REVIEW
ON
UNDERWATER HEARING

Reg. No. 02SH0004

Independent Project as a part fulfillment of
First Year M.Sc, (Speech and Hearing),
Submitted to The University of Mysore, Mysore.

INDIA INSTITUTE OF SPEECH AND HEARING
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JUNE - 2003

DEDICATED
TO
ACHCHAN, AMMA, SYAMA
&
GIRISH

Certificate

This is to certify that this Independent Project entitled **"REVIEW ON UNDERWATER HEARING"** is a bonafide work in part fulfillment for the degree of Master of Science (Speech and Hearing) of the student (Register No. 02SH0004).

Mysore

June, 2003

Director
All India Institute of Speech and Hearing
Mysore - 570 006

Certificate

This is to certify that this Independent Project entitled **"REVIEW ON UNDERWATER HEARING"** has been prepared under my supervision and guidance.

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Mysore

June, 2003

DECLARATION

This is to certify that this Independent Project entitled **"REVIEW ON UNDERWATER HEARING"** is the result of my own study under the guidance of **Mrs. P. Manjula,** Lecturer in Audiology, All India Institute of Speech and Hearing, Mysore and not been submitted earlier in any other University for the award of any Diploma or Degree.

Mysore,
June, 2003 Reg. No. 02SH0004

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PROLOGUE

The use of sound waves in water for the transmission of intelligence has been of interest primarily to nautical and naval personnel. Recent investigations have been done with a need for research in underwater speech communication in general and in underwater hearing in particular.

Water is an ideal medium for the transmission of sound. The velocity of sound in water is approximately five times that of sound in air, reducing the maximum time difference at which a sound from a single source arrives at the two ears from 200 msec to 160 µsec. Sound travels at 1500 m/s in water. This speed can be altered depending on the salinity, temperature and depth of water.

Sound in the oceans come from many sources - both natural and anthropogenic. Humans create underwater sounds mostly through boat traffic, especially the large shipping freighters, industrial activities such as drilling, mining and submarines.

Human beings, though have ears similar to those of marine mammals, human ears are not adapted for underwater hearing. Underwater sound recognition in humans is of similar sensitivity to that of fish, but of lesser sensitivity than marine mammals. The human auditory system has evolved to function in air borne environment. Bennett (cited by Smith, P.F., 1985) suggested that, whether in air or in water, the ear responds to particle velocity rather than to sound pressure. He stated that particle velocity at threshold was the same in air and in water.

Studies have shown that bone conduction pathway is important for underwater hearing (Hollien & Brandt, 1969). They tested the auditory system with the ear canal filled with water and then compared this with the sensitivity with an air bubble trapped in the external auditory meatus. They found no difference in sensitivity, concluding that underwater hearing was mediated by bone conduction.

At the best underwater hearing frequency, there is a loss of 40 dB in hearing sensitivity compared to air borne equivalent. Therefore, sounds have to be much louder underwater. For example, in air, when two stones are banged, it is perceived as a high frequency click but as a dull thud in water. (Underwater Acoustics, n.d.)

Underwater thresholds were found to be from 18 dB to 56 dB higher than air conduction thresholds, the difference increasing with frequency. The underwater threshold ranged over frequencies, between 58 dB and 74 dB with a minimum at about 100 Hz (air conduction threshold minimum is around 2000 Hz) and threshold SPL ranges over 35 dB. That is, maximum sensitivity is at 500 Hz. There is a lowering of the frequency of maximum sensitivity in water than in air (Brandt & Hollien, 1967). There is a tendency for increase in threshold SPL with increase in depth though not statistically significant (Brandt & Hollien, 1969).

In water, both the larger wavelengths of sound and relative transparency of the head to sound tend to minimize the effect of acoustic head shadow in causing intensity differences at the two ears (Norman, Phelps & Wightman, 1971). The transformation imposed on binaural localization cues by the increased speed of sound in water and the changes in acoustical impedance at the head-medium interface would preclude any effective sound localization by the human listener. But a study by

Feinstein (1973) indicated that the level at which the human binaural system function is comparable to that of at least two marine mammals (porpoise and sea lion) tested that can navigate by sound quite effectively. The development of human underwater sound navigation thus appears to be a reasonable prediction.

Professional underwater divers are exposed to intense noise that can reach SPL above 200 dB, thus causing temporary threshold shift (TTS) leading to permanent threshold shift (PTS), vertigo, nausea and vomiting. This impact is most likely when the frequency of sound coincides with the frequency at which the diver is most sensitive, which is typically around mid-frequencies (2000 Hz).

Noise induced hearing loss due to underwater noise exposure occurs at mid - frequencies at around 1000 Hz. Since mid frequencies are more important for understanding speech. Noise induced hearing loss due to underwater noise exposure may result in a greater hearing disability than that due to noise exposure in air.

The noise exposure hearing Damage Risk Criterion and the A-weighted scale in air are not suitable for underwater use. There is currently no widely accepted noise exposure limits or Damage Risk Criterion for underwater noise. Thus A-weighted scale is modified to produce an equivalent weighting scale called W-weighting scale. This was developed to assess the risk of damage to hearing from underwater noise (Al-Masri & Martin, 1996).

Studies by Al-Masri and Martin (1996) show that mean underwater threshold with and without steel earplugs (used as ear protective devices) have negligible effect on underwater minimum audible field (MAF). The result indicates that attenuation of sound pressure transmission through the auricular pathway does not have any effect on underwater MAF, thus confirming that bone conduction is important for underwater hearing.

Exposure of divers to intense noise in water is increasing, yet no general hearing-conversation standard for such exposures exists. Research is still being done on the same. A complete knowledge of underwater hearing would prove beneficial. Much of the information regarding underwater hearing is scattered in various sources such as journal articles, books and web pages.

This review, thus, tries to collect - within a single volume - the important findings from the diverse sources to enable readers to get a comprehensive and varied knowledge about the different aspects of underwater hearing.

Information on underwater hearing was collected from books, journal articles and through surfing the Internet. The information thus obtained were compiled and categorized under the following categories:

I. Underwater acoustics
II. Theories of underwater hearing and underwater hearing mechanism
III. Underwater hearing threshold
    i. Minimum Audible Field (MAF), air conduction or bone conduction thresholds
    ii. Hearing thresholds and factors affecting threshold

IV. Fetal hearing

V. Underwater noise exposure

VI. Underwater noise measurement

VII. Underwater Damage Risk Criterion (DRC)

VIII. Underwater Ear Protection Devices (EPDs)

REVIEW OF LITERATURE

I. UNDERWATER ACOUSTICS

The movement or vibration of an object in any medium generates sound. Actually, there is no sharp borderline between sounds and vibrations in water from a physical point of view. That sounds can readily be generated and propagated through water has been known since the earliest times, and both Aristotle and Leonardo da Vinci were aware that underwater sounds could be rendered audible to the human listener by means of special aids. In practice, sounds are so easily generated in water that one long outstanding naval problem is that of silencing submerged vessels to render them inaudible to hostile listeners. Similar problems may well be faced by many aquatic organisms, whose movements through water may inadvertently make them audible to listening predators (Hawkins & Myrberg Jr., 1983).

Water has many advantages over air for the transmission of sounds. Based on the density and relative inelasticity of water, sounds are propagated through it some four to five times faster than in air. Moreover, low frequency sounds in water have extremely long wavelengths, are relatively unaffected by scattering and absorption within the medium and may therefore travel great distance. Underwater sounds can be propagated halfway around the globe. Also, active echo ranging sonar systems exist which can resolve an object as small as a penny.

In water, as in air, an acoustic field may be described both as a pressure variation within the medium, and as a back-and-forth motion or oscillation of the component particles of the medium. The two quantities are related to one another, their relationship depending primarily upon the acoustic impedance of the medium that is upon its density and elasticity. The acoustic impedance of water is much higher than that of air and for a given pressure disturbance the particle speed and displacements are much less, by a factor of approximately 3600. The strong acoustical mismatch between the two media means that sound does not readily propagate from one to the other. An air-water interface is an exceedingly good reflector.

Table 1.1 compares the acoustical differences between air and water.

Table 1.1.

Acoustical differences between air and water

Quantity	*Symbol*	*Air at 20^{0}C*	*Sea water at 13^{0}C*	*Distilled water at20^0 C*
Density	P	0.00121 g cm^{-3}	1.026 gcm^{-3}	0.998 g cm-
Velocity of sound propagation	c	0.343 x 10^5 cm s^{-1}	**1.5x 10^{5}cms-^{1}**	1.48 xl0^5 cms^{-1}
Wavelength at 1 kHz	λ	0.343 m	1.5 m	1.48 m
Specific acoustic impedance	pc	41.5 g cm^{-2} s^{-1}	1.45x10^{5}gcm^{-2} s^{-1}	1.47xl0^{5}gcm^{-2} s^{-1}
Particle velocity for a sound intensity oflW cm^{-2}	μ	48.8 cm s$^-$	8.05cm s$^-$	8.06cm s^{-1}
*Sound pressure for a sound intensity of 1 W*cm^{-2}	P	2.04 x1O^4 dyn cm^{-2} (+16OdB//2x1O^4 dyncm$^{-2)}$	1.24 x 106 dyn cm^{-2} (+ 122dB//l dyncm^{-2})	1.24 x 105 dyn cm^{-2} (+122dB//l dyncm$^{-2)}$

(Note: From "Hearing and sound communications, " by Hawkins and Myrberg Jr., 1983, Bioacoustics: A comparative approach, London: Academic press, p. 349.)

It is common in underwater acoustics to express sound pressures in units of dynes- cm^{-2} , or microbars (1 dynes- cm^{-2} = μbar = 1 x 10-1 N m^{-2}), though the micropascal (1 |iPa = 1 x 10^{-6} N m^{-2} = 1 x 10^{-5} μ bar) is the standard unit of acoustical pressure. Particle motion can be expressed as the particle displacement (cm), velocity (cm s^{-1}) or acceleration (cm s^{-2}, while the sound intensity, or the rate at which acoustic energy flows through a unit area normal to the direction of propagation, is the product of the sound pressure and particle velocity (W cm$^{'2}$). All these quantities can be expressed, in decibels, as a logarithmic ratio, relative to a reference value it is important to remember that the reference quantities for water are usually quite different from those for air, and in this event direct comparison of sound levels in the two media is not possible.

