We are IntechOpen,
the world's leading publisher of Open Access books
Built by scientists, for scientists

4,400
Open access books available

117,000
International authors and editors

130M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

The Effect of Sonar on Human Hearing

Renzo Mora, Sara Penco and Luca Guastini
ENT Department, University of Genoa
Italy

1. Introduction

Human use of the Earth's oceans has steadily increased over the last century resulting in an increase in anthropogenically produced noise. This noise stems from a variety of sources including commercial shipping, oil drilling and exploration, scientific research and naval sonar. Sonar (for sound navigation and ranging) is a technique that uses sound propagation (usually underwater) to navigate, communicate or to localize: sonar may be used as a means of acoustic location (acoustic location in air was used before the introduction of radar). The term sonar is also used for the equipment used to generate and receive the sound. The range of frequencies used in sonar systems vary from infrasonic to ultrasonic. Sonar uses frequencies which are too much high-pitched (up to 120,000 cycles per second) for human ears to hear.

Although there is a growing concern among the public that human generated sounds in the marine environment could have deleterious impacts on aquatic organisms, only few studies address this concern on the effects of these sounds on the human auditory system. The effects of sound on the human auditory system have been the subject of several studies, but one question needs to be resolved yet: the effects caused by the naval sonar. For these reasons this chapter wants to show the effects of active middle frequency sonar on human.

Published data from humans under water in literature are scarce and sometimes use different terminology with regard to sound levels. For example sound pressure levels measured in air are normally reported with a reference pressure of 20μPa whereas levels measured in water are normally reported with a reference pressure of 1μPa. Therefore, in the diving environment it is recommended to use SPL (sound pressure level) threshold with reference pressure of one micropascal (1 μPa) for both water and air measurements in order to compare values from different sources.

The non-intuitive nature of decibels and the different reference values of air and water have led to a plethora of misconceptions concerning the magnitude and potential effects of noise levels in air and water. The magnitude of sound pressure levels in water is normally described by sound pressure on a dB scale relative to a reference root-meansquare (rms) pressure of 1 μPa (dB re 1 μPa).

For these misconceptions concerning the measurement of noise in the marine environment, studies on cetaceans have highlighted hearing damage and behavioural change at levels of sounds exposure lower than those that would cause physiological damage to the auditory system.

Continued emission of noise can increase the damage, due to the "habituation" to a familiar sound to which it is difficult to react more strongly. The "habituation" is known as being provoked by continued acoustical stimuli, reducing the hearing sensitivity to high-level

sounds; the hearing sensitivity may be regulated at both conductive (stapedial reflex) and sensorineural levels (adaptation). For these reasons, the introduction of new types of military sonar, such as low-frequency system, should proceed with caution; the low-frequency sounds produced by the systems will travel much farther than the mid-frequency sonar sounds currently causing concern. Studies on marine animals have demonstrated that changes in hair bundle density paralleled changes in hair cell nucleus density, indicating that entire hair cells disappeared following noise exposure; the inner ear damage is characterised by a permanent threshold elevation after an exposure to white noise ranging in intensity from 130 to 170 dB re 1 µPa for 24 h.

Although there are differences among the ears of different species, the basic processes of hearing are the same between marine and terrestrial mammals. For this reason, some of the previous considerations can be applied on humans. Although the true correlation between sonar and hearing damage is difficult to show, (absence of technical information, level of sound exposure and other environmental variables) this study wants to show the effects of sonar on human auditory system.

2. Introduction

Underwater acoustics is the study of the propagation of sound in water and the interaction of the mechanical waves that constitute sound with the water and its boundaries. The water may be in the ocean, a lake or a tank. The field of underwater acoustics is closely related to a number of other fields of acoustic study, including sonar, transduction, acoustic signal processing, acoustical oceanography, bioacoustics, and physical acoustics.

Underwater sound has probably been used by marine animals for millions of years. The science of underwater acoustics began in 1490, when Leonardo Da Vinci wrote: (Urick, 1993) "if you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you".

But only the 20th century, with the start of World War I, provided the impetus for the next wave of progress in underwater acoustics: anti-submarine listening systems were developed. In particular the development of sonar (Sound Navigation and Ranging) proceeded apace during the war, driven by the first large scale deployments of submarines.

In 1919, the first scientific paper on underwater acoustics was published, theoretically describing the refraction of sound waves produced by temperature and salinity gradients in the ocean. The range predictions of the paper were experimentally validated by transmission loss measurements (Lichte, 1919).

The next two decades saw the development of several applications of underwater acoustics: by the 1930s sonar systems were being used for passive listening systems and for active echo-ranging systems; these systems were used to good effect during World War II by both submarines and anti-submarine vessels. After World War II, the development of sonar systems was driven largely by the Cold War, resulting in advances in the theoretical and practical understanding of underwater acoustics, aided by computer-based techniques.

In the last decades, there is growing concern among the public that human generated sounds in the marine environment could have deleterious impacts on aquatic organisms: in the last years, much of interest in the effects of the human-generated sound has been focused on marine mammals (Parsons et al., 2008; Salami et al., 2010).

However, only few studies address this concern on the effects of these sounds on the human auditory system (Salami et al., 2010). The effects caused of sound on the human auditory

system have been the subject of several studies, but one question needs to be resolved yet; the effects by the naval sonar.

Although the true correlation between sonar and hearing damage is difficult to decide (absence of technical information; level of sound exposure; and other environmental variables), this chapter wants to show the effects of sonar on human hearing.

3. Fundamental concepts of sound propagation underwater

All sound, whether produced by a cowbell or a complicated electronic device, behaves in much the same manner. Sound originates as a wave motion by a vibrating source and requires for its transmission an elastic medium such as air or water. For example, consider a piston suspended in one of these mediums. As the piston is forced to move forward and backward, the medium is compressed on the forward stroke and decompressed or rarefied on the return stroke. Thus, a wave motion or series of compressions and rarefactions is caused to move from the source out through the medium. In the fluid medium the molecular motion is back and forth, parallel to the direction of the piston's movement. Because the fluid is compressible, this motion results in a series of detectable pressure changes. This series of compressions and rarefactions, such as is produced by the piston, constitutes a compressional wave train. Another way of explaining the phenomenon of acoustic wave propagation is to consider the medium of transmission as a loosely packed collection of mass elements connected by springy bumpers. A disturbance of the elements at some point (e.g., piston motion) moves along in the fluid by the successive extension and compression of the springs as the elements swing back and forth, each communicating its motion to its neighbor through the connecting bumpers. In this way, the agitation of a cluster of elements is propagated through the medium even though the individual elements do no more than move about their equilibrium positions without actually migrating. The sound wave propagates parallel to the source resulting in a longitudinal wave (Tindle, 2005).

A sound wave propagating underwater consists of alternating compressions and rarefactions of the water. These compressions and rarefactions are detected by a receiver, such as the human ear or a hydrophone, as changes in pressure. These waves may be man-made or naturally generated (Tindle, 2005).

Underwater acoustic propagation depends on many factors. The direction of sound propagation is determined by the sound speed gradients in the water. In the sea the vertical gradients are generally much larger than the horizontal ones (Sabra & Dowling, 2003). These facts, combined with a tendency for increasing sound speed with increasing depth due to the increasing pressure in the deep sea reverses the sound speed gradient in the thermocline creating an efficient waveguide at the depth corresponding to the minimum sound speed (Sabra & Dowling, 2003; Frosch, 1964; Snellen et al., 2001). At equatorial and temperate latitudes in the ocean the surface temperature is high enough to reverse the pressure effect, such that a sound speed minimum occurs at depth of a few hundred metres (Frosch, 1964; Snellen et al., 2001).

