HSE
Health & Safety
Executive

OFFSHORE TECHNOLOGY REPORT - OTO 95 009

NOISE EXPOSURE UNDER HYPERBARIC CONDITIONS

by

D H Robertson
and
M E Simpson

MaTSU
Culham, Abingdon
Oxfordshire
OX14 3DB

Date of Issue: March 1995 **Health and Safety Executive**

This report is published by the Health and Safety Executive as part of a series of reports of work which has been supported by funds provided by the Executive. Neither the Executive, nor the contractors concerned assume any liability for the reports nor do they necessarily reflect the views or policy of the Executive.

Reports in the OTO series may be obtained from HSE Information Services, Information Centre, Broad Lane, Sheffield S3 7HQ
Tel: 0742 892345, Fax: 0742 892333, Telex: 54556.

SUMMARY

Objective evidence exists that divers demonstrate a hearing deficit greater than would be expected from ageing effects alone. Deafness in divers may be caused by a number of factors other than exposure to excessive noise levels, eg barotrauma, ear infection etc. This review concentrates on the concern that exposure of commercial divers to noise while at work may cause a hearing deficit.

Sound pressure levels recorded both underwater and in diving chambers often exceed those allowable to workers onshore. However, the sound perceived by the diver is modified both in amplitude and in frequency when he is either underwater or in pressurised chambers. Broadly the effect of this modification is to attenuate the sound and thus offer some protection from high noise levels. The degree of attenuation varies with the frequency of the sound, however it is also possible under specific conditions associated with gas density for the sensitivity to particular frequencies to be amplified above that for normal atmospheric air.

The levels of sound observed from some underwater tools are of concern even after allowing for a significant de-sensitisation of the divers' hearing. Reports of tinnitus and temporary hearing loss following a dive are sure signs that the noise levels have been harmful. It is not possible at present to describe risk criteria for hearing damage due to noise exposures associated with diving.

The need is for further research in defining the sensitivity of the ear in hyperbaric conditions and defining typical noise spectra for diving operations. Practical steps can be undertaken in the meantime to improve the margins of safety by reducing the incidence of exposure to avoidable high amplitude sound.

CONTENTS

1. INTRODUCTION

Anecdotal evidence has existed for some time that divers experience a long-term hearing deficit. Objective measurements made over the last two decades generally indicate that divers do experience a hearing deficit that is greater than is expected from the normal ageing process. There is also evidence that divers are exposed to what is apparently excessive noise at the worksite. Direct analogy with topside workers would suggest that such exposures would cause deafness in divers.

Deafness in divers may be caused by a number of factors such as physical damage from barotrauma, inner or middle ear disfunction from decompression sickness, bacteriological infection or fungal attack, as well as from noise. High intensity sound can also cause damage to extra-auditory systems in the body. The purpose of this review is focus on the subject of noise and it's effect on hearing only. The aim in doing so is to concentrate on the knowledge presently available and thence to identify the research that is still required to enable risk criteria to be developed relating to hearing loss in divers due to noise exposure at work.

Specific project objectives are:

i. to identify whether it is likely that commercial divers are being exposed to excessive noise, with consequent temporary or permanent detriment to their hearing;

ii. to establish best advice based upon currently available information regarding exposure to high noise levels in hyperbaric conditions;

iii. to identify gaps in existing knowledge where further research is required to enable risk criteria to be developed and incorporated into OSD guidance on noise exposure limits in hyperbaric conditions.

Information was obtained by means of a literature search of published andunpublished material to identify data relevant to the above objectives. The literature was searched for information on:

- incidence of deafness in divers;

- the noise levels to which divers may be exposed, and any consequential temporary or permanent effects;

- means of noise transmission and attenuation characteristics for the wet and dry hyperbaric ear;

- current or proposed noise exposure limits.

In the interests of consistency, all sound pressure levels quoted in this review are referenced to 20μPa.

Contents

2. INCIDENCE OF HEARING LOSS IN DIVERS

Molvaer (1) measured hearing acuity in 194 professional divers, with a re-test of rather more than half this number after an interval of 6 years. The sound frequencies tested ranged from 0.125 kHz to 8 kHz. Standard reference data was taken from the International Organisation for Standardisation (2). At most frequencies, the divers had higher hearing thresholds than otologically normal subjects of the same age, both at the first and final examination (Figures 1 and 2). Molvaer found evidence of barotrauma, tympanic membrane rupture and other traumatic injuries in some subjects. However not all subjects who demonstrated a hearing deficit reported having experienced a traumatic injury, and none of the divers had suffered from ear diseases during the observation period (apart from external otitis during saturation in some subjects). Molvaer concluded by reference to other work that hearing loss in divers was multifactorial, but that high noise levels caused acute or insidious hearing loss.