Though particle velocities in water are exceedingly small, the motion is of great importance to many aquatic animals in conveying a sense of acoustic direction, especially since other directional cues may be less effective in water than in air.

Sound is far better for transmitting energy through water than the various classes of electromagnetic radiation, e.g. light and radio waves. This is primarily because it propagates over great distances with minimal absorption. Sound waves do diminish in amplitude as they diverge from a source, spreading over an increasingly greater area; however, relatively little absorption occurs. This is particularly so for low-frequency sounds. For a sound at 1 kHz, that absorption over and above the 6 dB loss per doubling of distance through spherical spreading is less than 0.00001 dB m^{-1}, rising to 0.001 dB m^{-1} at 10 kHz and 0.015 dB m^{-1}. at 50 kHz. Although reflective scattering and diffraction by small distributed inhomogeneities in the water also occur, their effect on transmission loss is small (Hawkins & Myrberg Jr., 1983).

The limitations of most real bodies of water for long-range sound propagation are due to their primary reflecting surfaces (the sea surface and sea-bed) and various other discontinuities in the medium - the latter resulting in the refraction of sound. Together, these phenomena severely impair simple spherical divergence and straight line propagation of sound. The principal factors causing refraction are variations in the velocity of propagation arising from variation in salinity, temperature and pressure. Strong gradients in the velocity of propagation with depth may give rise to a pronounced bending of sound waves.

Underwater sounds may often be severely degraded or altered during long-range transmission largely as a result of repeated reflection by the sea surface and seabed. Propagation along multiple paths leads to both destructive and constructive interference, which may alter the temporal characteristics, and introduce a high degree of diversity into signal structure, impairing detection and recognition. A sine wave of constant amplitude will show severe amplitude modulation, and short pulses will show long decay times after travelling only a few meters, especially through shallow water.

A further problem of signal detection for aquatic organisms is masking by the high and often variable level of background noise encountered under water (Khudsen; Myrberg; Urick; Wenz, cited by Hawkins & Myrberg Jr., 1983). The spectrum of the noise is heavily weighted towards the lower frequencies, and the advantages of low frequencies for long range propagation are counter balanced by their greater tendency to be masked by ambient noise. Masking may also occur as a result of reverberation.

Masking by ambient noise and reverberation may well provide the ultimate limit to sound detection for many aquatic organisms. Although it is to be expected that sound detection mechanisms will be adapted to reduce interference from noise, calls produced by animals should, likewise, be structured to enable easy detection and recognition despite the distortion and masking resulting from their passage through water.

II. THEORIES OF UNDERWATER HEARING IN HUMAN BEINGS

There are three theories of underwater hearing. One, the "tympanic" theory (Bauer, cited by Smith, P.F., 1985), states that underwater hearing is accomplished in essentially the same way as hearing in air. That is the sound enters the ear canal and vibrates the tympanic membrane with consequent transmission of energy to the cochlea through the ossicular chain. However, because the human ear is adapted (impedance matched) to function in air, and because the characteristic acoustic impedance of water is so much greater than that of air, a large impedance mismatch exists between the water and the immersed ear. Consequently, the human ear is not as sensitive to water borne as to air-borne sound, the loss of sensitivity being frequency dependent. Bauer's model predicts no loss of sensitivity at 1 kHz but an almost linear drop in sensitivity of about 12 dB/octave as frequency increases from 1 to 5 kHz.

A second theory is the bone-conduction (bone conduction) theory (Reysenbach de Haan, as cited by Smith, P.F. 1985), which states that because the impedance of the soft tissue is very close to that of water and because the impedance of the skull is not much greater, sound is readily transmitted from water to the cochlea through those tissues, by-passing the acoustically inefficient tympanic route. That is, the ear canal is acoustically transparent in water, and man's ossicular chain is not effective in water primarily because the ossicles lack sufficient mass. Further, because of cross-conduction through the skull, the two cochleae are not independently stimulated under water as they are in air and hence sound localization is not possible for man in water.

A third theory is the dual path theory of Sivian (as cited by Smith P.F., 1985) who theorized that underwater hearing in man is mediated by both tympanic and bone conduction mechanisms that are of approximately equal sensitivity at 1 kHz. At other frequencies, one or the other of the two paths may predominate. One implication of the dual-path theory is that, given the cochlea, a deficit in only one route may not result in deficient underwater hearing. Also, in some circumstances these two mechanisms may interact.

UNDERWATER HEARING MECHANISM IN HUMAN BEINGS

Early studies showed that the human ear is less sensitive in water than in air from 0.125-8 kHz that the greatest difference in sensitivity occurs at those frequencies at which the ear is most sensitive in air; and that the underwater audiometric function is rather flat in comparison to that in air (Hamilton; Montague and Strickland; Reysenbach de Haan; Wainwright; as cited by Smith P.F., 1985). Consequently, those authors concluded that underwater hearing in man is predominantly bone conduction hearing. However, alternate explanations of those results have also been offered in terms of the "tympanic" theory. For example, Bauer's model well described the data from some of these studies. Bennett (as cited by Smith, P.F., 1985) also supported the tympanic theory when he suggested that, whether in air or in water, the ear responds to particle velocity rather than to sound pressure. In Bennett's view, the middle ear acts as a mechanical transformer that transforms eardrum velocity to sound pressure in the cochlea. He stated that the particle velocity at threshold was the same in air as in water under the conditions of the experiment of Montague and Strickland. Bennett suggested that the major change in thresholds measured by Montague and Strickland might be attributed to the use of a velocity - sensitive device in media of different impedances. Thus,none of these early studies provide unambiguous evidence concerning mechanisms.

The dual path theory of underwater hearing received partial confirmation in experiments by Smith (1965, 1969) in which it was found that divers with depressed "tympanic" hearing thresholds but normal bone conduction threshold at 6 and 8 kHz (i.e., conductive losses) showed no loss of underwater hearing sensitivity in comparison to divers with normal hearing thresholds (HTLs) for both air and bone-conduction pathways. That finding, of course, is also consistent with the bone conduction theory and has been taken as evidence by other writers (Harris; Hollien, as cited by Smith, P.F., 1985) that underwater hearing is mediated by a bone conduction mechanism. Clearly, while the tympanic route may or may not play some role underwater hearing, bone conduction is certainly important, at least at the higher frequencies. No theory that fails to include a bone conduction mode can explain Smith's results. Nevertheless, it seems improbable that bone conduction is the only mechanism by which energy reaches the cochlea from the water. If the tympanic route were not functional in water, then divers should not be able to detect differences in the direction from which a sound emanates (Reysenbach de Haan, as cited by Smith, P.F., 1985).

III. UNDERWATER HEARING THRESHOLDS IN MAN

Sounds have to be much louder in water, than in air, to be heard. Underwater thresholds are reported to be 18 to 56 dB higher than the air conduction thresholds, the difference increasing with frequency (Brandt & Hollien, 1969). This investigation by Brandt and Hollien (1969) was instituted for the following reasons :

1. The underwater hearing threshold data in existence at the present time are not entirely consistent with respect to magnitude or effects of frequency. Additional clarifying data are thus desirable.
2. The underwater hearing threshold SPL, defines the minimum output power requirements of any speech communication system that uses a listener directly in the water medium.

Sinusoidal stimuli of 125, 250, 500, 1000, 2000, 4000, and 8000 Hz were used in this study. The stimuli were gated ON and OFF with a period of 500 msec, a 50% duty cycle, and a 2.5 msec rise-fall time. The attenuation rate of the recording attenuator was 8 dB/sec.

The research was carried out on eight adults (five males and three females) all were reasonably competent divers with experience in taking hearing tests in air. A clearly audible pulsing tone was generated from the projector. The diver varied the intensity of the test stimulus so that the signal was just audible, in the manner of the Bekesy technique. The underwater thresholds were obtained from the listeners during controlled breathing.

Table 2.1

Mean threshold SPL (decibels re 0.0002 \xbar) in air and water (12 and 35 ft, ear depth) as a function of frequency in eight listeners. Standard deviations (decibels) are in parantheses.

Condition	*Frequency (Hz)*						
	125	250	500	1000	2000	4000	8000
Water (35 ft)	70.83 (2.73)	69.53 (8.25)	56.17 (1.32)	54.20 (2.40)	67.50 (8.48)	73.37 (10.80)	72.60 (4.22)
Water (12 ft)	72.03 (4.56)	68.83 (9.67)	54.00 (3.25)	51.20 (5.66)	62.13 (2.76)	72.27 (8.08)	63.00 (7.08)
Difference (35-12 ft)	1.20	0.70	2.17	3.00	5.37	1.10	9.60
Air	51.17 (1.98)	42.80 (2.16)	25.64 (6.24)	26.34 (4.11)	15.40 (4.08)	31.80 (9.27)	17.97 (8.81)

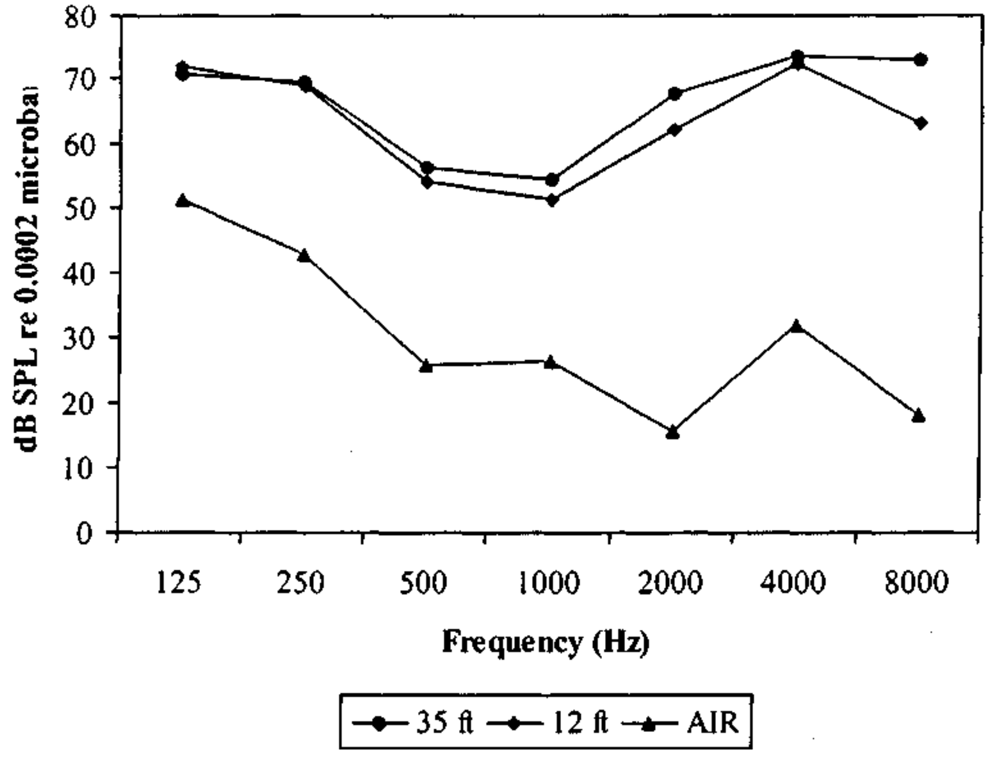

Figure 2.1: Mean threshold SPL in air and water (12 and 35 ft ear depth) as a function of frequency for eight listeners.