The presence of this minimum creates a special channel known as Deep Sound Channel, previously known as the SOFAR (sound fixing and ranging) channel, permitting guided propagation of underwater sound for thousands of kilometres without interaction with the sea surface or the seabed (Jian et al., 2009).

Another phenomenon in the deep sea is the formation of sound focussing areas known as Convergence Zones (Shvachko, 2008): in this case sound is refracted downward from a near-

surface source and then back up again. The horizontal distance from the source at which this occurs depends on the positive and negative sound speed gradients. A surface duct can also occur in both deep and moderately shallow water when there is upward refraction, for example due to cold surface temperatures.

In general, as sound propagates underwater there is a reduction in the sound intensity over increasing ranges, though in some circumstances a gain can be obtained due to focussing propagation loss (sometimes referred to as transmission loss) is a quantitative measure of the reduction in sound intensity between two points, normally the sound source and a distant receiver (Studenichnik, 2003).

The non-intuitive nature of decibels and the different reference values of air and water have led to a plethora of misconceptions concerning the magnitude and potential effects of noise levels in air and water (Chapman & Ellis, 1998). For this reason a convenient system is needed in order to measure and discuss acoustic parameters underwater.

Pressure is defined as a force per unit area. Although many people are familiar with the British units of pounds per square inch (psi), it has long been the convention in acoustics to use metric units, namely newtons per square meter (N/m^2), or dynes per square centimeter (dynes/cm^2). Of the two metric units, the dynes/cm^2 has been the most commonly used. It has an alternate name, microbar (bar), and is equivalent to approximately 1/1,000,000 of a standard atmosphere. For underwater sounds, a reference pressure of 1 bar was established from which all others were measured. The corresponding reference pressure for airborne sounds was 0.0002 bar, because this was the approximate intensity of a 1,000-Hz tone that was barely audible to human ears. The previously less commonly used N/m^2 also has an alternate name, a Pascal (Pa), and the reference standard derived from this was the micropascal (Pa), which is equivalent to $10^{-6}N/m^2$.

The decibel system was selected by acousticians for a number of logical reasons (Hood et al., 1991):

- it is a logarithmic system, which is convenient for dealing with large changes in quantities;
- it simplifies computations since multiplication and division are reduced to addition or subtraction, respectively;
- human senses have an approximate logarithmic response to stimuli such as light, sound, and heat: for example, the human ear perceives about the same change in loudness between 1 and 10 units of pressure as it perceives between 10 and 100 units of pressure;
- In the area of underwater acoustics, the primary interest is in ratios of power levels and signal levels rather than absolute numerical values.

In the decibel system, the bel is the fundamental division of a logarithmic scale for expressing the ratio of two amounts of power. The number of bels to express such a ratio is the logarithm to the base 10 of the ratio. Acousticians decided the bel was a unit too large for application in their field, and subsequently adopted the decibel (1/10 bel) as their basic logarithmic unit. The conversion factors in table 8-1 can in themselves be cumbersome to use, but when expressed in dB, only addition or subtraction is required. When converting from a pressure referenced to 1 bar to one referenced to 1 Pa, simply add 100dB. When converting from 0.0002 bar to 1 Pa, simply add 26dB. If converting from 1 Pa to the others, merely subtract the appropriate values.

With such a profusion of reference standards and measurement systems, there were ample opportunities for misunderstandings as an operator or planner consulted different sources

of acoustic information. For these reason, is commonly used a measurement in terms of pressure instead of intensity: the magnitude of sound pressure levels in water is normally described by sound pressure on a dB scale relative to a reference root-meansquare (rms) pressure of 1μPa (dB re 1 μPa) (Madesen, 2005).

About the propagation of sound, approximate values for fresh water and seawater, respectively, at atmospheric pressure are 1450 and 1500 m/s for the sound speed, and 1000 and 1030 kg/m³ for the density (Wolfson & Tomsovic, 2001; Leroy, 2008)

The ocean is not a homogeneous medium, and the speed of sound varies from point to point in the ocean. This variation in sound speed is one of the most important characteristics affecting the transmission of sound. The three main environmental factors affecting the speed of sound in the ocean are salinity, pressure, and temperature: the speed of sound in water increases with increasing pressure, temperature and salinity (Wolfson & Tomsovic, 2001; Leroy, 2008).

In particular (Wolfson & Tomsovic, 2001; Leroy, 2008):

- a change in salinity of one part per thousand will result in a change in sound speed of approximately 1.3 meters per second;
- pressure in most circumstances is more important than salinity, but in the sea its change is constant and thus predictable; it also causes a change in bulk modulus and density, and the result is an increase in sound speed of 0.017 m/sec for every meter of depth increase;
- temperature, the foremost factor affecting sound speed, usually decreases with depth, and this leads to an accompanying decrease in sound speed at the rate of approximately 3 m/sec per degree Celsius; below a depth of about 1,000 m, however, temperature is fairly constant, and the predominant factor affecting sound speed becomes pressure;

4. Sonar

Human use of the Earth's oceans has steadily increased over the last century resulting in an increase in anthropogenically produced noise. This noise stems from a variety of sources including commercial shipping, oil drilling and exploration, scientific research and naval sonar.

Sonar is an acronym for Sound Navigation and Ranging. There are two broad types of sonar (passive and active) in use (Salami et al., 2010):

- passive sonar is a listening device that can determine the presence, characteristics and direction of marine noise sources: these sources may include biological noise (animal communication) and human sounds (eg ship or submarine noise); passive sonar equipment is essentially an acoustic receiver which emits no sound and therefore has no potential to disturb marine life.
- active sonar is a technique that uses sound to determine relative positions of submerged objects (including submarines, fish, mines and wrecks of ships and aircraft) and the sea floor, by emitting a sound signal and listening for the echoes from the objects; many different types of active sonar are used throughout the world's oceans by private, commercial and military vessels; these systems mirror the purpose of sonars used by some marine animals (active sonar devices locate objects by the reflection of sound-waves and remain an important means of underwater detection and navigation).

The main types of active sonar are commercial, civilian and military sonars. The sonars used by military forces are (Gong et al., 2010; Kane et al., 2010):

- Low-frequency (LF): low frequency sonars have been defined as those that emit sound below 1000 Hz. These sonars are designed to provide theatre level protection, such as for an Aircraft Carrier Task Group out to many miles (up to 200 miles) from the ships. This is possible because of the extended propagation possible at low frequencies. Outputs are similar to medium frequency sonars (described below) but the sound travels further because of the significantly enhanced seawater propagation.
- Medium frequency (MF): medium frequency active sonars emit sounds at frequencies between (1000 and 10,000 Hz); these sonars represent a sliding scale of compromise between possible detection range and size of the transmission array; at the lower end of the frequency range (1000- 3000 Hz) the systems are capable of extended detection ranges using high output power, but the size of the transducer limits applications to large warships. These systems are designed to provide area protection for a small Task Group out to a few tens of miles.
- High frequency (HF): high frequency active sonars operate between approximately 30,000 and 500,000 Hz (30 kHz and 500 kHz); these systems allow increasingly greater resolution as the frequency increases but at the expense of range. The highest frequencies are only effective over short distances because of the rapid attenuation of high frequency sounds in seawater.

Typically high power military active sonars are operated infrequently during voyages and the sounds are not emitted continuously but as short bursts ('pings') during operation (Gong et al., 2010; Kane et al., 2010).

