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Evaluation of noise within the MK 12 SSDS helmet and its effect on divers' hearing

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Curley MD, KNAFELC ME. Evaluation of noise within the MK 12 SSDS helmet and its effect on divers' hearing. Undersea Biomed Res 1987; 14(3):187–204.—The noise inside the U.S. Navy MK 12 SSDS helmet was measured and its effect on the hearing of divers assessed. Seven male divers completed 20 dives while breathing air at simulated depths ranging from 1.8 to 30.5 msw with dive durations ranging from 40 to 120 min. Microphones recorded sound pressure levels inside the helmet while the diver was in the water and exercising. Average corrected sound intensity levels in the helmet ranged from 90.5 dB(A) at 1.8 msw to 97.3 dB(A) at 30.5 msw. Diver hearing threshold level shifts were recorded as a function of helmet noise exposure; moderate threshold shifts were observed at depths of 9.1 msw or deeper after 120-min dives. The hearing of all divers completing dives up to 120 min returned to predive levels within 24 h after noise exposure. However, dive durations in excess of 120 min at 9.1 and 20.1 msw resulted in substantial auditory shifts in 1 diver, which required 2–3 d to recover to predive levels. These results suggest that the impact of helmet noise on diver hearing should be included in planning operations using the MK 12 SSDS.

MK 12 SSDS
helmet noise
hearing
acoustics
threshold shifts
underwater
hyperbaric

It has been suggested that diving has a detrimental effect on hearing. Studies done by Coles (1) and Brady et al. (2) concluded that the number of years of diving experience has only a minor effect on the hearing threshold of divers. However, a study of professional divers by Molvær and Lehmann (3) found that these divers' hearing thresholds were elevated in the high frequencies when compared to the International Standards Organization's normality curves. This suggests that professional diving can lead to accelerated high-frequency hearing impairment.

The noise experienced by a diver in the hyperbaric environment is a function of several factors, including the apparatus used (e.g., dry helmet, neoprene hood, underwater tools), depth (pressure), breathing medium (e.g., air, helium-oxygen), and the ambient environment (e.g., undersea vs. chamber). The effects of noise on diver hearing under pressure may not be the same as in the normobaric environment.

When subjected to increased atmospheric pressure, the response of the human ear is altered (4). Further, for the dry-helmeted diver the breathing media and depth alter the acoustic impedance, which affects the relationship between sound pressure and intensity. Consequently, present hearing conservation guidelines for normobaric air are not directly applicable to hyperbaric noise exposures (5). Indeed, they may be overly conservative for use with a dry-helmeted diver breathing helium-oxygen mixtures at great depths (6).

Dry diving helmets are often used in underwater construction and salvage. The average noise inside unmanned U.S. Navy MK V diving helmets ranged from 93 dB(A) at the surface to 99 dB(A) at 61 meters of sea water (msw) (7). Noise inside a manned standard Siebe-Gorman helmet at 7.6 msw was found to average 95.5–99.5 dB(A), but the Superlite 17 helmet was very quiet (8). Sound intensity levels inside dry helmets used in deep diving systems may exceed 100 dB(A) at depths of 305 msw (9). From these reports it is clear that, in free-flow dry diving helmets, divers are subject to high sound levels while engaged in their work.

Because the effects of dry helmet noise on diver hearing under pressure are not yet predictable from data obtained under normobaric conditions, specific studies are required for particular combinations of equipment, gas pressure, and working environments. The primary diving apparatus used by the U.S. Navy for salvage and heavy work underwater is the MK 12 Surface Supported Diving System (SSDS). Over 9500 h have been spent diving the MK 12 SSDS, with increasing use of this system forecast for the future. The purposes of this study were to a) assess the noise within the U.S. Navy MK 12 SSDS helmet, and b) measure the effects of exposure to this helmet noise on diver hearing.

METHOD

Subjects

Six male U.S. Navy divers and 1 Royal Navy diver, ages 26–36 yr, served as diver-subjects. All men were volunteers in excellent health and physical condition as a result of physical training regimens completed before the dive series. All divers underwent extensive screening, including auditory evaluations before final selection. None of the subjects had a hearing threshold level (HTL) exceeding 20 dB in both ears at frequencies of 3000 and 4000 Hz as assessed by standard audiogram techniques. Otoscopic examination and auditory history revealed no significant abnormalities or contraindications to participation in the auditory studies. The divers were not screened for noise sensitivity.

Apparatus

Hyperbaric chamber

Acoustic studies were conducted in the Navy Experimental Diving Unit's (NEDU's) Ocean Simulation Facility (OSF), a hyperbaric living and working complex. Divers lived in the dry portion of the complex and worked under water in the OSF's 208-m^3 wet chamber. Two bicycle ergometers (Collins Pedalmate, Braintree, MA) were modified locally for use in the wet chamber. They were tilted in a 45° head-up position for the acoustic studies. Work load and rpms were controlled and monitored from outside the chamber. Control of sound instrumentation was conducted outside the pressurized chambers on the NEDU Medical Deck.

Diving system

The U.S. Navy MK 12 SSDS was used during all in-water tests (10). Divers wore the standard MK 12 SSDS components, including dry suit and outer garment (Fig. 1). Neoprene five-fingered gloves and booties were worn by the divers. Two identical helmets were used during the studies, hooked up to a 122-m umbilical consisting of

