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UNDERWATER HEARING IN MAN: I. SENSITIVITY

by

Paul F. Smith

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF12.524.004-9012D.01

Released by:

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COMMANDING OFFICER
Naval Submarine Medical Center

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SUMMARY PAGE—REPORT NO. 569

THE PROBLEM

To determine the underwater hearing sensitivity of free swimming divers and to investigate the relationship of underwater auditory sensitivity to air conduction and bone conduction auditory thresholds.

FINDINGS

Sensitivity to sound is markedly reduced upon immersion in water. Peak underwater sensitivity occurs at about one kilohertz, at which frequency divers with normal hearing levels can detect pure tones having a sound pressure level of about 61 to 64 decibels above .0002 dynes per square centimeter. Wet suit hoods reduce underwater sensitivity by 25 to 33 decibels over the frequency range 1 to 8 kilohertz.

APPLICATIONS

These findings may be used to establish underwater hearing standards with which the underwater hearing sensitivity of particular divers may be compared.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524.004-9012D—Physiological Psychology of the Ear Under Stress. The present report is No. 1 on this Work Unit. It was approved for publication on 28 February 1969 and designated as Submarine Medical Research Laboratory Report No. 569.

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ABSTRACT

All available research on the underwater hearing sensitivity of man is reviewed. New data on the underwater hearing of divers with known air conduction and bone conduction levels were presented. It is concluded that:

1. Man suffers a loss of sound pressure sensitivity upon immersion.

2. Underwater hearing sensitivity is frequency dependent with peak sensitivity being about 61 to 64 db above .0002 dynes per square centimeter at 1 kilohertz.

3. Air conduction auditory deficiencies are not reflected in underwater hearing levels unless the air conduction deficiencies are accompanied by bone conduction deficiencies.

4. Wet suit diving hoods reduce underwater sensitivity to sound by about 25 to 35 db at frequencies of one kilohertz and higher.

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UNDERWATER HEARING IN MAN: I. SENSITIVITY

I. INTRODUCTION

The human ear is a multi-componet acoustic detector embedded in a quasi-spherical baffle. The major components of the system are the pinna, the external auditory canal, the tympanic membrane, the middle ear including the tympanic cavity as well as the ossicular chain, and the cochlea. Each component has a role in determining the overall sensitivity of the ear, and each has so evolved that the human auditory system functions optimally in the terrestrial environment. To be sure, these components interact. For example, a change in the mobility of the middle ear ossicles will be accompanied by changes in standing wave patterns in the external auditory canal. However, in order to develop an idea as to how the human ear would function when immersed in water, each component will be considered independently in the following discussion.

The head, the baffle in which the auditory system is embedded, consists of soft tissues (muscle, neural tissue, cartilage) and bony tissues. The acoustic impedance of soft tissue is very similar to the impedance of sea water, the impedance of bone being only slightly greater[1, 2]. In air the head as a rigid obstacle in the sound field. That is, at certain frequencies the sound pressure level (SPL)* at the surface of the head is measurably greater than the SPL in a free sound field. This diffraction effect is due to the very large impedance mismatch existing between the air and the tissues of the head. Underwater, however, only very weak diffraction effects occur at the head, since the acoustic impedance of the head and the water are similar.

The pinna contributes to auditory effects in air, but being composed of soft tissues, it can have no acoustic function underwater.

In air, the external auditory canal exhibits the properties of a short, rigid-walled resonator. Its dimensions are such that the sound pressure acting on the tympanic membrane, the medial terminus of the canal, is considerably higher over the frequency range 2.0 to 6.0 kilohertz (kHz) than at the entrance to the canal[3]. This effect depends on the material that bounds the canal and on the wavelengths of airborne sound. Over the outer one-third to one-half of its length, the canal is cartilaginous, the inner portion is bony. If the ear canal is filled with water and the head submerged, then the outer portion of the canal is acoustically non-existent, the only true acoustic boundary being the bone surrounding the inner one-half to two-thirds of the canal. That is, the length of the external canal is effectively reduced by one-third to one-half its normal length upon immersion. This, coupled with the fact that the wavelengths of sound in water, for a given frequency are 4.5 times longer than the wavelengths in air, results in the resonant frequency of the canal being about 6.75 to 9.0 times higher in water than it is in air. Thus, over the frequency range of greatest sensitivity in air, two major contributors to that sensitivity are not functioning normally underwater. The combination of diffraction effects and ear canal resonance has been shown to enhance auditory sensitivity in air by up to 18 decibels (db) at about 2.5 kHz[3].

The acoustic impedance of the tympanic membrane and the middle ear system is matched to the acoustic impedance of the ear canal in air. With the canal filled with water there would exist a large impedance mismatch at the boundary, the tympanic membrane, with the impedance of the water-filled canal being considerably higher than the tympanic membrane middle ear system impedance. Such a boundary is a pressure release boundary. That is, positive pressures are reflected as negative pressures and vice versa. When the ratio of the impedances is very large, the sound pressure at the boundary is at all times close to zero[4]. If this boundary were equivalent to a water-air boundary, a 30 db power transmission loss and a 66 db pressure transmission loss would occur.

* All Sound Pressure Levels in this paper are referred to .0002 dynes per square centimeter.

Within limits, the ossicular chain of the middle ear will transmit to the cochlea whatever vibratory pattern the tympanic membrane exhibits. Since the middle ear and the cochlea are isolated from the external environment they may not be directly affected by immersion.

The characteristics of the medium, the head, the pinna, the canal, and the tympanic membrane/middle ear system may account for a reduction in sensitivity of about 84 db at 2.5 kHz upon immersion. At higher and lower frequencies the reduction in sensitivity may be less. In fact, since the impedance of the ear is frequency-dependent, being greater at .1 to .4 kHz than at 2.5 kHz[5], the loss of sensitivity may be less at low frequencies.

It is interesting to note here that cetacean evolution has proceeded in the direction of eliminating the pinna and occluding or constricting the external auditory canal, rather than increasing the size and acoustic impedance of these elements in order to maintain a mode of *operation similar to that of the* ears of land mammals[6, 7]. The tympanic membrane and middle ear of the whale have also been altered with the result that the cetacean, whose cochlea remains essentially as found in land mammals, is at least as sensitive to underwater sound as is man's to sound in air[8]. Similar functional elimination of the pinna and constriction of the external meatus is observed in the common seal **(Phoca vitulina)**, a more or less amphibious mammal for which acute hearing in air and underwater would have survival value. While it has a patent external ear canal, the seal closes this passage down completely when diving. This animal is reported to hear somewhat better underwater than in air, but the difference in sensitivity in the two media is quite small[9].

Apparently, the peripheral components of the auditory system of man may be expected to function with greatly reduced efficiency when man dives. Transmission of sound by way of the ear canal and eardrum is not the only mechanism for stimulating the cochlea, however. An alternative mechanism, bone conduction hearing, will be discussed in a review of the researches of other investigators, especially Sivian[10, 11], Ide[12], and Reysenbach de Haan[7].

II. PREVIOUS RESEARCH

An early report of underwater hearing in man was made by Stetter[13] who showed that man underwater was less sensitive to a 662 Hertz tone than the minnow **Phoxinus laevis L.** His rather straightforward approach is shown in Figure 1. The submerged subject indicated perception of tones by moving his finger. The intensity of the tone was varied by the experimenter who moved down a corridor while blowing a whistle. Since the experiment was performed without benefit of physical calibration, it is only possible to conclude from Stetter's experiment that man's underwater auditory sensitivity is less than that of **Phoxinus.** Experiments in the same laboratory, cited by Griffin[14], found that the SPL at threshold for the most sensitive individual of a sample of **Phoxinus** was about 20 db. Since Stetter's human subjects were less sensitive than the **average** of his minnows, man's underwater threshold sensitivity at 662 Hertz must be some SPL greater than 20 db as compared to an average threshold SPL of 2 db for man in air. Even this weak conclusion must be made cautiously since Parvulescu[15] has shown that the acoustic behavior of small tanks, such as used by Stetter, is practically unpredictable.

Sivian[16] reported some theoretical and experimental work he had done during World War II, but neglected to report certain details which may be of interest. In a theoretical analysis[10], Sivian concluded that a small bubble of air trapped in the external auditory meatus would have no important effect on underwater auditory sensitivity. The impedances of the water-filled canal and the eardrum were shown to be so poorly matched that the sound pressure activating the eardrum would be about 40 db lower than the incident waterborne sound pressure at a frequency of one kHz. Thus, the SPL required to produce a just-audible signal would be at least 40 db higher underwater than in air.