Edmonds (3) conducted a study of abalone divers, whose diving experience was considerable, but did not include any significant exposure to noise from underwater tools etc. Results indicated that over 60 % of the population studied had either unilateral or bilateral high frequency deafness, when referenced to the Australian Standards Association minimum standards (4). There were no obvious factors leading to otological pathology, other than diving. Excessive noise exposure was unlikely, other than that from their predominantly open-circuit breathing apparatus. Only one subject had previous experience in the armed forces where there may have been exposure to gunfire or explosives. None had caisson, helmet or saturation diving experience. There was no apparent evidence of middle ear barotrauma. Edmonds did not attempt to hypothesize on the specific cause of deafness in each individual diver. However the divers themselves generally attributed their hearing loss or associated tinnitus to a barotrauma incident in the past.

There is therefore evidence that divers suffer a hearing loss that is greater than would be predicted from ageing effects alone. The causal mechanism is probably due to a number of influences, with noise being a contributory factor.

Contents

3. NOISE LEVELS IN DIVING

3.1 Noise from Breathing Apparatus

Summitt (5) investigated noise levels in commercial diving helmets. Wide variations were recorded depending on helmet type, gas supply settings and even between individual helmets of the same make. Levels of between 92 and 113 dB(A) were noted at the ear position.

More recent work by Parvin (6) examined the noise generated by different forms of breathing apparatus. A bandmask produced unweighted sound pressure levels which peaked at 135 dB during exhalation and 105 dB during inhalation. The amplitude was predominantly at frequencies below 1 kHz.

Molvaer (7) measured the noise level of exhaust gas from a Superlite 17 helmet and Comex Pro bandmask at the diver's ear position. Both sets of equipment produced similar noise levels, in excess of 94 dB, in the frequency range 0.125 to 1 kHz. With both systems, sound pressure levels diminished above 1 kHz, to levels around 75 dB at 8 kHz.

3.2 Noise from External Sources

Tools can be a major contributor to excessive noise underwater. Nedwell (8) found that noise levels generated at a depth of 11m by five tools typically used by a diver were much in excess of levels normally permissible at the worksite in air (see Table 1). Molvaer (7) noted that when a water jet was operated in-water, the noise level recorded outside the helmet rose to 144.5 dB(A). Molvaer (7) also observed a Temporary Threshold Shift (TTS) which persisted for 2 hours post-dive after an exposure of approximately one hour to 115 dB using a rock drill underwater.

Al-Masri (9) noted a TTS of between 10-42 dB, together with nausea and vertigo, following exposure to noise underwater at between 130-190 dB. Anecdotally many divers accept tinnitus and muffled hearing as being normal to diving, provided the symptoms disappear within a few hours (5).

Diving chambers are a further source of noise exposure, primarily for the saturation diver whose exposure lasts for 24 hours a day. Murry (10) noted readings of 112 dB(A) during compression to 100ft in a chamber, while during decompression these were 108 dB(A). Peak levels were in the 2.4 to 4.8 kHz octave band. Thomas (11) reported levels of 115 to 118 dB in a chamber during blowdown. Summitt and Reimers (5) recorded sound levels of between 43 dB(A) and 121 dB(A) in a compression chamber during normal operations. The peak level was recorded while the chamber was being flushed, while levels of 116 dB(A) were noted during compression.

Sound pressure levels have been recorded in the range 70 dB to 115 dB in saturation chambers on a modern DSV. Peak levels in the living chamber were noted during activities such as showering. Sound pressure levels in the diving bell reached a higher peak of over 120 dB during an operational dive, with noise coming from DP thrusters, communications equipment etc (12). Propeller noise within harbours has been recorded at levels around 120 dB, with most of the energy being in the low frequencies (7).

Contents

Problems have also been reported with supervisor/diver communications due to high background noise masking the supervisors instructions to the diver (5). Further anecdotal evidence of high noise levels comes from dive supervisors who report that excessive thruster noise from the DSV in heavy weather affects the ability to communicate effectively with the bellman (12).

There is therefore overwhelming evidence that divers are exposed to sound pressure levels which, in atmospheric air, would be deemed excessive and damaging.

This review concentrates on the effects of noise on hearing under hyperbaric conditions. It is known that high sound pressure levels also affect extra auditory tissue but this is not the subject of this paper.

Contents

4. MECHANISM OF HEARING IN HYPERBARIC CONDITIONS

4.1 The Immersed Ear

The human ear is adapted to function most efficiently in air at atmospheric pressure. However the external ear of a diver wearing a neoprene hood or bandmask is exposed to water. There is therefore a large impedance mismatch between the water medium and the immersed eardrum. Consequently the air conduction (auricular) route has decreased sensitivity to water-borne as compared to air-borne sound (13,14).

Conversely the bone conduction route ie. transmission of sound through the tissues and bones of the head directly to the cochlea, is believed to contribute significantly to the ability to hear underwater. The impedance of soft tissue is close to that of the surrounding water, while the impedance of the skull is not much greater. Hence sound is more readily transmitted from water to the cochlea through these tissues.

Bone conduction is thought to dominate as a means of sound transmissionunderwater, although there appears to be some contribution from the auricular route. Evidence for this is taken from the ability of man to localise and detect sound direction underwater (14).

