 191 dB produced threshold shifts of 40 dB (two minutes post-exposure) but exposures at lower sound pressures for twenty minutes or less produced moderate or no threshold shifts. Non-auditory effects that were startling to the divers when first encountered were also investigated. They included spraying of water within face masks, a perceptible pressure, and visual-field displacements. Although annoying, none of the non-auditory effects was apparently immediately harmful to the divers.

INTRODUCTION

Since Langevin's developmental work on active sonar more than seventy years ago it has been known that intense water-borne sound can kill small fish and induce severe pain in humans (Wood and Loomis, 1927). Because Navy divers may be exposed to active sonars and noisy underwater tools, attempts have been made to formulate measures to control underwater noise exposure (Harris, 1961; Smith et al., 1970; Pearson, 1981; Rooney, 1979; Smith and Hunter, 1979; Smith, 1983, 1984, 1985), but the requisite data base is sparse.

There have been a few experiments in which unprotected divers have actually been exposed to intense noise levels in water (Montague and Strickland, 1961; Smith et al., 1970; Smith and Wojtowicz, 1985), but there are only fragmentary reports for divers who are protected from water-borne sound by wearing wet-suit hoods (Harris, 1961; Montague and Strickland, 1961; Smith 1965; but see Sterba, 1987A and 1987B). Montague and Strickland found that few of their 23 subjects would tolerate a sound pressure level (SPL) in excess of 179 dB re 20 μ Pa¹ while bare-headed; all but two subjects would tolerate 180 dB while wearing a hood. Smith (1965) found that two divers wearing hoods would tolerate exposure to 1900 Hz tone pulses (700 msec pulse length at a 5% duty cycle) at 169 dB for 30 minutes (in excess of 120 pulses) and they did not incur any threshold shift.

This report describes pilot studies undertaken as part of an effort to develop a hearing-conservation standard for divers exposed to intense noise in water. In these pilot studies temporary auditory-threshold shifts (TTSs) were measured in divers who wore wet-suit hoods while being exposed to very intense tone pulses. In subsequent experiments the use of hoods was avoided because they add an additional and large source of variance to experimental results (Smith, 1969) and because, as Montague and Strickland (1961) learned, the use of hoods may sometimes preclude obtaining any measurements whatsoever. However, certain non-auditory effects that can be startling to divers accompany immersion in underwater sound fields at the intensities used here. Those effects were also studied. Exposure SPLs used by Montague and Strickland were limited by their apparatus to 180 dB. In the present experiments exposure SPLs were limited only by the author's decision not to expose divers to intense cavitation. The present results are of interest primarily because they are the only results known to the author in which hooded divers were exposed to tones at controlled intensities up to and somewhat beyond the threshold of cavitation in shallow water.

I. TEMPORARY AUDITORY-THRESHOLD SHIFT TRIALS

METHOD

Subjects. The subjects were eight experienced divers ranging in age from 24 to 48 years. All had normal hearing in at least one ear up to and including 4 kHz. Three had hearing levels as great as 25 dB at 6 and 8 kHz.

Test sites. Two separate test sites were used, a salt-water estuary and a salt/fresh-water quarry pond. The maximum water depth in the river was 3.7 m at high tide and subjects stood on the bottom during exposures. Tests were run during slack water around high tide. In the pond the depth was 25.9 m, and the divers were tested while standing on the diving stage at either 11.0 or 14.9 m beneath the surface.

Apparatus. The exposure apparatus is sketched in Figure 1. Pure tone pulses (one-second duration at two- or four-second intervals) were delivered to a 10 kW amplifier which drove an array of nine mass-loaded bar transducers. The transducer array was suspended from an "I" beam as were two hydrophones and the diving stage (when used). One hydrophone was located at the level of the divers' heads about 1.2 m from the face of the transducer array. The second hydrophone was located 3.0 m from the array. Both hydrophones were calibrated by reciprocity prior to the experiment. The whole assembly was suspended from an overhead crane.

