# Protecting the hearing of divers from underwater noise

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**ABSTRACT**
Workplace health and safety regulations for the protection of hearing are well established but there appear to be no similar regulations for divers working underwater. Regulations developed for airborne noise cannot be applied directly to underwater noise because the human auditory system functions differently in water compared with air. There are, however, a number of studies of underwater hearing sensitivity and these could be used to adjust established in air noise criteria for use underwater. However, this would need to take account of the considerable spread in sensitivity between measurements. Consideration of the differences between air and water in the transmission of sound to the inner ear or cochlea where the sound is sensed may aid in this process.

## 1 INTRODUCTION
Divers working underwater are subject to the noise of a range of the power tools and machinery in construction of underwater infrastructure. They will also be subject to noise from many other sources over a much larger range of distances than in air because sound travels with much less absorption attenuation in water. Underwater construction activities such as pile driving can produce very high noise levels.

## 2 HEARING IN AIR AND WATER
Hearing evolved in water, so the terrestrial ear has evolved substantial adaptations to allow the auditory system to function effectively in air. Without these adaptations, less than 0.1% of the energy incident on the outer ear would reach the inner ear or cochlea where the sound is sensed because of the large mismatch in acoustic impedance between air and cochlea fluid. The outer and middle ear provide the impedance matching required to ensure that most of the energy reaches the cochlea (Yost, 1977; Gulick, 1989 and Gelfand, 1990). The outer ear including the ear canal provides a resonant chamber enhancing the pressure at the ear drum at frequencies above about 1 kHz and peaking at about 3 kHz. The middle ear contains the ossicular chain of three fine bones that link the ear drum to the oval window in the bone encasing the cochlear. The ossicular bones are articulated and held in place by ligaments. They provide a gain in pressure from the ear drum to the oval window partly by leverage and partly by focussing the acoustic forces onto the oval window since its area is much less than that of the ear drum. The cochlea fluid has an impedance similar to that of water, so that the adaptations that provide the impedance matching would not seem to be required to hear underwater.

Sound intensity (energy per unit area per second) $I$ in a plane wave is related to the root mean square acoustic pressure $p$ and particle velocity $u$ by (Kinsler and Frey, 1962)

$$I = pu = p^2/(\rho c) = \rho c u^2$$

where $\rho$ is density and $c$ is the speed of sound. For the same intensity in air and water,

$$\frac{p_w^2}{p_a^2} = \frac{\rho_w c_w}{\rho_a c_a} = 3710 \quad \text{and} \quad \frac{u_w^2}{u_a^2} = \frac{\rho_a c_a}{\rho_w c_w} = \frac{1}{3710}$$

where subscript $w$ denotes values in water or the cochlea fluid and $a$ the values in air. Hence for the same intensity, the pressure in water or the cochlea fluid is approximately 36 dB higher and the particle velocity 36 dB lower than in air. In other words, if the auditory chain provides a perfect match of impedances, there would be a pressure gain of 36 dB and a particle velocity attenuation of 36 dB between the air and the cochlea. Measurements of the pressure gains in the auditory system (e.g. Yost, 1977; Gulick et al., 1989) show that the total gain varies with frequency and is highest (≥ 30 dB) from a few hundred hertz to several kHz, decreasing with frequency below about 1 kHz. This indicates that the impedance matching is very effective over a wide frequency band. A level of 0 dB re 20 μPa in air would have the same intensity (0 dB re 1 pW/m$^2$) as 36 dB re 20 μPa or 62 dB re 1 μPa in water.

Underwater, the resonances in the outer ear and the ear canal are unlikely to be effective because the flesh of the outer ear and the ear canal has an acoustic impedance similar to that of water so does not provide the relatively non-compliant acoustic boundaries required for a resonant chamber. Transmission from the ear drum through the ossicular chain to the cochlea would be hampered by the fact that the interface at the ear drum, which matches the air impedance, now has the impedance of water in the ear canal. Different ideas have been suggested for the transmission paths for hearing underwater (see references below). The most likely involves bone conduction but there are issues that have yet to be resolved.

## 3 UNDERWATER HEARING MEASUREMENTS

There have been a number of studies that have measured hearing sensitivity underwater, most over the frequency range 125 Hz to 8 kHz (e.g. Hamilton, 1957; Brandt & Hollien, 1967; Shupack et al., 2005) and one from 25 Hz to 16 kHz (Parvin & Nedwell, 1995). Numbers of subjects varied from four to 21. While most of the resulting audiograms show generally similar spectral shapes, the means are spread over a range of about 15 dB with most results being within 10 dB, varying with frequency. Standard deviation of results within a study varied with frequency from 3 to 12 dB and the majority of studies overlap within the range of one standard deviation. Some of this variation may be due to the variation in the hearing sensitivity of individual subjects. Most studies noted that the subjects had "normal" hearing based on standard test in air, though "normal" encompasses a range of thresholds. Some of the variation may be due to the differences in experimental technique. Two studies were done in large lakes and the subjects were suspended below a barge at the centre (Hamilton, 1957; Brandt, & Hollien, 1967). This set up provided a quiet environment and minimised the effects of boundary reflections. One study (Parvin & Nedwell, 1995) was in a tank although they claim to have minimised the effects of tank modes by using a mid-water region where measurements showed sound level variation to be within ± 3 dB. Shupack et al. (2005) was in the open sea and may be limited by background noise at low frequencies.

Some broad comments can be made from a comparison of the measurements with a standard hearing threshold in air (e.g. minimum audible field - MAF, ISO 226:2003). Underwater hearing is most sensitive around 1 kHz, an octave or so below the most sensitive region for hearing in air. The intensity sensitivities (e.g. in pW/m$^2$) in water are similar to those in air at the lowest frequencies and less (thresholds are higher) than in air by amounts that increase with increasing frequency, from around 10 dB from 200 – 500 Hz to around 30 dB above 3 kHz (taking an average of the data). The largest differences generally occur at frequencies where the pressure gain for sound in air is highest, so is consistent with the expectation that this gain would not be realised underwater. However, a better comparison would probably be between hearing thresholds in air and water for each individual, given the variability between individuals. Brand & Hollien (1967) and Shupack et al. (2005) provide this and the differences between air and water thresholds are significantly less than the differences above (up to 20 dB less).

Noise protection criteria developed in air could be adjusted for use underwater by comparing the difference in sensitivities in air and water. Parvin & Nedwell (1995) proposed an "underwater weighting scale" analogous to the A-weighting scale, using their measurements, a standard MAF in air and A-weighting. However, this is likely to overestimate the weighting as discussed above. A better approach would be to average air water differences for individual subjects. In the meantime, a precautionary approach would be desirable, especially given the small sample and the spread of the data, such as using a threshold in air at the upper limit of the range of what is considered normal. Another consideration, as pointed out by McMinn (2013), is that A-weighting is less appropriate at the levels typical of hearing protection criteria.

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