Commercial and civilian sonars are generally designed to detect the sea floor (echo sounders), map the sea floor and search for sunken objects (sidescan sonars) and to locate fish (fish finders). Sonars of at least one of these types are fitted to nearly all vessels. Even some small boats have fish finding and echo sounders. The characteristics of these sonars are broadly similar to the high frequency military sonars described above (Gong et al., 2010; Kane et al., 2010).

5. Underwater hearing

The lowest audible SPL for a human diver with normal hearing is about 67 dB re 1 µPa, with greatest sensitivity occurring at frequencies around 1 kHz (Fothergill et al., 2001).

Dolphins and other toothed whales are renowned for their acute hearing sensitivity, especially in the frequency range 5 to 50 kHz (Mooney et al., 2009). Several species have hearing thresholds between 30 and 50 dB re 1 µPa in this frequency range. For example the hearing threshold of the killer whale occurs at an rms acoustic pressure of 0.02 mPa (and frequency 15 KHz), corresponding to an SPL threshold of 26 dB re 1 µPa (Simon et al., 2005). By comparison the most sensitive fish is the soldier fish, whose threshold is 0.32 mPa (50 dB re 1 µPa) at 1.3 kHz, whereas the lobster has a hearing threshold of 1.3 Pa at 70 Hz (122 dB re 1 µPa) (Patek & Oakley 2003).

It's evident as high levels of underwater sound create a potential hazard to marine and amphibious animals as well as to human divers (Steevens et al., 1999). Recently, for these reasons, guidelines for exposure of human divers and marine mammals to underwater sound are reported by different organizations: human divers exposed to SPL above 154 dB re 1 µPa in the frequency range 0.6 to 2.5 kHz are reported to experience changes in their heart rate or breathing frequency, diver aversion to low frequency sound is dependent upon sound pressure level and center frequency (Fothergill et al., 2009; Steevens et al., 1999).

The potential for active sonar to impact on a species is dependent on the ability of the species to hear the sound. Species hear sounds over different frequencies ranges, and the efficiency of sound detection varies markedly with frequency. Additionally, species behavioural responses to a detected sound may vary according to the sensitivity of the species to disturbance and what activities the animals are engaged in at the time.

Determination of potential impact on a species must therefore include estimation of the ability of the species to detect the sound, and the likelihood of disturbance to critical activities such as feeding or parental protection of juveniles.

5.1 Effect of sonar on marine animals

In terrestrial habitats, increasing sound levels have been shown to induce various effects across taxa including behavioural changes, temporary physiological alterations and permanent anatomical damage. While it is apparent that anthropogenic noise may affect marine animals, we know relatively less about the actual causes or mechanisms of these effects.

We can usually see things that are miles away, but if you have ever snorkelled, you know that vision is limited to a few tens of meters underwater. Vision is the best way to sense distant objects in air, but sound is the best way to sense objects that are far away under the sea. Low frequency sounds can travel hundreds of miles in the right conditions. When mammals entered the ocean tens of millions of years ago, they evolved mechanisms to sense objects by listening for echoes from their own sounds, and to use sound to communicate over long distances.

Modern ships generate enough noise from their engines and propellers to have reduced the range over which whales can communicate. The low frequency noise from ships travels so well in the ocean that it has raised the noise levels ten to one hundred times compared to a century ago (Stocker, 2004).

Marine mammals are of particular concern regarding the effects of noise as they typically have sensitive underwater hearing and they use sound for important activities such as communicating, orienting and finding prey.

It has been suggested that overexposure to noise could induce permanent physiological damage and deleterious behavioural alterations. For these reasons: there has been growing concern that the noise humans have introduced into the sea might disrupt the behaviour of marine mammals (Salami et al., 2010).

Some marine animals, such as whales and dolphins, use echolocation systems similar to active sonar to locate predators and prey. It is feared that sonar transmitters could confuse these animals and cause them to lose their way, perhaps preventing them from feeding and mating. Recent articles report findings to the effect that military sonar may be inducing some whales to experience decompression sickness (and resultant beachings) (Parsons et al., 2008).

These temporally and spatially overlapping events seem to indicate that high-intensity sonar may instigate some marine mammal strandings. Recent work has suggested that sonar exposure could induce a variety of effects in marine mammals including changes in dive profile, acoustically induced bubble formation or decompression sickness (Salami et al., 2010).

High-powered sonar transmitters can kill marine animals. In the Bahamas in 2000, a trial by the US Navy of a 230 decibel transmitter in the frequency range 3 to 7 kHz resulted in the beaching of sixteen whales, seven of which were found dead. The Navy accepted blame in a

report published in the Boston Globe on 1/1/2002. Continued emission of noise can increase the damage, due to the "habituation" to a familiar sound to which it is difficult to react more strongly (Sypin, 2008). The "habituation" is known as being provoked by continued acoustical stimuli, reducing the hearing sensitivity to high-level sounds; the hearing sensitivity may be regulated at both conductive (stapedial reflex) and sensorineural levels (adaptation) (Sypin, 2008).

However, these hypotheses typically lack controlled experimental conditions to best evaluate potentially deleterious noise effects. Thus, the actual mechanisms that may be initiated by sonar exposure, which could actually result in multi-species strandings, have yet to be empirically supported.

Introduction of new types of military sonar, such as low-frequency system, should proceed with caution; the low-frequency sounds produced by the systems will travel much farther than the mid-frequency sonar sounds currently causing concern (Salami et al., 2010). However, at low powers, sonar can protect marine mammals against collisions with ships.

Different studies pointed out that the possible effects of the low-frequency sonar on marine mammals could include (Simmonds & Lopez-Jurado, 1991):

- Death from lung hemorrhage or other tissue trauma;
- Temporary or permanent hearing loss or impairment;
- Disruption of feeding, breeding, nursing, acoustic communication and sensing, or other vital behavior and, if the disruption is severe, frequent, or long lasting, possible decreases in individual survival and productivity and corresponding decreases in population size and productivity;
- Psychological and physiological stress, making animals more vulnerable to disease, parasites and predation;
- Changes in the distribution, abundance, or productivity of important marine mammal prey species and subsequent decreases in both individual marine mammal survival and productivity and in population size and productivity. These changes in prey species possibly could be caused both directly and indirectly by the low-frequency sonar transmissions: for example, transmissions conceivably could kill or impair development of the eggs and larval forms of one or more important marine mammal prey species; they might also disrupt feeding, spawning, and other vital functions or cause shifts in distribution patterns of certain important prey species and make some prey species more vulnerable to disease, parasites, and being eaten by other predators.

Although these evidences, recent studies showed the absence of side effects on marine animals: the sensory tissue of the inner ears did not show morphological damage even several days post-sound exposure; similarly, gross- and histopathology observations demonstrated no effects on nonauditory tissues (Popper et al., 2007).

The exposure to high frequency sonar (200-214 dB re 1 μPa) can determinate an hearing shifts of the marine animal: in particular recent report show as these data also imply that the animal must be very close to the source and/or exposed repeatedly in a short period time (Mooney et al., 2009):

- Assuming a usual sound attenuation rate of 6 dB per doubling of distance, the dB level used in high frequency sonar would be the received level approximately 40 m from the sonar source, a distance that can be considered 'close' with respect to naval ships;
- The animal would then have to maintain at most that distance for the approximate 2–2.5 min of operating the sonar to receive a level of exposure of near 214 dB;

- The animal could be located closer to the sonar source and receive a more intense signal.