It should be noted that the presence of an air bubble trapped in the outer ear canal will tend to slightly improve the auditory sensitivity (14). Measurements made without an air bubble being present against the ear drum may therefore be optimistic when used subsequently to assess the degree of protection provided by threshold shifts for the immersed ear.

Thus both auricular and bone conduction routes can function underwater, but the relative efficiencies are reversed compared to one atmosphere air. The exact proportion of auditory sensitivity contributed by each of these routes in the immersed ear is as yet not fully understood.

4.1.1 Perception of Sound Underwater - The Immersed Ear

Considerable work has been undertaken to define the change in threshold of hearing when the head is immersed in water (9,13,15,16,17,18). However both Smith (13) and Al-Masri et al (14) point out that the experimental validity of earlier studies is open to question. These early studies have often failed to take account of underwater ambient noise levels, procedures have not always been standardised and results may have been skewed by small sample sizes.

The early results reported by Hamilton (15) indicated that the minimum underwater hearing threshold at 4m water depth was 44 to 60 dB above that in air. The threshold shift was frequency dependent, with the greatest loss occurring at 4kHz. Greatest sensitivity was measured at low frequency, at 0.125 kHz. Subsequent studies have reported a wide range of values for underwater hearing thresholds. In the low frequency range Smith (13) suggests that the ear underwater may be more sensitive below 0.125 kHz than in air. More recent work by Al-Masri (9) reports an underwater hearing threshold of 29 dB at 0.5 kHz rising to 60 dB at 8 kHz (Figure 3). Maximum underwater sensitivity was noted in the range 0.5 to 1 kHz. He goes on to say that as the depth of the dive increases, the coupling across the wet ear drum will improve and one will expect the sensitivity of the ear to increase at the lower frequencies. This is

Contents

based on the view that low frequencies are transmitted by the auricular route, whereas frequencies above 1 kHz are transmitted predominately by bone conduction. The background noise in Al-Masri's experiments was quoted as being less than 18 dB for frequencies greater than 0.125 kHz. This appears to be the most relevant information on immersed ear hearing threshold shifts presently available.

Smith (13) has identified that ultrasonic frequencies can be heard by divers underwater. The frequencies detected ranged from 16 kHz up to 225 kHz, although the perceived pitch was in the range 8-9 kHz.

There is therefore general agreement that the ear under-water is more sensitive at low frequencies than at high frequencies, whereas in air peak sensitives occur at around 3 kHz. However at all but very high, and possibly very low, frequencies the immersed ear is still less sensitive than in air, although there is no general agreement between the various researchers on the precise values to be attributed to each frequency band.

Existing 'A' weighting scales and exposure limits are designed to take account of the human ear's sensitivity to a particular range of frequencies in air only. Thus hearing conservation measures for hearing in air will be inappropriate for the underwater environment where the range of audible frequencies is much greater at both ends of the spectrum, and where sensitivity is greater at the lower frequencies.

4.2 The Dry Ear

Rather less attention appears to have been paid to the hearing mechanism of the pressurised dry ear. There are experimental difficulties in determining threshold shifts in hyperbaric chambers, not least in screening out local background noise and calibrating audiometry equipment. Nevertheless results from work in the early 1970s indicate threshold shifts due to the pressurised environment.

Fluur (19) investigated the roles of auricular and bone conduction in hyperbaric air in a chamber at pressures from 1 to 11 ATA. No breathing apparatus or helmets were worn. The maximum elevation of hearing threshold by auricular conduction was found to be 30-40 dB in the middle frequency range. It is probable that the effect of dense gas is to change the compliance of the eardrum and the associated impedance of the middle ear. As a consequence, sensitivity to sound pressure waves is affected.

Both Fluur (19) and Thomas et al (11) found that bone conduction thresholds were not materially affected by elevated pressures. It was assumed that bone conduction may even be slightly enhanced by improved coupling at increased gaseous pressure. However the coupling between the tissues and a gaseous medium remains relatively poor, and hence bone conduction continues to make only a limited contribution to hearing. On the other hand the auricular route will be affected by increased pressure, with the greatest loss of sensitivity occurring in the first 1-2 ATS of pressure (11). But despite this loss of sensitivity, the auricular pathway to the inner ear remains dominant, although both mechanisms will continue to function under dry hyperbaric conditions.

Contents

4.2.1 Perception of Sound Under Dry Hyperbaric Conditions

The reduction in sensitivity to sound pressure in heliox has been found to vary with high and low frequencies, and at different gas densities. Farmer (20) investigated the human auditory response during a heliox saturation dive to 180 metres. Results varied during the compression phase, with elevated auricular thresholds averaging 14 dB at 0.25, 0.5 and 1 kHz. An average elevated threshold of 25 dB for 2 and 4 kHz was noted. Greater elevation in the thresholds at lower frequencies was noted during the bottom phase of the dive (average of 26 dB at 0.25, 0.5 and 1 kHz, and 23 dB for 2 and 4 kHz).