(Note: Table 2.1 and Figure 2.1. From " Underwater hearing thresholds in man, " by John F. Brandt and Harry Hollien, 1967, The Journal of the Acoustical Society of America, 42, p.969).

The investigation was concerned with underwater hearing thresholds at two ear depths and in air. Mean threshold SPLs for eight divers as a function of test frequency are listed in Table 2.1. The mean threshold SPL values are graphed in Figure 2.1.

The underwater thresholds are from 18 to 56 dB higher than the air-conduction thresholds, the difference, in general, increasing with frequency. The underwater thresholds range over frequency between 58 and 74 dB (a range of about 16 dB) with a minimum at about 500 Hz. The air-conduction thresholds, on the other hand, have a minimum around 2000 Hz and the threshold SPL ranges over about 35 dB.

In general, the difference between air and water conduction thresholds increases with frequency. They range from about 18 dB at 125 Hz to about 56 dB at 8000 Hz. The water conduction threshold SPL was measured by the method of minimum audible field (MAF). The air conduction-threshold SPL, on the other hand, was measured by the method of minimum audible pressure (MAP).

Although the test frequency was not a statistically significant factor in the water conduction thresholds, there was a tendency for a maximum sensitivity to occur at 500 Hz. The lowering of the frequency of maximum sensitivity in water compared to that in air in seen.

Underwater hearing thresholds in man as a function of water depth

Brandt and Hollien (1969) used sinusoidal stimuli of 125, 250, 1000, 2000, and 8000 Hz, which were gated ON and OFF with a period of 500 msec, a 50% duty cycle, and a 2.5 msec rise-and-fall time. The attenuation rate of the recording attenuator was 8 dB/sec. Air-conduction thresholds were obtained.

The research was carried out on six adult listeners (4 males and 2 females) who were competent divers with experience in taking hearing tests in air and water. The SPL of the test stimulus was first presented at a high enough SPL to be clearly audible. The diver listener varied the SPL of the stimulus around the audibility-threshold level in the manner of the Bekesy technique.

The above investigation was concerned with underwater hearing thresholds for pure tones at three ear depths, 35, 70 and 105 ft, and in air. Mean threshold SPLs for six divers as a function of frequency are depicted in Table 2.2 are graphed in Figure 2.2. The lower curve represents air conduction thresholds and the three upper curves represent underwater thresholds. No statistically significant differences in threshold SPL due to ear depth were apparent.

Tahle2.2.

Mean threshold SPL (decibels re : 0.0002 \xbar) in air and water (three ear depths) as a function of frequency for six listeners. Standard deviations (decibels) are in parentheses

Conditions	*Frequency (Hz)*				
	125	250	1000	2000	8000
Water (35 ft)	66.8 (5.6)	68.5 **(5.7)**	64.3 (7.9)	68.8 (6.6)	81.2 (14.0)
Water (70 ft)	66.7 (5-8)	66.2 (2.2)	65.3 (7.2)	71.3 (9.5)	78.2 (14.6)
Water (105 ft)	68.2 (9.2)	60.7 (8.4)	72.8 (12.6)	74.8 (13.7)	80.8 (14.4)
Mean threshold (taken over depth	67.2 (7.30	67.2 (7.1)	67.3 (10.3)	71.6 (10.6)	80.1 (14.4)
Air		37.5 (2.5)	17.8 (3.4)	11.2 (7-3)	
Difference (Water-Air)		29.7	49.7	60.4	

(Note: From " Underwater hearing thresholds in man as a function of water depth, " by John F. Brandt & Harry Hollien, 1969, The Journal of the Acoustical Society of America, 46, p. 894.)

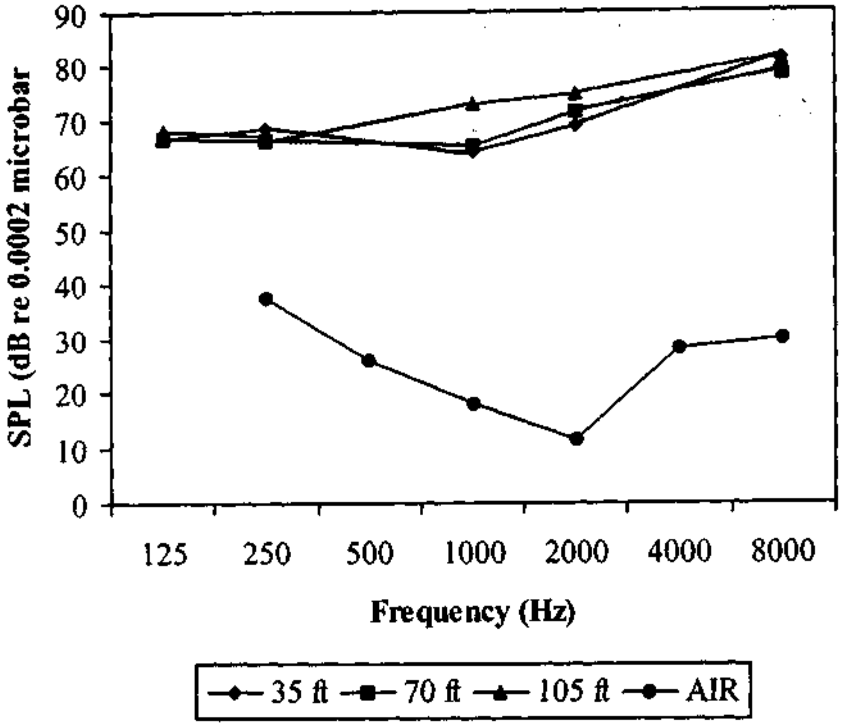

Figure 2.2: Mean threshold SPL (decibels re : 0.0002 microbar) as a function of test frequency in air and water at three depths, N = 6 diver/listeners.

(Note: From " Underwater hearing thresholds in man as a function of water depth, " by John F. Brandt & Harry Hollien, 1969, The Journal of the Acoustical Society of America, 46, p. 894.)

The underwater thresholds are from 30 to 60 dB higher than the air conduction, the difference increasing with test frequency. The underwater thresholds vary in frequency from 67 to 80 dB SPL, a range of about 13 dB, with a mean threshold of about 70 dB SPL.

The experiment can be summarized by reporting that increases in ear depth from 12 ft (previous experiment) to 150 ft (present experiment) and the concomitant positive increases in water pressure corresponding.increases in atmospheric pressure have no effect upon free-field underwater hearing threshold in the frequency range between 12.5 and 8000 Hz.

Effect of air bubbles in the external auditory meatus on underwater hearing thresholds

Sivian (as cited by Hollein and Brandt, 1969), in a theoretical discussion of underwater hearing, suggested that a bubble of air trapped in the external ear canal would provide a high impedance to sound conduction, which of course, would not be present if no air was so trapped.

The research was carried out on seven subjects (four males and three females) who were competent divers and experienced in taking hearing tests in air and in water. The diver or listener varied the stimulus SPL around the audibility threshold in the manner of the Bekesy technique by activating a water and pressure-proofed hand switch.

The thresholds were obtained for two conditions of the external meatus : (1) with an air bubble present and (2) without an air bubble present.

Table 2.3 and Figure 2.3. present the mean threshold SPL (decibels re : 0.0002 µbar) as a function of test frequency for seven divers or listeners in air and in water. The two upper curves represent water thresholds under the two conditions of the external meatus. As may be observed, the thresholds obtained for the two underwater conditions are remarkably similar, which demonstrates that the presence or absence of bubbles of air in the external auditory meatus is unimportant to underwater auditory thresholds.

Table 2.3:

Mean threshold SPL (decibels re : 0.0002 \xbar) in air and water (12 ft depth) for seven diverg/ subjects as a function of frequency. The experimental conditions are the contents of the external meatus. Standard deviations (decibels) are in parentheses.

Condition	*125 Hz*	*250 Hz*	*1000 Hz*	*2000 Hz*	*8000 Hz*
Water (air bubble)	71.2 (6.0)	71.0 (8.8)	70.3 (8.6)	68.1 **(5.5)**	81.9 (11.1)
Water (no air bubble)	69.6 (7.0)	65.0 (5-7)	70.4 (4.1)	68.1 (7.6)	80.6 (13.7)
Mean thresholds (over condition)	70.8 (6.6)	68.0 (8.0)	70.4 (6.7)	68.1 (6.6)	81.2 (12.5)
Air (surface)		39.4 (3.5)	19.0 **(2.3)**	8.9 **(2.2)**	
Difference (water-air)		28.6	51.4	59.2	

(Note: From "Effect of air bubbles in the external auditory meatus on underwater hearing thresholds", by Harry Hollien & John F.Brandt, 1969, The Journal of the Acoustical Society of America, 46, p. 386)