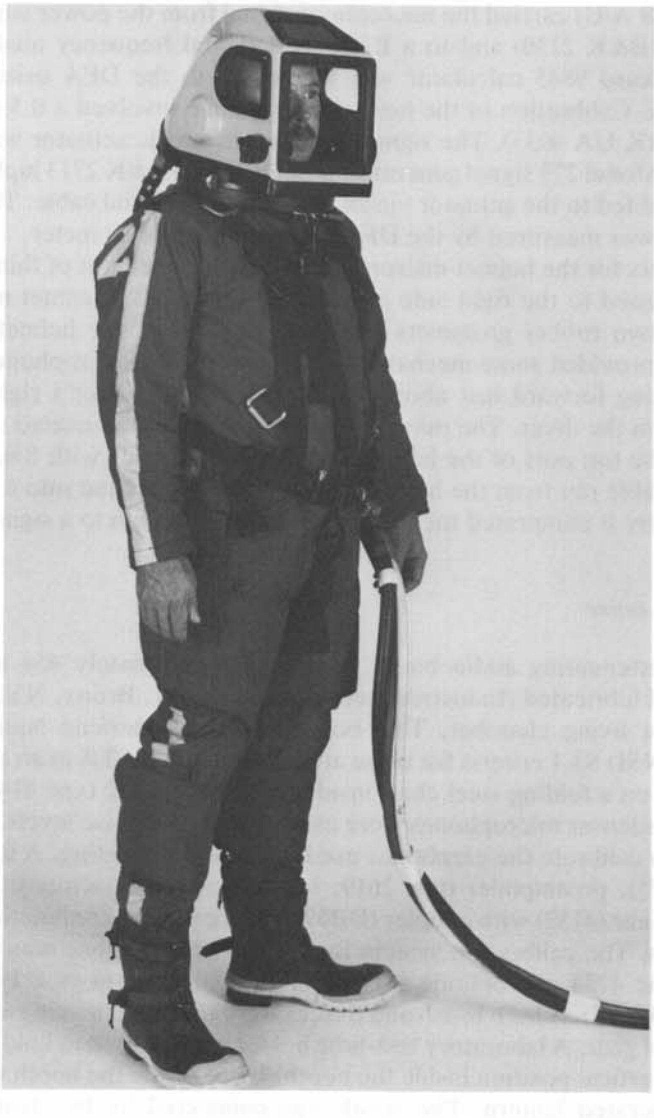

Fig. 1. U.S. Navy MK 12 Surface Supported Diving System (SSDS).

gas hose, pneumofathometer, communication cable, and strength member. Compressed air was supplied to the helmet by air banks.

Helmet noise

A Bruel and Kjaer (B&K) type 4134, half-inch pressure response condenser microphone with accompanying dehumidifier (B&K UA0308) and preamplifier (B&K 2619) were placed inside the diving helmet and used to measure sound levels. The microphone signal was obtained using a B&K 2807 two-channel microphone power supply and a 15-m custom water-blocked sound cable (Hamburg Associates, Jupiter, FL) with electrical characteristics identical to those found in B&K cable A00028. Coaxial cable (RG 188 A/U) carried the microphone signal from the power supply to a sound-level meter (B&K 2230) and to a B&K 2131 digital frequency analyzer (DFA). A Hewlett Packard 9845 calculator was connected to the DFA using an IEEE 488 interface bus. Calibration of the helmet microphone involved a 0.5-in. electrostatic actuator (B&K UA 0033). The signal to the electrostatic actuator was generated by a Wavetech Model 273 signal generator, amplified by a B&K 2713 high-voltage power amplifier, and fed to the actuator via an RG 188 A/U coaxial cable. The output of the microphone was measured by the DFA and the sound-level meter.

Two mounts for the helmet microphone were fashioned out of thin, stainless steel rod and fastened to the right side port of the helmet. The helmet microphone was placed into two rubber grommets and then attached to the helmet with nylon tie wraps. This provided some mechanical attenuation. The microphone was held horizontally, facing forward just above the location of the diver's right ear when the helmet was on the diver. The microphone assembly was connected to a cable which penetrated the top port of the helmet through O-ring seals with Swagelock fittings. The sound cable ran from the helmet, through the water, and into a dry chamber of the OSF where it penetrated the pressure hull and then ran to a signal amplifier.

Audio booth noise

A sound-attenuating audio booth weighing approximately 454 kg was custom-designed and fabricated (Industrial Acoustics Company, Bronx, NY) to fit inside the OSF's Alpha living chamber. This booth met the American National Standards Institute (ANSI) S3.1 criteria for noise attenuation at 1.0 ATA in an air environment. Subjects sat on a folding steel chair inside the booth. B&K type 4144 1-in. pressure response condenser microphones were used to measure noise levels inside the audio booth and to calibrate the earphones used in audiogram testing. A 0.5–1-in. adaptor (type DB0375), preamplifier type 2619, 1-in. electrostatic actuator (type UA0023), and artificial ear (4152) with coupler (DB0909) were used in conjunction with the 4144 microphones. The calibration system for the 4144 microphone was identical to that used with the 4134 microphone except for the substitution of a 1-in. electrostatic actuator (UA0023). A bulb brush and tissues were used for cleaning and drying sound measurement gear. A laboratory test-tube holder was adapted to hold the microphone in a stable, vertical position inside the booth. Light inside the booth was provided by a battery-operated lantern. The booth was connected to the chamber ventilation system through a muffler.

Hearing assessment

A Tracor RA400 microprocessor audiometer (Tracor Instruments, Austin, TX) with matched Telephonics TDH-39-P 10-ohm earphones mounted in MX-41 cushions was used to administer audiograms. During audiometry testing a Switchcraft response button was used.

Procedure

Hyperbaric environment

Helmet noise and diver hearing data were acquired during 10 d of daily "workup" dives followed by 7 d of diving during an air saturation dive. For dives at 1.8 msw, the OSF complex was not pressurized; the diver simply descended into the wet chamber until his chest was 1.8 m under the water. During 9.1-msw dives, the OSF complex was pressurized to 1.7 atmospheres absolute [ATA (7.3 msw)], with the diver's in-water depth being 9.1 msw. The 20.1- and 30.5-msw dive data were obtained during the 7-d air saturation dive. The complex was pressurized to 2.8 ATA (18.3 msw) or 3.8 ATA (28.7 msw) with the diver's in-water depth being 20.1 or 30.5 msw. Audiometry was always conducted at a depth 1.8 msw shallower than the in-water dive depth.

Gas flow to the helmet was maintained between 167 and 173 actual liters/min (ALPM). Helmet flow was computed continuously by a Hewlett-Packard HP 1000 computer using readings from a differential pressure transducer (Validyne DP-9). The pressure transducer was connected to a laminar flow element (LFE). Helmet flow was corrected for gas composition and changes in helmet depth and temperature above or below that at the LFE. Computer readings were used as the standard, with a flow nomogram corrected for the same variables as backup. This rate of gas flow is required to ensure adequate ventilation and CO_2 washout for a heavily exercising diver in this diving system (10).

Carbon dioxide levels inside the manned audio booth were closely monitored. Hearing tests commenced when CO_2 levels were 2.0 mmHg [0.26% surface equivalent value (SEV)] or below as monitored in the booth, and terminated if booth CO_2 levels exceeded 13 mmHg (1.7% SEV) continuously for 10 min or reached 15 mmHg (2.0% SEV) at any time. (*Note:* The termination criterion was never reached.)

Water temperature for all dives was 10 ± 1°C. Carbon dioxide levels inside the living chambers were maintained below 3.8 mmHg (0.5% SEV). Oxygen percentage inside the complex was maintained between 20.5 and 21.5%, with relative humidity kept between 50 and 60%.