Auditory threshold measurements were made at the test site using a tape recorded pulse-tone group audiometric test or an Ambco portable audiometer. Precision was limited to 5 dB by either procedure. Testing was done in a single-walled ten-man audiometric booth that was set up at the dive site. Ambient noise levels within the booth were satisfactory (ANSI S3.1-1977) for audiometry above 500 Hz using TDH-39 earphones in MX-41 cushions.

Procedure. Each day of the experiment baseline and post-experiment audiometric testing was done in a certified clinical audiometric facility at the Naval Submarine Medical Research Laboratory (NSMRL) before departing for and upon return from the test site.

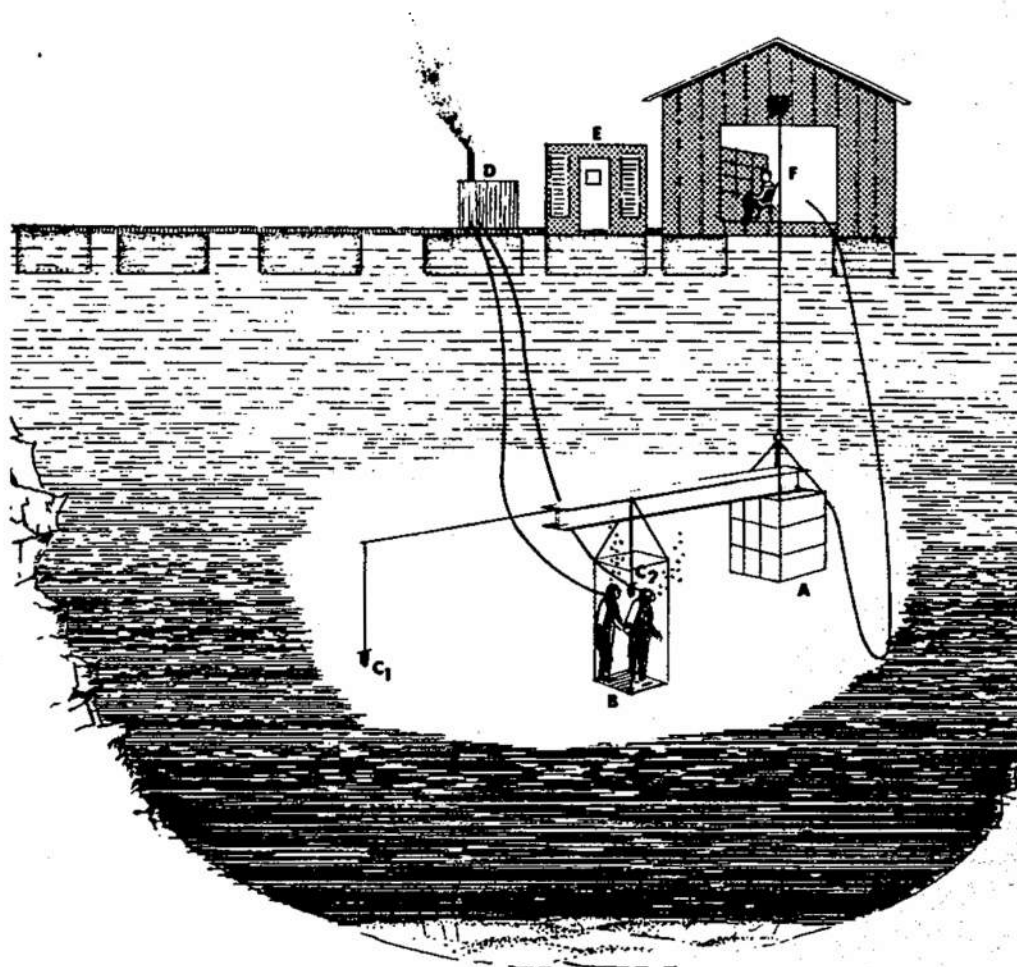


Figure 1. Sketch of the exposure apparatus. The transducer array (A), the diving stage (B), and two hydrophones (C_1 , C_2) were attached to an "I" beam that was suspended from an overhead crane. On a cat-walk from the shore to the test barge were the structure housing the machinery for the heated wet suits used on some dives (D) and the ten-man booth (E) that was used for audiometry. Electronics to drive the transducer array were located within the barge (F).