In addition, three secondary effects were considered which could further alter underwater sensitivity. These were: (a) decreased

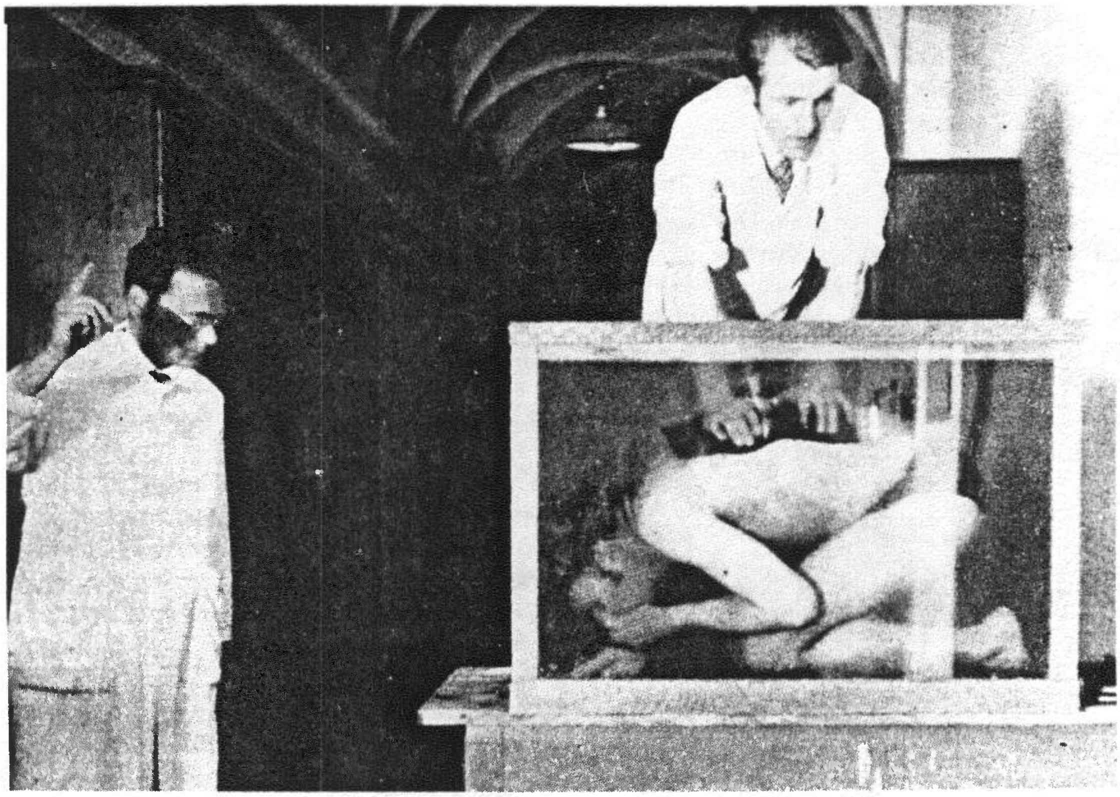

Figure 1.—Test Procedure Used by Stetter in the First Measurement of Underwater Hearing Sensitivity in Man. From Stetter[13].

sensitivity resulting from static pressure imbalance across the eardrum; (b) ambient and propulsion noise levels; and (c) the effects of the diver's head and body on the sound field. The effect of (a) is known to be of great importance in both air conduction (AC) and bone conduction (BC) hearing at certain frequencies. This could be a problem for an underwater swimmer, if he did not completely equalize middle ear and ambient pressures; (b) was dismissed as being unimportant in quiet water with the diver at rest; and (c) was thought to be of great importance. Sivian maintained that the head and body of man are much more compressible than water. Thus, the head would exert a pressure release effect when ensonified and reduce the SPL at the entrance to the canal.

Sivian also estimated that an SPL in water of 43 db would be sufficient to set the mastoid process into vibration at an amplitude at which BC threshold with occluded ear canals is reached in air. Neglecting the secondary effects, which would have similar magnitudes for both ear drum hearing and bone conduction hearing, the two threshold estimates are similar. That is, for man underwater an incident SPL to 40 db will produce a sensation of hearing through "eardrum" hearing and a SPL of 43 db will produce a sensation of hearing by BC. Allowing for the assumed pressure release effect of the diver's head, Sivian suggested that, to a very rough approximation, the human underwater auditory threshold may be about 45 to 55 db plus an allowance for static pressure imbalance across the tympanic membrane.

Sivian then conducted an experiment in a YMCA swimming pool measuring 60′ x 18′ x 6′ 5″[11]. The tests were conducted in the early morning hours on a Sunday, so as to minimize interference by extraneous noise. The sound source was a 12″ moving coil loudspeaker which was mounted about 15″ above the surface of the pool and driven by a 6-A audiometer. AC testing was carried out with the subject's (S's) chin just above the surface of the water. Underwater tests were conducted with Ss standing in lead-weighted sandals on the bottom of the pool. The Ss' heads were 9″ to 15″ below the surface. During the tests the noise level in air, as measured by an RA-358 Sound Level Meter, was 45 db. Underwater noise levels were not measured. The thresholds were recorded in terms of the attenuator settings on the 6-A audiometer. No physical calibrations were performed. Results are shown in Table I.

TABLE I—Results of Sivian's Experiment

Observer	Audiometer Setting DB		Difference (DB)	
	Water	Air		
G.	75	30	45)	
K.	95	53	42)	1000 cycles
O.	75	30	45)	
			Avg. 44	
G.	85	38	47)	
K.	105	60	45)	3000 cycles
O.	88	33	55)	
			Avg. 49	

One of Sivians observers, observed "K", had a substantial "aerial" hearing deficiency. It may be seen in Table I that his underwater hearing thresholds deviated from observers G and O by about the same amount as did his AC hearing. Sivian took this as evidence that underwater hearing is "eardrum" hearing rather than BC hearing. The average differences in audiometer settings for hearing in air and hearing underwater were 44 db at 1000 Hz and 49 db at 3000 Hz. These values are in general agreement with Sivian's theoretical analysis.

Ide[12] conducted experiments in underwater hearing on breath-holding swimmers in the Spring of 1944. He measured underwater hearing thresholds for intermittent continuous wave (CW) signals over the frequency range .1 to 6.0 kHz and for speech. The speech signals were taken from a disk recording of Navy alphabetical code words. Both CW and speech signals were transmitted underwater from a Naval Research Laboratory Model X-2, underwater loudspeaker.

Ide failed to report many important methodological details. No information is given on how the SPL at the diver's head was estimated and controlled or on the specifics of the test procedure. Underwater ambient noise levels were not reported. Except for surface wave sounds, which were apparently not heard at depths of three feet and greater, the swimmers did not report hearing any underwater background noise. AC hearing levels of Ss were not reported. Apparently, the tests were conducted at depths of three to six feet in water which was 35 to 40 feet deep. It was reported that "Audiometer-type tests" were used and Ss were three men listening underwater with the unaided ear.

Although quantitative data for speech reception thresholds were not given, it was reported that intelligibility fell off "long before the limit of hearing was reached." Swimmers on the beach about 500 yards from the source heard the speech signals clearly by putting their ears to the bottom in one or two feet of water.

Ide's results for keyed CW signals are presented in Figure 2, which shows the underwater hearing sensitivity of man to be rather flat across the frequency range tested relative to the audiometric function for hearing in air. The difference in SPL between thresholds in air and underwater was 65 to 70 db. However, it is to be noted that the bottom curve in Figure 2 is not for Ide's subjects, but represents "normal hearing in air" and seems to have been taken from another source.

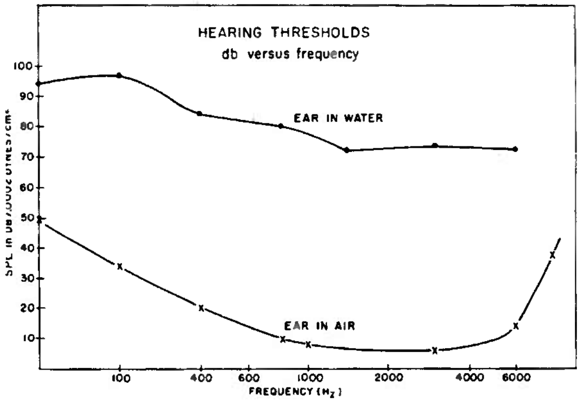

Figure 2.—Ide's Results: The upper curve represents the underwater hearing sensitivity of three brath-holding divers. The lower curve apparently represents normal hearing levels in air.

Ide cites Sivian's first memo on underwater hearing,[10] but apparently was unaware of Sivian's swimming pool experiment[11]. Ide accepted Sivian's hypotheses concerning the impedance mismatch at the eardrum and the unimportance of an air bubble in the ear. He concluded that the 20 to 25 db difference between his measurement and Sivian's prediction was a reasonable allowance for the combined influence of the pressure release effect of the diver's body and the static pressure imbalance across the tympanic membrane (Sivian's "secondary" effects).

In later studies on the ability of underwater swimmers to localize sound sources, Ide found that the binaural sensation was enhanced when the divers wore a four-inch wide strip of half-inch thick sponge rubber running mid-sagitally from the forehead to the base of the skull. A helmet, designed to enhance binaural hearing underwater, was developed and is shown in Figure 3. Without the use of such a device, all underwater sounds appeared to Ide's subjects to originate directly overhead. If additional widths of foam rubber were used, overall auditory sensitivity fell off. Ide believed that, as Sivian had hypothesized, eardrum hearing and BC hearing have approximately equal sensitivities underwater. "Sound received through areas midway between the ears, particularly the top and back of the head, can have no directional character but does contribute to the overall loudness." Thus, the sound reaching the inner ear by the eardrum route is to some extent masked by the sound arriving via the bone conduction route. The helmet was designed to reduce the masking effect of the bone-conducted sound. However, some divers were able to localize sound sources underwater without the use of the helmet and

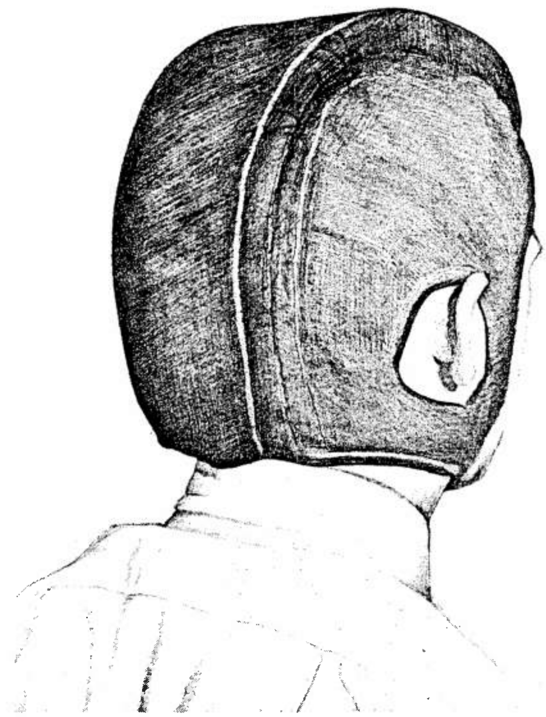

Figure 3.—Helmet Designed by Ide to Enhance the Binaural Effect Underwater.

others were able to do so bareheaded after a period of practice with the hood. Ide also mentioned that the binaural effect was subject to fatigue and was impaired by minor ear injuries. Localization ability was best when the divers was upright in the water.

