Human Hearing in the Underwater Environment

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Hearing is a key sense that informs us about our environment. The cues we obtain from sounds grab our attention, allow us to communicate, and warn us of danger. Human hearing has evolved to detect sounds in air. As a result, anyone who has tried snorkeling or Scuba diving or have put their head underwater in a bathtub has noticed that the world sounds very different. With ears underwater, sounds seem quieter, as though the listener has cotton stuffed in their ears. Moreover, in air, when one hears a sound, one can usually tell if it is coming from the left or right and, to a lesser degree, if it is from the front or back. Underwater, although a diver can hear a boat's engine, identifying where the sound is coming from is challenging. This is because early terrestrial vertebrates evolved to hear well in air, and these adaptations are not the same as those needed for the underwater hearing abilities possessed by aquatic ancestors.

It makes evolutionary sense that human in-air hearing is better than their underwater hearing. Nevertheless, human underwater hearing may not be quite as bad as you think. The goal of this article is to introduce the field of human underwater hearing and to touch on several aspects of the topic that investigators have explored over the last century. It includes discussions of the mechanism of hearing underwater, underwater hearing thresholds, sound localization, and concerns about noise exposure and potential hearing damage. This article presents a broad overview of peer-reviewed literature and government technical reports.

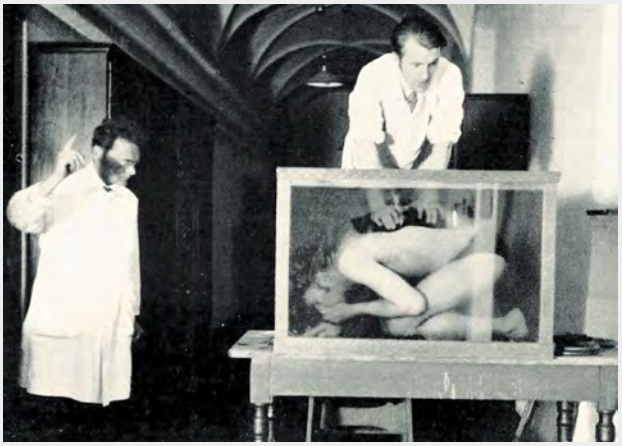
Of Minnows and Men

Stetter (1929), a well-known German investigator of fish hearing, published a famous image of a research subject submerged in a clear-sided tank (**Figure 1**). Stetter's experiment compared the underwater hearing ability of humans with that of the common minnow (*Phoxinus laevis* L.) to a 662-Hz tone produced by a whistle. To adjust the level of the signal, another experimenter walked up and down a hall outside of the room blowing the whistle. The subject would move their finger if they could hear the sound. Details on the minnow testing were not as clear in the paper, but the conclusion reached by the investigators was that the minnow's hearing was much more sensitive than the human's. This is possibly the first article on human underwater hearing.

How Do We Hear Underwater?

From this early study, it was established that minnows and many other fishes have more sensitive underwater hearing than humans. Why is this? Keep in mind that vertebrate hearing evolved in the earliest fishes to function in water (Fay and Popper, 2000). Once early vertebrates came onto land, they could not hear unless

Figure 1. *Classic image depicting possibly the first experiment in human underwater hearing. While Stetter is keeping the subject submerged (**right**), another scientist in a different room is blowing a whistle while moving closer and further from the subject. Karl Von Frisch (**left**), later winning the Nobel Prize, is observing the subject's responses. From Stetter (1929), used with permission.*



they adapted to the terrestrial environment. Let's "dive" deeper into what is going on between these two different environments and their effects on these auditory systems.

The most important differences between air and water in this context are their relative density and compressibility that, when combined, define the acoustic impedance of these two fluids. The acoustic impedance of the human head is very similar to that of water, which is unsurprising because most human soft tissues are close to 80% water. When surrounded by air, the high acoustic impedance of our heads reflects most sound energy, whereas underwater, sound travels through our heads instead of being reflected off them. Unfortunately, this removes the ability of the outer ear to "catch" and focus sound onto the tympanic membrane (eardrum).