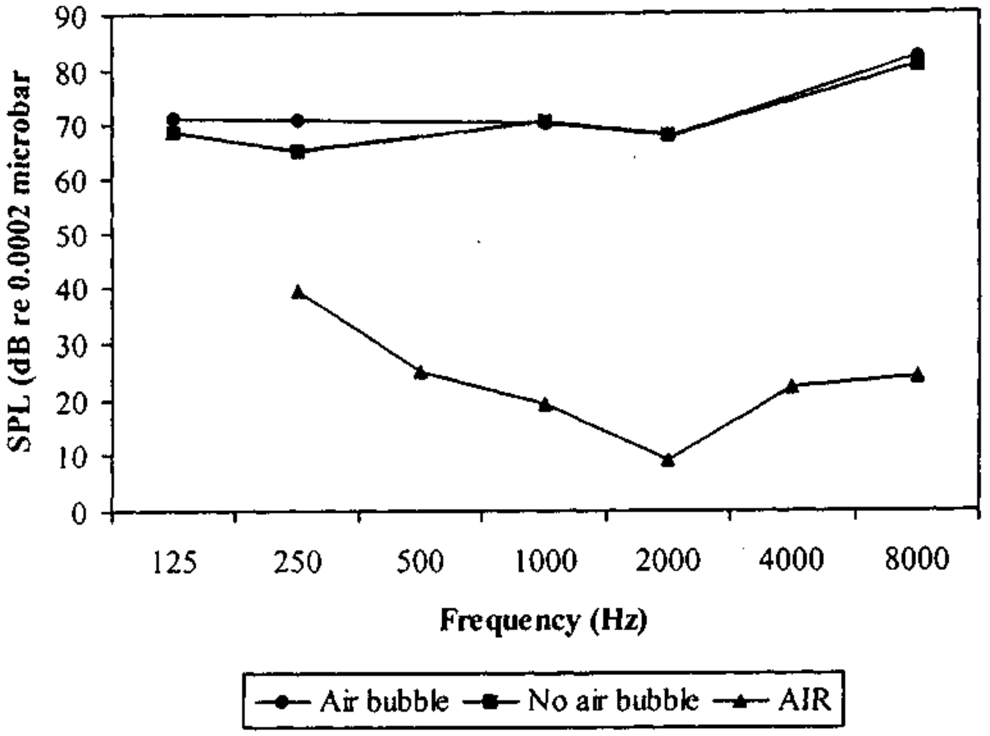

Figure2.3: Mean threshold SPL (decibles re : 0.0002 microbar) as a function of test frequency in air and water (with and without air bubbles), N = 7 divers / listeners. (Note: From "Effect of air bubbles in the external auditory meatus on underwater hearing thresholds ", by Harry Hollien & John F.Brandt. 1969. The Journal of the Acoustical Society of America, 46, p.386)

If man is to work effectively underwater, he will have to be able to navigate reliably. To do so, undoubtedly he will have to possess, or be able to develop, directional hearing in water to a degree that approximates condition in air.

It had been assumed, until very recently, that the transformations imposed on binaural localization cues by the increased speed of sound in water and the changes in acoustical impedance at the head-medium interface would preclude any effective sound localization by the human listener.

Being strongly committed to a bone conduction theory of underwater hearing, Hollien (1973) expressed some surprise that his subjects could perform well above chance on an underwater auditory localization task. In subsequent experiments by Hollien's group, Feinstein (1973) demonstrated that the mean minimum audible angle (M.A.A.) under water is about 7.3° for white-noise sources. Though localization in water is not as precise as in air, the difference in accuracy is largely explained by the difference in the velocity of sound in the two media.

Andersen and Christensen (as cited by Smith, P.F., 1985) doubted that inertial or compressional bone conduction mechanisms could explain their underwater data on sound localization, but they stated that the osseotympanic route might play a role. Hollien restated the bone conduction theory in terms of "force and amplitude relationships" and denied that the external auditory mechanisms could play an effective role in underwater hearing. He speculated on various bone conduction mechanisms that might account for underwater localization but felt unable to make a definitive statement. Also, citing other theoretical and experimental research in hearing by bone conduction, Harris argued that when the skull is ensonified in water, sufficient time and intensity disparities might exist at the two cochleae to permit auditory localization by bone conduction mechanisms.

An experiment was undertaken to determine the acuity of the human underwater sound localization response in the context of earlier localization acuity data obtained from several marine mammals (Dudok van Heel; Gentry; Mohl, as cited by Feinstein, S.H., 1973). All of the experiment was conducted on the Acoustic Barge of the Defense Research Establishment Atlantic, located at Birch Cove, Nova Scotia. All subjects (mean age 25.3 years) were male amateur SCUBA divers with normal hearing in the 250 to 8000 Hz range. Prior to being tested, the divers were briefed on the use of the apparatus, the configuration of the equipment, and the purpose of the experiment. When their turn came to be tested, they were instructed to enter the water and swim down to the test cage where they set the projectors at a predetermined angle. The diver was instructed to hold his breath when he was ready to listen and respond with either a right or left response on every trial. One of the projectors was energized according to a predetermined random sequence of 15 right and 15 left signals. The number of angles tested on a single dive depended on the temperature of the water.

The stimuli used in the present experiments were 20 msec pulses with 10 µsec rise-fall times, occurring at the rate of 1 /sec and composed of either a 3.5 kHz sine waves, 6.5 kHz sine waves, or broad-band white noise (20 to 20000 Hz).

Table2.4:

Comparison of localization acuity in several marine mammals and man

Animal	*Investigator*	*Frequency in kHz*	*Minimum audible angle*
Porpoise	Dudok van heel (1959)	6.0	7.9°
		3.5	11.0°
		2.0	12.6°
Seal	Mohl (1968)	2.0	3.1_0
Sea Lion	Gentry (1967)	6.0	10.0°
		3.5	15.0°
Man (water)	Feinstein (Experiment 2)	6.5	11.3°
		3.5	11.5°
		White Noise (20-20 000 Hz)	7.3°

(Note: From "Acuity of the human sound localization response underwater, " by Stephen H. Feinstein, 1973, The Journal of the Acoustical Society of America, 53, p. 397)

Table 2.4 presents a comparison of the MAAs obtained from three marine mammals and man. While the test procedures did follow the same basic paradigm, different statistical procedures were used to determine the MAA. In addition, there were difference in test environments and signal characteristics. Therefore, comparisons of this kind must be made with a degree of caution.

Inspection of Table 2.4 will indicate that the level at which the human binaural system functions (within the frequency range tested) is comparable to that of at least two marine mammals that can navigate by sound quite effectively. The development of human underwater sound navigation thus appears to be a reasonable prediction.

Al-Masri and Martin (1996) studied underwater minimum audible field (MAF) and the relationship between the MAF in air and underwater, by dividing the experiment into MAF measurements in air and underwater.

The underwater and in-air hearing thresholds of 54 normally hearing sport divers were tested using the procedures recommended by the British Society of Audiology. Great care was taken to minimize the level of underwater ambient noise which was found to be caused by both ground vibration and the transmission of airborne noise. The temperature of water was maintained at 35°C for subjects' comfort. The MAF measurements in air were conducted according to ISO - 8253-2.

The subject's hearing thresholds were tested, in air and under water, using 1/3-octave bands of random noise because these test signals were found to provide a superior sound field uniformity compared to pure tones and FM tones. The mean values of the MAF in air and underwater, with air and with air removed from the ear canals, are plotted in Figure 2.4.

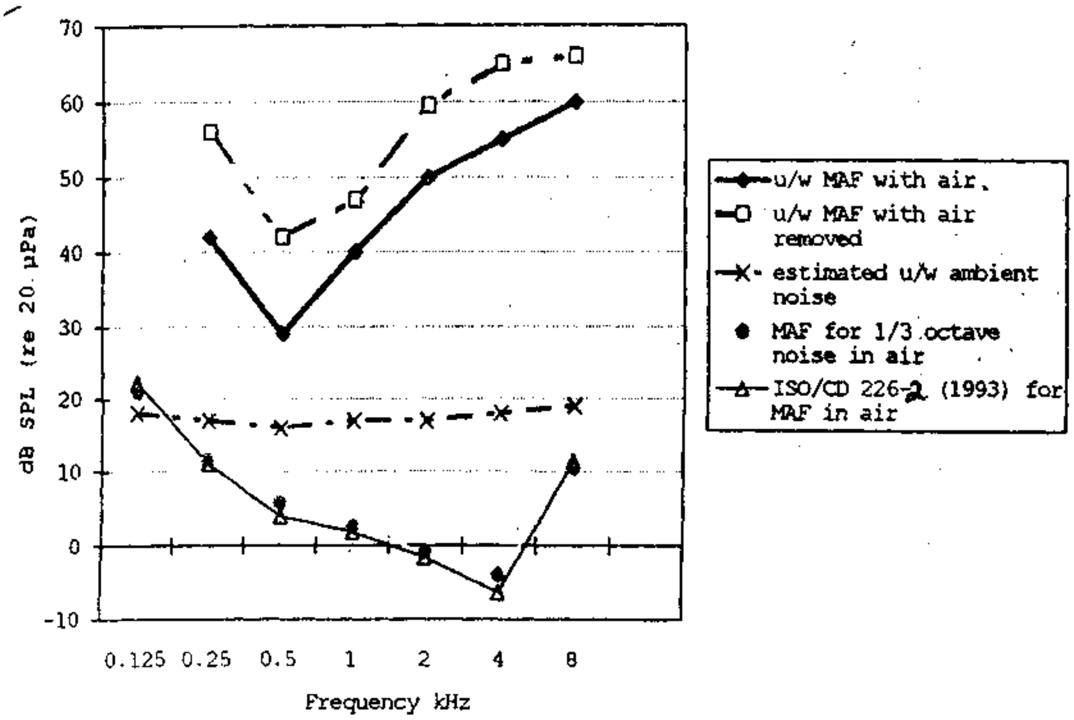

Figure 2.4 : Comparison between the mean MAF values for 1/3 -octave band noise in air and underwater.

(Note: From "Underwater hearing and occupational noise exposure, " by Al-Masri & Martin, 1996, Scientific Basis of Noise Induced Hearing Loss, New York: Thieme Medical Publishers, Inc., p. 121.)

It is seen that MAF in air measured in this study is within 2 dB of ISO/CD 226-2. The underwater MAF curves are frequency dependent and are significantly higher than the estimated underwater ambient noise levels at all frequencies.

The maximum ear sensitivity underwater (lowest MAF value) is located around 0.5 kHz. The underwater MAF value with air trapped in the ear canals is 42 dBSPL at 0.25 kHz decreasing to a minimum value of 29 dB at 0.5 kHz followed by an increase to a maximum of 61 dB at 4 kHz. The underwater MAF curve with air removed from the ear canals is significantly higher by 5-17 dB at all frequencies than the MAF curve with air in the ear canals, except at 8 kHz.

Frequency range of the ear in water

A number of experiments on underwater hearing sensitivity have been done. In general, agreement among the experiments is very poor. The results of Hollien's group have however, been reproduced repeatedly (Brandt and Hollien; Brandt; Hollien and Brandt, as cited by Smith, P.F., 1985) and may be taken as representative of normative HTLs for the frequencies tested. Brandt and Hollien found, for example, that the differences between water-borne and air-borne threshold SPLs ranged in their subjects from 18 dB at 0.125 kHz to 56 dB at 8 kHz.