In other trials Ide found the use of ear plugs enhanced the binaural effect for some swimmers. This effect was attributed to the equalization of the paths to the two ears. The

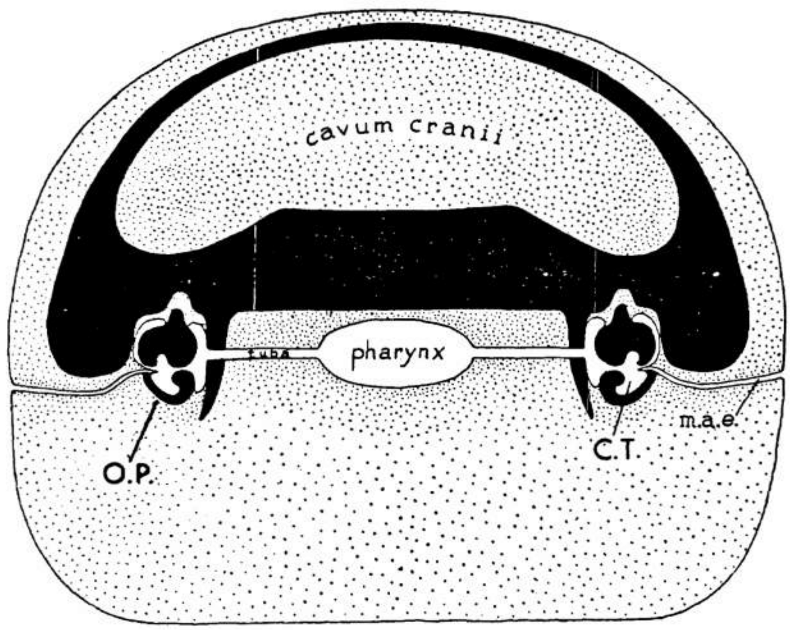

Figure 4.—Schematic Dorsoventral Section through the Skull of the Odontoceti at the Level of the Hearing Apparatus, C.T., cavum tympani; m.a.e., meatus acusticus externus;O.P., os petrotympanicum. (From Reysenbach de Haan[7]).

most effective ear plug used was a Western Electric ear phone base with a rubber dam across its outer surface.

Ide also found that, when using the diving helmet, no appreciable reduction in loudness of sound occurred, as long as the width of the sponge rubber strip was four inches or less. If more than a four inch width of rubber was used, a very noticeable reduction in loudness of sounds occurred. Ide attributed this effect to the pressure release action of the sponge rubber.

In his monograph, "Hearing in Whales," Reysenbach de Haan[7], frequently compared the structure of the ears of whales, other aquatic animals, and land animals. He noted that in whales and other aquatic mammals, the pinna is either greatly reduced in size, or is in fact missing. Further, the external auditory canal is greatly reduced in size. In the most completely aquatic mammals — the cetaceans — it is plugged up or completely collapsed. He performed an experiment which showed that a canal running through whale blubber could have no acoustic significance over the frequency range 3 to 20 kHz, since the blubber and water transmit sound about equally well. He also discussed changes in the middle ear structure of whales and argued that the impedance of the middle ear of whales is matched to the impedance of the water medium.

Reysenbach de Haan argued that, if a human head were immersed in water, it would derive no benefit from the pinna or the external auditory canal, and the middle ear system could not possibly function well underwater. Thus, a man underwater would not be very sensitive to sound. Further, like Sivian, Reysenbach de Haan believed that the skull would vibrate as a whole when ensonified. The motion of the skull relative to the middle ear ossicles would result in hearing by inertial bone conduction. In the whale, isolation of the entire ear from the skull is achieved by the suspension of the hearing apparatus in the dense **os petrotympanicum** below the skull. This arrangement is shown in Figure 4. Thus, vibrations of the skull have no effect on the functioning of the ears. In man, however, there is no isolation of the ears from the skull and both ears would be similarly influenced when the head is ensonified. Thus, according to Reysenbach de Haan, directional hearing for man underwater would be impossible. In order to test these hypotheses he measured the underwater sensitivity of three normal-hearing men under two conditions. In one condition, the divers had their ear canals filled with air. In the other condition, the ear canals were filled with water. No description of how these conditions were obtained or controlled is given. Results of the threshold test are given in Figure 5.

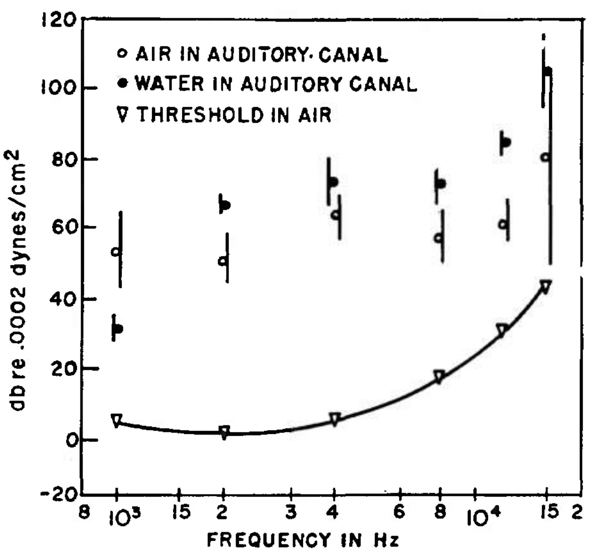

Figure 5.—Reysenbach de Haan's Comparison of the Threshold Audiograms of Man in Air and Underwater with and without Water in the Auditory Canal.

In further trials the divers descended to various depths at various distances from the sound source while signals were emitted. The signals were short pulses and sweep tones in the frequency range 1 to 16 kHz. The subjects were unable to determine the direction of the source.

The four studies just reviewed, apparently, all used breath-holding divers as subjects with the exception of one homing trial reported by Ide for a diver using Lambertsen diving equipment. Equalization of pressure across the tympanic membrane can be accomplished during breath-holding dives, but is not an automatic process for many swimmers. It is known that pressure imbalances corresponding to 50 cm of water can be endured without great discomfort, but have profound effects on both AC and BC hearing[17]. It may well be that pressure imbalance effects are responsible for some of the differences in the thresholds reported by Sivian, Ide, and Reysenbach de Haan. Supplying S with breathing air at the same pressure as the ambient water pressure, would enable better control over equalization and would permit testing at depths at which surface reflections can be safely ignored or more adequately controlled.

Another characteristic of these four studies was that SPL measurements were not made at the locus of the diver's head. Reysenbach de Haan came closest to providing adequate measurement, but his procedure still entailed extrapolations based on assumed, but not measured, spreading loss and reflection effects. Measurement of SPL at the divers' heads would make such assumptions unnecessary.

Further, ambient noise levels were not measured in any of the four studies discussed. The fact that noise levels in air above a pool are low (Sivian) gives but limited information concerning levels in the pool. Nor, is it sufficient that divers not hear any noise other than test signals (Ide). In order to insure no masking effect is present, ambient noise levels should be at least 10 dB, perhaps 20 dB, below true threshold levels. Measurement of Spectrum Levels as low as 30 to 35 dB, a level at least 10 dB lower than most reported underwater thresholds, are not difficult and may be accomplished with minimal equipment.

Experiments to be reviewed subsequently were generally executed under much improved conditions. They were all conducted in quiet fresh water pools in which the water temperature varied between 69 and 74°F, with divers equipped with Self-Contained Breathing Apparatus (SCUBA). In most cases, head depth was between 10 to 13 feet and the head to sound source distance was 3-6 feet. All investigators report AC but not BC data for their subjects.