Furthermore, the tympanic membrane and ossicles (middle ear bones) normally match the acoustic impedance of air-conducted sound and transmit the vibration to the fluid-filled cochlea. When stimulated via this sound path, the ossicular vibration produces a displacement wave in the fluid of the cochlea. Underwater, this traditional pathway is ineffective because sound energy transmission would have to travel from water (ear canal) to air (middle ear) and back to fluid (inner ear). Instead, sound energy is conducted through the skull directly to the ossicles and cochlea.

Like the human head underwater, the minnow's body is also "acoustically transparent." Fish ears have dense otoliths in contact with the sensory hair cells of the auditory region of the ear. As sound travels through the minnow's body, there is a relative lag between the motion of the dense otolith and surrounding tissues. This results in the ciliary bundles of the sensory cells being "bent" and therefore stimulated, allowing the minnow to hear the sound.

Humans do not have otoliths. Without the sound energy being transmitted through the traditional lower impedance pathway, the displacements produced in the cochlea of the human inner ear are much smaller than the sensory organ had evolved to detect. Smaller displacements mean less stimulation of the sensory hair cells and reduced hearing sensitivity, as discussed in **Underwater Hearing Thresholds**.

Preliminary evidence for this underwater acoustic pathway came from studies by Wainwright (1958) who had divers plug up their ears with their fingers. The divers were still able to detect sounds, although it was later pointed out that the bones in the fingers could still be transmitting the sound to the cochlea and the tissue of the finger would also be acoustically transparent (Smith, 1969).

Later, Hollien and Brandt (1969) had divers wear ear plugs underwater. Interestingly, the investigators had the divers put the ear plugs in prior to submersion, thereby trapping the air within the ear canal. In theory, this would eliminate the impedance mismatch around the tympanic membrane, which it did, but it ultimately just moved the mismatch of the air/water interface to the location of the ear plugs. Regardless, hearing thresholds were no different between tests with and without ear plugs, supporting the direct inner ear stimulation hypothesis.

Further evidence for direct inner ear stimulation comes from a study by Smith (1969). Smith tested underwater hearing thresholds in divers with known impaired in-air hearing but normal in-air bone conduction thresholds. In-air bone conduction hearing bypasses the outer and middle ear, so Smith was comparing whether air-conducted or bone-conducted thresholds better predicted the divers' underwater thresholds. The results from the underwater testing revealed no evidence of raised underwater hearing thresholds regardless of the divers' in-air hearing thresholds.

Hollien and Feinstein (1975) then tested diver hearing with three scenarios: (1) bare headed, (2) wearing a neoprene dive hood, and (3) wearing a neoprene hood with rubber tubes inserted into the ear canal through holes in the hood. As discussed in **Underwater Noise Exposure and Hearing Conservation**, neoprene is an effective blocker of sound transmission, especially at frequencies above 500 Hz. In the Hollien and Feinstein study, the divers' hearing thresholds were significantly higher in scenarios 2 and 3 where the hood reduced direct inner ear stimulation and tubes to the ear canal had no effect on hearing thresholds.

In summary, humans can hear underwater but not through the traditional in-air hearing pathway. There is evidence that sound transmission underwater to the cochlea is occurring directly through the skull, but what kind of impact does this have on human hearing sensitivity?

Underwater Hearing Thresholds

Defining the average underwater hearing threshold is challenging. One issue is that most human testing has been conducted with just a handful of subjects per experiment due to the complexities of testing underwater. Still, human underwater hearing has been tested by at least eight different research teams, building a foundation of information on hearing thresholds in divers. At the same time, the only thing that all the conclusions constructed by these teams have in common is that they are different.