Thomas et al (11) subsequently reported that at depth, little or no change occurred in sensitivity at 2 kHz, even at 300 metres, compared to surface values. Results at 0.5, 1 and 3 kHz indicated a progressive hearing loss with depth compared to surface values. Smith's (13) later predictions were in broad agreement with the experimental findings of Thomas et al. Smith calculated a 10 dB loss in 10 ATAs air and 12 dB loss at 30 ATAs in heliox. Smith (13) further predicted that any attenuation would be restricted to low frequencies. These calculations were based upon the acoustic impedance mismatch due to the pressurised environment. Molvaer (21) identified a 36 dB loss at 0.5 kHz at 100 metres in air, and a 22 dB loss at 0.125 kHz at 60 metres. His findings reinforce the view that substantial shifts in sensitivity will occur in the low frequency range.

On the other hand Thomas et al (11) found that sensitivity at 6 kHz was enhanced by 20 dB at 30 metres. This enhanced sensitivity remained with increased pressure, but diminished in value as depth increased. This enhanced sensitivity is thought to be due to resonance within the outer and middle ear cavities, which is in turn dependent on the gas density (Figure 4).

The variation in results at different frequencies make it difficult to reach definitive conclusions about the changes in auditory sensitivity caused by the hyperbaric environment. While it can be assumed that some attenuation is gained in the middle range of frequencies, the findings from Thomas et al (11) relating to no change at 2 kHz, and increased sensitivity at 6 kHz, indicate that interpreting sound dose requires some caution. Simply weighting the sound frequencies as in the form of the 'A' weighting, may be misleading when estimating noise dose in dry hyperbaric conditions.

Contents

5. SOUND ATTENUATION CHARACTERISTICS OF DIVING EQUIPMENT

It has previously been assumed that a hood or bandmask provides attenuation and hence protection for the diver from water-borne sounds, typically in the region of 10-37 dB for a neoprene hood (7,13). A lightweight helmet such as a DSI Superlite was previously believed to provide between 40 and 55 dB attenuation (7).

More recent work by Parvin (6) identified that a bandmask provides 25 dB protection at 2 kHz and 45 dB at 8 kHz. However, at frequencies below 2 kHz the bandmask offers little or no attenuation.

A lightweight helmet (DSI Superlite 17) was found by Parvin (6) to have an increasing attenuation at the ear position of 15 dB at 0.2 kHz to 65 dB at 4 kHz (Figure 5).

It can be deduced from these results that a diving helmet such as the Superlite containing pressurised gas offers slightly better protection from low frequency sounds than, for example, a bandmask. Conversely for higher frequency sounds (above 1 kHz) loss of sensitivity of the immersed ear combined with the transmission loss across the bandmask hood appear to give better protection than the helmet. However, these results may only be valid at relatively shallow depths, since the attenuation provided by the bandmask hood will probably diminish with compression, while the increased density of the gas inside the helmet at depth may also slightly enhance the sound coupling.

Contents

6. DISCUSSION

The evidence for a higher incidence of hearing deficit in divers compared to the norm is convincing. The causes of deafness in divers are many and varied, often associated with barotrauma. The particular question to be addressed by this review is to indicate whether exposure to noise is a major factor contributing to thehearing deficit in divers.

There are a number of instances when divers have undertaken noisy tasks underwater. Tools used for grinding, cleaning and drilling are known to generate high noise levels. A particularly noisy environment is thought to exist in habitats though no appropriate sound pressure recordings have been obtained for this particular environment. Working for prolonged periods in noisy environments or with noisy tools has induced tinnitus and an elevation in hearing thresholds in divers. This is a sure sign that the noise levels are harmful.

Not all commercial divers spend their time at the work-site using excessively noisy equipment. The question remains as to whether the noise levels experienced in routine commercial diving operations are likely to constitute a hazard to hearing. Certainly the sound pressure levels recorded within diving helmets and chambers would constitute a hearing hazard in air at one atmosphere. However, the ear has its peak efficiency in atmospheric pressure air and the auditory sensitivity is broadly reduced in pressurised gaseous environments or when the ear is immersed in water. This reduction in sensitivity is due to changes in compliance and impedance mismatches within the auricular pathway. Bone conduction effectively remains unaltered in practical diving gaseous environments but is enhanced when the head is immersed. This enhancement in bone conduction is due to the improved coupling between water and the tissues of the head which are of a similar density. Generally, however, the enhanced bone conduction is insufficient to overcome the de-sensitisation of the auricular route and the nett effect is a general depression of auditory sensitivity when the head is immersed.

The broad de-sensitisation of the auricular pathway to different degrees in both water and pressurised gas means that sound pressure waves reaching the inner ear are generally attenuated. This offers some protection to the organ within the inner ear which may be damaged by exposure to excessive sound pressure levels.