Hamilton[18] used a modified method of limits in which he tested two divers, sitting side by side, at the same time. A calibration hydrophone was suspended halfway between the two heads. His subjects were four young, experienced divers with normal or better than normal hearing levels. His results are shown in Figure 6, along with the results of three subsequent studies. Hamilton also found that his subjects most commonly reported no change in apparent loudness of tones when they plugged their ears with their index fingers. Hamilton reasoned that

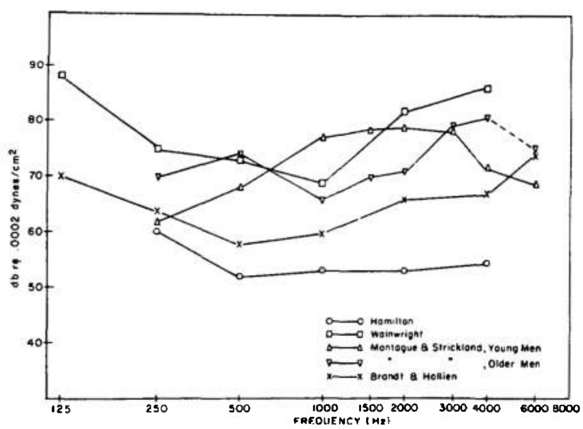

Figure 6.—Composite Results of Four Studies of Underwater Hearing Sensitivity in Man.

if underwater hearing is mediated by the ear canal route, then plugging the ears ought to result in a decrease in loudness. No enhancement in sensitivity due to the occlusion effect, such as is seen in BC hearing in air, is to be expected if underwater hearing is mediated by the bone conduction route, since the ear is already occluded by water. These results, and the fact that the magnitude of the difference between AC and underwater (UW) hearing levels was of the same order of magnitude as previous estimates of the difference

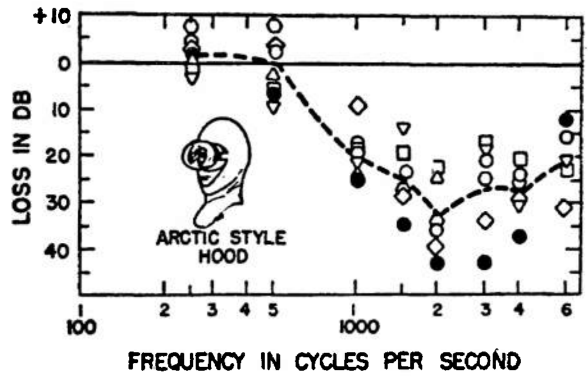

Figure 7.—The Attenuation of Underwater Sound by a 3/16-inch Foam Neoprene Arctic Hood Plotted for Individual Divers. (The insert shows a diver's head while wearing the hood and a mask. From Montague and Strickland[20]).

between AC and BC, were taken as evidence that underwater hearing may be mediated by bone conduction.

Wainwright[19] obtained underwater hearing thresholds by the method of limits on two subjects, both of whom had depressed AC and BC hearing levels (Submarine Medical Center records) at 4 and 8 kHz. His subjects used closed circuit SCUBA to avoid interference from bubble noise produced by open circuit SCUBA. Hamilton and later investigators used Ss equipped with open circuit SCUBA, but controlled the noise levels by instructing divers to adopt a controlled breathing routine during which testing was accomplished while the divers held their breath. Wainwright's data are presented in Figure 6. He also found no effect on UW by occluding the ears with fingers. Wainwright held that the difference between his data and Sivian's prediction of threshold sensitivity at one kHz is a reasonable allowance for the pressure release effect of the swimmer's body. He further explained the difference between his and Ide's data as due to pressure imbalance across the eardrums of Ide's Ss. Wainwright neglected to cite Hamilton, hence, no explanation of the evident discrepancies between these two sets of data was offered.

Montague and Strickland[20], citing the discrepancies between the data of Wainwright and Hamilton, and also between Sivian and Ide, undertook to redetermine underwater thresholds. With the exception that a fixed-frequency Békésy technique was employed to determine AC and UW thresholds, their procedures were very similar to Wainwright's and differed from Hamilton's only in that one S, rather than two, was tested at a time. Montague and Strickland tested a sample of four young men whose AC hearing was much like that of Hamilton's sample, and a sample of three men all of whom exhibited some depressed AC hearing levels. The results are plotted in Figure 6.

Montague and Strickland reported each individual's results for AC and UW rather than simply reporting mean values. These data reveal a rather large variability in UW in comparison to AC. Reysenbach de Haan had commented that the accuracy of individual measurements of UW thresholds was about 10 dB which he considered to be not bad under the circumstances of the testing situation. Montague and Strickland felt these differences may reflect wide individual differences in BC sensitivity. They note, however, that both intra- as well as inter- subject variability is greater for UW than AC thresholds.

Montague and Strickland also obtained data on the sound-attenuating properties of divers' foam neoprene hoods by comparing UW thresholds of their subjects while wearing hoods with their UW thresholds while bareheaded. These data, presented in Figure 7, show that hoods have little or no effect on UW sensitivity at 250 and 500 Hz, but depress sensitivity over the frequency range 1 to 6 kHz. Similar results were obtained regardless of whether the hoods were 3/16, ¼ or 3/8 inch thick. It was also found that exposing about two inches of the diver's forehead almost completely restored bareheaded UW sensitivity but no systematic measurements were reported on this point.

In discussing their results, Montague and Strickland point out that the loss of auditory sensitivity which accompanies immersion is greatest at those frequencies for which hearing is most acute in air. This effect, they felt, may be due to the impedance mismatch of the ear and the water and/or to the loss of ear-canal resonances. They were not able to explain the discrepancies between Wainwright's and Hamiltin's findings and showed that correcting UW by AC hearing levels did not reduce the discrepancies.

A program of research in underwater hearing in man has been initiated by the Communication Sciences Laboratory (CSL), of the University of Florida. These studies,[21, 22] when referred to collectively, will be cited as the CSL studies.

Brandt and Hollien[21] of CSL instituted a study of underwater hearing threshold sensitivity in man, partly because "... 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." Using procedures identical with those of Montague and Strickland they produced results which, as may be seen in Figure 6, were similar to Hamilton's.

Brandt and Hollien apparently used Ss who exhibited depressed high-frequency AC hearing levels. The procedure used for determining AC hearing levels was to pick up signals from the underwater sound source used for UW threshold determinations and deliver this signal to earphones. Unfortunately, AC testing was done in an environment in which airborne noise levels were quite high and the resutling AC levels were found to be 10 to 15 dB higher at 1 kHz and below than levels observed in subsequent tests under standard laboratory conditions. Above one kHz, however, the measured AC levels were presumably valid.

Brandt and Hollien measured UW thresholds at depths of 12 and 35 feet and found a small, consistent, but statistically non-significant ($n = 3$) decrease in sensitivity with depth. They found no significant ($n = 8$) frequency dependent differences in UW sensitivity although their data typically exhibit peaks in the UW audiometric function at 500 or 1000 Hz. They found, however, that differences between AC and UW sensitivity increased with frequency.

In subsequent work, Brandt[22] investigated the effects of depths to 105 feet, and helium-oxygen breathing mixtures on UW hearing levels. No significant effect on UW hearing due to depth was found. Breathing a helium-oxygen mixture at 105 foot depth resulted in a 5 dB reduction in threshold sensitivity which was attributed to the presence of the helium-oxygen mixture in the middle ear cavity.

The results of the four studies just reviewed, presumably accomplished under rather good environmental control, are not much more consistent than those of the four earlier studies. It is possible to discover differences in procedure, subjects, test environment, and so on, which might be responsible for the various results, but the effects of such differences on the experimental results are probably very small. By and large, the experiments of Hamilton, Wainwright, Montague and Strickland, and Brandt and Hollien may be considered as directly comparable.

Furthermore, these latter studies have not advanced understanding of the mechanism of underwater hearing beyond that provided by Sivian and Ide. Not a single author reports BC audiometric data on his experimental Ss, in spite of the fact that all discuss the possible importance of BC in underwater hearing. Only Brandt and Hollien have attempted to systematically vary conditions in the middle ear in an effort to determine possible involvement of these structures in underwater hearing. For the most part, the latest studies had been undertaken in order to obtain normative data—a worthy and necessary goal, but not a sufficient one. Without an understanding of the mechanism of underwater hearing, the development of communications and sensing devices for divers may not proceed in the most efficacious direction.

III. EXPERIMENTS

The experiments described below were accomplished in conjunction with a study of the effects of sonar transmissions on the hearing of underwater swimmers which culminated in the establishment of safety standards for divers working in proximity to operating AN/SQS-26 sonar systems. The work on threshold sensitivity described in this report provided information required to interpret adequately the sonar exposure data.

In an earlier report,[23] it was shown that, for frequencies of six and eight kHz, the greater the auditory sensitivity of a subject in air (AC) the greater the loss of auditory sensitivity suffered by that subject upon immersion in water. That finding was taken as evidence that underwater hearing may be predominantly BC hearing. Since that work had been done using breath-holding Ss in a very small pool, it was thought desirable to obtain further data on a sample of divers equipped with SCUBA under more acoustically controlled conditions.

A. Experiment I. Underwater Hearing Thresholds for Normal and Abnormal Ears.

1. Subjects.

The subjects in this experiment were 16 male divers from various commands. Five divers were from the USS TRINGA (ASR16), three from the staff of the Escape Training Tank of the Submarine School. The balance of Ss in the sample were from the Submarine Medical Center including three medical officers, who were students in the School of Submarine Medicine, and five members of the research and technical staff of the Submarine Medical Research Laboratory. With the exception of the three student medical officers, all were qualified Navy divers, or had well over one year of diving experience. The five members from the Submarine Medical Research Laboratory were highly skilled observers who had previously served in a variety of psychological and physiological experiments in diving medicine. The three divers from the Escape Training Tank had similar, but less extensive experience. Some of the TRINGA divers had served in a previous underwater hearing experiment on the effects if sonar transmissions on the hearing of divers. Of this group, eleven men had normal hearing (no hearing level greater than +10 dB), three had predominantly AC losses at a single frequency (6 kHz) and two had mixed AC and BC losses at some frequencies.