After completing a predive audiogram, the diver dressed in the MK 12 SSDS diving gear. The diver's "on-gas" time commenced when the MK 12 helmet was placed on the diver. The diver then descended into the water and mounted an underwater ergometer. After pedaling the ergometer at 60 rpm for 6 min against a 50-W work resistance, the diver rested for 4 min on the ergometer. This 6-min-work, 4-min-rest cycle continued throughout the scheduled length of the dive. Approximately 3 min before the end of the dive, the diver was removed from the water and sat down on a stool in the OSF trunk with the helmet still on. The helmet was removed at exactly the end of the scheduled dive duration. The diver was undressed quickly and moved to the audio booth. Once the diver was unhatted, the audiogram test was started within 3 min.

Calibrations

Before the start of testing, the audiometer and headsets were calibrated and met ANSI specifications as certified by Tele-Acoustics, Titusville, FL. The sound measurement system was calibrated before and after the study in a 1.0 ATA air environment to ensure all equipment performed in a stable manner. Before the study began, 0.5- and 1-in microphones were arbitrarily selected as the primary microphones around which the rest of the sound measurement gear would be adjusted. All other microphones had their sensitivity established relative to these primary microphones. This was accomplished by placing the sound-level calibrator over the primary microphone and preamplifier, and adjusting the sound-level meter and DFA until both read 94.0 dB at 1 kHz in the octave band mode. The responses of all other microphones to the sound-level calibrator were then recorded; no further adjustments were made to the recording equipment.

The primary microphone was calibrated using the electrostatic actuator. A 500-Hz, 5-V signal was fed into the power amplifier. The amplifier was adjusted until both the sound-level meter and DFA read 70 dB at 1 kHz. The voltage level of the power amplifier associated with this signal was recorded both on the DFA and the digital voltmeter. The microphone frequency response was then recorded at frequencies of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. This calibration procedure was conducted before and after the saturation dive in a 1.0 ATA air environment.

An electrostatic calibration was then conducted on each backup microphone with the voltage output of the power amplifier adjusted until the relative microphone output matched that seen with the sound-level calibrator. For example, if a secondary microphone produced a 93.5 dB output in response to the sound-level calibrator, the 0.5-dB variance from the primary microphone was taken into account. The electrostatic actuator was placed on the secondary microphone, and the power amplifier voltage was adjusted until the DFA and sound-level meter read 0.5 dB down at 1000 Hz, i.e., 69.5 dB. The power amplifier voltage associated with this acoustic level was recorded. The microphone frequency response was then recorded, leaving the power amplifier voltage output unchanged.

The sound measurement system outside the chamber was checked daily for instrumentation drift. Each morning the helmet microphone (type 4134), artificial ear microphone (type 4144), and earphones were calibrated in the audio booth. A voltage signal was sent to the actuator for the helmet microphone based on the previously determined voltage at 1.0 ATA in air, which yielded a microphone response of 70 dB at 1000 Hz. The response of the microphone at depth to this voltage was measured and recorded at 21 frequencies from 100 to 10,000 Hz using the DFA in the third-octave band mode. These recorded values were used to correct sound levels for loss of microphone sensitivity during the dive. After completion of each in-water dive the microphone was dried manually and the above procedure repeated. (*Note:* Although a slight mist was observed occasionally on the diaphragm of the microphones after a dive, no droplets of water were seen. Previous experience indicated that the presence of a droplet of water on the diaphragm would lead to a cessation of microphone response once a voltage was applied.)

Calibration of the 1-in. (4144) microphone was similar to the procedure described for the helmet microphone, except that a 1-in. electrostatic actuator was used. When calibrated, the 1-in. microphone was installed into the artificial ear. A plastic cylindrical sleeve was then placed onto the artificial ear coupler. The artificial ear was set on the microphone stand and connected to the interior patch panel of the booth. The earphone to be calibrated was removed from its headset, placed evenly into the center of the sleeve, and the spring-tensioned arm applied 500-g force to the back of the earphone to ensure proper coupling.

Calibration of the audiometer and its earphones was accomplished as follows. When set to 70 dB HTL on the surface, the audiometer produced a signal that yielded responses from the earphone within ANSI S3.6 1969 specifications. At depth, the responses of the earphone to the delivery of this signal at frequencies of 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz were received by the microphone in the artificial ear and transmitted to the DFA. Readings in the octave mode on the DFA were recorded manually for each earphone. To assess variability in readings due to technician or equipment technique, at least two calibrations for each earphone at each frequency were conducted both pre- and postdive. An audiometer attenuator linearity check was also performed each time an earphone was calibrated.

After calibration, each earphone was removed from the artificial ear and placed back into its respective headset. The 1-in. microphone was then installed in a vertical position in the interior audio booth microphone stand for recording background audio booth noise levels.

Audiometry

Before each audiogram, the inside audio technician established communication with topside personnel, donned the headsets, listened for tones in both earphones, and depressed the response switch to ensure proper functioning of all equipment. Both inside and topside audio technicians queried the diver as to his health. In addition, his ears were examined periodically with an otoscope for the purpose of detecting ear canal and tympanic membrane status. The diver entered the audio booth and sat quietly, facing the door. The audio tender repeated instructions to the diver, placed the earphones on the diver's head, and handed the diver the response switch. Each diver was instructed to sit quietly, breathe normally, relax his jaw, and refrain from repositioning his headset or placing his hands over or on the earphones. The diver signaled by hand that he was ready to start the test, and the door was shut. The ventilation system flow to the audio booth was reduced, and the remainder of the OSF's environmental conditioning system blowers were secured. An ''all-quiet'' mode was observed by personnel both inside and outside the chamber complex. All divers except the audio tender and the subject lay down in their bunks and did not talk.

Each audiogram was administered in the automatic mode at frequencies of 500 Hz, and at 1, 2, 3, 4, 6, and 8 kHz using standard U.S. Navy audiometric procedures. The diver responded by depressing the response button when he perceived the tone, and releasing the button when the tone went away. The complex continued in the all-quiet mode during audiometry. Follow-up audiograms were taken usually before the diver went to sleep in the evening after the dive, and twice the next day.

Noise data collection

During the in-water dives, helmet sound data were recorded continuously during 10 min of each hour of the dive, both while the diver was exercising and while resting. Each sample covered one full work-rest cycle. The sound data were gathered by the DFA in 128-s packets, averaged and displayed in dB by third octave, and then transferred and stored in the calculator. Corrections for gas density, helmet temperature, and microphone response were entered into the calculator for each dive. The calculator produced a printout in the format of time vs. level vs. frequency for each dive. An overall dive sound-intensity level was calculated, with a reference level of 10^{-12} W/m^2.