Prior to each exposure, subjects were administered an air-conduction hearing test. They then dove to the stage singly or (usually) in pairs and positioned themselves so that their heads were adjacent to the 1.2 m hydrophone. When they signaled "ready" (by hand line) they were exposed to 3500 Hz tone pulses for up to one hour. At the completion of the exposure period, the diver supervisor signaled the divers to surface. Next, auditory thresholds were measured again as soon as possible after the end of the exposure period. Temporary threshold shifts were computed as the difference between post- and pre-exposure audiograms.

For most tests the divers wore full wet suits with hoods and face masks and they breathed compressed air supplied by self-contained underwater breathing apparatus. At 14.9 m the divers wore a hot-water heated suit that was also undergoing evaluation.

The input signal to the projector array was monitored on an oscilloscope in order to avoid exposing divers to intense cavitation. The onset of cavitation is accompanied by decoupling of the transducers from the water and that effect produces visible distortion in the negative portion of the sinusoidal input waveform. The divers soon learned to detect cavitation by the appearance of a faint mist in the water moving from the transducer array toward the divers. That phenomenon is due to clouds of microbubbles being formed near the face of the transducer and forced away from it from by the sonic radiation pressure.

RESULTS

Table 1 summarizes the exposure conditions run to completion. Several trials in which the dive was aborted are not shown. In the river, dives were aborted because of excessive chilling of the stationary divers or because a strong current interfered with the ability of the diver to maintain his position. At the higher exposure levels, acoustically induced cavitation frequently occurred (especially at the shallow river site), and divers were instructed to surface when this was observed. Thus, for example, three attempts were made to run at 192 dB at depths of 11.0 and 14.9 m but cavitation invariably occurred at that SPL even at the greater depth. None of the several aborted exposures produced measurable TTS.

Table 1. Summary of test conditions

Condition	Duration (min)	Duty cycle (%)	SPL dB/ 20 uPa	Depth meters	N
1	5	25	183	3.7	1
2	5	25	189	3.7	4
3	5	50	189	3.7	2
4	20	25	189	3.7	7
5	20	50	189	3.7	6
6	60	50	182	3.7	2
7	20	50	191	11.0	5
8	20	25	191	14.9	2
9	60	50	189	14.9	2

It was not possible to measure TTS at a fixed post-exposure time at all frequencies or for all divers. Estimate of the TTS that existed two minutes post-exposure (TTS₂) were obtained by plotting the data for all divers in a given condition and test frequency on log (time)/linear (TTS) graph paper and fitting a group TTS recovery line by eye. Where that line intersected log two minutes was taken as the group TTS₂. This procedure precludes assessment of inter-subject variability of course. An alternative procedure would have been to compute TTS₂ for each subject using empirical recovery models such as that given by Ward et al. (1958). A comparison of the Ward et al. procedure and the graphic procedures for data at 4 kHz revealed that the graphic procedure produced slightly larger estimates of group TTS₂ than the mathematical procedure.

The exposure conditions for which reasonable estimates of group TTS₂ could be made are shown in Table 2. The maximum TTS₂ occurred when two divers were exposed for 60 minutes at an SPL of 189 dB and a 50% duty cycle. Generally, maximum TTS₂ occurred at 4 and 6 kHz. Moderate TTS occurred at 3 kHz (rarely) and 8 kHz under some conditions. TTS was not observed at test frequencies of 1 and 2 kHz under any exposure condition.

Two completed exposure conditions in Table 1 are not listed in Table 2. Two subjects exposed to 182 dB for one hour at a 50% duty cycle (test 6) showed no consistent TTS. No TTS was observed in one diver exposed at 183 dB for 5 minutes. As has been mentioned, none of the brief aborted runs produced TTS although exposure levels were sometimes close to the cavitation threshold.