2. **Apparatus.**

The complete underwater threshold measurement apparatus is schematized in Figure 8. A Hewlett-Packard Model 200 ABR oscillator generated pure tones, the frequency being measured by a General Radio Type 1142-A frequency discriminator. A Grason-Stadler Model 829E electronic switch, operated manually, was used to deliver the signals with a 10 millisecond rise-fall time to a Hewlett-Packard Model 350 D decade attenuator which controlled the signal level. An 80 watt Altec Model 1569A amplifier drove a magneto/strictive underwater transducer. The transducer was a Navy Underwater Sound Laboratory product type XU-1210. The frequency response of this unit is not flat, but is usable for threshold measurements over the frequency range 500 to 8000 Hz. Also shown in Figure 8 is the diving stage showing the arrangement of the underwater equipment. Calibrations of the underwater threshold measurement system were performed with a calibrated hydrophone and a Ballantine Model 302C battery-operated voltmeter which were loaned by the Navy Underwater Sound Laboratory. These are also shown in Figue 8. AC thresholds were measured using a Maico Model E-2 audiometer in series with a precision decade attenuator. BC levels were measured using a Sonotone Model AE-21 audiometer and a Sonotone Cat 21:308 bone vibrator mounted in a helmet type holder which is described elsewhere.[24]

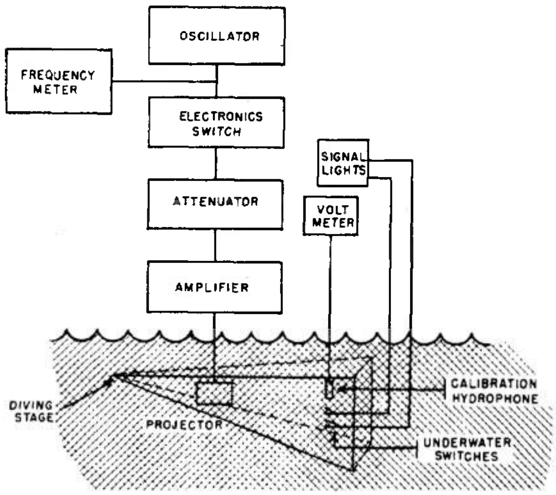

Figure 8.—Schematic Diagram of Apparatus for Measuring Underwater Thresholds. (See text for description).

A diving stage was constructed of ¾″ free-flooding steel pipe and wood. The stage consisted essentially of two right triangles joined together at the vertices with the bases held apart by two four-foot sections of steel pipe. A 2″ x 4″ wooden cross member provided a seat for the diver. By hooking his fins under a lower 2″ x 4″ cross member the diver could remain motionless in still water and have both hands free to operate signal switches. The overall length of the stage was ten feet. The base itself was a rectangle five feet high by four feet wide. The sound source was mounted on a cross bar at a distance of eight feet from the locus of the diver's head. A small hydrophone, used for calibration and monitoring, was mounted on the stage adjacent to the locus of the diver's head. Measurements indicated no significant differences in SPL across the rectangular portion of the stage at the level of the diver's head. Also suspended from the top of the rectangular section were two underwater switches with which the diver signalled the surface. The underwater switches were constructed as follows:

Two Minneapolis Honeywell mercury switches AS445C30 were wired tip to tip so they form a double pole throw switch. This switch was connected to the end of a rubberized three-wire cable and embedded in a Scotchcast Splicing Kit (No. 82-A1). The free end of the splicing kit from which no wire emerged was sealed with a rubber plug. Care had to be taken to insure that large bubbles did not form when filling the mold with resin as such bubbles weaken the overall structure and limit the depth at which the switch may be safely used. The switches had been tested for implosion at a depth of 90 feet.

These switches when held in a vertical position with the free end up caused a "yes" light to shine topside. If the free end of the switch is pointed downward, a "no" light is lit. The diver used two such switches. One signalled whether or not the diver was holding his breath and ready for testing, the other signalled whether or not the diver heard a tone.

The stage with all of the underwater equipment, was suspended from a catwalk near the center of Millstone Quarry Pond (a fresh water test facility operated by the Navy Underwater Sound Laboratory) at such a depth that the diver's head was 15 feet below the surface in 75 to 80 feet of water.

3. Calibration Procedure.

On the basis of prior studies, the ambient noise level in the pond was estimated by NUSL personnel to be about 34 dB at one kHz sloping to a lesser level at 8 kHz.

Prior to and immediately following each day's work, the underwater threshold measurement system was calibrated. Because of the proximity to the surface and the rather large subject-to-sound-source distance, it was necessary to use a frequency discriminator to insure exact replication of test frequencies from trial to trial since very slight errors in setting the frequency resulted in as much as 7-10 dB differences in SPL at the diver's head.

4. Procedure.

AC and BC data were obtained by standard audiometric methods. At the beginning of each underwater threshold measurement run, S dove to the stage, sat on the crossbar, stabilized, equalized middle ear pressures, and otherwise prepared for testing. When S was ready to begin a test run he held his breath and signalled the surface with one of the two underwater switches. Upon observing the diver's "ready" signal, the experimenter listened through the monitoring system for all extraneous bubble noise to cease, then began testing. The intensity of discrete tones was varied in 5-dB steps in alternate descending and ascending series. S responded by operating the second switch. At least four series (two descending and two ascending) were run at each frequency tested (1 to 8 kHz).

Divers were tested both bareheaded and with hoods. Except for two thinner models worn by two men, the hoods were made of 3/8 inch neoprene and nylon and covered the skull completely, except for the nose and mouth regions and small areas of cheek bone. A typical hood is shown in Figure 9. The order of testing with and without hoods was alternated from S to S, so that half of the men were tested bareheaded first and then with the hood, and half were tested with the hood first. Divers came to the surface between runs in order to don or doff hoods. In all cases, the hoods and the divers' heads were wetted before the hood was put on, in order to minimize air pockets under the hood.

5. Results.

Mean results for eight normal-hearing divers in the bare-headed condition are shown in Figure 10. Calibration errors resulted in the loss of data on three Ss. An analysis of variance on the octave points 1 through 8 kHz yielded a significant linear trend for the data. The best fitting line has a slope of about 8 dB per octave. Medians were within 2 dB of the means at all frequencies.

The mean AC and BC hearing levels of these eight men with respect to population norms (audiometric zero) are shown in Figure 11. The AC, BC and UW hearing levels of the five men exhibiting depressed hearing levels were plotted with respect to the performance of the "normal" group. These results are shown in Figure 12. The plots for the three divers with predominantly AC losses at six kHz are labelled A, B, and C. Plots D and E are for the two divers with mixed losses. Inspection of these five composite audiograms reveals that there is, generally, no loss in UW sensitivity in divers A, B or C with respect to the normal group at six kHz, or any other frequency at which they deviate from the median AC hearing level of the normal group that is not accompanied by a similar BC deviation. Divers D and E, who have marked BC deviations, also exhibit marked UW deviations. It is interesting to note that the extent to which the latter divers deviate from the UW hearing levels of the "normal" divers is somewhat less than the magnitude of their AC and BC deviations.

Figure 9.—Foam Neoprene Wet Suit Hood Used by Most Divers in the Present Study.

Data obtained on the attenuating properties of diver's hoods is presented in Figure 13. The sample includes one man in the depressed BC group and two normal hearing men not represented elsewhere. The data in Figure 13 are based on relative signal input levels.

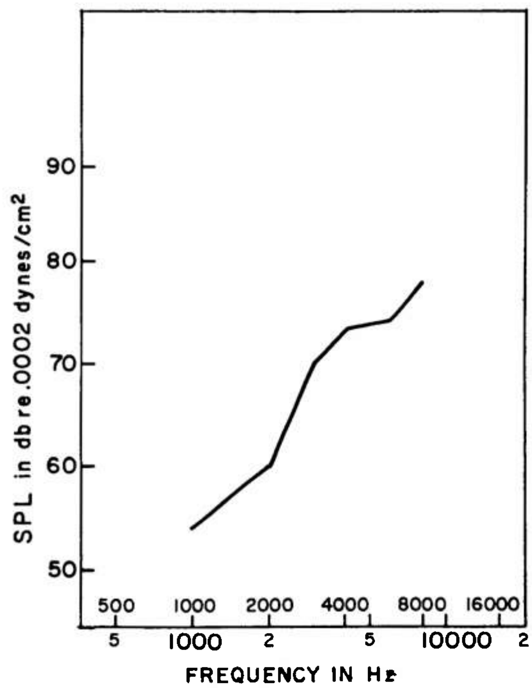

Figure 10.—Mean Underwater Hearing Thresholds for Eight Divers Exhibiting Mean Air Conduction and Bone Conduction Hearing Levels as Shown in Figure 11.

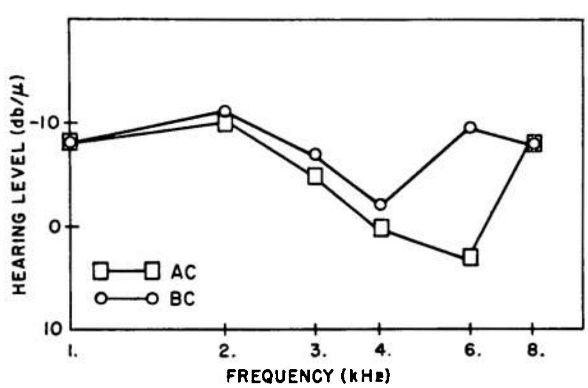

Figure 11.—Mean Air Conduction and Bone Conduction Hearing Levels for Eight Divers Classified as Normal Hearing Subjects.