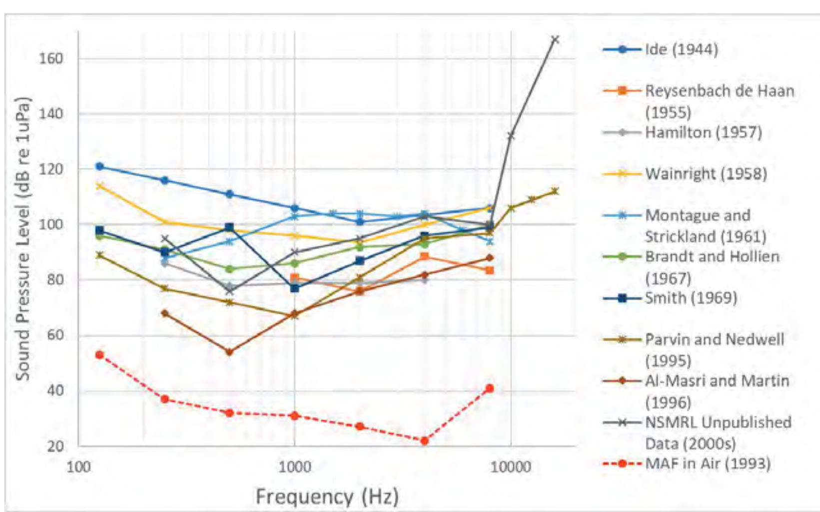
Two methodological approaches are consistent among all the studies. (1) Breath holding by the subjects was done to reduce noise during sound presentations, and (2) underwater hearing was measured as minimum audible field (MAF) audiograms. This means that the subjects are facing a sound projector and detecting and responding to the free sound field to which their heads are exposed. In most cases, this sound field is then calibrated by placing a hydrophone where the location of the head would be to measure the sound level. The calibration procedures are challenging underwater because creating an anechoic (nonreflective) environment is nearly impossible. There is also the problem of removing or limiting environmental noises from the test site.

The first underwater testing of multiple frequencies to measure human hearing was conducted by Ide (1944) of the United States Naval Research Laboratory (**Figure 2**). The methods were not detailed and the background noise as well as the sound measurements at the swimmers' heads were not reported, making these data challenging to interpret.

Several studies were then conducted in the 1950s and early 1960s, with threshold results between experiments varying 10-15 dB at each frequency (**Figure 2**) (Hamilton, 1957; Wainwright, 1958; Montague and Strickland, 1961). Although each team used similar approaches to measure hearing, the likely reasons for these equivocal results are background noise in testing environments, insufficient data on the subjects' in-air air conduction and bone conduction thresholds, and challenges with calibrating the sound fields underwater. Thus, although these studies began to map out human underwater hearing abilities, uncertainty remained about the sensitivity and frequency range. This uncertainty was partially alleviated by two research groups that emerged in the late 1960s and early 1970s, both of which advanced understanding of how humans hear underwater.

The first group formed at the Communication Sciences Laboratory at the University of Florida, Gainesville, and was led by Harry Hollien and included John Brandt and Stephen Feinstein among others. In 1967, the group built their Diver Communication Research System (DICORS) to conduct standardized, calibrated testing of human hearing and communication under water (Brandt and

Figure 2. *Human underwater hearing thresholds. NSMRL, Naval Submarine Medical Research Laboratory; MAF, minimum audible field. MAF data from International Standards Organization (1993). Figure modified from Al-Masri and Martin (1996).*



Hollien, 1967). This system included a seat to keep a weighted diver in place, transducers (speakers) at known distances, calibrated hydrophones at the location of the diver, and mechanisms for the diver and researchers on the surface to communicate.

The team conducted much of their research at the Underwater Sound Reference Division of the Naval Research Laboratory, Orlando, Florida, test facility at Bugg Spring, which was an extremely quiet, nonreverberant testing environment. Due to the controlled testing environments, the hearing thresholds obtained by this team were long considered one of the gold standards for underwater hearing in humans. Although their data (Brandt and Hollien, 1967) were not that different from the data obtained in previous studies (**Figure 2**), the rigorous testing procedures and quiet location supported the accuracy of their results. They also tested whether water depth affected thresholds but failed to find a significant difference of thresholds for depths ranging between 3.7 m and 32 m (Hollien and Brandt, 1969).