Unfortunately, the protective de-sensitisation of the immersed or pressurised dry ear is not consistent for all sound frequencies. The regions of least attenuation for the dry ear are in the mid frequencies around 2 kHz. In addition there is the possibility of amplification of frequencies in the region of 6 kHz due to resonance within the outer and middle ear canals at certain gas densities. For the immersed ear it would appear that a peak sensitivity occurs between 0.5 and 1.0 kHz with the possibility that frequencies below 0.125 kHz also may be amplified to above the sound pressure levels perceived in 1 ATA air.

The implications of this non-uniform change in auditory sensitivity with respect to diving are complex. With a uniform de-sensitisation across the audible spectrum of frequencies it should be possible to factor the conventional 'A' weighting for calculating hyperbaric noise doses. However, because some frequency bands are probably amplified and the degree of amplification may in some cases depend upon

Contents

the diving depth and the gas mix being breathed, a simple factoring of the 'A' weighted scale is inappropriate. This problem is further complicated by the ability to perceive ultrasonic sound waves as audible sound in the 8 kHz band. The implications of this are that sounds which are normally outside the audible spectrum may contribute to the hyperbaric sound dose. One thing that is clear is that a conventional weighting system is inappropriate for assessing noise doses associated with diving.

There is a need for research to devise a practical method for assessing the relevant sound dose received by divers. Without this it will be difficult to establish credible noise exposure limits for the industry.

Until a method for assessing a hyperbaric noise dose has been established it is clear that some practical steps can be taken to reduce unnecessary noise exposure to divers so as to increase the margins of safety. For example, the sound levels within most diving chambers during compression are high and can be sustained for significant periods of time. The noise dose received by the occupants can be immediately reduced by the use of ear-defenders and in the longer-term by developing suitable silencer systems and reducing turbulence in flow lines etc. There are a few other operational procedures which can be addressed in this manner, eg shower pumps in transfer locks, slam of chamber doors and locks etc. On the other hand, the low frequency noise dose from open circuit breathing apparatus or DSV thrusters may probably prove impossible to reduce. The attenuation of low frequencies offered by helmets and hoods is minimal and it is unlikely that the sound can be eliminated at source. The basilar membrane in the inner ear is especially susceptible to damage from intense low frequency sound, thus exposure to frequencies below 1 kHz are of particular concern.

Exposure to low frequency sound while diving should be the subject of further investigation. If low frequency sound is shown to be a significant factor in noise dose, the practical solution is probably to limit exposure times to these frequencies.

An obvious area for immediate attention is the likely exposure to high levels of sound within habitats and from underwater tools. From the limited amount of data that are presently available, regarding hearing threshold shifts and attenuation by diving helmets, it would appear that sound pressure levels in excess of around 130 dB outside the helmet should be avoided. Likewise exposure times to sound pressure levels in chambers and habitats in excess of around 110 dB should be severely limited.

Noise surveys are required to define the sound pressure levels at different frequencies that are likely to be experienced by divers in a variety of work locations.

Because of the possible enhanced sensitivity of the hyperbaric ear for specific frequencies, measuring simple sound pressure levels at the work-site is inappropriate. A full frequency analysis is required before a relevant hazard analysis can be undertaken. As some of the frequencies of concern (<0.125 kHz) are below the detection thresholds for much of the presently available equipment, it may not be possible to fully assess noise at the work-site for some time. Further research is required to determine the most appropriate techniques and standards for assessing noise exposures to divers.

Contents

7. CONCLUSIONS

1. Anecdotal evidence of deafness in divers has been in existence for many years, more recently this has been confirmed by objective experiments. Experienced divers demonstrate a progressive hearing loss that is greater than would be expected from the normal ageing process.

2. The cause of deafness in divers is probably multifactorial due to damage from degrees of barotrauma, bacterial infection, fungal attack etc, as well as exposure to excessive noise.

3. The sound pressure levels associated with diving have often been shown to exceed those permissible at the work site for onshore workers.

4. Exposure to hyperbaric conditions broadly has the effect of reducing hearing sensitivity. This in turn probably provides some protection from excessive noise levels associated with working under pressure.

5. The shift in hearing sensitivity at pressure is not linear across the audible spectrum of frequencies when compared to normal atmospheric pressure. Indeed, at specific frequencies the hyperbaric ear may be more sensitive than in atmospheric air. Thus a conventional weighting used for sound assessments could be inappropriate for use in pressurised environments.

6. Hearing conservation criteria appropriate for use with diving operations will probably have to take account of the specific environmental conditions where particular noise doses are received eg pressure and gas mixture. This will inevitably create a complicated standard which may be difficult to enforce.

7. At present the sensitivity of the ear in both dry and wet hyperbaric conditions is not fully described. Further research is required before definitive thresholds of hearing for the primary diving conditions can be defined and thus appropriate noise exposure limitations established.

8. Relevant noise audits are required from working habitats and while underwater tools are being used.

9. The risk of chronic hearing loss in divers can be reduced in the short term by introducing sound attenuation devices into chambers. In the longer term the design of equipment can be reassessed so as to minimise avoidable noise.

Contents

9. REFERENCES

1. Molvaer O I. Hearing Deterioration in professional divers: an epidemiologic study. Undersea Biomedical Research Vol 17, No 3, 1990.