B. **Subsidiary Experiment.**

Data were also obtained on the effects of depth on the attenuating properties of diver's hoods. For these tests the Escape Training Tank of the Navy Submarine School was used. All machinery in the Training Tank building that was not essential to the operations was shut down to reduce the noise level within the Tank. The work was carried out in the evening in order to minimize the effects of traffic noise. Nevertheless, a relatively high ambient level was present throughout the test which prevented obtaining bareheaded threshold sensitivities comparable to those reported above. However, the ambient level appeared to be well below UW thresholds with hoods at one and four kHz.

Underwater signal and noise levels were measured with the system described as follows:

The hydrophone is a 3-inch long barium titanate cylinder which was constructed by the Massa Division of the Dynamics Corporation of America to Navy Underwater Sound Laboratory specifications. This unit, designated XU-7595, was calibrated in February 1962 by NUSL. Its calibration at specific frequencies was checked prior to use in this experiment and found not to have varied significantly. The hydrophone was connected to the "2 MEG" input connector of a Massa Model M-185 Amplifier and Power Supply. The gain of the M-185 is nominally 0 to 60 dB. The output of the M-185 was connected to a Dynatronics Model 720 Electronic Band Pass Filter. This instrument has selectable fixed percentage bandwidths, a 20 dB gain capability, and an operating frequency range of 1 to 10,000 Hz. The filter was operated with a nominal fixed ratio bandwidth of ±2.3% of center frequency. This facilitated estimation of the noise level in a critical band around the various test frequencies used in the experiment. The output of the filter was read with a Ballantine Model 302C battery operated Electronic Voltmeter.

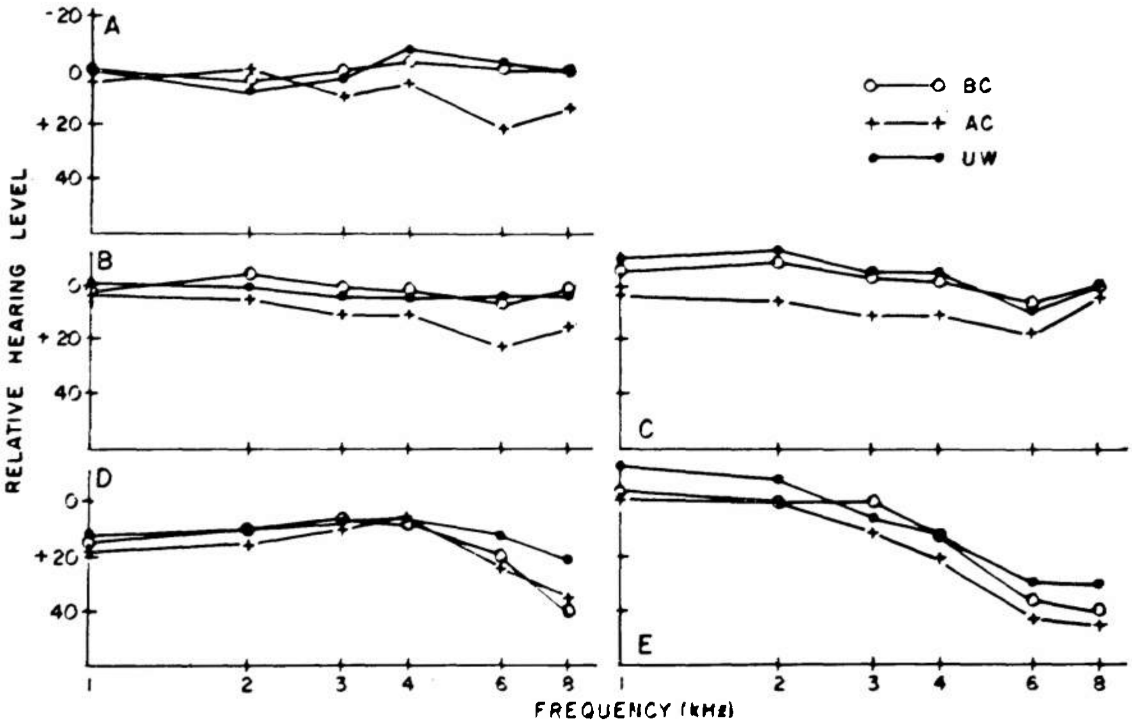

Figure 12.—Individual Air Conduction, Bone Conduction and Underwater Hearing Levels of Five Men Exhibiting Depressed Air Conduction Hearing Levels Plotted with Respect to Mean Hearing Levels of Eight Normal Men shown in Figures 10 and 11.

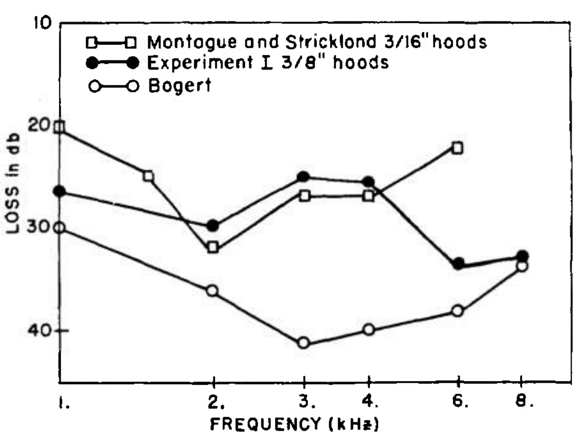

Figure 13.—Attenuation Provided by Divers' 3/8 inch Wet Suit Hoods. (Montague and Strickland's means and data from Bogert are shown for comparison. Thickness of hood used by Bogert was not specified).

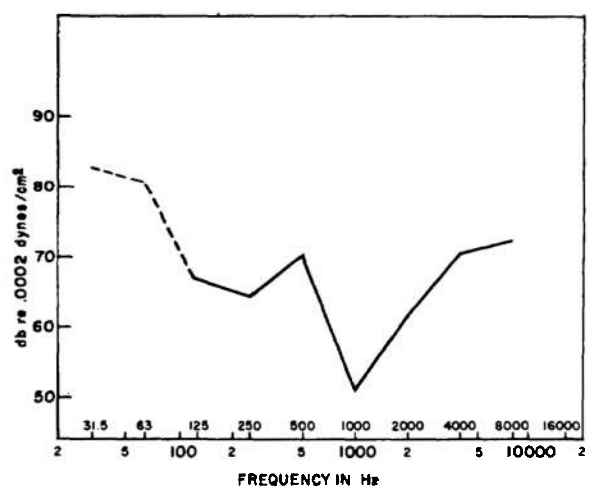

Figure 14.—Mean Underwater Hearing Thresholds for Five Men with no Significant Bone Conduction Hearing Deficiency.

Tests with electronic signals of known frequency and amplitude applied to the input of the M-185 permitted determination of the operating characteristics of the system. The bandwidth of the system (the frequency distance between half power points) was found to vary between ± 2.64% and ± 3.06% of center frequency over the frequency range 1 to 8 kHz. Similar small variations in bandwidth were observed at randomly sampled frequencies below one kHz. The overall maximum gain of the system was found to be 81.5 dB over the range 10 to 10,000 Hz. Noise levels, with the input to the Massa amplifier shorted, measured over the frequency range 10 to 10,000 Hz varied between 0 and —7 dB re 1 millivolt (mv) with the peak levels occurring at 60 and 300 Hz. Noise levels with the XU-7595 hydrophone connected to the input and with the hydrophone isolated from water and earth in a quiet sound proof room were within one dB of the shorted input noise levels except at 300 Hz where the noise level was + 3 dB/mv. Using this system in conjunction with the power addition law, it was found possible to measure voltages accurately (less the .5 dB error) down to — 130 dB/volt. Levels about 10 dB lower could be estimated within ± 2 dB. In terms of the sensitivity of the XU-7595, it was possible to measure narrow band noise levels as low as 34 to 44 dB.

Two divers who had served as Ss at Millstone Point were used. The threshold measuring apparatus was the same as described earlier with two exceptions. In place of the magneto-strictive projector, a J-11 transducer, loaned by the Navy Underwater Sound Reference Division of the Naval Research Laboratories, was used as a sound source. A continuously variable attenuator in series with the decade attenuator was added to the circuit to facilitate threshold determinations.

Underwater thresholds at 250, 1000 and 4000 Hz with and without hoods were measured at depths of 33, 66 and 99 feet. The hoods used were made of 3/8″ nylon lined neoprene and were the same hoods the two subjects had used at Millstone. Inadvertently, one diver did not remove his hood at 66 feet. The other diver kept his on during both runs at 66 feet. Consequently, data are available only for the 33 and 99 foot depths. Thresholds with hoods in place were approximately the same at 1 and 4 kHz for these two divers as their thresholds with hoods measured at Millstone Pond at a 15 foot depth. The difference in thresholds with and without hood were smaller than differences obtained at Millstone Pond but were approximately the same at both the 33 and 99 foot depths. Differences in thresholds at 250 Hz with and without hoods were about 5 to 10 dB at both depths.

C. **Experiment II** — Repeatability of Underwater Threshold Measurements.

In view of comments by previous investigators concerning the variability of underwater threshold measurements[7, 20], it was thought desirable to assess the reliability of UW threshold measurements directly by obtaining data on the same Ss over widely spaced test trials. Underwater threshold testing with bareheaded divers had been confined to frequencies above 500 Hz, because of a pressing requirement for information for use in conjunction with a project of higher priority. In this experiment, it was possible to obtain data on five divers at frequencies of 32 Hz to 8,000 Hz.