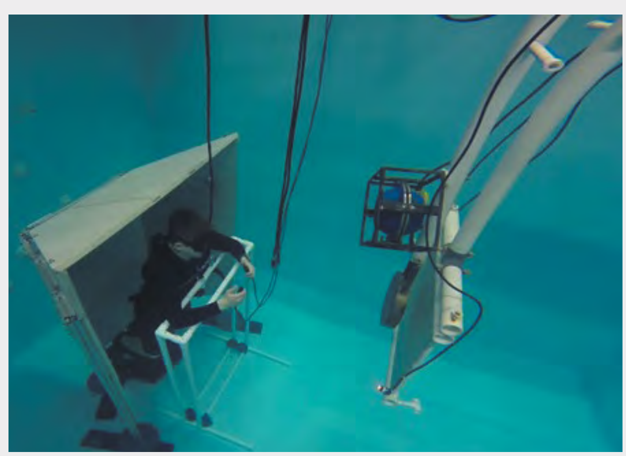
The other key research team that worked on underwater hearing starting in the 1960s and lasting through the 1990s was led by Paul Smith of the Naval Submarine Medical Research Laboratory (NSMRL) at the New London Submarine Base in Groton, Connecticut. Smith's efforts in the underwater realm kicked off research that continues at the NSMRL today, covered everything from underwater hearing thresholds to diver aversion to sound, and also produced early recommendations on hearing conservation.

Smith's (1969) underwater hearing threshold testing was the first to include examination of bone conduction thresholds in air. This was critical because the pathway for bone conduction in air appears to mirror the underwater direct inner ear stimulation. Smith recruited US Navy subjects with normal air conduction and bone conduction hearing as well as some with reduced air conduction and bone conduction responses. The study was done in a deep, quiet pond (75-80 ft) with the subjects in the middle of the pond at a depth of 4.5 m. Like Hollien's team, Smith built a platform that housed the diver, transducer, and reference hydrophones all at fixed locations. The underwater hearing thresholds obtained in this study matched those in Brandt and Hollien (1967) (**Figure 2**), establishing the importance of running experiments in quiet environments. An interesting finding was that the divers with reduced bone conduction thresholds also had reduced underwater hearing thresholds, further supporting the direct inner ear stimulation hypothesis.

Following Hollien and Smith, beginning in the 1990s and extending to today, two other groups entered the underwater hearing field. The initial studies were conducted by Mohammad Al-Masri, University of Portsmouth, Portsmouth, United Kingdom, in 1993 (reviewed by Al-Masri and Martin, 1996) and then carried forward by Parvin and Nedwell (1995) through the rest of the 1990s. These teams built on the lessons learned from previous research, creating as quiet an environment as possible, and reducing the ambient levels in their test tank to ~44 dB re 1 μPa by acoustically isolating the tank from the surrounding laboratory environment (compared with ~60 dB re 1 μPa in Smith's [1969] experiments). In addition, the investigators characterized the sound levels in the tank environment so that the level at the diver's head was as well defined as possible. They also conducted in-air hearing tests on all divers (mix of Navy and recreational) to confirm that they had "normal" hearing. All these efforts resulted in underwater hearing thresholds that were significantly lower (15-20 dB lower at many frequencies) than any measured previously (**Figure 2**).

The second group beginning to work in this field in the 1990s was out of the NSMRL (Fothergill et al., 2002, 2018). This program reinvigorated the underwater hearing research that Smith had started in the 1960s but focused on concerns of US Navy divers being exposed

Figure 3. *Diver participating in an underwater hearing test in the NSMRL dive pool.*



to low-frequency sonar. The reimagined team was led by Ed Cudahy and gained momentum in the 2000s. Cudahy and his team often conducted hearing studies at the Naval Undersea Warfare Center Newport Dodge Pond Acoustic Test Facility. This testing environment is known for its low ambient noise and minimal reflection except from the surface. Although the NSMRL underwater thresholds were not quite as sensitive as those in the United Kingdom (**Figure 2**), procedures established by Cudahy's team are still in use today (**Figure 3**) as we continue to expand knowledge of underwater hearing in humans.

Between the two groups, over 100 divers (mix of Navy and recreational) were tested, resulting in the largest sample size of divers measured. The underwater thresholds from the United Kingdom resulted in significantly lower thresholds detected at many frequencies (**Figure 2**) and ultimately became the benchmark for underwater hearing thresholds. These measurements still apply to today's guidance. These increased sensitivities are likely due to the emphasis placed on lowered ambient-noise levels in the testing environments.