2. International Organisation for Standardisation Draft International Standard (ISO/DIS) 7029. Acoustics-threshold of hearing by air conduction as a function of age and sex for otologically normal persons. Geneva, ISO, 1982

3. Edmonds C. Hearing Loss with Frequent Diving. Undersea Biomedical Research Vol 12, No 1, 1985.

4. Australian Standard No 2299 for underwater air breathing operations. Australian Government Printing Office 1979.

5. Summitt and Reimers. Noise: A Hazard to Divers and Hyperbaric Chamber Personnel. Aerospace Medicine, November 1971.

6. Parvin S J. Sources of Noise Exposure for the Helmeted Diver. Vol 31: Subtech '93.

7. Molvaer, O I. Hearing damage risk to divers operating noisy tools under water. Scandinavian Journal of Work, Environment and Health, Vol 7, 1981.

8. Nedwell J. Underwater Tool Noise : Implications for Hearing Loss. Vol 31 : Subtech '93.

9. Al-Masri, M. Underwater Hearing Thresholds. Vol 31: Subtech '93.

10. Murry, T. Hyperbaric Chamber Noise during a dive to 100 ft. Journal of Acoustical Society of America Vol 51, 1972.

11. Thomas, W G et al. Human Auditory Thresholds during deep, saturation, helium-oxygen dives. Journal of Acoustical Society of America, 1974, Vol 55.

12. Unpublished report of a confidential noise audit of diving operations on a modern DSV. 1994.

13. Smith, P F. Toward a Standard for Hearing Conservation for Underwater and Hyperbaric Environments. Journal of Auditory Research, 1985, 25, 221-238.

14. Al-Masri, M; Martin, A; Nedwell, J. Underwater Hearing: A Review. University of Southampton Institute of Sound and Vibration Research Technical Report No. 212, May 1993.

15. Hamilton, P. Underwater Hearing Thresholds. Journal of Acoustical Society of America Vol 29 No 7, 1957.

16. Montague, W. Sensitivity of the Water Immersed Ear to High and Low Frequency Tones. Journal of Acoustical Society of America, 1961.

Contents

17. Hollien, H. Effect of Air Bubbles on the External Auditory Meatus in Underwater Hearing Thresholds. Journal of Acoustical Society of America. Vol. 46 No. 5, 1969.

18. Hollien, H. Underwater Hearing Thresholds in Man. Journal of Acoustical Society of America, Vol 42 No 5, 1967.

19. Fluur E. Hearing in Hyperbaric Air. Aerospace Medicine, August, 1966.

20. Farmer J C. Human Auditory Responses During Hyperbaric Helium-Oxygen Exposures. Surgical Forum, 1971.

21. Molvaer, O I. Noise in a Standard Diving Helmet. Nutec Report 28-82, 1982.

Contents

Tool Type	**Position**	**dB (1in)**
Small Drill	Side of Head Rear of Head	127 120
Large Drill	Side of Head Rear of Head	123 118
Impact Wrench	Side of Head Under Hood 1m from Tool	160 151 161
Small Grinder	Side of Head Under Hood 1m from Tool	118 111 124
Large Grinder	Side of Head Under Hood 1m from Tool	122 120
Cox's Bolt Gun	Side of Head Under Hood 1m from Tool	150 149 151

Table 1: Summary of Overall Sound Levels in dB re 20 μPa from use of Tools Underwater (12)