Adjustments to noise data

During calibrations, the response of the microphone to a voltage that yielded 70 dB in a 1.0 ATA air environment was recorded at 21 frequencies at the test depths. The difference between the microphone's response at 1.0 ATA and the response at depth was noted, and labeled microphone attenuation. Overall microphone attenuation factors were obtained by averaging the daily predive responses of the microphones to the electrostatic calibration procedure. This mean attenuation was calculated for each dive by third octaves and added to the measured sound level at depth. This was accomplished by programming the calculator appropriately.

A correction for the impedance of the medium was also made. This was necessary to compare sound levels measured at the surface with sound levels measured at depth (4). The characteristic impedance (Z) of a gaseous medium is a function of $Z = dc$, where d = density, and c = sonic velocity. Values d and c were obtained from the U.S. Navy Diving Gas Manual (11) for the test depths, gas composition as assessed by mass spectrometers, and gas temperatures measured in the helmet. The characteristic impedance Z_s (s = surface) of 1.0 ATA air and the impedance Z_d (d = depth) of the gas mix at depth (e.g., 3.0 ATA, 79% N_2:21% O_2) were used to calculate a correction for impedance as:

$$10 \log Z_s/Z_d.$$

Essentially, this procedure converts sound pressure levels to sound intensity levels (SILs) which may be compared across media.

The mean third-octave band levels were corrected by the calculator for microphone sensitivity losses and the impedance of the medium. The corrected third-octave bands were then combined using the formula:

$$L_{\mathrm{comb}} = 10 \mathrm{Log}_{10} \left(\sum 10^{L_i/10}\right),$$

where L_i = the individually corrected octave band levels. This yielded an overall SIL. SILs in dB(A) were also computed by applying a correction for A-weighting to each octave band intensity level before summation across bands.

RESULTS

1.8 msw/1.2 ATA dives

Eight dives, each lasting 60 min, were completed at a diver depth of 1.8 msw. The average corrected SIL in the helmet was 95.8 dB, or 90.5 dB(A). Variability in

SILs between dives at this depth was minimal: SD = 2.3 dB, or 0.8 dB(A). Figure 2 presents the averaged corrected SILs by frequency for this depth. Low frequency noise (100–160 Hz) was prominent, as were the levels at 500, 800, 2000, and 2500 Hz. Table 1 presents noise level by frequency for each individual dive. Across dives the SILs at each frequency were relatively homogeneous.

The average corrected SIL(A) yielded a permitted exposure time of 155 min, by U.S. Navy criteria (12). Table 2 presents the median temporary threshold-level shift (TTS) by frequency immediately postdive for both ears of the 7 divers. The left ear displayed greater shifts than the right ear in most divers, especially at frequencies of 3000 and 4000 Hz. However, shifts greater than 15 dB were not observed. Individual variation in sensitivity to noise exposure was apparent after these dives of relatively homogeneous sound intensity levels. As shown in Table 3, divers B, D, and F were more sensitive to the effects of helmet noise than the other divers. These observations are reinforced by the wide range of shifts recorded at each frequency. Negative TTSs (i.e., −5, −10, etc.) were found after exposure to helmet noise for 60 min. Shifts of −5 may be expected due to measurement error. However, the −10 shifts shown by divers E, F, and G are unusual and may reflect inattention during the predive audiogram testing or an actual change in sensitivity. One can only speculate, because the divers indicated they were attentive, the equipment was functioning properly, and procedures were followed as indicated. Perhaps the slight change in pressure of 0.18 ATA (corresponding to 1.8 msw) was sufficient to equalize pressure in their middle ear during the dive and alter their sensitivity in the postdive audiogram.

All divers' hearing returned to within ± 5 dB of the predive audiogram level at all frequencies within 24 h after termination of exposure to helmet noise.

9.1 msw/1.9 ATA dives

Seven dives of 120-min duration and 1 dive of 180-min duration were completed at a depth of 9.1 msw. The 120-min dives averaged 95.9 dB, or 92.4 dB(A), with only minimal variation between dives [SD = 0.8 dB; 1.3 dB(A)]. This represents an overall average increase of 1.9 dB(A) in the helmet SIL compared to SIL observed during 1.8 msw dives. Figure 2 also presents the average overall SIL by frequency for the 7 dives of 120 min at 9.1 msw. Again, low-frequency noise was prominent at 100–160 Hz, with an elevated plateau displayed from 500 to 2500 Hz. This represents a rather broad-band noise source. Table 1 presents the noise data by frequency and individual dive. Variability within a frequency across dives was somewhat greater than that found at 1.8 msw, as evidenced by the SD at 9.1 msw. The range of average helmet SIL(A)s across dives was from 90.7 dB(A) (diver B) to 94.0 dB(A) (diver F), a magnitude of 3.3 dB(A). Examination of the specific frequency data from these 2 dives reveals that diver F's dive was noisier, especially in the frequencies from 315 to 4000 Hz. As the same helmet, microphone, gas flow, and other parameters were used for these dives, we are unable to identify with confidence the cause of the variations in helmet noise levels greater than approximately 2 dB, which is the measurement tolerance of the B&K recording system. However, the size and position of the head of the diver may have contributed to this variability.

The 3-h dive was undertaken with diver D, who had been noted previously to have sensitive hearing after a 120-min dive. Helmet noise levels were similar to those found during the 2-h dives and are presented in Table 1.