The data shown in Figure 2.5 is from Brandt and Hollien (1967) and Smith (as cited by Smith, P.F., 1985), plotted to yield differences in auditory threshold intensity levels both in water and in air, as a function of frequency.

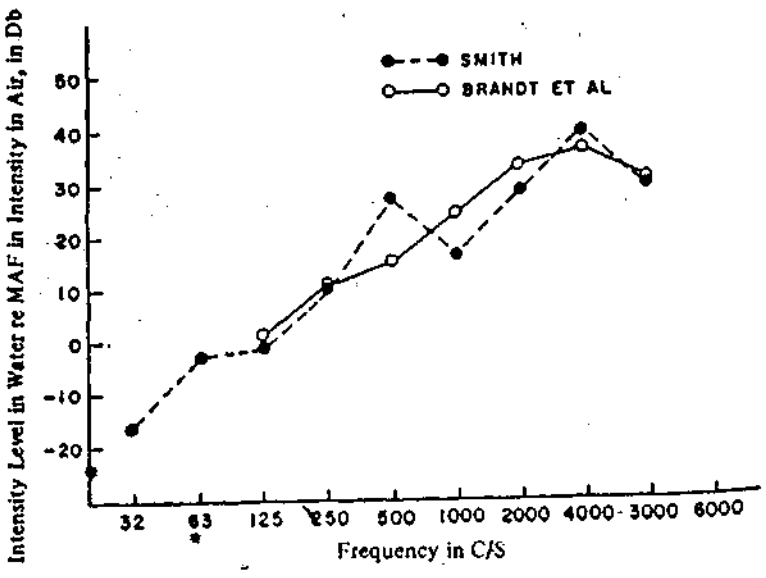

Figure 2.5 : Differences in auditory-threshold intensity levels as a function of frequency.

(Note: From "Toward a standard for hearing conservation for under water and hyperbaric environments, " by Paul F.Smith, 1985, The Journal of Auditory Research, 25, p. 226.)

Figure 2.5 shows that at 0.125 kHz the auditory threshold intensity levels are essentially equivalent in air and in water. Indeed, at frequencies below 0.125 kHz man may be more sensitive to sound in water than in air (in agreement with Bauer). From 0.125 to 4 kHz the difference in threshold sensitivity increases at a rate of about 7-8 dB/octave, that is, less than the 12-dB slope predicted by Bauer. Above 4 kHz the threshold difference becomes smaller. Comparison of threshold intensity levels in Figure 2.5 shows that the difference in sensitivity of the ear in the two media is by no means as large as the 50-70 dB usually mentioned in the literature (Adolfson and Berghage, as cited by Smith, P.F., 1985).

The audibility of "ultrasonic" frequencies in water has also been demonstrated. Bishop (as cited by Smith P.F., 1985) found that divers could clearly hear a signal of 30 kHz at 137 dB. They did not reliably hear the signal of 32 kHz at 132 dB. Deatherage, Jeffress and Blodgett (as cited by Smith, P.F., 1985) reported hearing a 50 kHz signal when any part of the skull was immersed in a bucket of water containing a sound projector. They reported the threshold for a totally immersed swimmer exposed to 50 kHz to be about 140 dB. During informal (unpublished) tests, using an arrangement similar to that of Deatherage, Jeffress and Blodgett (as cited by Smith, P.F., 1985) it was found that subjects could hear up to 128 kHz (the system limit), but signal levels were not measured. Also, the underwater hearing threshold of one diver at a depth of 12 ft was found to be about 134 dB at 48 kHz.

The observations of Bishop, Deatherage, Jeffress and Blodgett and of those at U.S. Naval Submarine Medical Research Laboratory (as cited by Smith, P.F., 1985) demonstrated that hearing in water at "ultrasonic" frequencies does occur and is mediated by a bone conduction mechanism.

No comparable psychoacoustic data for water-immersed divers hearing at frequencies above 16 kHz are available, either for frequency range or in the perception of pitch. Nevertheless, given sufficient amplitude, underwater sound can certainly be perceived by divers over a much wider frequency range than is the case for air-conduction hearing in air.

Since man's hearing is more sensitive in water than in air at frequencies below 0.125 kHz and is clearly more sensitive in water than in air at frequencies above 16 kHz, if follows that hearing conservation standards for divers ought to encompass a much wider frequency range, both at lower and at higher frequencies, than do such standards for usual industrial situations.

Dynamic range of the ear in water

In general, in the frequency range of 0.25 - 8 kHz, man's sensitivity to sound is reduced upon submersion in water. Montague and Strickland (as cited by Smith, P.F., 1985) have shown that, at 1.5 kHz, reduced sensitivity is accompanied by an increased tolerance to intense sound. Their divers would briefly tolerate SPLs as high as 165 to 175 dB. They measured temporary threshold shifts (TTS) beginning some 5 min after each exposure and reported average TTSs of 6 and 7 dB at 3 and 4 kHz, respectively.

Smith, Howard, Harris and Waterman (cited by Smith, P.F., 1985) exposed 6 men in water to pure tones of 1.25 sec duration at 3.5 kHz, repeated every 2.5 sec for a period of 15 min; SPLs of 168 and 178 dB were used. TTS was measured at 2 min post-exposure (TTS2) and compared to TTS2 induced by similar exposures at lower levels in air. The results indicated that the SPL of tones of 3.5 kHz in water must be about 68 dB higher than the SPL of tones^in air,in order to induce comparable magnitudes of TTS. This corresponds to an intensity difference of about 33 dB, which compares well with the differences in auditory-threshold intensities in air and in water at 3.4 kHz as shown in Figure 2.5.

Corso and Levine (cited by Smith, P.F., 1985) plotted equal-loudness contours for bone conduction hearing at frequencies as high as 95 kHz. They found that equal-loudness contours appear to converge at about 85 kHz. This is an important result since it indicates that the high-frequency content of broadband noise, and especially impulse noise, may be of greater importance in water than in air.

Thus, while the dynamic range of the ear may be similar in water and in air, in the frequency range from 1.5 to 3.5 kHz it may become quite small at very high frequencies. No data exist on the dynamic range of the immersed ear at frequencies below 1.5 kHz.

IV. FETAL HEARING

The fetus develops in a dynamic environment that provides stimulation and nutrition, yet at times can be potentially hazardous. A variety of agents external to the fetal niche, such as sounds and vibrations, impact the organism directly. Knowledge of fetal reactions to environmental sounds has stimulated interest in prenatal learning, and at the same time, created concern that the fetal auditory system may be adversely affected by intense noise. Exposure to maternal vocalization during prenatal life may contribute to speech perception and voice recognition by the newborn. The out come of these early experiences may prove beneficial later in life. On the other hand, noise exposures that are hazardous to the hearing of adults may be hazardous also to the hearing of the fetus. (Lalande, Hetu & Lambert, as cited by Gerhardt, K.J., Pierson, L.L. & Abrams, R.M., 1996).

The fetal sound environment is composed of a variety of internally generated noises, as well as many sounds originating from the environment of its mother. The stimulus used to produce a fetal response is altered as it passes from an air medium through the abdominal wall and uterus and into the amniotic fluid. Sounds generated inside the mother and present in the uterus are associated with maternal respiratory, cardiovascular, intestinal, and laryngeal activity, and by physical movements. Internal sounds are predominately low frequency (<100 Hz) and reach 90 dB sound pressure level (SPL, re: 20 µPa). Spectral levels decrease as frequency increases, and are as low as 40 dB for higher frequencies. Higher frequencies up to 5000 Hz are attenuated by approximately 20 dB. Exogenous low-frequency sounds less than 250 Hz penetrate the uterus with very little reduction in sound pressure (<5 dB). Some enhancement of low-frequency sound pressures has been reported in both humans and sheep.

Response of fetus to exogenous sounds

It is fabled in the Indian ancient epic "Mahabaratha" that 'Abhimanyu' the son of Arjuna learnt while still in his mother's womb when she over heard a conversation between lord Krishna and the Pandavas!

Fetal heart rate responses, body and limb movements, and fetal eye blinks are common indices of fetal responsiveness to both high and low intensity airborne sounds. Various transducers have been used to elicit fetal responses including loudspeakers, earphones, door bells, etc. placed near the abdomen.

Lecanuet, Granier-Deferre and Busnel (as cited by Gerhardt, K.J., Pierson, L.L. & Abrams, R.M., 1996) revealed that intense airborne stimulation (above 105 dBSPL) produced short-latency fetal heart rate accelerations accompanied by motor responses. Less intense stimulation (below 100 dB) still produced heart rate accelerations, but fewer motor responses. When the amplitude or the frequency of the stimulus increased, motor and cardiac accelerations increased during either quiet or active sleep (Kisilevsky, Muir, and Low, as cited by Gerhardt, K.J., Pierson, L.L. & Abrams, R.M., 1996). The magnitude of the response is influenced by the behavioral state of the fetus during the time of stimulation. Schmidt, Boos, Gniers, Auer and Schulze (as cited by Gerhardt, K.J., Pierson L.L. & Abram, R.M., 1996) found that stimulation produced stronger responses during quiet and active wakefulness than during the different stages of sleep.

Human fetal auditory responsiveness begins about the 24th week of gestation. During the next 15 weeks exogenous sound may have an effect on fetal behavior and central nervous system development. The positive benefits of sound, for example, speech perception and voice recognition in the newborn, may result from direct stimulation of prosodic features of the maternal voice heard by the fetus prenatally. On the other hand, intense sounds such as those found during vibroacoustic stimulating testing evoke atypical changes in fetal behavioral state and fetal movements that persisted long after stimulation.

Querleu, Renard, Boutteville and Crepin, (as cited by Gerhardt, K.J., Pierson, L.L. & Abrams, R.M., 1996) speculated that sound pressures in the fetal environment may pass easily into the inner ear through the external canal and middle ear because the impedance of the fluids found in the ear canal and middle ear are the same as the impedance of fluids found in the inner ear. Thus, middle ear amplification provided by the ossicular chain would not be necessary for efficient sound delivery to the cochlea according to Querleu's reasoning.

Noise-induced shifts in fetal sheep Auditory Brainstem Responses (ABR):

The possibility of noise-induced, prenatal hearing loss, with or without regard for a critically susceptible period for noise damage, is of practical as well as scientific interest.

