Marine Mammal Acoustics

Anja Reckendorf, Lars Seidelin, and Magnus Wahlberg

Contents

Supplementary Information The online version contains supplementary material available at [https://doi.org/10.1007/978-3-031-06836-2_2].

D. Brennecke et al. (eds.), *Marine Mammals*, https://doi.org/10.1007/978-3-031-06836-2_2

Learning goals

- Understanding acoustics and its importance for marine mammals
- Knowledge about the diverse ways marine mammals use sound
- Understanding how human-made sounds can affect marine mammals

1 Introduction

We live in a world of sounds: both natural and human-made (anthropogenic) ones. So do the animals with which we share this planet. Many of them depend on their abilities to navigate the *soundscape* to survive. Marine mammals use sound both for sensing their surroundings and to communicate, sometimes over long distances. Knowledge of bioacoustics and the physics of sound are important, both when trying to understand the lives of marine mammals and also when trying to protect them from human disturbances.

The underwater world contains many different sounds, which can have natural causes like thunder, winds, animal sounds and rain, or be man-made. Marine mammals are well adapted to natural sounds; they react appropriately to sounds of interest to them. 'Noise pollution' is the sum of all additional, unnatural sounds which disturb animals. Sounds are not heard equally well by all animals. An acoustic signal which is important to one species may be without interest or disturbing to another. It is difficult to assess the impact of noise on animals, as we often need to address the effects on different species separately.

2 The physics of sound

Sounds are waves, somewhat similar to ocean waves you can see rolling in on a beach or that you create yourself in your bathtub. Sound waves can be generated by, for example, a vibrating membrane. Particles of the surrounding medium are set in motion by the membrane and move from side to side, condensing and relaxing the medium. Sound wave propagation is therefore dependent on the oscillation of matter surrounding the sound source. Accordingly, sound needs a medium to propagate. The medium can be a gas (such as air), liquid (such as water) or a solid (such as the seafloor). In outer space, where there is no medium, sound cannot propagate.

The particles in the medium do not actually travel with the sound wave. They oscillate and end up in the same location where they started after the wave has passed. For an animated graphic of sound propagation click ► here and ► here.

A sound wave is a *longitudinal* wave. The medium's particles move back and forth parallel to the direction in which the sound wave travels. In contrast, in a *transverse wave* (such as an electromagnetic wave), the particles or field move perpendicular to the direction in which the wave is travelling. Water waves are more complicated: here, the particles move in a circular fashion.

Check online supplementary animated graphic ◘ Fig. S1.

The easiest described sounds are 'pure tones', or sinusoidal waves. They can also be called signal 'atoms', as any kind of sound can be constructed out of sinusoidal waves. Sinusoidal waves are defined by their amplitude, frequency and phase (◘ Fig. 1).

Amplitude

Amplitude measures the local pressure fluctuation created by the movement of the particles, measured in pascals (Pa; or newton/m^2, N/m^2; ◘ Fig. 1). One pascal equals the pressure generated by 1 newton over an area of 1 m^2. In air, one pascal is a very high sound level, similar to noise generated by cars on a highway at a close distance. Compared to the atmospheric pressure, which is around 100 kPa at the surface of the Earth, the pressure fluctuations generated by most sounds are small.

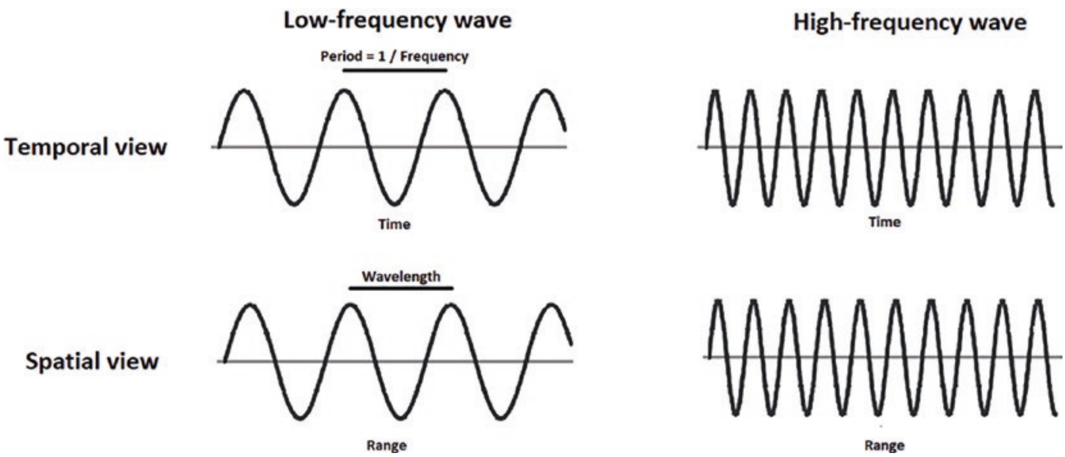


Fig. 1 Left top: A sound wave, depicted as a function of time (recorded at a certain position). Left bottom: The same sound wave, depicted as a function of range (recorded at several locations). Right top and bottom: a sound wave of higher frequency, depicted as a function of time and range. A sinusoidal sound wave is characterized by its 'height' (amplitude), frequency and phase (determining at which time the peak occurs)

Frequency

Frequency is defined by the number of wave cycles in 1 s, measured in hertz (Hz). Thus, 1 Hz is one cycle/sec, while a kilohertz (kHz) is one thousand cycles per second.