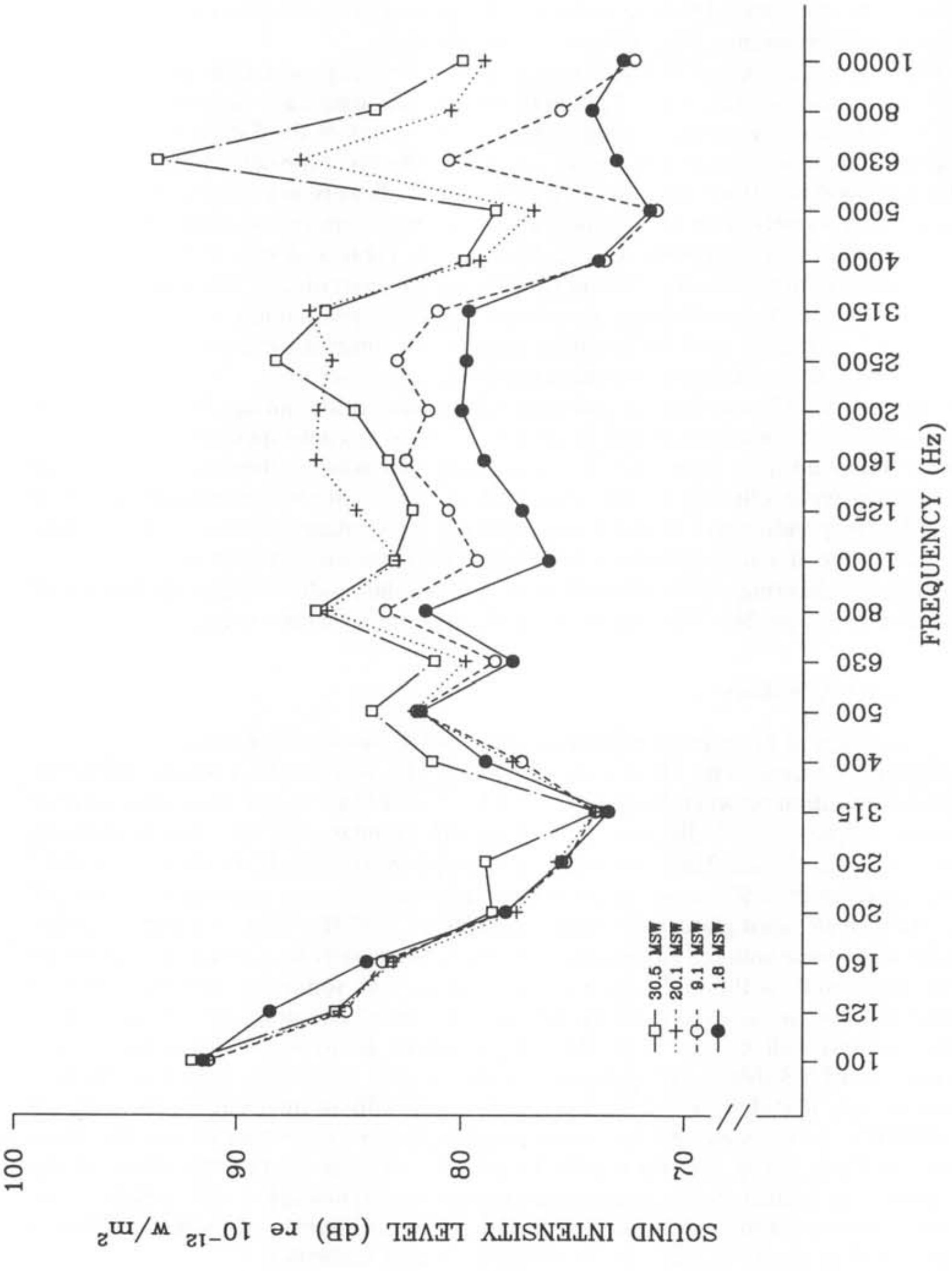

Fig. 2. Mean sound intensity levels by one-third octave inside the MK 12 SSDS helmet during dives at simulated depths of 1.8, 9.1, 20.1, and 30.5 msw.

TABLE 1

OVERALL MK 12 SSDS CORRECTED HELMET NOISE IN DB(A), DB, AND ONE-THIRD OCTAVE BAND LEVELS BY FREQUENCY (DB) FOR DIVES AT 1.8, 9.1, 20.1, AND 30.5 MSW

Depth, msw	Diver	Dive Duration, min	Helmet Noise,		Frequency, Hz																				
			dB(A)	dB	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
1.8	A	60	90.3	94.1	89.1	85.4	84.1	77.1	75.5	72.8	78.2	82.8	78.5	81.4	75.7	80.0	77.0	80.3	81.1	78.6	74.5	70.8	74.0	74.2	72.8
	B	60	90.5	97.2	94.9	88.0	84.6	78.7	76.6	75.8	81.9	83.5	79.5	80.5	78.7	79.0	78.4	79.2	78.4	78.3	74.5	72.4	72.8	72.0	72.9
	C	60	89.8	93.6	87.6	87.4	82.8	77.3	75.2	72.7	77.3	80.7	77.6	82.9	75.8	76.6	79.6	77.0	79.5	80.4	73.1	70.6	68.6	70.4	70.8
	D	60	90.4	92.9	87.4	83.1	79.7	75.6	74.3	72.1	77.7	80.7	76.8	82.6	76.1	78.4	80.3	81.7	79.9	79.5	73.1	70.5	68.1	71.5	72.0
	E	60	90.7	96.3	91.5	90.9	85.8	78.3	76.1	73.8	79.4	82.1	76.9	80.8	76.6	77.2	78.8	79.6	80.6	80.9	75.8	73.1	76.9	78.4	73.7
	F	60	90.0	98.8	96.6	92.4	85.2	79.7	75.5	73.6	79.9	81.2	76.5	79.4	75.4	73.8	77.2	78.3	79.7	78.2	73.6	70.9	76.4	77.0	73.2
	G	60	90.0	95.0	92.2	85.7	81.4	76.1	74.7	72.3	78.4	81.3	76.4	81.4	74.5	77.1	80.5	79.3	76.8	81.5	73.3	71.8	72.8	72.2	71.2
		X̄	90.5	95.8	91.5	88.5	84.2	78.0	75.5	73.4	78.9	81.8	77.7	81.6	76.1	77.3	79.0	80.0	79.8	79.7	73.9	76.6	73.1	74.2	72.8
		SD	0.8	2.3	3.3	4.0	3.0	1.9	0.8	1.2	1.5	1.0	1.2	1.4	1.2	1.9	1.4	2.3	1.7	1.3	1.0	1.0	3.3	3.2	1.5
9.1	A	120	92.2	95.0	90.6	83.7	80.0	76.2	74.3	72.2	79.5	82.6	78.2	84.3	77.9	79.4	80.8	84.0	82.5	80.1	73.5	71.7	80.9	73.6	71.0
	B	120	90.7	97.0	94.9	86.6	83.5	78.1	75.0	73.4	77.0	81.1	77.8	81.6	78.5	79.1	79.3	78.8	80.7	79.8	74.3	70.8	79.6	75.0	70.9
	C	120	93.1	95.4	88.7	85.4	86.4	78.4	74.9	74.5	73.8	80.0	78.0	84.1	78.6	80.8	84.5	81.9	85.5	81.9	70.6	69.1	82.0	76.2	72.0
	D	120	93.1	95.1	89.5	83.4	83.6	77.1	74.6	74.6	76.0	81.6	78.7	84.3	80.0	82.5	85.5	83.0	83.8	81.2	72.1	70.0	75.0	74.1	72.3
	E	120	93.2	96.8	91.2	87.8	87.9	80.7	76.8	73.7	76.4	80.8	79.2	82.6	80.6	81.9	82.7	81.1	82.6	83.9	76.1	75.7	85.1	81.7	76.6
	F	120	94.0	96.3	90.2	84.2	83.1	78.6	75.6	76.3	80.7	86.7	80.6	82.3	82.0	82.3	82.8	81.6	86.0	81.6	77.6	71.5	85.1	78.2	73.7
	G	120	90.8	95.8	93.5	84.8	80.2	76.6	75.6	73.5	77.4	81.3	76.8	78.2	77.2	78.2	81.6	80.3	79.5	79.5	70.9	70.6	76.7	70.7	69.4
		X̄	92.4	95.9	91.2	85.1	83.5	78.0	75.3	74.0	77.3	82.0	78.5	83.4	79.3	80.6	82.5	81.5	82.9	81.1	73.6	71.3	80.6	75.6	72.3
		SD	1.3	0.8	2.2	1.6	2.9	1.5	0.8	1.3	2.3	2.2	1.2	1.0	1.7	1.7	2.1	1.7	2.4	1.5	2.6	2.1	3.9	3.5	2.3
9.1	D	180	93.2	97.1	94.1	84.6	84.2	77.5	74.5	74.7	76.1	81.3	78.1	83.6	80.1	83.0	84.8	83.3	84.1	81.6	72.9	70.7	78.2	75.5	72.6
20.1	A	120	96.1	97.7	91.6	86.7	83.9	77.6	76.4	72.9	77.3	82.4	78.9	86.6	82.1	83.7	85.8	88.8	86.5	85.7	79.5	76.3	85.0	77.3	75.0
	D	120	95.5	97.6	92.6	84.7	82.1	78.4	75.6	74.9	77.9	83.4	80.5	84.6	81.5	84.9	85.9	84.8	84.5	87.6	77.8	76.5	85.6	81.0	78.0
	E	120	96.7	98.2	90.4	87.7	85.9	77.2	74.9	74.5	76.9	81.7	81.2	86.4	84.5	86.1	87.3	84.8	88.5	85.7	78.6	74.5	89.0	79.7	78.7
	G	120	96.9	97.9	90.3	82.6	80.1	76.8	75.9	73.5	78.8	81.1	78.6	86.3	83.2	84.1	87.0	87.4	83.8	88.3	80.9	79.7	89.2	83.9	84.2
		X̄	96.3	97.8	91.2	85.4	83.0	77.5	75.7	74.0	77.7	82.1	79.8	86.0	82.8	84.7	86.5	86.4	85.8	86.8	79.2	76.8	87.2	80.5	79.0
		SD	0.6	0.3	1.1	2.3	2.5	0.7	0.6	0.9	0.8	1.0	1.3	0.9	1.3	1.1	0.8	2.0	2.1	1.3	1.3	2.2	2.2	2.8	3.8
30.5	F	40	97.3	99.0	92.0	85.6	83.1	78.6	78.9	73.9	81.3	84.0	81.2	86.5	83.0	82.2	83.3	84.3	88.3	86.1	79.9	78.5	93.6	83.9	80.0