1. **Subjects.**

All divers in the subsequent work had normal BC hearing levels. Three of the divers had participated in previous underwater hearing studies. All five were experienced observers on the staff of the Submarine Medical Center.

2. **Apparatus.**

The Altec amplifier used previously had been replaced with a McIntosh Model MI-200AB 200-watt power amplifier. In all other respects the equipment was the same as previously described. All electronic equipment was mounted in a building some distance from the diving site, necessitating running about 150 feet of cable.

The J-11 transducer was found to have reasonably good output characteristics down to 250 Hz. Distortion increased considerably below this frequency. Nevertheless, an attempt was made to obtain indicative data down to 32 Hz at which frequency the J-11 output has practically a triangular waveform. The J-11 was mounted on the diving stage with the face of the transducer about one yard from the subjects head.

3. Procedure.

Testing depth was 20 feet. Each diver made three or four runs, each separated by at least twenty-four hours. Hoods were not worn. In all other respects the procedure was the same as in Experiment I.

4. Results.

The results of the underwater threshold measurements are presented in Figure 14. Maximum sensitivity was observed at one kHz. The slight elevation of 500 Hz with respect to 250 Hz occurred consistantly for every diver on every run.

The variability from session to session was at times quite large as may be seen in Table II. This variance could not be attributed to any particular source. It is perhaps significant that the greatest variability was observed in the two most experienced divers. Data from several random samplings of trials for each man were selected and mean audiometric functions computed. The results tended to reproduce the values in Figure 14.

D. Interpretation of Results.

The results of the preliminary experiment and Experiment I are consistent with the hypothesis that UW hearing is primarily BC hearing. However, Sivian's hypothesis of equivalent sensitivities for eardrum and BC hearing underwater has not been tested. Further, the role of BC in underwater hearing has been clearly demonstrated only for the frequencies of 6 and 8 kHz, but the results for subject C in Experiment I suggest that dependance of UW on BC, and the independance of UW from depressed AC, holds for frequencies as low as one kHz. In the absence of clearly contradictory evidence, therefore, it may be provisionally concluded that UW is directly related to BC.

The results of Experiments I and II are presented in Figure 15 along with the results of the preliminary study. It will be noted that although the results of Experiment I agree well with the results of Experiment II, they indicate a sensitivity some 15 to 20 dB greater than found in the preliminary study. This discrepancy may be due in part to the fact that Ss in the earlier study, not being equipped with SCUBA, could not equalize middle ear pressures with ambient pressures, and the fact that the mean BC sensitivity of

TABLE II—Variability of Underwater Threshold Measurements

Subject No.	Number of Trials	Years Diving	Frequency (Hz) 125	250	500	1000	2000	4000	8000	Subjects Mean Range
1	3	2	11	8	23	11	6	6	3	9.71
2	3	5-6	10	11	5	7	11	1	7	7.42
3	4	2	5	5	1	7	5	7	24	7.71
4	4	18-20	17	11	4	19	16	12	29	15.42
5	4	18-20	8	9	14	23	17	20	3	13.42
Mean Ranges			10.2	8.8	9.4	13.4	11.0	9.2	13.2	10.73

Notes: (1) Entries under frequency headings are the differences between the highest and lowest threshold measurements observed for each subject over the number of trials indicated in the second column.

(2) The third column gives the approxiamte length of diving experience for each subject.

the earlier group was somewhat depressed with respect to the latter two groups. The mean BC hearing levels of all three samples are shown in Figure 16. If the curves in Figure 15 are adjusted in accordance with the BC hearing levels shown in Figure 16, the resulting values, plotted in Figure 17, show that the discrepancy between the earlier and the latter studies are reduced somewhat over the frequency range 1 to 8 kHz.

These findings will now be discussed in relation to the experiments reviewed earlier. The preliminary experiment and Experiments I and II just presented will be referred to collectively as the SMRL studies.

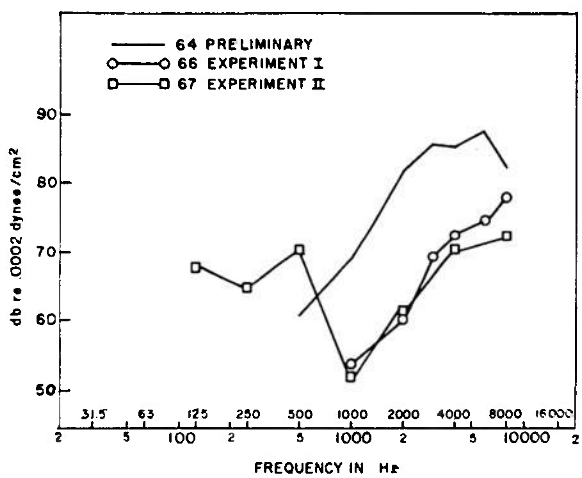

Figure 15.—Results of Three Determinations at SMRL of Underwater-Hearing Threshold Levels.

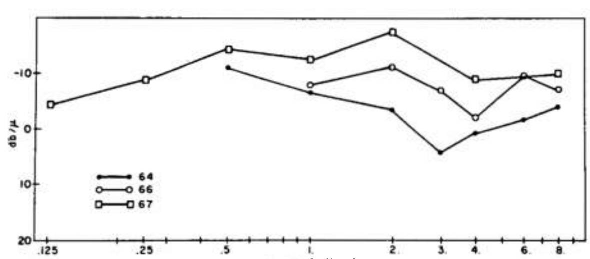

Figure 16.—Mean Bone Conduction Hearing Levels of the Groups Used in the Underwater Hearing Threshold Experiments of Figure 15.

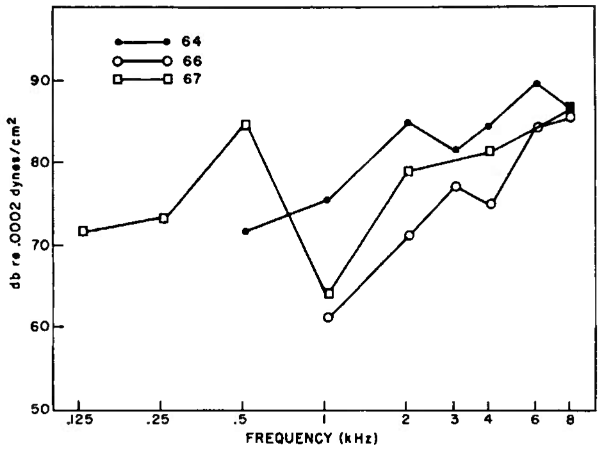

Figure 17.—Underwater Hearing Thresholds Adjusted for Bone Conduction Hearing Levels.

IV. DISCUSSION AND CONCLUSION

There are a number of conclusions which may be drawn from the research accomplished to date on underwater hearing in man. The first of these is that man suffers a loss of sensitivity to sound pressure when immersed in water. All studies show this effect clearly. Stetter's results are ambiguous, but seem to indicate a rather small loss of sensitivity in comparison to the loss found in later work. Sivian's results cannot be precisely interpreted in terms of SPL, since no sound pressure measurements were made. If it is assumed that his two normal-hearing Ss had mean AC thresholds of about four db at one kHz and — 6 db at three kHz, (population mean threshold levels), then the average UW threshold SPL's would be about 49 and 45 db, respectively. These values are rather low in comparison to most other determinations, but nevertheless indicate a rather large loss of pressure sensitivity.

While it is certain that a loss of auditory sensitivity accompanies immersion, it is desirable to know the magnitude of the loss. It is probable that different magnitudes of loss occur, depending on whether or not the diver is breathing compressed air. The studies using divers without SCUBA will, therefore, be considered apart from those studies using divers equipped with SCUBA.

It is difficult to interpret the apparent discrepancy between Ide's data and Sivian's swimming pool results. Neither investigator seems to have employed underwater sound level measurement equipment, and both failed to report crucial experimental details which might have held clues regarding the apparent discrepancy. Ide's subjects were apparently listening at a depth of six feet whereas Sivian's were at about one foot. However, Reysenbach de Haan's data for the waterfilled ear over the range 2 to 8 kHz are in good agreement with Ide's data in that same range. A serious discrepancy is evident at one kHz where Reysenbach de Haan reports a mean threshold value of about 32 dB, Ide reports 78 dB and Sivian perhaps about 49 dB.

The only study conducted with divers not using SCUBA in which measurements of the sound pressure at the diver's head were made, and in which repeated test trials were employed, is the preliminary SMRL experiment conducted in a small pool. These results show a loss of sensitivity about 10 to 15 dB greater than Ide or Reysenbach de Haan report at frequencies of 2 kHz and higher. With due reservation for the possibility of extreme calibration errors in such a small pool, these data, corrected for BC, probably are most truly representative of underwater hearing thresholds for breath-holding divers near the surface.