However, the animal would still need to remain within a close range long enough to receive al level of exposure that would induce auditory threshold shifts, a potentially unlikely situation: all scenarios entail the subject being relatively close to the sonar source for a 'prolonged' duration (Mooney et al., 2009).

Exceptions may be if the sonar signals are rapidly repeated (which is unlikely due to overlap of returning echoes) or if oceanographic conditions are such that sound levels do not attenuate regularly over short distances (i.e. less than several 100 m) and thus remain intense. Perhaps such a situation could occur with multiple sonar sources over steep bathymetric conditions (Mooney et al., 2009).

These data show as repeated exposures are necessary to generate effects. It's evident as the effects of sound on marine animals could potentially include increased stress, damage to organs, the circulatory and nervous systems; long-term effects may alter feeding and reproductive patterns in a way that could affect the fish population as a whole. In the limited existing research on the effects of sound on marine animals hearing and behavior, different scientists have discovered that exposure to some very loud sounds, such as seismic air guns, can produce no effect, or result in a range of effects from temporary hearing loss to more lasting damage to the haircells of marine animal' inner ears. But it is hard to say that effects on one species indicate that another species will be affected in the same way by the same signal.

Furthermore, subtle behavioural changes are also associated with sonar exposure. Animals that prolong apnea must optimize the size and use of their oxygen stores, and must deal with the accumulation of lactic acid if they rely upon anaerobic metabolism (Popper et al. , 2007).

Pathologies related to effects of pressure are well known among human divers, but marine mammals appear to have developed adaptations to avoid most mechanical and physiological effect. The hazard of bubble formation during decompression is best known for humans breathing compressed gases, but empirical studies and theoretical considerations have shown that breath-hold divers can develop supersaturation and possible decompression-related problems when they return to the surface. Supersaturation has not been measured during normal diving behaviour of wild marine mammals but rather in specially designed experiments performed by trained subjects (Tyack, 2006).

Recent reports show the presence of gas and fat emboli in marine animals during exposure to naval sonar (Tyack, 2006).These reports suggest that exposure to sonar sounds may cause a decompression-like syndrome in deep-diving whales either by changing their normal diving behaviour or by a direct acoustic effect that triggers bubble growth (Tyack, 2006). The latter scenario would, however, only seem to happen for animals with 100–223% supersaturated tissues within tens of meters from a sonar where the received levels exceed 210 dB re 1 μPa (Tyack, 2006). Nonetheless, the geographical pattern of strandings suggests that animals are impacted at ranges significantly greater than those required for acoustically driven bubble growth, implying that the observed pathologies may follow from a behavioural response that has adverse physiological consequences (Tyack, 2006).

In order to further understand these pathophysiological mechanisms, recent experiences examined post-mortem and studied histopathologically different marine animals (Ziphius cavirostris, Mesoplodon densirostris and Mesoplodon europaeus) after exposure to midfrequency sonar activity: no inflammatory or neoplastic processes were noted, and no

pathogens were identified. Macroscopically, whales had severe, diffuse congestion and haemorrhage, especially around the acoustic jaw fat, ears, brain, and kidneys. Gas bubble-associated lesions and fat embolism were observed in the vessels and parenchyma of vital organs. In vivo bubble formation associated with sonar exposure that may have been exacerbated by modified diving behaviour caused nitrogen supersaturation above a threshold value normally tolerated by the tissues (as occurs in decompression sickness). Alternatively, the effect that sonar has on tissues that have been supersaturated with nitrogen gas could be such that it lowers the threshold for the expansion of in vivo bubble precursors (gas nuclei). Exclusively or in combination, these mechanisms may enhance and maintain bubble growth or initiate embolism. Severely injured whales died or became stranded and died due to cardiovascular collapse during beaching. These injures are apparently induced by exposure to mid-frequency sonar signals and particularly affects deep, long-duration, repetitive-diving species like whales (Fernández et al., 2005).

5.2 Effects of sonar on human hearing

Relying on one's hearing it is extremely difficult to orientate oneself under water. Because of the high speed of sound under water, it is perceived by both ears virtually simultaneously and the orientation error may be possible. Bad orientation under water is also due to the prevalent bone conductivity. Sufficient audial orientation is possible to be acquired only after systematic training. The diving suit isolates the human ear from the surrounding water medium. That is why sound waves penetrate the helmet and the layer of air but reach the eardrum partly absorbed and scattered. In this case, sound perception through air conductivity is insignificant.

However, while diving without a helmet, which is possible in warm water, sound is perceived just like in the air. If the rubber helmet fits tightly, sound is well perceived because of bone conductivity – sound waves are transmitted through the bones of the human skull. With no helmet, a diver can hear very well, with a rubber helmet – fairly well, and with a metal one – very bad.

The development of underwater technology commonly results in a noisy working environment for commercial divers (Tindle & Deane, 2005). Also, the increasing use of active low-frequency sonar by submarines and ships raises the risk of accidental exposure to low frequency underwater sounds. While hearing conservation programs based on recognized risks from measurable sound pressure levels exist to prevent occupational hearing loss for most normal working environments, there are no equivalent guidelines for noise exposure underwater.

The Threshold Limit Values (TLVs) represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech. For Threshold Limit - Ceiling Values (TLV-C) the concentration should not be exceeded during any part of the working day (ACGIH, 1998).

In particular the "American Conference of Governmental Industrial Hygienists (ACGIH)" has established permissible ultrasound exposure levels. These recommended limits (set at the middle frequencies of the one-third octave bands from 10 kHz to 50 kHz) are designed to prevent possible hearing loss caused by the subharmonics of the set frequencies, rather than the ultrasonic sound itself. These TLVs represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech. Previous TLVs for frequencies in the 10 kHz to 20 kHz

range, set to prevent subjective effects, are referenced in a cautionary note below. The 8-hour time-weighted average (TWA) values are an extension of the TLVs for noise, which is an 8-hour TWA of 85 dBA for sound below 10 kHz. The ceiling values may be verified by using an integrating sound level meter with slow detection and 1/3 octave bands. All instrumentation should have adequate frequency response and should meet the specifications of ANSI S1.4-1983 and International Electrotechnical Commission (IEC) 804 (ACGIH, 1998).

Measuring any source suspected of producing sound at levels exceeding the ACGIH recommended limits requires the use of a precision sound level meter, equipped with a suitable microphone of adequate frequency response, and a portable third-octave filter set. Consult with the Assistant Regional Administrator for Technical Support for guidance (ACGIH, 1998).

TVLs for Ultrasound			
	One-third Octave-Band Level		
	Measure in Air in dB Re:20 μ Pa; Head in Air		Measure in Water in dB Re:20 μ Pa; Head in Water
Mid-Frequency of Third-Octave Band (kHz)	Ceiling Values	8-hour TWA	Ceiling Values
10	105[A]	88[A]	167
12.5	105[A]	89[A]	167
16	105[A]	92[A]	167
20	105[A]	94[A]	167
25	110[B]	--	172
31.5	115[B]	--	177
40	115[B]	--	177
50	115[B]	--	177
63	115[B]	--	177
80	115[B]	--	177
100	115[B]	--	177

[A]*Subjective annoyance and discomfort may occur in some individuals at levels between 75 and 105 dB for the frequencies from 10 kHz to 20 kHz especially if they are tonal in nature. Hearing protection or engineering controls may be needed to prevent subjective effects. Tonal sounds in frequencies below 10 kHz might also need to be reduced to 80 dB.*

[B]*These values assume that human coupling with water or other substrate exists. These thresholds may be raised by 30 dB when there is no possibility that the ultrasound can couple with the body by touching water or some other medium. [When the ultrasound source directly contacts the body, the values in the table do not apply. The vibration level at the mastoid bone must be used.] Acceleration Values 15 dB above the reference of 1g rms should be avoided by reduction of exposure or isolation of the body from the coupling source. (g = acceleration due to the force of gravity, 9.80665 meters/second; rms = root-mean-square).*

Table 1. (ACGIH, 1998).