TABLE 2

MEDIAN HTL SHIFTS IN BOTH EARS FROM DIVERS EXPOSED TO MK 12 SSDS HELMET NOISE. NUMBERS (dB) REPRESENT THE DIFFERENCES IN HTLs AT EACH FREQUENCY BETWEEN PRE- AND POSTDIVE AUDIOGRAMS

Dive			Left Ear							Right Ear						
			Frequencies, kHz													
Depth, msw	Duration, min	No.	0.5	1	2	3	4	6	8	0.5	1	2	3	4	6	8
1.8	60	7	0	5	5	15	15	0	0	0	0	5	5	5	0	0
9.1	120	7	5	5	15	20	20	10	5	0	5	10	10	5	5	5
	180	1	−5	5	40	35	25	10	0	10	10	20	30	15	5	10
20.1	120	4	5	10	18	20	18	18	5	3	5	13	8	13	3	0

Table 2 shows that TTS increased at most frequencies when the dives were lengthened from 60 to 120 min and the depth increased from 1.8 to 9.1 msw. Substantial shifts of 20 dB were observed in the left ear at 3000 and 4000 Hz. Again, the left ear revealed greater shifts than the right ear after helmet noise exposure. Individual TTSs immediately post-120-min dives at 9.1 msw are presented in Table 3. Once again divers B, D, and F displayed larger shifts than the other divers. Diver D also incurred a substantial auditory shift in his right ear.

The average noise level inside the helmet was 93 dB(A) during diver D's 3-h dive. Immediately postdive he recorded HTL shifts of 25–40 dB in his left ear at frequencies of 2–4 kHz, and in the right ear shifts of 15–30 dB at the same frequencies. At the 24-h-postdive mark he still had TTS of 10 dB from predive levels at the frequencies of 3 and 4 kHz. By 72 h postdive his hearing had recovered to predive levels.

20.1 msw/3.0 ATA dives

Four dives of 2-h duration were accomplished at 20.1 msw. The average corrected noise level in the helmet was 97.8 dB, or 96.3 dB(A). Variability in sound levels between dives was minimal [SD = 0.3 dB; 0.6 dB(A)]. Figure 2 presents the corrected SILs (in dB) by frequency for dives at 20.1 msw. As found at shallower depths, the prominent peaks of sound were located at 100–160 Hz, and between 1600 and 3150 Hz. Table 1 presents the noise data by frequency for each individual dive. Across dives the SILs at each frequency were relatively homogeneous. The overall SILs for these dives were 5.8 dB(A) higher than for dives at 1.8 msw, and 3.9 dB(A) higher than at 9.1 msw.

With an overall dB(A) level of 96.3, the permitted exposure time by U.S. Navy criteria is 60 min for exposure to noise of this level in a 1.0 ATA air environment. The median TTSs due to this noise exposure are presented in Table 3. Shifts were more prominent in the left ear than in the right ear, again similar to the results found after dives at 1.8 and 9.1 msw. However, diver D displayed shifts of 55 and 35 dB at 2 and 3 kHz, respectively, after a 2-h dive at 20.1 msw. His hearing at these frequen-

TABLE 3

HEARING THRESHOLD LEVEL SHIFTS IMMEDIATELY POSTDIVE AFTER EXPOSURE TO MK 12 SSDS HELMET NOISE. NUMBERS REPRESENT DIFFERENCE IN HTLs BETWEEN PRE- AND POSTDIVE AUDIOGRAMS AT EACH FREQUENCY