Support for the possibility that noise exposures during fetal life result in changes in hearing sensitivity was provided in demographic studies of children whose mothers were exposed to noise during pregnancy. Both research found an increased risk of hearing loss in children whose mothers were occupationally exposed to hazardous noise levels. There was a significant increase in threshold to 4000 Hz pure tones when the exposure included a strong component of low-frequency noise.

An experiment reported by Griffiths, Pierson, Gerhardt, Abrams and Peter (as cited by Gerhardt, K.J., Pierson, L.L. & Abrams, R.M, 1996) evaluated the effect of an intense noise exposure on the ABRs of in utero fetal sheep. Ewes carrying fetuses with gestational ages between 124 and 29 days (average gestational period is 145 days) were prepared for sterile surgery following standard protocols. The animal was anesthetized, the abdomen and uterus were incised, and the fetal head was exteriorized. The fetal skull was exposed, stainless steel screw electrodes were secured at the vertex and at both mastoids, and a bone oscillator was fixed on the occipital bone. The scalp incision was closed and the fetus was returned to the uterus. The uterus and abdomen of the ewe were closed and the electrode leads and bone oscillator wire were passed through the maternal flank and stored in a pouch sutured to the side of the ewe.

After recovery from surgery, the ewe was placed in a cart and wheeled into a sound treated booth. The electrode leads and bone oscillator wire were connected to an evoked potential unit and ABRs were recorded to tone bursts (0.5, 1, 2, and 4 kHz) and clicks delivered through the bone oscillator. Stimulus levels were referenced to normal hearing adult subjects using the bone oscillator placed on the mastoid. Latency-intensity functions and thresholds were recorded before, immediately after a noise exposure, and 24-96 hours later. The noise exposure (120 dBSPL broadband for 16 hours) was delivered to the ewe through loudspeakers in the sound-treated booth.

Mean pre - and post - exposure latencies evoked by clicks are plotted against stimulus level for each of waves 1-1V in Figure 4.1. Pre - to post - latency shifts can be observed as a vertical difference between the pre - exposure (solid lines) and post - exposure (dashed lines) latency-intensity functions. The latency differences in these functions were significant for wave IV at all stimulus levels. Latency-intensity functions for waves III and II differed statistically at the higher stimulus levels. Latency-intensity functions for wave IV were different for the 4 kHz tone burst, but not for the lower frequencies. Following the recovery period, absolute wave latencies to all stimuli decreased to post - exposure values.

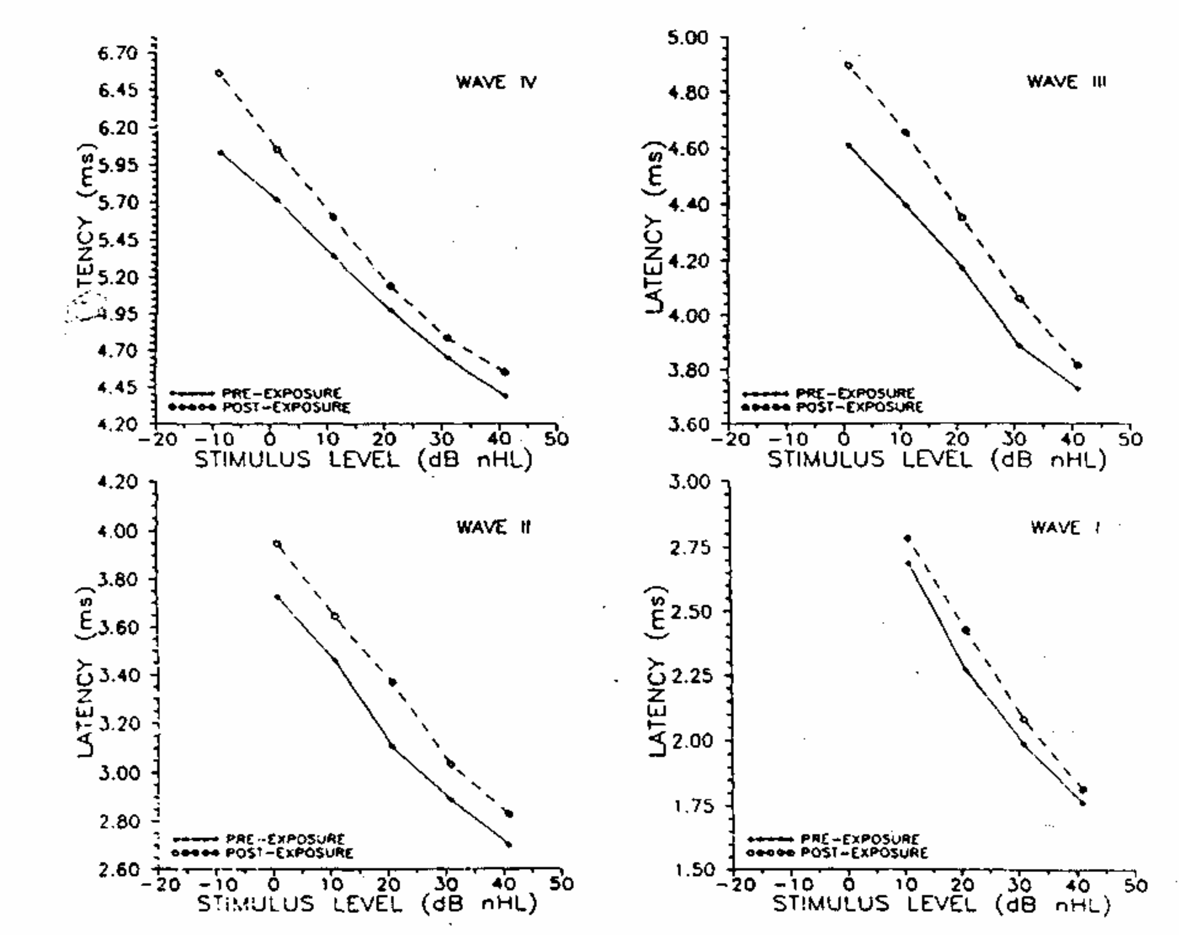

Figure 4.1 : Click-evoked ABR latency-intensity functions for waves I-IVin thepre- and postexposure test conditions

(Note: From "Fetal response to intense sounds, " by Gernhadt, Pierson & Abrams, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p.237)

Mean ABR thresholds to all stimuli are plotted in Figure 4.2 by condition (pre-exposure, post - exposure, and recovery). The average pre - to post - exposure threshold shift was 8 dB and the average shift from post exposure to recovery was 5 dB. ABR threshold shifts noted in Figure 4.2 were statistically significant for all stimulus types except 1 kHz.

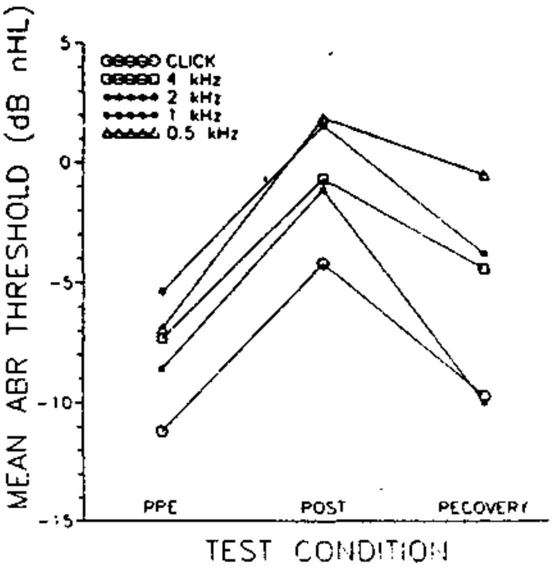

Figure 4.2 : Mean ABR thresholds to clicks and 4, 2, 1 and 0.5 kHz tone bursts recorded during preexposure, postexposure and recovery test conditions

(Note: From "Fetal response to intense sounds, " by Gernhadt, Pierson & Abrams, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p.238)

Shifts in thresholds and latencies of the ABR recorded from in utero fetuses can be produced by noise exposures delivered to the mother. The documentation of recovery after noise exposure is suggestive of temporary hearing loss.

V. UNDERWATER NOISE EXPOSURE

Jacques Cousteau (n.d.) popularized the idea of the sea as a silent underwater world, but those who dive for a living or for sport know that actually it is noisy. (Underwater hearing of humans, n.d.). Containing developments in underwater, sound technology are converting the "silent world" to a rather noisy work environment. (National Research Council, cited by Smith, P.F., 1985). Sound in the ocean come from many different sources, both natural and anthropogenic (made by humans).

Humans create underwater sound mostly through boat traffic, especially the large shipping freighters. Other human noise contributors include industrial activity such as drilling, mining and military surveillance operations that use sonar (Sound Navigation And Ranging). Several acoustic devices and noisy tools are used in diving activities while other sound sources, having uses unrelated to diving, are often operating in areas where divers are working. Seismic profilers used in off- shore oil exploration commonly use compressed air guns ("boomers") that have source levels of 200 dB SPL (20µ Pa). New underwater power tools like jet cleaning tools, rock drills and stud guns are extremely noisy (Mittleman; Molvar & Gjestland, cited by Smith, P.F., 1985).

Natural noise sources include earthquakes, wind, underwater landslides, rainstorms on the surface, icebergs breaking off and last but not least, animals!

Humans create sound by expelling lots of air over the vocal folds. Aquatic animals do not have the luxury of wasting so much oxygen. Therefore, animals in the marine environment have developed a way to create amazing repertoires of sound with minimal use of air. Shrimps and other crustaceans create sound through cavitation. They close their craws at extremely high speed producing air bubbles that 'pop' and create intense amounts of sound. Fish also make sounds. They do so by vibrating the air in their swim bladders. Seals and sea lions produce great underwater growls and roars by moving their larynx to create sound. However, the most acoustically accomplished of all the animals in the ocean, are the cetaceans (whales & dolphins). The sounds that cetaceans can produce underwater include echolocation clicks, whistles, chirps and songs! (Underwater Acoustics, n.d.).

The role of noise as a pollutant and a source of industrial injury (deafness) is well recognized in air, and there are well defined standards which are used to set the maximum acceptable level of noise in the workplace. However, there are no equivalent standards for underwater noise exposure, despite considerable evidences that divers suffer from deafness.