The frequency is closely related to the wave's *pitch*, which is the animal's perception of how 'high' (*treble*) or 'low' (*bass*) the sound is. Decreasing the frequency lowers the sound's pitch and makes it more 'bass-like', while increasing the frequency raises it (making the sound more 'treble-like'; Fig. 1). Different species of animals have their best hearing at different frequencies: humans hear best at 2–4 kHz, while porpoises hear best at 100–140 kHz.

Intensity

Another useful unit is the *intensity* of the wave, which is defined as $I = p^2/(\rho c)$, where p is the sound pressure (measured in Pa), ρ is the density of the medium (in kg/m^3) and c is the speed of sound in the specific medium (in m/s). Intensity is measured in units of W/m^2 (watts/metre^2). Intensity is related, but not identical to, how loud humans and other animals perceive sound (for humans, the latter is called the *loudness* of the sound).

It is important to understand the basics of pressure and intensity before we move on to discuss how well animals hear. When comparing hearing in air and underwater, it makes a difference if we report hearing thresholds (i.e. the weakest sound an animal can here) in pressure or intensity units. As we will see below, when measured in units of pascals, underwater hearing thresholds seem higher than aerial ones. However, this does not necessarily mean that marine mammals hear worse underwater than terrestrial mammals hear in air. The difference is to a large part a matter of the composition of the medium in which the sound propagates. Because water is denser than air, a pascal of sound underwater carries less intensity than a pascal of sound in air. Thus, comparing in-air and underwater sound levels is by no means trivial. When reporting thresholds in units of intensity, some marine mammals (such as seals, which live a semi-aquatic lifestyle) have similar hearing thresholds in air and underwater, while others (such as dolphins, which are entirely aquatic) have poorer hearing in air but extremely sensitive hearing underwater.

Sound levels expressed as decibels

Because the span in sound pressures that can be observed in nature is huge, the sound amplitude scale is often compressed into a logarithmic scale, known as *the decibel scale*. Decibels are calculated as

$$\mathrm{dB} = 20\log_{10}\left(p / p_0\right)$$

where $\log_{10}$ is the base-10 logarithm, p is the measured pressure (in Pa), and p_0 is the so-called *reference pressure*, which is p_0 = 20 μPa (micropascals) for airborne sounds, and p_0 = 1 μPa for underwater sound. The reference pressure in air is close to the human hearing threshold at 1 kHz. In this way, the hearing threshold of humans at this frequency is 0 dB re 20 μPa (try to calculate this yourself). The underwater reference pressure does not have any biological meaning but has been hand-picked by a scientific committee. To indicate which reference pressure is used, in-air sound pressure levels are reported as dB re 20 μPa and underwater as dB re 1 μPa (◘ Fig. 2).

Because of the differences in reference units as well as in speed of sound and density of air and water, it is not easy to compare in-air decibel levels with underwater ones. A sound signal of equal pressure in both media is 26 dB higher in water than in air (due to the different reference pressures), and a sound of equal intensity is 62 dB higher in water than in air (due to different reference pressures and impedances).

Let's compare the decibel scales in air and underwater (◘ Fig. 2). In air, the scale of audible sounds spans from the hearing threshold, which for most mammals is lower than 20 μPa up to about 100 Pa, around the *threshold of pain*. This means a difference of 6–7 orders of magnitude between the lowest and highest point of the audible scale. In decibel units, the biologically relevant in-air scale is from a bit less than 0 dB to more than 130 dB re 20 μPa. In water, the lowest hearing thresholds of marine mammals are about 100–1000 μPa (which in decibels become 40–60 dB re 1 μPa), while the threshold of pain is probably beyond 1 or 10 kPa (180–200 dB re 1 μPa). The loudest sounds that can be produced in air, such as sounds from rifle shots and jet engines, can be up to around 180 dB re 20 μPa. Beyond this sound level, the air molecules cannot maintain the extremely large particle motions and start to behave in ways not easily described by physics. Underwater, the loudest animal sounds are produced by sperm whales, which sometimes click at about 240 dB re 1 μPa, if recorded at a distance of 1 m. Even louder sounds exist, but these are mainly of human origin, such as the sounds from sonars and underwater explosions. Remember though that to directly compare the sound intensity in air and underwater, you have to subtract 62 dB from the underwater decibels.

Another important feature of a sound wave is its frequency content. Young humans can hear from about 20 Hz up to 20 kHz. With age, the upper hearing limit is rapidly decreasing so most people older than 50 years have a hard time hearing sounds above 10 kHz. Humans hear best at 2–4 kHz, which is significantly higher than the frequencies where we emphasise our speech, at a few 100s of hertz (◘ Fig. 3).