Contents

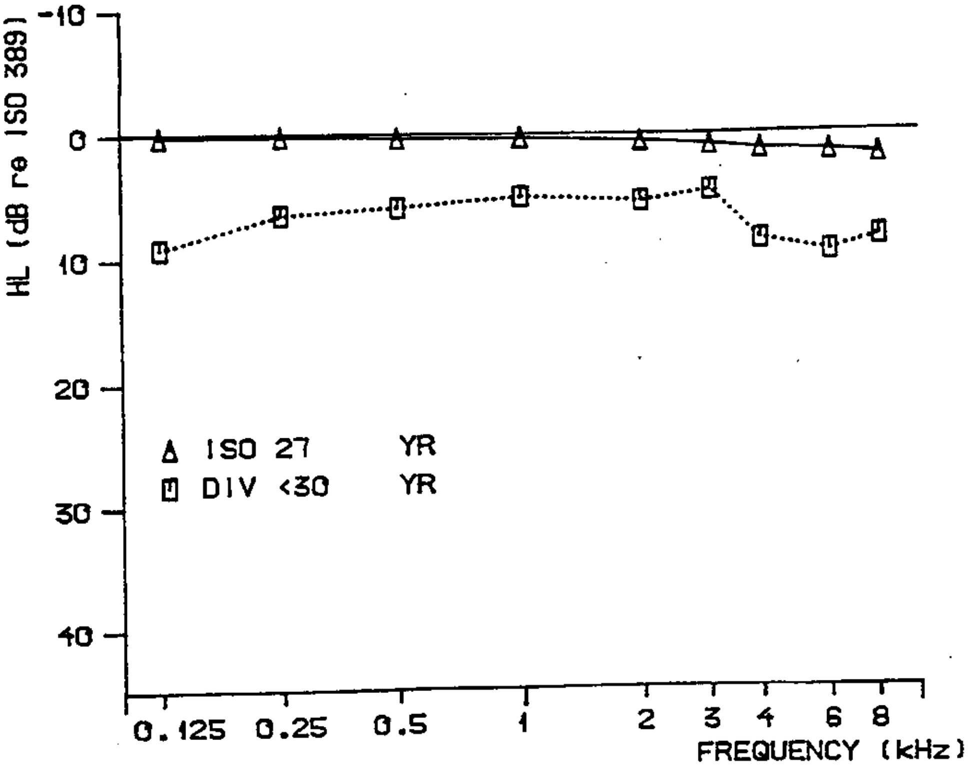


Figure 1: Mean Hearing Level in Divers <30 Years of Age at Second Test Compared to Normal (ISO) Subjects (1)

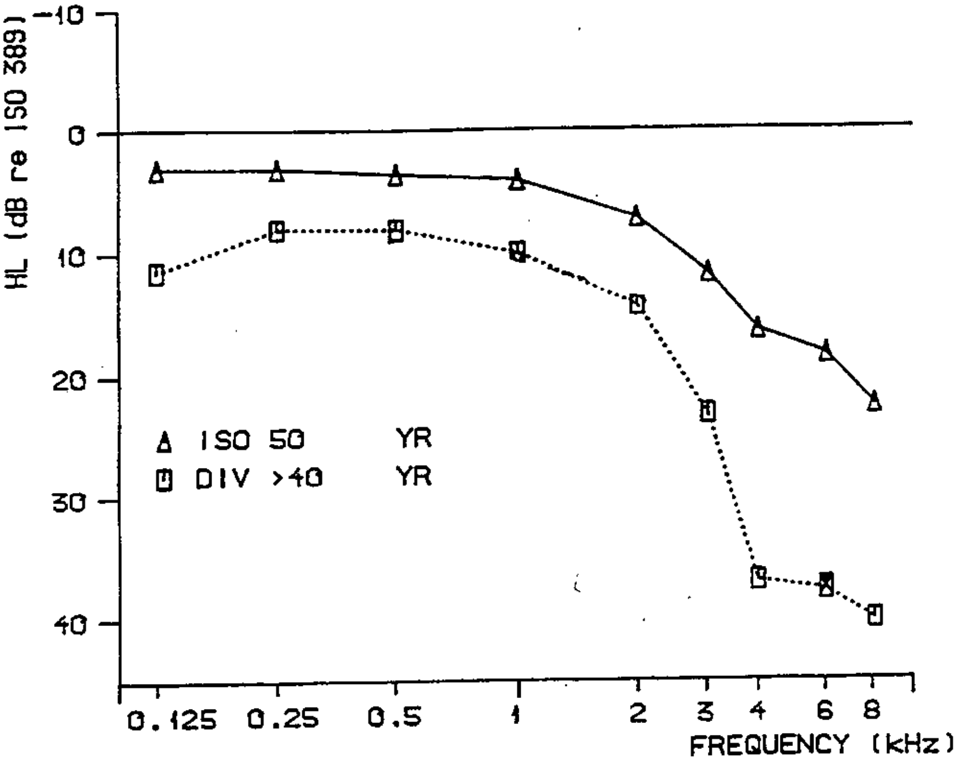


Figure 2: Mean Hearing Level in Divers >40 Years of Age at Second Test Compared to Normal (ISO) Subjects (1)

Contents

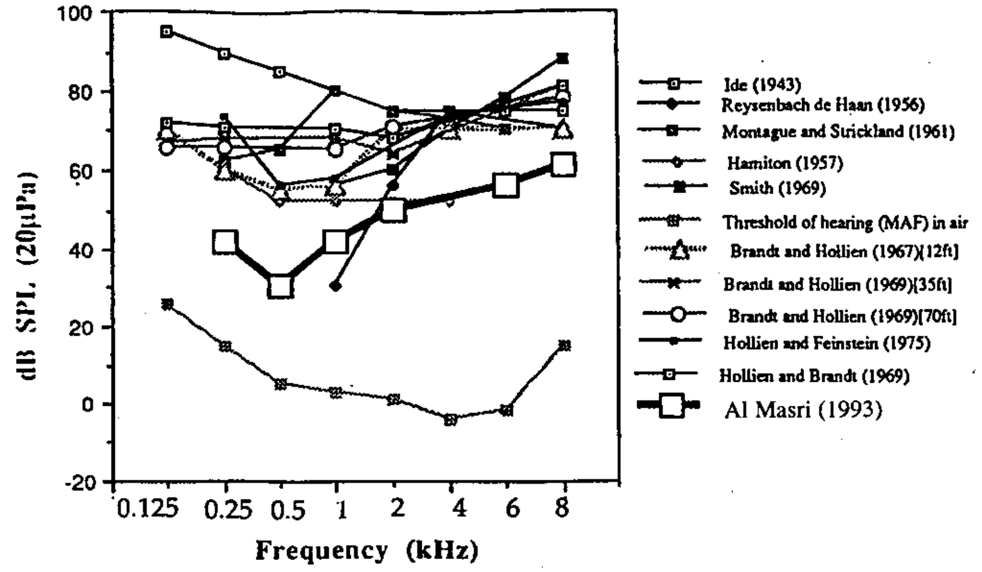


Figure 3: Comparison between mean Underwater Minimum Audible Field Measured by Al-Masri, and Previous Research (9)