Comment. The TTS₂ of 40 dB that occurred with the 60 min exposure at 189 dB indicates a very hazardous exposure condition. What is important about these results is that exposure for up to 20 minutes to pure tone pulses at the maximum SPLs that can be sustained in water produces relatively moderate or non-existent auditory threshold shifts when divers are protected by wet-suit hoods.

Table 2. Estimates of median temporary auditory-threshold shifts at two minutes (TTS₂) after exposure for various test conditions listed in Table 1. No significant threshold shifts were observed for frequencies below 4 kHz. Blank cells are conditions not run. Cells containing (-) marks indicate TTS could not be estimated because recovery had occurred before audiometry began.

Exposure duration/ duty cycle	Test	SPL 189 dB Frequency (kHz)			Test	SPL 191 dB Frequency (kHz)		
		4	6	8		4	6	8
60 min./ 50%	9	40	40	-				
20 min./ 50%	5	17	11	12	7	23	28	17
20 min./ 25%	4	10	16	8	8	-	-	-
5 min./ 50%	3	-	-	-				
5 min./ 25%	2	7	-	10				

 1 All SPLs in this report are referenced to 20 uPa. Add 26 dB for SPL referenced to 1 uPa.

II. NON-AUDITORY EFFECTS

During the course of the TTS work some divers spontaneously reported certain non-auditory effects. Specifically, at the highest SPLs some divers reported that a mild force was felt pressing on the faceplate or pushing them away from the transducer. In addition, any water carried in the face mask would burst into a spray. A third effect noted by some divers was that the transducer seemed to move slightly with each tone pulse. Not all such effects were initially reported by all divers. Some observed a particular effect (if at all) only after other divers had described the effect to them. These effects were so startling to the divers that a special effort was made to obtain data relating to the onset of each of these effects: pressure, spray, and motion.

METHOD

Subjects. Five diver-observers, all staff members of NSMRL, were subjects. All were accustomed to observing in a variety of psychophysical studies. Two were first class divers with substantial experience as assistants and subjects in diving medical research; and three observers were NSMRL diving scientists.

Procedure. Each diver made three separate dives. A single diver positioned himself on the stage so that the 1.2 m hydrophone was adjacent to his head just above the shoulder. On each dive the observer would attend to only one of the three non-auditory effects and attempt to signal when the phenomenon first occurred. On the diver's "ready" signal a series of one-second duration tones were presented at two-second intervals. The SPL of the first tone was 170 dB and each succeeding pulse was about 1.5 dB more intense. The tone series continued until the observer signaled that the effect of interest had occurred or until an SPL at the divers head of 192.4 dB was reached. Three ascending runs were made on each dive. The diver then surfaced and gave a verbal description of what he had observed. Since the verbal reports were made in the presence of all other team members the observations cannot be considered as independent.

Auditory thresholds were measured before and after the experiment.

Table 3. Divers' remarks on non-auditory phenomena: The SPL column gives the threshold for the onset of the effect and is the median of three trials for each diver.

Man #	Event	SPL	Comments
1	Splash	216.8	Misting, water bounces off mask into eyes.
	Pressure	216.8	No definite sensation of pressure. More a feeling of ears jangling.
	Motion	206.8	Wires and transducer move to the right. When the transducer returns to the center it does not oscillate. Returns to center just in time for next pulse.
2	Splash	218.4	No misting or splashing but water jiggled. Diver focused on a shadow for reference.
	Pressure	218.4	Definite pressure sensation.
	Motion	218.4	First time (pulse) only. The transducer twisted counter-clockwise. The bottom of the transducer moved to the right. The transducer was blurred and seemed to vibrate. It was indistinct.
3	Splash	216.8	Splash effect occurred just prior to or just when cavitation occurred.
	Pressure	218.4	Not observed. Cavitation occurred.
	Motion	218.4	No motion observed.
4	Splash	213.9	Movement of water followed by misting. Not irritating.
	Pressure	213.9	Faint pressure.
	Motion	210.5	Transducer moved to right and back towards observer. No twisting.
5	Splash	212.5	Water jiggled, no misting
	Pressure	212.5	Diver signaled "stop" but made no report.
	Motion	213.9	Slight movement, "two degree" twist, no oscillation.