Combining the results of the body of research on hearing thresholds, we can draw some conclusions. Overall, it appears that there is around a 30-60 dB increase in sensitivity between equivalent air and water thresholds (**Figure 2**). There is somewhat of a U-shaped threshold curve, with thresholds increasing fairly quickly above 10 kHz. These studies have established average thresholds for a frequency range from 250 Hz to 16 kHz, showing greatest sensitivity between 500 and 1,000 Hz.

In summary, the most important finding from the studies described here is that human hearing underwater is much less sensitive than in air. Many researchers have measured human underwater hearing thresholds. Although the methodologies used were fairly similar, the results vary. Just as in air, measuring hearing in as quiet a place as possible is critical when testing near the threshold of hearing. As researchers learned to minimize ambient noise and refine their techniques, they expanded their knowledge of the range and sensitivity of human underwater hearing.

Where Is That Sound Coming From?

In air, humans use several cues to identify the direction of a sound. Two of the critical cues are interaural time difference (ITD) and interaural level difference (ILD). The ITD is defined as the time interval between when a sound is perceived by one ear versus the other ear, and the ILD is the difference in loudness between the two ears. Both features take advantage of the acoustic shadowing provided by the head. After reaching one ear, sound must travel around the head before reaching the other ear. The human auditory system is sensitive enough to process these differences in time of arrival and loudness to determine the direction of sounds. This is a simplified explanation of the process; in actuality, humans use additional cues to refine the ability to determine direction (Middlebrooks and Green, 1991).

When submerged, sound travels through the head instead of going around like it does in air. Furthermore, sound travels about 340 m/s in air and 1,480 m/s in water, and so the sound reaches both ears so close in time that the brain cannot differentiate between arrival times. In combination, these differences effectively eliminate directional cues. Without the directional cues of ILD and ITD, sound should appear to be coming from all directions equally. Humans certainly cannot localize sound in water as effectively as they can in air, but with enough practice, they are not completely lost underwater either.

Feinstein (1973) ran a series of studies measuring minimum audible angles (MAAs) for divers to test the ability to discriminate sounds coming from different directions. The MAA is the smallest angular separation at which two sounds are perceived as coming from distinct directions. Once the sounds originate closer to one another than the MAA, the listener perceives the sounds as coming from the same location.

Feinstein (1973) had divers wearing neoprene hoods with holes at the ears sit on a custom-built platform that kept their head in a fixed position. Two speakers were set up in a way that allowed them to be offset from each other by a known angle of separation. The diver would pull one of two ropes to signal if the sound was coming from the left or right speaker. The stimuli were either a 3.5-kHz tone, a 6.5-kHz tone, or white noise. The MAA for each stimulus was 21.5°, 14.5°, and 9.8°, respectively. A second study provided training to the divers by letting them know when they made a mistake. Following the training, the divers improved to 11.3°, 11.5°, and 7.3°, respectively. Feinstein determined that sound localization underwater is on average around three times poorer than comparable studies conducted in air.

More directional hearing studies were conducted by a French team led primarily by Sophie Savel (Savel and Drake, 2014). They found that lower frequency sounds and white noise were easier to discriminate than higher frequencies. Divers were able to identify angles to the left and right successfully but had severe challenges with front/back discrimination. They did find that divers in general were more successful at all localization studies with experience, something that Feinstein (1973) also noticed. This included experience and training with the experiment cues as well as general diving experience (i.e., total number of career dives).

Interestingly, in one of their studies, Savel et al. (2009) had divers wear neoprene hoods with holes cut around the ears. They also plugged the ear canal with homemade neoprene ear plugs. When the ears were plugged with neoprene, the divers' ability to localize sound dropped significantly, suggesting that the ear conduction pathway could play a role in sound localization underwater. The authors postulated that a phase difference at the cochlea between the arriving direct inner ear stimulated sound and ear conducted sound could provide some directional cue. This hypothesis needs further investigation, but Savel et al. are not the first to notice a drop in localization capabilities when the ear canals are blocked by neoprene (Norman et al., 1971).

Underwater Noise Exposure and Hearing Conservation

There are many sources of underwater biological sounds ranging from marine mammals to fishes and invertebrates, although there has been no record of any of these sounds being of obvious concern to human hearing. Rather, anthropogenic or human-made sounds underwater are the primary sources of concern.