Depth, msw	Diver	Dive Duration, min	Helmet Noise, dB(A)	Left Ear, Hz							Right Ear, Hz						
				500	1000	2000	3000	4000	6000	8000	500	1000	2000	3000	4000	6000	8000
1.8	A	60	92.4	−5	5	0	15	25	10	5	0	0	5	−5	0	10	5
	B	60	90.3	0	−5	10	20	25	0	0	0	0	5	10	10	−5	−5
	C	60	90.5	0	0	5	0	−5	0	0	5	5	−5	0	10	−5	10
	D	60	89.8	−5	5	15	25	25	0	−5	0	5	10	20	15	0	5
	E	60	90.4	5	5	5	5	10	10	−10	−5	0	5	5	5	0	0
	F	60	90.7	5	5	10	20	25	−10	0	10	5	10	0	0	5	−5
	G	60	90.0	0	−5	−5	5	0	−15	0	−5	0	5	5	0	0	0
9.1	A	120	92.2	5	10	15	20	25	−5	10	0	−5	5	0	10	20	5
	B	120	90.7	0	5	20	25	25	10	5	0	0	5	10	5	10	5
	C	120	93.1	10	5	0	10	10	−10	−15	0	5	−5	0	−10	5	5
	D	120	93.1	−5	0	20	30	25	10	0	5	10	15	30	15	0	5
	E	120	93.2	5	5	10	15	20	10	15	10	5	15	10	5	5	0
	F	120	94.0	10	15	25	30	25	25	15	0	5	10	15	10	−5	−5
	G	120	90.8	0	5	10	10	15	15	0	5	5	10	5	0	15	20
9.1	D	180	93.2	−5	5	40	35	25	10	0	10	10	20	30	15	5	10
20.1	A	120	96.1	10	15	20	20	20	15	10	5	5	15	5	15	5	0
	D	120	95.5	0	10	55	35	25	20	15	5	5	20	20	15	0	−5
	E	120	96.7	5	10	10	20	15	20	−5	−5	10	5	10	10	10	0
	G	120	96.9	5	10	15	15	15	15	0	0	5	10	5	5	0	15

cies required more than 48 h to recover to predive levels. This diver also exhibited the largest HTL shifts on shallower dives, although the magnitude of shift at 20.1 msw was substantially greater at 2 kHz (i.e., 55 dB) than observed before.

30.5 msw/4.0 ATA dive

One dive with a scheduled duration of 120 min was undertaken at 30.5 msw. Due to factors unrelated to the sound studies, only one 10-min sound sample was collected and a postdive audiogram was unavailable. The SILs associated with this sample are also presented in Fig. 2 and Table 1. Again, peak SILs were observed at 100, 800, 2500, and 6300 Hz, with the shape of the noise spectra similar to those found at other depths.

General findings

All divers' hearing returned to within +5 dB of their prestudy reference levels within 5 d after they surfaced from the saturation dive. No evidence of residual permanent auditory damage was noted by physical examination, audiometry, or diver verbal reports.

Subjective symptoms reported by the divers immediately after removal from helmet noise included fullness in both ears and ringing in both ears (more pronounced in the left ear). Our most sensitive diver, diver D, underwent an otoscopic examination after his postdive audiogram following a 3-h dive. His left ear canal was clear, with the canal tissue pink-red with blood vessels prominent. His tympanic membrane was intact but red streaking was noted on the membrane. His right ear exhibited a clear canal, with no evidence of prominent blood vessels or red streaking on the tympanic membrane.

Of the 7 diver subjects, diver D seemed most sensitive and diver C least sensitive to the effects of MK 12 SSDS helmet noise, with the remaining 5 divers' hearing sensitivity falling between these two extremes. Table 3 reveals the consistency of divers' hearing sensitivity across depths. We conclude that our diver-subject sample represents a wide cross section of subjects with varying levels of sensitivity. Whether this sample is representative of the population of U.S. Navy and Royal Navy divers is unknown.

DISCUSSION

The average sound intensity levels noted in the MK 12 SSDS helmet at simulated depths of 1.8 to 30.5 msw are similar to results obtained with different diving helmets using increased pressures of air as the breathing medium (7, 8). In all cases, however, the SILs in these helmets could be limiting factors to the duration of time a diver can work while wearing them. As an example, at a depth of 20.1 msw the U.S. Navy Permissible Exposure Time for a helmet noise equivalent to 96 dB(A) is 1 h. By standard U.S. Navy air decompression tables, the diver would be limited to 50 min at this depth so as not to incur a decompression obligation which would extend the diver's in-water time to 68 min (i.e., 21.3 msw schedule for 60 min). Further, these calculations do not account for helmet noise exposure during entry and exit from the water nor during travel from different depths.

Among the important aspects of helmet noise that must be considered are SIL (loudness) and frequency range. Sound intensity levels of certain magnitudes can impact on a person's hearing threshold with transient or permanent compromise of hearing acuity with repeated exposures. The frequency spectrum of noise can impact on the intelligibility of communications by masking the sounds produced by human speech.

Two characteristics of MK 12 SSDS helmet noise deserve attention. First, as the helmet supply pressure increases, the SILs in the helmet increase (Fig. 3). This is of importance because as the diver descends deeper and/or his umbilical length increases, the helmet gas supply pressure must be increased (10). This results in higher helmet noise levels. Second, the gas exhaust valve of the MK 12 SSDS helmet is located on the left side of the helmet. This is the probable cause for the increased threshold shift observed in the diver's left ear when compared to his right ear. The breathing gas enters the helmet through a diffuser in the front of the helmet and exits through the exhaust valve in the left side of the helmet. Passage of the gas through the valve orifices contributes to the measured noise dose.

Reports from divers using the MK 12 SSDS in U.S. Navy operational diving commands indicate that divers normally have a difficult time hearing communications from personnel on the surface. Often these divers find it necessary to reduce manually the flow of breathing gas to the helmet so as to improve the intelligibility of messages received from the surface. This results in the diver setting the helmet supply gas flow at a level that ensures adequate communication but fails to ensure adequate washout of expired CO_2 in the helmet. In at least 2 cases of diver unconsciousness, investigators suspect that the failure of divers to increase helmet gas flow after reducing flow to communicate with the surface was a primary cause of these accidents.

An examination of the frequency spectrum in the helmet reveals peak noise levels between 800 and 3150 Hz. This frequency range also encompasses the range of male human speech articulation in a conversational tone (13). Thus it is plausible that divers are experiencing difficulty in understanding verbal communications from the surface given the noise levels in the helmet at these critical frequencies. The divers, therefore, use their only means of improving the system, which involves turning down the gas flow to reduce the overall noise in the helmet. Given that a gas flow of 170 ALPM is required to support a heavily exercising MK 12 SSDS diver (14), engineering modifications should be made to reduce noise and/or the effects of this noise on the diver. Possible solutions might include some sort of nonobtrusive hearing protection, movement of the earphones from the helmet shell onto a beanie that the diver would wear directly over his ears, engineering redesign of valves and ports, and the inclusion of sound-attenuating material in the helmet and gas delivery system.