RESULTS

Post-exposure thresholds were measured beginning six to seven minutes after the last of the three dives for each subject. These exposures induced TTSs of 5 to 10 dB at various frequencies (mostly 4 and 6 kHz) in four of the five divers (nine of ten ears). The fifth diver incurred a TTS of 15 dB at 4 kHz (left ear only) that dissipated within 24 hours. He also incurred a threshold shift of 20 dB at 6 kHz in his left ear that persisted for several days.

Because of a lack of experience with such phenomena, the divers could not adopt common criteria for judging the onset of the effects. Some observers reported spraying when the water in their masks rippled violently, while others waited until the water actually burst into a spray. For these reasons the data are presented in Table 3 in raw form. Obviously, a more systematic procedure would have been desirable but time was not available.

DISCUSSION

The highest SPLs used in this study are at or above the threshold of cavitation. However, such cavitation as did occur was weak. One diver (a sonarman) discovered that he could turn the cavitation on and off merely by moving a few inches toward or away from the transducer. Apparently, his suited body was acting as a reflector and his movements altered the intensity of the standing wave that existed between him and the transducer. Also, with one diver on the stage at a depth of 11 m, cavitation would rarely occur at 191 dB; but with two divers present, cavitation always occurred at that level.

The pressure sensation felt by the divers has a verifiable physical cause in the radiation pressure that is a function of the sound power radiated by the source (Wood and Loomis 1927; Borgnis, 1953). Wood and Loomis found that radiation pressure was perceptible if a rod is attached to a glass plate and, with the rod held between the fingers, the plate is pushed down into an oil bath toward a sound source. Apparently the radiation pressure was perceptible to the divers. However, not all divers reported this phenomenon reliably.

The splashing, spraying, or misting of water in the face mask also has a well known cause. Wood and Loomis (1927) reported that when an intense sound beam from an immersed transducer strikes the surface of the liquid, a jet or spray of droplets is thrown up from the surface and a mist is formed. The size of the droplets and the density of the aerosol vary with the frequency and intensity of the sound and the surface tension of the liquid. The effect occurs when the sound intensity exceeds some critical value related to the surface tension of the liquid (Blitz, 1967).

Because of the large mass of the transducer array and the diving stage, the motion of the transducer that was reported by the observers could not have been due to actual relative motion between the sound source and the divers. Yet, this effect also may have a purely physical basis. If the radiation pressure presses the faceplate in toward the diver's eyes, then the light coming from the transducer would be differentially refracted at the faceplate giving the impression that everything in the visual field moved when the sound came on. However, Montague and Strickland (1961) said that the oculo-gyral effect (an apparent rotation of the visual field) reported by their divers was probably due to direct acoustical stimulation of the vestibular apparatus, a phenomenon known as the Tullio effect. In air, displacements of the visual field can be seen at 125 dB by about half of the subjects exposed to acoustical transients (Parker, et al., 1978). Montague and Strickland found with two divers wearing hoods the visual effects began at about 175 dB. Visual-field shifts were not reported in the current study below about 181 dB. Only more systematic experimentation can determine whether or not the Tullio effect occurs in intense underwater sound fields.

Any of these effects, or a combination of them, may interfere with the job performance of a diver. The divers in this study agreed that the exposures were unpleasant. However, at the sound levels utilized in this study the non-auditory effects do not appear to pose an immediate health or safety hazard and can be tolerated by divers. The diver-observers felt that since the effects occurred only when the sound was on, overall performance would not be affected if the sound were intermittent, such as occurring in bursts of 2 or 3 seconds every 20 or 30 seconds.