There is one kind of noise that divers cannot avoid: the sound of their own breathing. The bubbles produced during respiration in Scuba and surface-supplied air are quite noisy. Indeed, this is the reason why divers are required to breath-hold during the hearing tests. The bubble noise is not dangerous to humans, but it is not quiet. This was one of the reasons for the development of the rebreathing system.

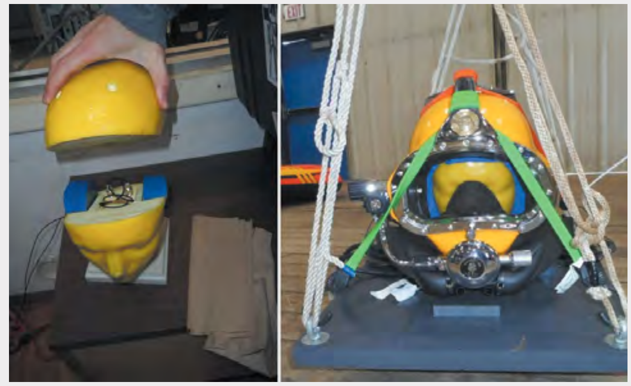


Figure 4. *NSMRL head simulant (Ned Stark;* ***left****) used for testing sound transmission in the Kirby Morgan 37 dive helmet (****right****).*

Breathing noise is also a concern in helmeted divers. The NSMRL and others in the US Navy (Curley and Knafelc, 1987) have documented that the sound levels measured during inhalation and exhalation in the standard Kirby Morgan dive helmets (**Figure 4**) often exceed the traditional 85 dBA hearing safety limits. These helmets are the current standard for working divers. Divers also use a valve to blow air into the helmet to defog the faceplate, which greatly exceeds the limits. An additive effect is created by the communication system within the helmet. Divers must often turn the sound level up to effectively hear and communicate with people on the surface.

Looking beyond diver-produced noise, there are many external anthropogenic sources of sound that could potentially impact divers (e.g., underwater explosions, tool noise, pile driving, sonar, or boat noise). Any of these sources could generate high levels of acoustic energy. Knowing that hearing underwater is different than in air, how does one determine what is safe or unsafe in terms of human exposure? This is where the problem gets challenging!

We now assume for the sake of a discussion that the divers have wet ears (i.e., nonhelmeted). The two primary challenges for providing safety guidance underwater are the lack of personal protective equipment and the differences in underwater hearing abilities compared with in-air hearing.

Let's start by talking about the types of protection that exist. Wearing earplugs or any kind of over-ear sound protection has little value. First, earplugs block the ear canals that can compromise the diver's ability to equalize the pressure in the middle ear as they move up and down in the water. More importantly, if humans detect sound through direct inner ear stimulation, then blocking the traditional air conduction pathway is not an effective means for preventing noise-induced hearing damage.

Currently, the only effective method of hearing protection underwater is the aforementioned neoprene hood. Numerous studies (reviewed by Fothergill et al., 2018) have characterized the effectiveness of a neoprene hood at increasing hearing thresholds in divers. As mentioned in **Underwater Hearing Thresholds**, a hood is effective at attenuating frequencies at 500 Hz and above, with the amount of attenuation increasing with frequency (as much as 20-30 dB of attenuation), although some of these effects are reduced with increases in pressure (Fothergill et al., 2018).

Therefore, divers exposed to certain SONAR systems or any tool that produces a lot of high-frequency energy can be protected from hearing damage by wearing a neoprene hood. However, just about all the noise sources that were mentioned create broadband signals with a lot of low-frequency energy below 500 Hz in addition to high frequencies. Thus, a hood provides little-to-no protection from much of the acoustic energy from many underwater tools, explosives, pile driving, and boat noise.

Moreover, in many operations with underwater tools, divers wear helmets so that they can have dry ears. The NSMRL recently completed a data collection to explore the energy transfer function of the Kirby Morgan dive helmets (**Figure 4**). The measurements show that frequencies down to at least 50 Hz are attenuated by the helmet. Again, attenuation increases with frequency, and in the case of the helmet, there is a dip in attenuation at the resonance frequency of the helmet. Although the helmet provides more attenuation than the hood, the sound is being delivered via the more sensitive airborne mechanism of hearing. Therefore, the net effect at most frequencies is that the recommended exposure limits with a helmet will be lower than with a hood. This is especially true at lower frequencies. Thus, divers have few options for underwater hearing protection. Safety guidance for divers exposed to underwater noise must therefore account for the limitations in personal protection equipment.