Different studies highlighted as behavioural and memory disturbances, intellectual impairment, depression, and other long-term neuropsychiatric changes are well known in professional divers: these symptoms are probably caused by repeated focal ischemia due to intravascular gas bubbles and hyalinosis of the walls of small blood vessels (Reul et al., 1995). The lesions were predominantly in the subcortical white matter and basal ganglia, suggesting a vascular pathogenesis (Reul et al., 1995).

Other studies highlight as diving puts the inner ear at risk. Inner ear barotrauma and inner ear decompression can lead to permanent sensorineural hearing loss, tinnitus and vertigo (Klingmann et al., 2004).

Inner ear barotrauma is related to pressure changes in the middle and inner ear. Barotrauma refers to tissue damage that occurs when a gas-filled body space (e.g., lungs, middle ear) fails to equalize its internal pressure to accommodate changes in ambient pressure. The behaviour of gasses at depth is governed by Boyle's law: the volume of a gas varies inversely with pressure. During descent, as ambient pressure increases, the volume of gas-filled spaces decreases unless internal pressure is equalized. If the pressure is not equalized by a larger volume of gas, the space will be filled by tissue engorged with fluid and blood. This process underlies the common "squeezes" of descent that affect the middle ear, external auditory canal, mask, sinuses and teeth. Barotrauma of the inner ear during descent develops when middle ear clearing fails and the eustachian tube is blocked and locked (Klingmann et al., 2004). Under these conditions, the raised intracranial pressure brought about by forceful efforts to equalize pressure might be transmitted to the inner ear through a patent cochlear aqueduct. These pressure forces may cause rupture of Reissner's or the basilar membrane and/or labyrinthine window fistula with consequent impairment of inner ear functions (Klingmann et al., 2004). Symptoms often occur during ascent when expanding air in the middle ear is forced through a round window membrane fistula into the inner ear. The resulting gas bubble in the labyrinth expands during ascent and replaces the perilymph fluids. Barotrauma of the inner ear during ascent is a result of a blocked eustachian tube with air expanding in the middle ear forcing the tympanic membrane into the auditory canal. As a result, the oval window membrane is dislocated into the middle ear and the round window membrane is forced into the inner ear with increasing tension on both membranes (Klingmann et al., 2004). When there is an abrupt pressure equalization, either because of a tympanic membrane rupture or because the blocked eustachian tube releases the increased middle ear pressure, the oval and round window membranes snap back to their original position causing a pressure wave running through the inner ear.

Whether uneventful scuba diving in the absence of a decompression incident is a risk factor for cochlear disorders is a matter of debate. Most studies of diving associated hearing loss reveal an association with occupational noise exposure.

Different reports showed as divers exposed to high levels of underwater sound can suffer from dizziness, hearing damage, somnolence, lightheadedness inability to concentrate or other injuries to other sensitive organs, depending on the frequency and intensity of the sound. This may include neurological symptoms such as blurred vision, lightheadedness, vibratory sensations in hands, arms and legs, and tremors in upper extremities (Fothergill et al., 2009; Steevens et al., 1999).

Most reports of diving injury have concentrated on acute injuries rather than chronic disability e.g. deafness. Hence, while many divers reported aural symptoms, few attributed them to diving. It is possible that repeated hyperbaric exposure among very experienced divers may be responsible for their aural symptoms, despite the lack of an obvious acute injury for many. The cause(s) of the aural disorders described above are unknown. Different authors have reported that hearing loss in divers may be due to external ear canal obstruction, tympanic membrane perforation, middle ear disorders and sensorineural hearing damage (Taylor et al., 2006). However, aural barotrauma is the most likely cause (as it is a relatively common occurrence). It is known that the strain exerted upon the tympanic membrane (TM) and middle ear from minor barotrauma results in reversible impairment of

the recoiling capacity of the TM elastic fibrils. It has been postulated that, if this barotrauma is repeated over lengthy periods, the TM changes could become irreversible (Taylor et al., 2006). Hence, hearing loss is a possible outcome (Taylor et al., 2006).

Sub-clinical brain and inner ear injury may offer an alternative explanation. Different authors found that divers had significantly more hyper-intense lesions of the sub-cortical cerebral white matter (on MRI) compared to controls (Taylor et al., 2006): these authors concluded that long term recreational diving may cause central nervous system degeneration even if diving incidents have not occurred. The exact mechanism of this degeneration remains unclear although paradoxical gas embolism, through a patent foramen ovale, has been postulated (Taylor et al., 2006).

However, the association between diving and hearing loss, in the absence of clinically apparent diving injury, may not be as clear cut. Therefore, the effect of acoustic trauma or potential harmful effects of increased pressure and partial pressures of breathing gases cannot be differentiated. In fact the following well-recognized factors can affect the inner ear in divers: inner ear decompression sickness, noise, and potentially chronic effects of the breathing gases.

A number of studies have compared the hearing threshold in professional divers (Klingmann et al., 2004):

- In 1961 in a group of 62 Royal Navy divers and submarine escape training instructors, a high-frequency hearing loss was found in most of the divers. However, these divers had been exposed to gunfire and machinery noise during their naval careers, and noise could not be excluded as the causative mechanism.

- An intriguing finding was a prevalence of 60% of hearing impairment in a group of abalone divers who had not been exposed to noise. These divers, however, had been subjected to an extraordinary compression decompression stress by a mean history of 6 years of diving with an average diving depth of 15 to 20 m during 4 hours on 100 days per year. The divers with recognizable hearing loss in that study remembered having barotrauma in the past. Therefore, residual damage after diving accidents may mask putative chronic effects of breathing air under hyperbaric conditions. In addition, hearing thresholds found in divers were compared with thresholds of controls from a different study.

- One hundred sixty-four professional Norwegian divers were subdivided into different age groups and hearing thresholds were compared with a standard population from Norway. Young divers were found to have better hearing compared with the reference group, and with increasing age this difference decreased. The authors claimed that hearing deteriorates faster in professional divers with increasing age. These results were confirmed when 116 divers were reexamined 5 years later. Noise at work and barotrauma were thought to contribute to the rapid deterioration of hearing in the professional divers.

It is postulated that the human hearing range is reduced from 130 dB in air to 55 to 60 dB in water. The reduction causes the diver to be less resistant to noise underwater because acoustic energy underwater does not resolve as fast as in air. In addition, sawing, drilling, and grinding underwater may give rise to noise levels of 90 to 105 dB, and noise from the air stream venting inside underwater helmets can reach average noise levels of 93 to 99.5 dB. Most of the studies examined professional divers who had been exposed to gunfire or other noise at work. Noise was likely the main cause of the altered pure-tone thresholds (Molvaer & Albrektsen, 1990; Molvaer & Lehmann 1985).

This interpretation is supported by the fact that puretone thresholds of divers who had been exposed to noise underwater are similar to those obtained from control subjects who had been exposed to noise on land. In a cross-sectional study, auditory function was compared in Norwegian construction divers and workshop workers. Both groups had been exposed to noise, and divers had less hearing impairment at low frequencies (0.25 and 0.5 kHz) (Skogstad et al., 1999).