A critical examination of the experiments using SCUBA equipped divers reveals a number of factors which could account for the divergent findings. For example, Hamilton's data were obtained by testing two divers simultaneously. It may be that there was subconscious influence of one diver on the responses of other. Such influences are not unknown in psychophysical experiments. If such were the case, the data reported by Hamilton may be more nearly related to the thresholds of his more sensitive Ss than to the true mean of the group. Wainwright's divers used a closed circuit breathing apparatus to avoid the high noise level associated with open circuit SCUBA. Wainwright measured the noise level produced by the closed circuit SCUBA and found the level "well below that of the threshold of hearing underwater" Closed circuit SCUBA, while not as noisy as open circuit SCUBA, is nevertheless much noisier than is normal breathing in free air. The diver hears venting and flow noises every time he inhales or exhales or, depending on the type of closed circuit SCUBA in use, cycling noises due to the passage of air from canisters to breathing bags. These noises are not heard by the diver through the water but by "Tubal" conduction — through the mouth and nose and the Eustachian tube. Very little of this noise is radiated into the water. These noises subside somewhat, or even completely, in non-automatic systems, if the diver holds his breath, but apparently Wainwright's Ss did not do so. The most important factor in Wainwright's results is that his Ss had depressed AC and BC hearing levels at frequencies above one kHz. However, if allowance is made for these hearing losses, Wainwright's data still differ considerably from Hamilton's. Montague and Strickland's results tend to agree with Wainwright's rather than with Hamilton's.

Hamilton[26] suggested possible reasons for the discrepancy between his data and those of Montague and Strickland. The most important of these concerned the fact that during bareheaded threshold measurements Monague's and Strickland's Ss wore hoods pushed back off their heads, whereas Hamilton's wore no hoods at all. Hamilton suggested that the hood might have acted as a pressure release device and reduced the SPL at the head. Figure 18 is a photograph of a Submarine Medical Center diver with a similar hood in this position. It is apparent that the hood, being rather bunched up and very near, if not in contact with, the mastoid process, could have such an effect at the back and base of the skull. BC vibrator placement in this area is known to produce lower thresholds than are obtained with the vibrator placed on the forehead[27].

Figure 18.—Divers Wet Suit Hood Pushed to the Back of the Head in the Manner of Montague and Strickland's Study.

The CSL data generally fall between those of Hamilton and Montague and Strickland, but are somewhat closer to Hamilton's. It must be remembered, however, that Brandt and Hollien's S's had, on the average, depressed AC hearing levels at the higher frequencies. If the depressed AC levels of Brandt and Hollien's Ss are taken into account, then their data and those of Hamilton appear to be in rather good agreement. However, the BC hearing levels of the Communication Sciences Laboratory, Univ. of Fla., (CSL) and Hamilton's Ss were not reported. A correction for AC levels may be meaningless.

It is possible to continue pointing out factors which might account for the various discrepancies cited, but to do so would not be fruitful. It is clear, however, that the magnitude of the differences observed cannot be attributed to random sampling errors. The CSL team have been able to reproduce their results within reasonable limits. Experiment II reported in this paper also supports this idea.

In Experiment II, the variation from trial to trial for the younger divers is almost within the limits of accuracy of good clinical audiometry. The discrepancies between the studies of Hamilton, Wainwright, Montague and Strickland, Brandt and Hollien, and the present work must therefore reflect systematic biases. Considering the reasonable agreement between the CSL and the SMRL data, and considering the repeatability demonstrated by both laboratories, it may be argued that the underwater sensitivity of divers using SCUBA breathing apparatus is best described by the combined results of the CSL and SMRL studies. However, since the BC levels of the CSL subjects were not reported, it may be argued that the SMRL data, corrected for BC, are most descriptive of the UW of the general population. The discrepancy between the corrected data of SMRL Experiment I and II, and the variability from trial to trial observed in Experiment II reflect the magnitude of error of measurement for UW data.

A second conclusion that may be drawn is that UW is frequency-dependent. Most studies reviewed, report a peak sensitivity at some frequency, or at least indicate frequency regions over which UW is more or less than for other regions. The CSL studies indicate peak sensitivity at 500 or 1000 Hz, but found that differences in sensitivity were not statistically significant. The finding of a significant linear trend from 1 to 8 kHz in Experiment I may be due to the fact that the SMRL sample was more highly selected, hence perhaps more homigeneous, than the CSL sample.

The possibility that the observed frequency-dependence was due to the mean BC of the sample was examined by analyzing the variance of the UW measurements adjusted for BC. A significant linear trend over the frequency range 1 to 8 kHz was again observed. Thus, the effect is not dependent on BC levels of this particular sample.

As pointed out by Brandt and Hollien,[21] it is evident that peak UW occurs at a lower frequency than does peak AC. It also appears that the region of maximum sensitivity is much more narrow underwater than in air.

A third conclusion is that, at least at the higher frequencies, depressed AC is not reflected in UW unless the AC deficiency is accompanied by a BC deficiency. As indicated previously, this latter conclusion may not be interpreted as indicating that underwater hearing is primarily BC hearing. Sivian's hypothesis of equal sensitivity for "eardrum" and BC hearing underwater has not been tested by the experiments reported here. Sivian believed that his results indicated that underwater hearing was "eardrum" hearing not BC hearing. This conclusion was based on the relation of the results of observer "K" to the results of the two other observers. However, Sivian did not state explicity that the depressed AC of his observer "K" was accompanied by normal BC. Only if this were the case, would Sivian's conclusion be valid, because, by his own hypothesis of equivalent sensitivities for eardrum and BC pathways, depressed hearing levels in just one modality (AC or BC but not both) would not be reflected in depressed UW.

Sivian's data do not stand alone in urging caution to the conclusion that UW hearing is primarily BC hearing. Ample justification for the suspicion that useful "eardrum" hearing occurs underwater is found in Ide's work with the binaural effect and an observation by Bauer[28] that placement of an underwater earphone directly over the ear canal results in greater loudness than when the earphone (a modified bone conduction receiver constructed by NUSL) was placed elsewhere on the skull. Hamilton's and Wainwright's observations that occluding the ears with the fingers does not change UW loudness, does not support the notion that the ear canal route has no role in underwater hearing. Since human tissue has about the same acoustic impedance as sea water, the finger cannot function as an effective ear plug for underwater sound. It is abundantly clear, however, that underwater hearing levels observed in man are not due simply to the impedance mismatch between the water and the air-adapted ear.

Finally, it may be concluded that the diver's wet suit hood reduces underwater sensitivity considerably at frequencies of one kHz and above. The data obtained in Experiment I on the attenuating properties of diver's hoods are not in exact agreement with the data of Montague and Strickland[20] shown in Figure 12, but the differences are not large. They are in marked disagreement only at 3 and 4 kHz from physical measurements obtained by R. J. Bogert of NUSL, by wrapping an EDO BQR-7 hydrophone in a neoprene celltite rubber diving hood and measuring the resulting sensitivity decrement[25].

The results for depths to 99 feet indicate that the attenuating properties of diver's hoods may not be due to the pressure release action of the entrapped air cells. Since the volume of these cells is diminished considerably at 99 feet, the hood's ability to act as a pressure release device is diminished.

Informal observations in a small swimming pool and at Millstone Point tended to corroborate Montague and Strickland's observation that varying thickness of hoods (from 1/8″ to 3/8″) had similar effects on thresholds. However, loose fitting hoods did not seem to provide as much attenuation as well fitting or tightly fitting hoods. Furthermore, as Montague and Strickland indicated, the amount of bone exposed to the water also seems to be important. Harris[29] observed that lifting the hood away from one cheek bone had the effect of increasing the loudness of a 3.5 kHz pure tone by about 15 dB. These observations also tend to favor the view that the damping effect of the hood on the skull rather than a pressure release effect produces the observed attenuation.

Regardless of the manner in which the hood acts to reduce underwater sensitivity to sound, these findings are of interest in that they indicate that foam neoprene hoods further impair the ability of a diver to use his ears to obtain information about events occurring in the aquatic environment. On the positive side, such hoods are very good underwater analogs of ear muffs used in noisy environments in air.

V. SUMMARY

Sivian hypothesized that the eardrum route and bone conduction pathways may be equally effective in producing underwater hearing in man. Sivian's own experiment led him to conclude that underwater hearing is mediated by the eardrum. Ide's results tend to support Sivian's original hypothesis. With one exception, none of the research reported subsequently has tested Sivian's hypothesis, or, in fact, any other hypothesis concerning the mode of operation of the water-immersed ear. Reysenbach de Haan is the only investigator, other than Sivian, who has articulated a theoretical position. Reysenbach de Haan argued on comparative anatomical grounds that the human eardrum-middle ear system could not function well under water and that underwater hearing in man would occur by bone conduction. His finding that his subjects could not localize sound underwater was held to support his bone conduction theory of underwater hearing. Ide's results on the binaural sense are contradictory and indicate that simple bone conduction mechanism is not solely responsible for man's underwater hearing sensitivity.

Although all subsequent authors mention the possible importance of bone conduction to underwater hearing, none has reported bone conduction data on their subjects. Fresh experimental evidence has been presented in this report which indicates that depressed air conduction hearing levels are not reflected in depressed underwater sensitivity, unless the depressed air conduction hearing level is accompanied by depressed bone conduction sensitivity. It is clear that this finding is not at variance with Sivian's original hypothesis. It has also been shown that underwater hearing sensitivity is frequency-dependent with peak sensitivity occurring at about one kHz.

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13. ABSTRACT

All available research on the underwater hearing sensitivity of man is reviewed. New data on the underwater hearing of divers with known AC and BC levels are presented. It is concluded that:

1. Man suffers a loss of sound pressure sensitivity upon immersion.

2. Underwater hearing sensitivity is frequency dependent with peak sensitivity being about 61 to 64 dB above .0002 decibels per square centimeter at 1 kiloHertz.

3. Air conduction auditory deficiencies are not reflected in underwater hearing levels unless the air conduction deficiencies are accompanied by bone conduction deficiencies.

4. Wet suit diving hoods reduce underwater sensitivity to sound by about 25 to 35 dB at frequencies of 1 kiloHertz and higher.

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