Effects of underwater noise on hearing:

As in air, effects of exposure to underwater noise may result in temporary and permanent sensorineural hearing loss. More seriously, high exposure levels may produce vertigo, nausea and vomiting that can be fatal.

Mantague and Strickland (cited by Smith, P.F., 1985) found that divers briefly tolerate SPLs as high as 165 to 175dB. They measured TTS beginning some 5 minutes after each exposure and reported average TTS of 6 dB and 7 dB at 3 kHz and 4 kHz, respectively. The results leave no doubt that prolonged exposure conditions would produce greater amounts of TTS. TTS-producing noise exposures will, if continuously experienced, produce some permanent hearing damage.

Corso and Levine (cited by Smith, P.F., 1985) plotted equal loudness contours for bone condition hearing frequencies as high as 95 kHz. They found that equal loudness contours appear to converge at about 85 kHz. This is an important result since it indicates that the high frequency content of broad band noise and especially impulse noise, may be of greater importance in water than air. The cochlea is partially protected from intense high frequencies in air by filtering action of the ear canal and middle ear system. This protection is not afforded in underwater exposure to noise. Deatherage, Jeffress and Blodgett (as cited by Smith, P.F.,1985) warned that strong bone conduction stimulation at ultrasound frequencies, while seldom producing aural pain, will produce several sensation including dizziness were reported by some subjects while listening to signals at 50-108 kHz, but only one subject, with repeated and relatively prolonged exposures, experienced long lasting tinnitus.

Other non - auditory effects of noise in water

Physical effects:

On several occasions during various (unpublished) experiments under water, using high-intensity sound, divers have reported that gauges became erratic, breathing regulators would free-flow, water carried in face mask tended to jiggle or ripple, and something fogging occurred within the face mask at SPL s well above 174 dB. Divers have reported that these phenomena are annoying.

Vestibular disturbances:

Montague and Strickland (as cited by Smith, P.F., 1985) reported that at SPL s of 165 dB or more, all of their divers experimented a visual effect that most of them described as a rotational movement of visual field (oculo - gyral effect). This effect occurred at the onset of a 1.5 kHz signal and was maintained until the tone was stopped. With prolonged or continuous signals and with increased intensities above 165 dB, the effect was more marked. They found that wet-suit hoods provided about 10 dB protection from it. Thus, the vestibular system may be stimulated either directly or through cochlea by intense underwater sound.

Neurological effects:

Two cases of neurological disturbances during experimental exposures to 15 minutes of continuous underwater sound were described by Steevens, Russell, Knafelo, Smith, Hopkins and Clark (1999). Sound exposure in the first case consisted of a warble tone with center frequency of 240 Hz and a sound pressure level of 160 dB re : 1 microPa. Symptoms during exposure consisted of somnolence, light headedness and inability to concentrate. No apparent effect on hearing was noticed. In the second case, a center frequency of 1000 Hz at 181 dB was used light headedness, agitation, inability to concentrate and head vibrations were noted during the exposure. The diver also exhibited a temporary threshold shift of 19.2 dB. In both cases, overt symptoms resolved within 30 minutes after exposure, but both divers reported recurrent symptoms days to weeks after the exposures.

Other physiological effects:

Duykers and Percy (as cited by Smith, P.F., 1985) and Smith and Hunter (as cited by Smith, P.F., 1985) found that at very intense underwater exposure levels, large experimental animals incurred some lung damage.

Rooney (as cited by Smith, P.F., 1985) stated that significant biological effects have been observed at levels as low as 0.1 W/cm^2. He calculated that at 31 kHz, sound intensities in water as low as 154 dB might produce biological effects in divers that could have long term health consequences. MacKay (as cited by Smith, P.F., 1985) found that a diver undergoing decompression might be at risk. Many long-term health hazards are insidious in that they produce minimal effects over short periods of time or their effects are masked or misinterpreted.

VI. UNDERWATER NOISE MEASUREMENTS

Underwater sounds are monitored by means of hydrophones, which can respond to sound pressure, or particle motion, depending on specific requirements. Normally, sound pressure-sensitive hydrophones are used for most underwater acoustic measurements, since sound pressure predominate in water. Transducers of sound pressure hydrophones are generally manufactured from piezoelectric or electrostrictive materials like quartz, Rochelle salt, barium titanate or lead zirconate. These substances, which generate an electrical voltage when compressed, are available in wide range of shapes and sizes including discs, spheres, cylinders and rings. To provide a flat broad - band frequency response the transducer is operated well below its resonance frequency (which depends upon its physical dimensions). For detecting sounds in water, the transducers need no special coupling and are often simply coated with a thin layer of an acoustically transparent waterproofing material, or immersed in a bag of castor oil. The electrical impedance of such a transducer is mainly capacitative, and it must therefore be connected to a matching preamplifier with very high impedance. The preamplifier is usually placed close to the transducer and submerged with it. The output of the transducer alone is rather low (typically less than -100 dB V"^{1} for a sound pressure of 1 dyne cm"^{2}).

It is common to include about 20-30 dB gain in the preamplifier to allow the output signals to be fed through a long cable to the sea surface without degradation. Some additional gain may be necessary before the received signal is suitable for recording or display. Most simple sound pressure hydrophones are omni directional and can only be made directional by coupling together several widely spaced transducers. To achieve significant directionality the dimensions of the transducer array must approach one wavelength of the sound frequency being examined. At 100 Hz, the transducer would need to be some 15 m wide!

Particle velocity hydrophones are inherently directional, since velocity is a vector quantity. In general, velocity transducers are constructed from seismic accelerometers, which are coupled to the water by embedding in a Perspex shell, suspended as a pendulum. The output of such hydrophones is low since particle velocity amplitudes in water are very small. In addition, the hydrophones are highly susceptible to local water movements and turbulence because of their freedom of movement. To enable a full set of particle velocity measurements, at least three transducers are required, oriented at mutual right angles.

Underwater sound projectors are now readily available. Cheap, low quality projectors are sold for transmitting sounds into swimming pools, or for use by SCUBA divers. They have the disadvantage that they are not pressure compensated, and cannot be submerged to depths greater than a few meters. Good quality broad - band transducers, like the type J9 and Jl 1 projectors produced for the US Navy are very costly, but are better able to generate the low frequencies detected by fish. Such broad - band transducers usually operate on the moving coil principle, like a conventional loudspeaker, but lack the cone attached to the latter and incorporate an air - filled bag which acts as a pressure compensation device at depth. High frequency sounds (above a few kHz) can be projected from piezoelectric transducers like those employed in the construction of hydrophones. However, to achieve high efficiency the transducers are driven at or near their resonance frequencies (Hawkins and MyrbergJr., 1983)

VII. UNDERWATER DAMAGE RISK CRITERION (DRC)

Underwater, occupational noise hazards to hearing are well recognized. Unfortunately, there are currently no widely accepted noise exposure limits or hearing damage risk criterion applicable for underwater use. Professional underwater divers are regularly exposed to intense noise that can reach sound pressure levels (SPL s) above 200 dB (Al-Masri & Martin, 1996).

The current noise exposure limits and hearing damage risk criteria in air use the A-weighting, sound level scale. Direct transposition of these well-established limits from air to underwater use is not a simple task. This is because the hearing thresholds and hearing mechanisms underwater are different from those in air. The most practical method of producing similar limits for underwater noise exposure would be to modify the limits in air. This would involve using the relationship between the thresholds of hearing in air and water as a correction factor to modify the A-weighting scale for underwater use. The assumption underlying this approach is that levels equal noise exposure above the hearing thresholds in air and water will cause equal amounts of noise-induced hearing loss. This assumption is reasonable, because noise induced hearing loss is recognized as being due to cochlear damage and the cochleae are embedded in the temporal bone and not directly affected by immersion in water.

Modification of A-weighting scale for underwater use would involve subtraction at each frequency of the difference between the MAF values for 1/3 octave band noise in air and underwater. This assumes the relationship between the 40 phon curve and the MAF curve at each frequency is constant in air and in water. The new underwater scale is called the W-weighting scale (Al-Masri and Martin, 1996).

Table 7.1:

Mathematical steps used to derive W-weighting scale from A-weighting scale

Frequency (kHz)	*0.25*	*0.5*	*1*	*2*	*4*	**5**
MAF underwater (dB SPL)	**42**	**29**	**42**	**50**	**56**	**61**
MAF of 1/3 -octave band noise in air	**12**	**6**	**3**	**-1**	**-4**	**10**
Δ (dB) = MAF underwater - MAF in air	**30**	**23**	**39**	**51**	**60**	**51**
A-weighting scale (dB SPL)	**-8**	**-3**	**0**	**1**	**1**	**-1**
W-weighting scale - A -weighting **Δ**	**-38**	**-26**	**-39**	**-50**	**-59**	**-52**

Data are rounded to the nearest 1 dB.

(Note: From "Underwater hearing and occupational noise exposure, " by Al-Masri & Martin, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p. 131)

It is apparent that the explanation of the cause for NIHL in air at 4 kHz applies to NIHL due to underwater noise exposure that occurs at mid frequencies around 1 kHz. The inverse of the A-weighting scale and W-weighting scale and the MAF curves in air and underwater are plotted below (Al-Masri and Martin, 1996).

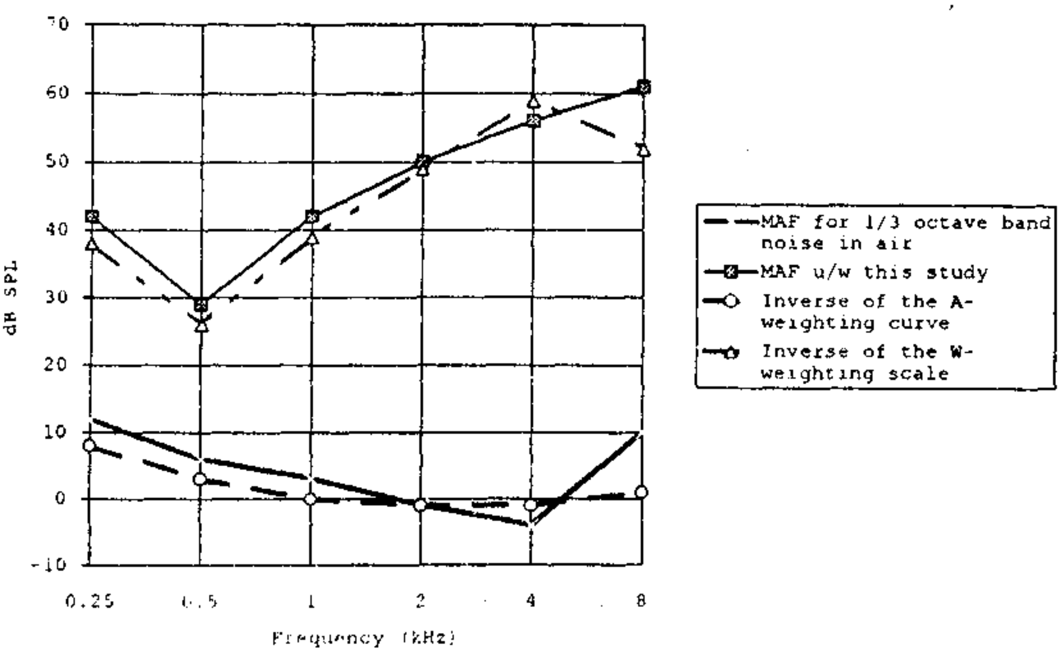

Figure 7.1: Relationship between MAF in air, MAF underwater, the inverse of the A-weighting curve, and the inverse of the W-weighting curve.