The in-air community has a wealth of human and animal studies that determined the upper limit of exposures that would induce hearing damage, such as temporary threshold shifts (TTSs) and permanent threshold shifts (PTSs) in hearing (reviewed by Clark 1991; Melnick 1991). TTS is defined as a temporary loss of hearing sensitivity after exposure to sound. Hearing conservation standards for in-air noise consider the onset of TTS as defining the upper limit of safe noise exposure. PTS is a shift in hearing sensitivity at a frequency or range of frequencies that does not resolve with time.

Unfortunately, data for the underwater onset of the TTS are extremely sparse. Only a few studies have been conducted on this topic, and the results, although incredibly valuable, are challenging to interpret due to the small sample size, high variance among divers, and challenges associated with measuring hearing immediately postdiving (reviewed by Smith et al., 1988). Additional studies later conducted by investigators at the NSMRL and in the United Kingdom attempted to measure diver aversion to low frequencies up to 2,500 Hz (reviewed by Fothergill et al., 2002).

To establish an international hearing conservation limit for divers, the United Kingdom and NSMRL worked together in the early 2000s to merge the extensive United Kingdom hearing threshold data with the underwater TTS and aversion data. Most of these studies and the underwater noise guidance for divers are not publicly available so they cannot be discussed in any detail. However, suffice it to say that this guidance is used consistently and has proven effective in protecting divers.

In addition to providing guidance for noise exposure related to hearing concerns, the NSMRL also works with organizations that are involved with underwater explosives (UNDEX). These communities are typically concerned with injuries to the lungs and other air-filled structures. There is established safe standoff guidance for underwater blasts, and the NSMRL continues to explore how to improve on and expand the guidance. Obviously, investigators cannot knowingly expose divers to the UNDEX to establish injury data, so instead physical model simulants (**Figure 5**) have been developed to better understand the injury mechanisms associated with blast exposure. Another entire article could be written on underwater blast injuries and the research associated with the protection of divers so, for now, we direct readers to Cudahy and Parvin (2001) as an excellent primer on the topic.

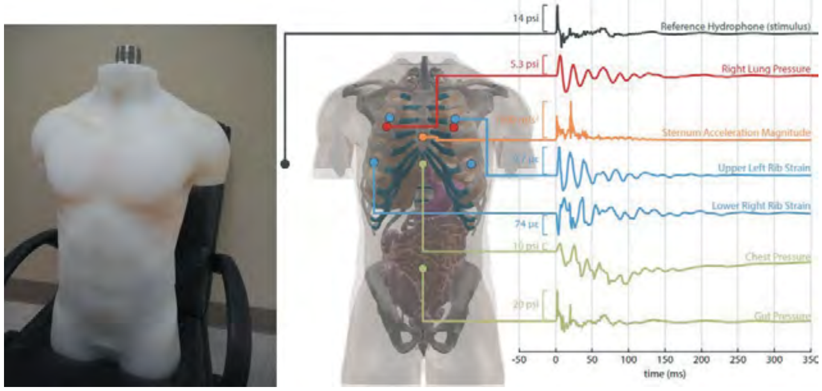


Figure 5. *NSMRL human torso simulant (QUantitative Instrumented Torso [QUINT]; **left**) used to predict impact of high-energy, impulsive sources on internal organs (**right**).*

Conclusions

We have presented an overview of the field of underwater hearing. Although not every topic could be covered in detail, our goal was to provide a general understanding of how human hearing underwater is different than that in air and what humans' underwater hearing capabilities are. Exposure to loud sounds underwater is a concern for divers, and in many situations, the limited hearing protection that is available is not effective. The NSMRL continues to conduct research to improve safety guidance for Navy divers, but our efforts would not be possible without standing on the shoulders of all the scientists who established the field before us.

Acknowledgments

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