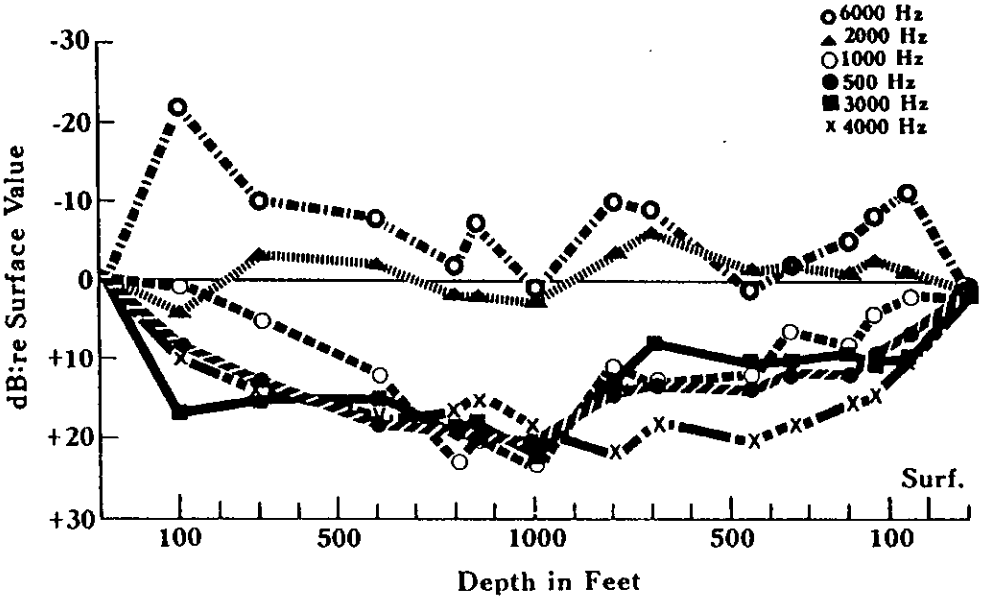
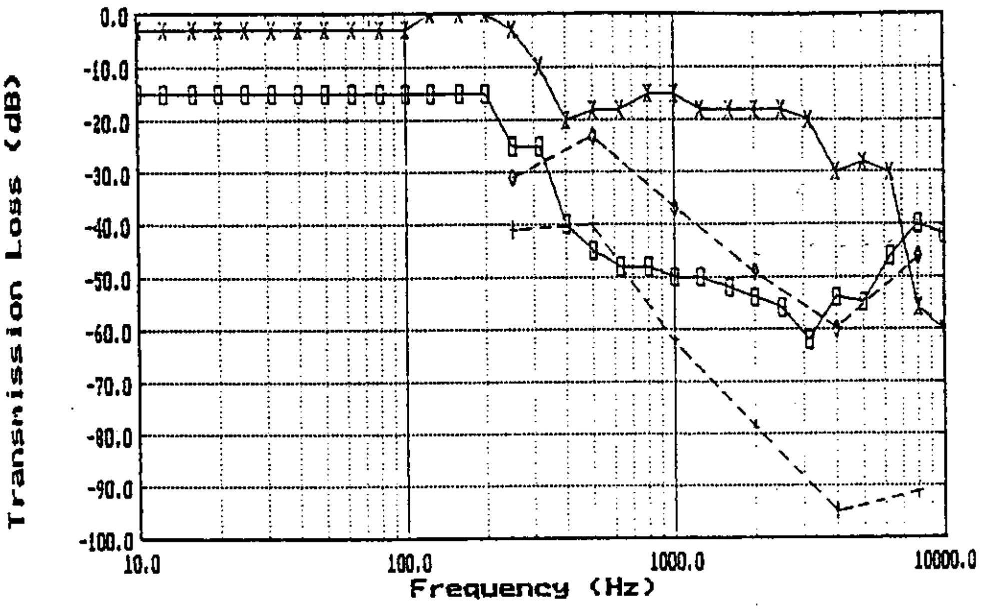


Figure 4: Mean Thresholds for Six Different Frequencies as a Function of Depth. All Thresholds are Measured Relative to Surface Threshold (11)

Contents



[] Ear Position X Mouth Position ◊ Wetted Ear+ Wetted Ear & Hood

Figure 5: Transmission Loss of DSI Superlite 17 Helmet (6)

Contents