(Note: From "Underwater hearing and occupational noise exposure, " by Al-Masri & Martin, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p. 131)

It can be seen that the A-weighting scale accounts for increased sensitivity of the ear in air over the frequency range 1 to 6 kHz. In contrast, the W-weighting scale accounts for the increased sensitivity of the ear underwater over the frequency range 0.25 to 1 kHz. Thus, the maximum sensitivity of the ear underwater is located at the low frequencies around 0.5 kHz, where the hearing threshold is 20 to 30 dB less than at 2 to 4 kHz so NIHL due to underwater noise exposure may result in greater hearing disability than that in air. This has two implications. First, the current hearing damage risk criterion in air may be unsuitable for underwater use. Second, direct transposition of the current noise limits from air to underwater may provide less protection against hearing disablement than the current limits of air. Therefore, considerable caution needs to be exercised in applying limits expressed in terms of dB (W).

VIII. UNDERWATER EAR PROTECTIVE DEVICES

The underwater sources of high intensity sound or pressure waves include underwater explosions and in some cases, sonar. Low intensity sonar such as depth finders and fish finders do not produce pressure waves of intensity dangerous to a diver.

It is advisable for the diver to wear the standard *V** inch (0.64 cm) neoprene hood for ear protection. This hood is made of from a closed-cell foam neoprene, which scatters and reflects much of the sound. This hood and diver's suit mean that the level of sound received by the diver's ear is reduced thus lessening any potential impact on diver's hearing. This hood offers adequate protection when the ultrasonic pulse are of 4 msec duration, are levels up to 100 watts, and are to head -to-source distances as short as 4 inches (10 cm). (Human contacts with the underwater world, n.d.)

The diving suit isolates the human ear from the surrounding water medium. That is why sound waves penetrate the helmet and the layer of air but reach the eardrum partly absorbed and scattered. In this case, sound perception through air conduction is insignificant.

However, while diving without a helmet, which is possible in warm water, sound is perceived just like in the air. If the rubber helmet fits tightly, sound is well perceived because of bone conductivity - sound waves are transmitted through the bones of the human skull. With no helmet, a diver can hear very well, with a rubber helmet - fairly well and with a metal one-very bad. A neoprene wet suit is an effective barrier to sound at frequencies above 1000 Hz, and it becomes more of a barrier as frequency increases. (Human contact with the underwater world, n.d.)

Studies by Al-Masri and Martin (1996) gave evidence that steel ear plugs were practical to use underwater for blocking the ear canals. The experiment was carried out using 24 normally hearing sport divers. Thresholds were measured in air and underwater with and without the ear plugs using 1/3 octave band noise stimuli and sound field audiometry.

The mean MAF results in air with and without ear plugs and difference between them are plotted below.

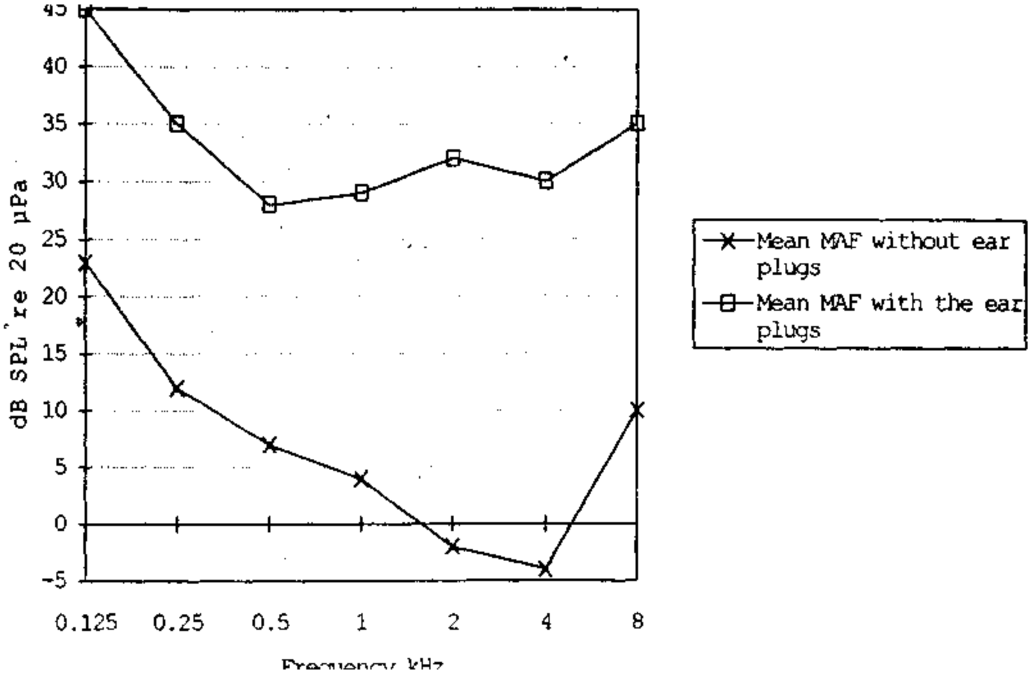

Figure 8.1: The mean difference in air between the MAF using 1/3 octave band noise with and without steel earplugs.

(Note: From "Underwater hearing and occupational noise exposure, " by Al-Masri & Martin, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p. 126)

The Figure 8.1 shows that, in air, the hearing thresholds of the subjects are increased when they wore steel ear plugs. The mean difference between the thresholds with and without ear plugs in 21 dB (range 10-35 dB) at 0.125-0.5 kHz and increases with increasing frequency to a maximum of 35 dB at 4 kHz.

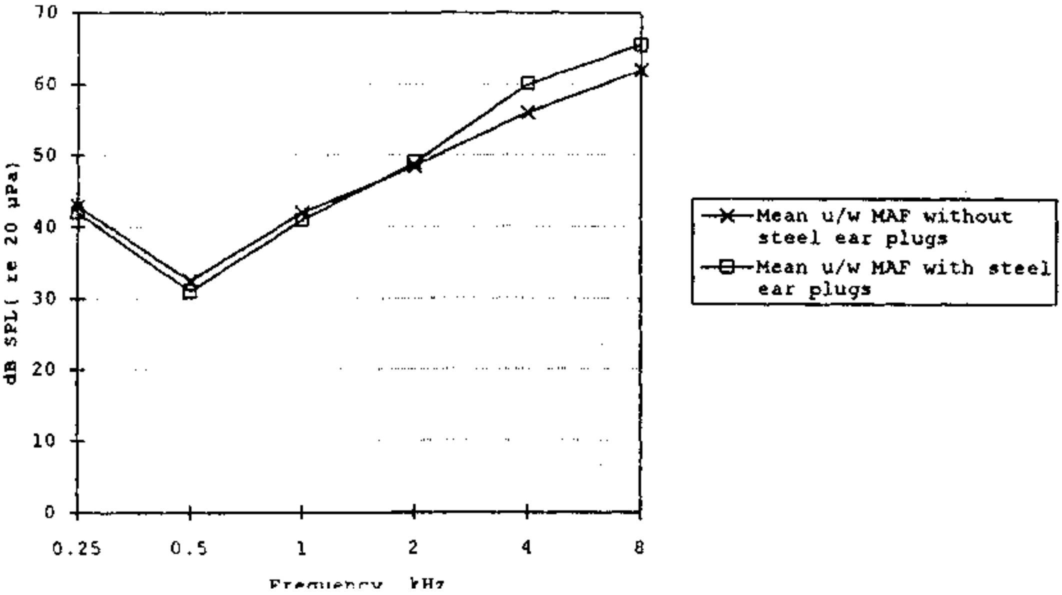

Figure8.2: Underwater MAF curves with and without the steel earplugs

(Note: From "Underwater hearing and occupational noise exposure, " by Al-Masri & Martin, 1996, Scientific basis of noise induced hearing loss, New York: Thieme Publishers, Inc., p. 127)

The Figure 8.2 shows the mean underwater thresholds with and without the plugs. It is clear that the steel ear plugs have a negligible effect on the underwater MAF. The curves with and without the ear plugs are the same to within 4 dB, at all frequencies. The results indicate that attenuation of the sound pressure transmission through the auricular pathway does not have any effect on the underwater. Much is the strong evidence supporting the hypothesis that bone conduction pathway is important in underwater hearing mechanism.

EPILOGUE

Even though the human ears are similar to the ears of aquatic mammals, the functioning is very different, as human ears are not adapted to hearing underwater. It is the bone conduction that predominantly helps in hearing underwater. The hearing thresholds are also increased underwater.

The sources of noise underwater are various. It can be natural or anthropogenic. Continuing developments in underwater sound technology are converting the 'silent world' to a rather noisy work environment. Several acoustic devices and noisy tools are used in diving activities, while other sound sources having uses unrelated to diving, are often operating in areas where divers are working.

Underwater noise exposure is hazardous to ear and other body system and also interferes with job performance of divers. Though different EPDs are being used, there is not any particular EPD that can completely protect the divers' ears from the underwater noise, as hearing under water is through bone conduction. With a few exceptions, the potential for noise from such sources to damage hearing is not much assessed. Exposure of divers to intense noise in water is increasing, yet no general hearing conservation standard for such exposure exists. No well-developed theoretical basis exists for extrapolating current hearing conservation standards for airborne noise to the underwater situation. Further research has to be carried out in order to establish an appropriate standard.

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