Our results indicate that moderate hearing threshold shifts occur following unexceptional air diving exposures (1–2 h) in the MK 12 SSDS. These HTL shifts subside after auditory rest periods of 24 h. For some divers, continuous exposure to helmet noise for periods in excess of 2 h at depths as shallow as 9.1 msw may be hazardous to their hearing. We have no data on the effects of repeated daily exposures to MK 12 SSDS helmet noise on HTLs. The diver-subjects were not screened for their sensitivity to noise but rather on their possession of good hearing as assessed by the audiogram. To our knowledge, divers are not routinely screened for sensitivity to

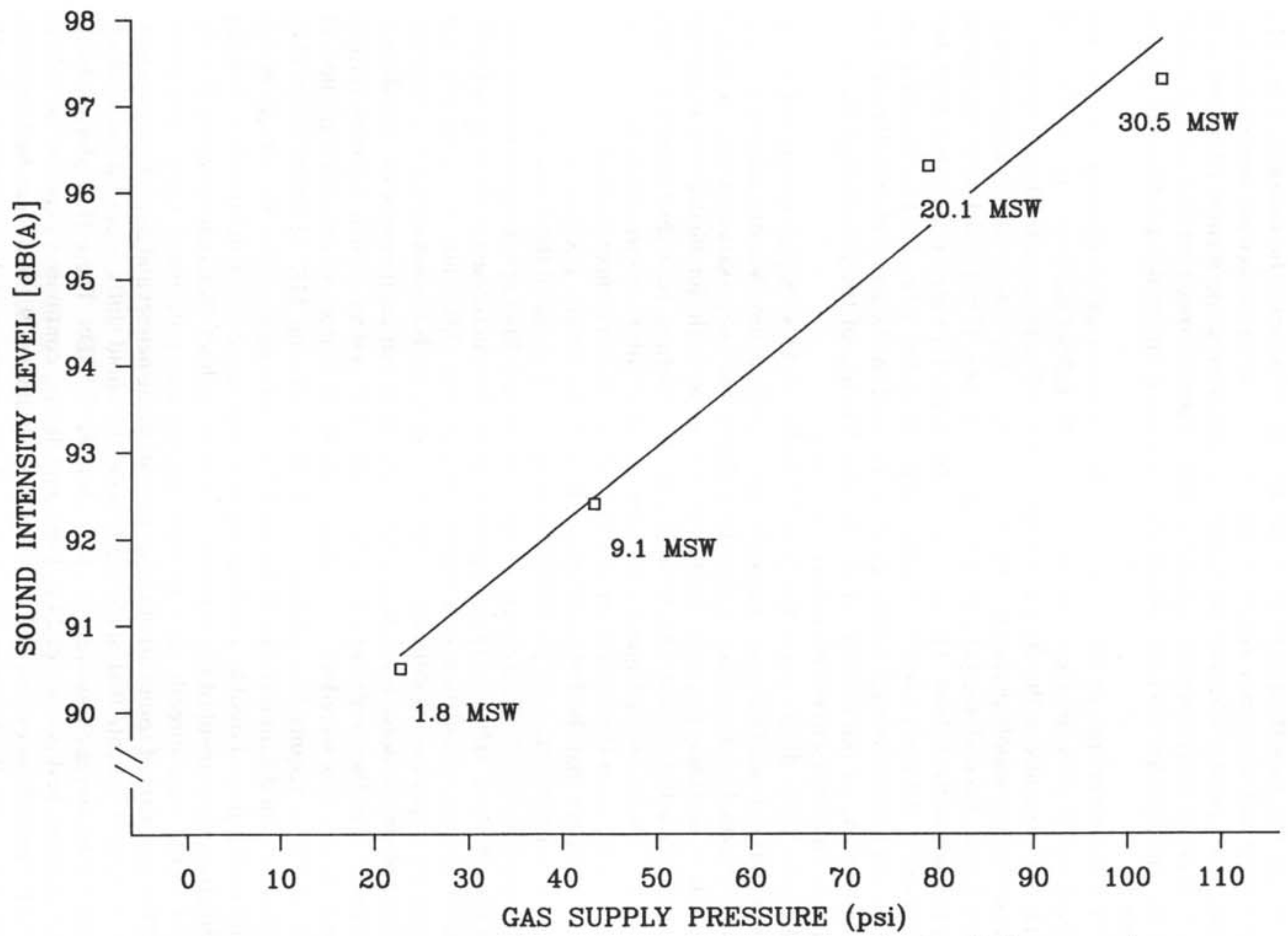

Fig. 3. Sound intensity levels [dB(A)] in the MK 12 SSDS helmet at 4 simulated depths as a function of helmet gas supply pressure.

noise by the U.S. Navy or any other institution. Yet these seemingly innocuous (by U.S. Navy standards) dives resulted in severe HTLs for 1 diver and significant shifts (>25 dB) in 2 other divers. Based on the results of this study, the development of tests of sensitivity to helmet noise which have predictive validity would appear useful. Such a test would be appropriate for individuals considering diving as a career.

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Curley MD, Knafelc ME. Evaluation du bruit á l'intérieur du casque MK 12 SSDS et son effet sur l'audition des plongeurs. Undersea Biomed Res 1987; 14(3):187–204.—Le bruit á l'intérieur du casque MK 12 SSDS de la Marine américaine fut mesuré et son effet sur l'audition des plongeurs fut évalué. Sept plongeurs mâles complétèrent 20 plongées en respirant de l'air à des profondeurs simulées variant de 1.8 à 30.5 msw avec des temps de plongée de 40 à 120 min. Des microphones enregistrèrent les niveaux de la pression du son à l'intérieur du casque chez le plongeur pendant un exercice dans l'eau. La moyenne corrigée des niveaux d'intensité du son dans le casque, varia de 90.5 dB(A) à 1.8 msw jusqu'à 97.3 dB(A) à 30.5 msw. Les déplacements dans le seuil auditif du plongeur furent documentés comme une fonction de l'exposition du bruit dans le casque; des changements modérés de seuil furent observés à des profondeurs de 9.1 msw et plus après des plongées de 120 min. L'audition de tous les plongeurs qui complétèrent des plongées jusqu'à 120 min rétourna aux niveaux pré-plongée en moins de 24 h après l'exposition au bruit. Toutefois, les durées de plongée de plus de 120 min à 9.1 et 20.1 msw résultèrent en des changements auditifs substantiels chez 1 plongeur, lequel nécessita 2–3 jours pour récupérer aux niveaux d'avant-plongée. Ces résultats suggèrent que l'impact du bruit dans le casque sur l'audition du plongeur devrait être inclu dans la plannification des opérations utilisant le MK 12 SSDS.

MK 12 SSDS
bruit dans le casque
audition
acoustique
changements de seuil
sous l'eau
hyperbare

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