Another study from Skogstad et al examined 54 occupational divers at the beginning of their diving career and 3 years later. That study subdivided the divers into groups of low exposure (100 dives in 3 years) and high exposure (100 dives in 3 years). Skogstad and coworkers did not find a statistically significant difference for both ears combined between both groups (Skogstad et al., 2000).

One should expect that divers with high exposure to diving should have poorer hearing levels because they have more contact with breathing gases under increased ambient pressure and work longer underwater and therefore spend more time in a noisy environment. However, the low exposure group might have worked in a noisy environment, too, when they were not underwater (Klingmann et al., 2004).

These findings are confirmed by the data of Benton, who examined 281 commercial divers. He investigated the audiometric records of a group of United Kingdom professional divers, all of whom had been examined by an approved medical examiner. All divers underwent a hearing test between 1989 and 1992 and had a minimum of 5 years of diving experience. The divers were divided into 7 age groups ranging from 25 to 60 years. The median hearing level thresholds were compared with the predicted values for otologically healthy individuals, the comparison revealed that the median hearing threshold values of the divers lay between the predicted median and predicted upper quartile values (Klingmann et al., 2004). Within the older group (40 years), the median and predicted median values of the divers were similar. The author postulated that these results show as the divers had no impairment of the inner ear function compared with a non diving control group.

This short revision of the literature highlights that the data on the effect of marine noise on diver are few and sometimes in contrast. However it's important to remember that, although different injuries (dizziness, hearing damage, etc) have been reported, the single most important issue related to diver safety resulting from low frequency sonar is that of disorientation due to vestibular stimulation. Whilst exposure to sonar transmissions below a level necessary to cause disorientation can give rise to temporary hearing threshold shifts, these are considered operationally acceptable for diving operations over limited periods (Salami et al., 2010).

This effect of sonar on diver is related to its duration too: studies on marine animals have demonstrated that changes in hair bundle density paralleled changes in hair cell nucleus density, indicating that entire hair cells disappeared after noise exposure; the inner ear damage is characterized by a permanent threshold elevation after an exposure to white noise ranging in intensity from 130 to 170 dB re 1 µPa for 24 h (Salami et al., 2010; Smith et al., 2006).

Although there are differences among the ears of different species, the basic processes of hearing are the same between marine and terrestrial mammals. For this reason, some of the previous considerations can be applied on humans (Salami et al., 2010; Popper & Fav, 2000).

In particular we had done a personal experience on ten male divers with normal hearing; the divers were exposed to active sonar of the Italian Navy for more than 100 exposures, each of at least 1-h duration, in the course of 6 months (Salami et al., 2010): all the subjects

have been exposed to active sonar of the Italian Navy (Hull MF), at a frequency of 7.5 kHz and an intensity of 230 dB re 1 µ Pa. All the divers have had more than 100 exposures of at least 1 h, for six months, in the winter time (from October to April). The diver was exposed to the sonar at a constant depth of 3 m and at a distance from the sonar reducing progressively from 300 to 30 m. Each subject was instructed to stop the exposure in case of pain, tinnitus, vertigo, or hearing loss.

Before, at the end, and six months after the end of noise exposures, all the divers underwent the following instrumental examinations: pure-tone audiometry, Carhart test, Peyser test, thresholds of discomfort test (TDT), tympanometry, transient evoked otoacoustic emissions (TEOAE) with linear click emission, distortion product otoacoustic emissions (DPOAE), and auditory brainstem response (ABR) by MK 12-ABR (Amplifon—Italy) (Chapman & Ellis, 1998).

At the end of the exposure, the absence of TEOAE and DPOAE was observed in all the divers, the positive Peyser and TDT tests, observed in 7/10 and 10/10 divers, and the worsening of the mean air and bone audiometric thresholds, especially at the 4,000 and 8,000 frequencies, highlights the pathophysiologic features of continued and intense sound stimulation of the cochlea (Chapman &Ellis, 2008).

The injuries occur first in the first row of the outer hair cells, then in the inner hair cells, and subsequently in the second and third rows; the temporary threshold shift, at the Peyser test, observed in 9/10 of the divers, shows the presence of an auditory adaptation to the noise and underlines the risk of increasing the hearing damage: it is well established that a single exposure to a severe sound can result in direct mechanical damage to the delicate tissues of the peripheral auditory apparatus, including components of the middle ear (tympanic membrane, ossicles) and inner ear (organ of Corti); in contrast, regular exposure to less intense, but still noisy sounds, involves the insidious destruction of inner-ear components that eventually and unavoidably leads to an elevation in hearing levels.

The results of the TDT test confirm the correlation between the acoustic reflex threshold and the loudness discomfort level for people with hearing damage (Olsen, 1999).

Following a noise exposure, the hearing damage could also be due to the loss of the protective effect of the efferent fibres, perhaps mediated by the lateral olivocochlear neurons that synapse beneath the inner hair cells (Attanasio et al., 1999).

The transitory auditory injury observed in our test group may also be related to the hyperbaric work environment: oxygen toxicity is a problem in diving and can have fatal consequences in the water; past experiences made on divers, highlighted the significant presence of hearing disturbances and disorientation, and demonstrated changes of the Central Nervous System in hyperbaric conditions (Cakir et al., 2006).

Experiences done on animals (guinea pig) showed that repeated hyperbaric exposures that were considered to be safe did cause damage to the cochlear system (Zheng & Gong, 1992). These modifications are characterised by: alterations in the metabolism and in the concentration of neurotransmitters; block of intercellular oxidation processes; accumulation of carbon dioxide.

At the last control, the complete recovery observed in all the divers shows the temporary negative effects of repeated and lasting exposure to active sonar (Hull MF) and demonstrates the absence of permanent noise-induced hearing loss in divers exposed to active sonar (Salami et al., 2010).

The frequencies used in sonar are above the human hearing threshold (Gong et al., 2010; Kane et al., 2010): as because the power of ultrasonic sonar rapidly falls off with distance, a

safe operating distance is 10 meters or greater. Diving may be conducted around this type of sonar provided the diver does not stay within the sonar focus beam. None of the above avoids the need for positive safety measures to be adopted when divers are working on or very close to sonar sources which are inactivated. The possibility of accidental activation must be precluded.

Since physical damage and impairment of the auditory system is caused both by high peak pressure and energy flux, safety limits for sound exposure should include both a maximum received energy fluid level and a maximum received peak–peak pressure level (impulse noise can have very high peak sound levels, but carry very little energy) (Madesen, 2005).

As different studies give only basic instructions governing hearing conservation and noise abatement, while they do not address exposure to waterborne sound, the instructions should provide field guidance for determining safe diving distances from transmitting sonar.

Sonar with an intensity level of about 230 dB re 1 μ Pa may cause on divers: slight visual-field shifts (probably due to direct stimulation of the semicircular canals), fogging of the face plate, spraying of any water within the mask, and other effects. In particular in the presence of long sonar pulses (one second or longer), depth gauges may become erratic and regulators may tend to free-flow. Different divers experienced these phenomena during controlled research report that while these effects are unpleasant, they are tolerable. Similar data are not available for un-hooded divers but visual-field shifts may occur for these divers at lower levels. If divers need to be exposed to such conditions, they must be carefully briefed and, if feasible, given short training exposures under carefully controlled conditions. As the probability of physiological damage increases markedly with sound pressurese increase, fully protected divers must not be exposed to intensity level superior to 215 dB re 1 μPa for any reason.