Two other consequences of exposure to high sound pressures were noted by the divers: regulators would occasionally free-flow and depth gauges became erratic. The divers considered neither effect to be more than a minor annoyance.

Protective effects of divers hoods: The power output of modern sonar systems may be limited only by the ingenuity of system designers, but the signal level that exists in water is limited by the cavitation threshold (Liddiard, 1953; Flynn, 1964). Within 10 to 15 meters of the surface, the cavitation limit for frequencies below 15 kHz is not much greater than a sound pressure of 1 to 2 atm (194 to 200 dB peak-to-peak, Esche, 1952; Rusby, 1970). Thus, divers working in the vicinity of transmitting sonars could be exposed to sound levels up to but not higher than the threshold of cavitation. The exposure levels used in the present studies are close to that limit.

All exposures during these experiments were done with the divers wearing full wet suits and hoods. The sound attenuating properties of wet-suit hoods have been documented at threshold levels (Montague and Strickland, 1961; Smith, 1969; Norman, et al., 1971; Hollien and Feinstein, 1975). The present results suggest that about the same attenuation is provided at the SPLs used here. At 3 to 4 kHz, hoods provide an average of about 25 dB attenuation. Thus, a typical diver in a sound field close to the cavitation threshold (say 192 dB) would be experiencing a stimulus equivalent to an SPL of about 167 dB for a bare-headed diver. Subtracting 68 dB to estimate the equivalent SPL in air (Smith et al., 1970) yields an equivalent airborne SPL of 99 dB. Continuous exposure for over two hours to that SPL is permitted by current hearing-conservation standards (Occupational Safety and Health Administration, 1983).

Montague and Strickland (1961) found that in addition to the visual effects, bareheaded divers could "feel" the sound at levels about 10 dB below tolerance levels. The sensation was felt mainly in the face but one unsuited diver felt the sound in the gut. With a continuous tone, divers in the Montague and Strickland study reported that the visual effects were more pronounced than with pulsed tones, and one diver reported some dizziness. Two bareheaded divers subjected by Smith and Wojtowicz (1985) to intense continuous tones reported that their heads vibrated; one of those felt a tickling in his middle ear, and a third diver thought that the sound made his eyes water. The present observers did not report those phenomena.

Because of limitations in their apparatus, Montague and Strickland could not determine tolerance limits for their hooded divers. They stated, however, that the threshold for the oculo-gyral effect was elevated by about 10 dB when hoods were worn. It is likely that if the oculo-gyral effect is indeed a manifestation of the Tullio phenomenon, then the diver-observers in the present study might have observed motion at lower intensities than reported in Table 2 if they were not wearing hoods. The pressure sensation and the spraying are clearly physical phenomena that may not be affected much by the presence of hoods.

Conclusions: Divers wearing full wet suits with hoods who are exposed to SPLs close to the threshold of cavitation will experience disturbing non-auditory effects, but they do not appear to pose an immediate hazard and with experience those effects can be tolerated. Exposures to pure tone pulses at 3500 Hz equivalent to 20 minutes at a 50% duty cycle and at SPLs up to 191 dB produce only moderate TTS. This suggests that while routine exposures to similar conditions ought to be administratively controlled, occasional, brief exposures such as experienced by the divers in this study can be endured without undue hazard to fully suited divers.

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Wet-suited and hooded divers were exposed to 3500 hertz tone pulses (25% and 50% duty cycles) at sound pressure levels up to 192 dB above 20 micropascal for durations of up to one hour. Temporary auditory-threshold shifts were measured. An exposure of sixty minutes at 191 dB produced threshold shifts of 40 dB (two minutes post-exposure) but exposures at lower sound pressures for twenty minutes or less produced moderate or no threshold shifts. Non-auditory effects that were startling to the divers when first encountered were also investigated. They included spraying of water within face masks, a perceptible pressure, and visual-field displacements. Although annoying, none of the non-auditory effects was apparently immediately harmful to the divers.						
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