A distinction is made between in-water hearing and in-gas hearing (Tompkins, 2007):

- in-water hearing occurs when the skull is directly in contact with the water, as when the head is bare or covered with a wet-suit hood.
- in-gas hearing occurs when the skull is surrounded by gas as in the MK 21 diving helmet.

In-water hearing occurs by bone conduction—sound incident anywhere on the skull is transmitted to the inner ear, bypassing the external and middle ear. In gas hearing occurs in the normal way—sound enters the external ear canal and stimulates the inner ear through the middle ear.

For these reasons, if the diver is helmeted, it's necessary to use greater distance from the sonar source.

It's also important to identify the type of diving equipment: wet-suit un-hooded, wet-suit hooded, helmeted; wet-suit hooded diver can safely get closer to a sonar source. If the type of sonar is unknown, start diving at 600–3,000 yards, depending on diving equipment (use greater distance if helmeted), and move in to limits of diver comfort.

Helmeted divers experience reduced sensitivity to sound pressure as depth increases.

The sonar presents different effect on divers, according to the intensity (low, medium, high):

- low-frequency sonar generates a dense, high-energy pulse of sound that can be harmful at higher power levels. As a variety of sensations may result from exposure to low-frequency sonar, it is necessary to inform divers when exposure is likely and to brief them regarding possible effects; specifically, that they can expect to hear and feel it. Sensations may include mild dizziness or vertigo, skin tingling, vibratory sensations in

the throat and abdominal fullness. Divers should also be briefed that voice communications are likely to be affected by the underwater sound to the extent that line pulls or other forms of communication may become necessary (Crum & Mao, 1996).

- Medium and high frequency sonars: some military anti-submarine sonar-equipped ships do pulse high intensity pressure waves dangerous to a diver. It is prudent to suspend diving operations if a high-powered sonar transponder is being operated in the area. When using a diver-held pinger system, it is advisable for the diver to wear the standard 1/4 inch (0.64 cm) neoprene hood for ear protection. Experiments have shown that such a hood offers adequate protection when the ultrasonic pulses are of 4 ms duration, are repeated once per second for acoustic source levels up to 100 watts, and are at head-to-source distances as short as 4 inches (10 cm).

6. Conclusion

The power of the sonar systems, the noise that they produce and the distance they can travel can undoubtedly have an effect on marine life. Marine animals may experience gross damage to ears, damage to body tissue, masking of communication, interference with ability to acoustically interpret their environment and also interference with food finding. Long term effects caused by sonar are almost impossible to identify. Many whales that are fatally impacted can sink to the bottom of the ocean; therefore the true death toll cannot be estimated. There are widespread concerns about the danger of high intensity sonar to marine mammals, marine ecosystems and the health of our depleted oceans. Low frequency sonar can travel hundreds of miles through our oceans at considerable intensities.

It is currently difficult to provide an evaluation of the effectiveness and adequacy of the measures taken and planned for the protection of the marine environment against effects from underwater noise. One of the reasons for this is that there are still gaps in our understanding on the effects of underwater noise on marine life. There is evidence that certain activities can generate noise levels that have the potential to be harmful to marine mammals, fish and human, yet, the exact nature of the effects (temporary threshold shift, masking, behavioural response) are not totally understood. The poor understanding of effects means that any regulation and mitigation measures are likely to be based on precaution. This makes it urgent to gather data on the effects of underwater noise in order to apply appropriate regulation and /or mitigation measures.

Underwater noise has the potential to affect marine life in various ways and in some cases over relatively large areas and time scales. It is difficult to assess to what degree the introduction of underwater noise affects the overall quality status as there is little data to allow us to quantify noise levels across the exposition area. However, most of the intensities of anthropogenic sounds exceed by several order of magnitude the ambient sounds in the marine environment that occur naturally, such as sounds that are induced by rain, wind and waves. Underwater noise can have a range of impacts on marine life such as injury, permanent or temporary hearing loss, behavioural responses and masking of biological relevant signals. However, there are many uncertainties in assessing effects of noise due to the difficulties in observing individual level effects, let alone population level consequences of acoustic disturbance. From a conservation perspective, it is important to assess whether anthropogenic sound has a significant effect on populations (animals and humans). This is also important in assessing the impacts of noise in relation or addition to other stressors either to assess cumulative impacts and/or to focus protection efforts. All factors impacting

on populations are cumulative and must be assessed together by discussing the significance of effects. There is currently no information available on the cumulative effects of the factors listed above. No agreed assessment framework for cumulative effects of diverse human activities exists yet.
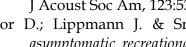
Although these evidences, our results show the temporary negative effects of repeated and lasting exposure to active sonar on the divers. In particular our data demonstrate the absence of permanent noise-induced hearing loss in divers exposed to active sonar.

7. References

ACGIH. (1998). TLVs and BEIs *Threshold limit values for chemical substances and physical agents*. 117, ISBN:1-88-2417-23-2

Attanasio G.; Barbara M.; Buongiorno G.; Cordier A.; Mafera B.; Piccoli F.; Nostro G. & Filipo R. (1999). *Protective effect of the cochlear efferent system during noise exposure.* Ann N Y Acad Sci, 28:361–367, ISSN 00778923

Cakir BO.; Ercan I.; Civelek S.; Körpinar S.; Toklu AS.; Gedik O.; Işik G.; Sayin I. & Turgut S. (2006). *Negative effect of immediate hyperbaric oxygen therapy in acute acoustic trauma.* Otol Neurotol, 27:478–483, ISSN 15317129

Chapman DMF & Ellis DD (1998). *The elusive decibel: thoughts on sonars and marine mammals.* Can Acoust, 26:29–31, ISSN 07116659

Crum L.A. & Mao Y. (1996). *Acoustically enhanced bubble growth at low frequencies and its implications for human diver and marine mammal safety.* Journal of the Acoustical Society of America, 99:2898-2907, ISSN 15208524

Fav RR & Popper AN. (2000). *Evolution of hearing in vertebrates: the inner ears and processing.* Hear Res;149:1–10 ISSN 03785955

Fernández A.; Edwards JF.; Rodríguez F.; Espinosa de los Monteros A.; Herráez P.; Castro P.; Jaber JR.; Martín V. & Arbelo M. (2005). *"Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals.* Vet Pathol. Jul;42(4):446-57, ISSN 15442217

Fothergill DM.; Sims JR. & Curley MD. (2001). *Recreational scuba divers' aversion to low-frequency underwater sound.* Undersea Hyperb Med, 28:9-18, ISSN 10662936

Frosch RA. (1964). *Underwater Sound: Deep-Ocean Propagation: Variations of temperature and pressure have great influence on the propagation of sound in the ocean.* Science, 146:889-94, ISSN 00368075

Gong Z.; Andrews M.; Jagannathan S.; Patel R.; Jech JM.; Makris NC. & Ratial P. (2006). *Low-frequency target strength and abundance of shoaling Atlantic herring (Clupea harengus) in the gulf of maine during the ocean acoustic waveguide remote sensing experiment.* J Acoust Soc Am., 2010;127:104-23, ISSN 15208524

Hood LJ.; Berlin CI. & Parkins CW. (1991). *Measurement of sound.* Otolaryngol Clin North Am., 24:233-51 ISSN 00306665

Jian YJ.; Zhang J.; Liu QS. & Wang YF. (2009). *Effect of Mesoscale eddies on underwater sound propagation.* Applied Acoustics, 70:432-440, ISSN 0003682X

Kane AS.; Song J, Halvorsen MB.; Miller DL.; Salierno JD.; Wysocki LE.; Zeddies D. & Popper AN. (2010). *Exposure of fish to high-intensity sonar does not induce acute pathology.* J Fish Biol, 76:1825-40, ISSN 0022-1112

Klingmann C.; Benton P.; Schellinger P. & Knauth M. (2004). *A safe treatment concept for divers with acute inner ear disorders.* Laryngoscope. Nov;114(11):2048-50, ISSN 0023852X.

Leroy CC.; Robinson SP. & Goldsmith MJ. (2008). *A new equation for the accurate calculation of sound speed in all oceans.* J Acoust Soc Am.;124:2774-82, ISSN 15208524

Lichte H. (1919) *On the influence of horizontal temperature layers in sea water on the range of underwater sound signals.* Physik. Z. 17 (385)

Madesen PT (2005*). Marine mammals and noise: problems with root mean square sound pressure levels for transients.* J Acoust Soc Am 117:3952–3957, ISSN 15208524

Molvaer OI. & Albrektsen G. (1990). *Hearing deterioration in professional divers: an epidemiologic study.* Undersea Biomed Res.;17:231246.

Molvaer OI & Lehmann EH. (1985). *Hearing acuity in professional divers.* Undersea Biomed Res.;12:333-349, ISSN 00935387

Mooney TA.; Nachtigall PE. & Vlachos S. (2009). *Sonar-induced temporary hearing loss in dolphins.* Biol Lett.;5:565-7, ISSN 17449561

Olsen SO. (1999). *The relationship between the uncomfortable loudness level and the acoustic reXex threshold for pure tones in normally-hearing and impaired listeners — a meta analysis.* Audiology, 38:61–68, ISSN 00206091

Parsons ECM.; Dolman SJ.; Wright AJ.; Rose NA. & Burns WCG (2008). *Navy sonar and cetaceans: just how much does the gun need to smoke before we act?* Mar Pollut Bull 56:1248–1257, ISSN 0025-326X

Patek SN.& Oakley TH. (2003). *Comparative tests of evolutionary trade-offs in a palinurid lobster acoustic system.* Evolution. 57:2082-100, ISSN 00143820

Popper AN.; Halvorsen MB.; Kane A.; Miller DL.; Smith ME.; Song J.; Stein P. & Wysocki LE. (2007). *The effects of high-intensity, low-frequency active sonar on rainbow trout.* J Acoust Soc Am;122:623-35, ISSN 15208524

Reul J, Weis J, Jung A, Willmes K, Thron (1995*). A. Central nervous system lesions and cervical disc herniations in amateur divers.* Lancet. Jun 3;345(8962):1403-5, ISSN 01406736

Sabra KG. & Dowling DR. (2003). *Effect of ocean currents on the performance of a time-reversing array in shallow water.* J Acoust Soc Am., 114:3125-35, ISSN 15208524

Salami A, Dellepiane M, Crippa B, Guastini L, Mora R. (2010). *The effect of active sonar for the protection of moored and anchored warships on the human hearing.* Eur Arch Otorhinolaryngol, 267:207–211, ISSN 0937-4477

Shvachko LV. (2008). *Structure of the sound field in convergence zones of the tropical pacific.* Acoustical Physics, 54:228-237, ISSN 10637710

Simmonds MP, Lopez-Jurado LF. (1991). *Whales and the Military.* Nature 351:448.

Simon M.; Wahlberg M.; Ugarte F. & Miller LA. (2005). *Acoustic characteristics of underwater tail slaps used by Norwegian and Icelandic killer whales (Orcinus orca) to debilitate herring (Clupea harengus).* J Exp Biol;208:2459-66, ISSN 0022-0949

Skogstad M.; Haldorsen T. & Arnesen AR. (2000). *Auditory function among young occupational divers: a 3-year follow-up study.* Scand Audiol., 29:245-252, ISSN 0105-0397

Skogstad M.; Haldorsen T. & Kjuus H. (1999). *Pulmonary and auditory function among experienced construction divers: a cross-sectional study.* Aviat Space Environ Med., 70:644-649, ISSN 0095-6562

Smith ME.; CoYn AB.; Miller DL. & Popper AN. (2006). *Anatomical and functional recovery of the goldfish (Carassius auratus) ear following noise exposure.* J Exp Biol, 209:4193–4202, ISSN 0022-0949

Snellen M.; Simons DG.; Siderius M.; Sellschopp J. & Nielsen PL. (2001). *An evaluation of the accuracy of shallow water matched field inversion results.* J Acoust Soc Am., 109(2):514-27, ISSN 15208524

Steevens CC.; Russell KL.; Knafelc ME.; Smith PF.; Hopkins EW. & Clark JB. (1999). *Noise-induced neurologic disturbances in divers exposed to intense water-borne sound: two case reports.* Undersea Hyperb Med, 26: 261–5, ISSN: 1066-2936

Stocker M. (2004). *Ocean noise could injure more than mammals.* Nature, 430:291, ISSN 14764687

Studenichnik NV. (2003). *Intensity and space–time characteristics of the sound field in the underwater sound channel of the black sea.* Acoustical physics, 49;207-16, ISSN 10637710

Sypin AY. (2008*). Hearing sensitivity during target presence and absence while a whale echolocates.* J Acoust Soc Am, 123:534-541, ISSN 15208524

Taylor D.; Lippmann J. & Smith D. (2006). *The absence of hearing loss in otologically asymptomatic recreational scuba divers.* Undersea Hyperb Med, 33(2):135-141, ISSN 1066-2936

Tindle CT. & Deane GB. (2005). *Shallow water sound propagation with surface waves.* J Acoust Soc Am., 117:2783-94, ISSN 15208524

Tompkins O. (2007). *Ears and air travel.* AAOHN J, 55:336, ISSN 0891-0162

Tyack PL.; Johnson M.; Soto NA.; Sturlese A. & Madsen PT. (2006). *Extreme diving of beaked whales.* J Exp Biol, 209(Pt 21):4238-53, ISSN 14779145

Urick, Robert J. (1983). *Principles of Underwater Sound, 3rd Edition.* McGraw-Hill, ISBN 0070660875, New York

Wolfson MA & Tomsovic S. (2001). *On the stability of long-range sound propagation through a structured ocean.* J Acoust Soc Am. 109:2693-703, ISSN 15208524

Zheng XY. & Gong JH. (1992). *Cochlear degeneration in guinea pigs after repeated hyperbaric exposures.* Aviat Space Environ Med, 63:360–363, ISSN 0095-6562

Sonar Systems

Edited by Prof. Nikolai Kolev

The book is an edited collection of research articles covering the current state of sonar systems, the signal processing methods and their applications prepared by experts in the field. The first section is dedicated to the theory and applications of innovative synthetic aperture, interferometric, multistatic sonars and modeling and simulation. Special section in the book is dedicated to sonar signal processing methods covering: passive sonar array beamforming, direction of arrival estimation, signal detection and classification using DEMON and LOFAR principles, adaptive matched field signal processing. The image processing techniques include: image denoising, detection and classification of artificial mine like objects and application of hidden Markov model and artificial neural networks for signal classification. The biology applications include the analysis of biosonar capabilities and underwater sound influence on human hearing. The marine science applications include fish species target strength modeling, identification and discrimination from bottom scattering and pelagic biomass neural network estimation methods. Marine geology has place in the book with geomorphological parameters estimation from side scan sonar images. The book will be interesting not only for specialists in the area but also for readers as a guide in sonar systems principles of operation, signal processing methods and marine applications.

INTECH
open science | open minds