► Example

Human hearing is not fine-tuned to the frequencies at which we communicate. But why do we speak at different frequencies than our best hearing occurs? A crowded bus ride may give you a hint. You can easily continue talking to your friend nearby, in spite of all the noise of other people talking around you. If a baby starts crying however—and babies cry in the 2–4 kHz range where humans hear best—you may stop your conversation to see if any help is needed or soon consider switching to another bus to continue your conversation. Our hearing seems to be evolutionary tuned to listen in for infants that need to be comforted. ◄

The speed at which a sound wave travels is different for every medium. It depends on the density, temperature and a few other parameters, like ambient pressure and (for underwater

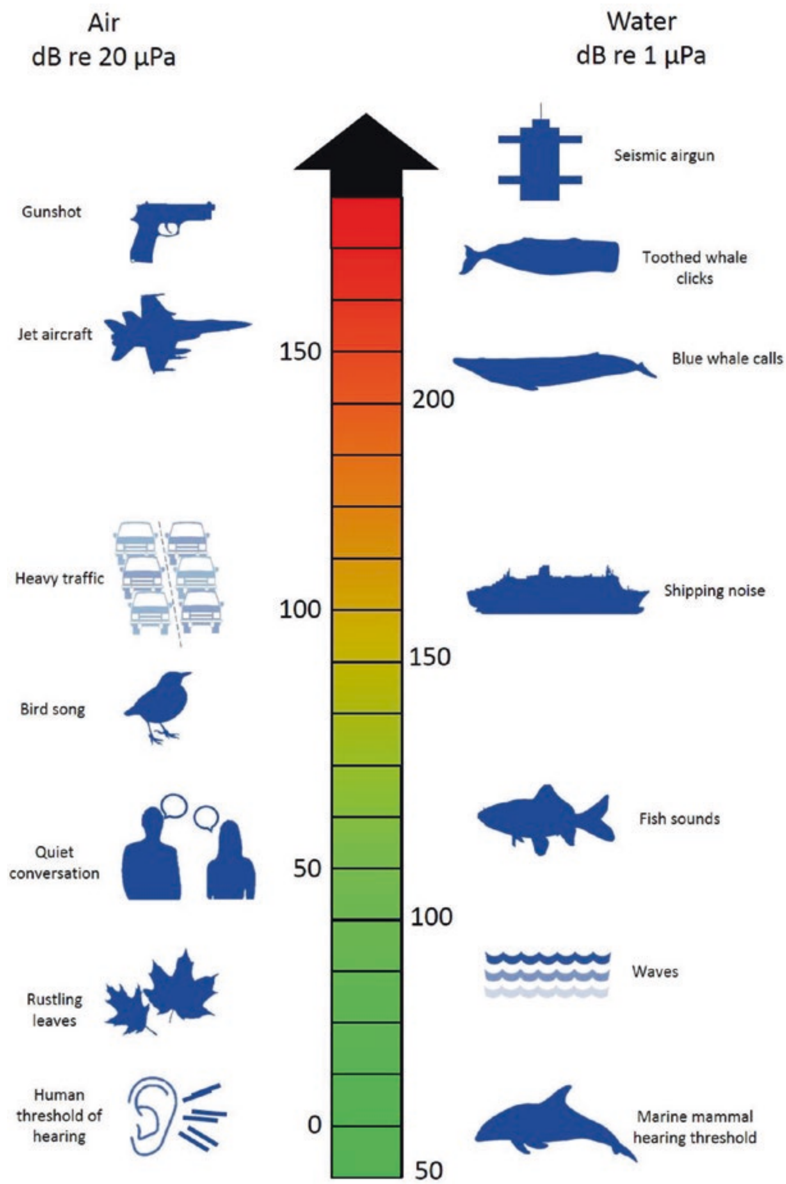
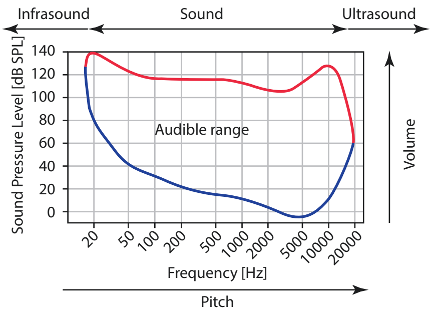


Fig. 2 In-air and underwater decibel scales. The reference pressure for airborne sounds is dB re 20 µPa, while dB re 1 µPa is the reference pressure for underwater sounds. The water dB scale is shifted by 62 dB, so that in-air and underwater sounds at the same vertical location have the same acoustic intensity

sound) salinity. In air, the speed of sound is 330–340 m/s, and in water 1450–1500 m/s. Thus, sound travels about 4.4 times faster underwater than in air.

The different acoustic properties of air and water have implications for the way we perceive sound in the two media. For example, an important cue when listening for sounds is to determine their direction. Many animals, and humans, do this primarily by gauging the difference in timing or intensity of the sound received at each ear. Both timing and intensity differences will become smaller in water. Due to the high speed of sound transmission underwater, sound is received at both ears closer in time than for airborne sounds. Furthermore, for a signal with a certain frequency content, the wavelength is longer



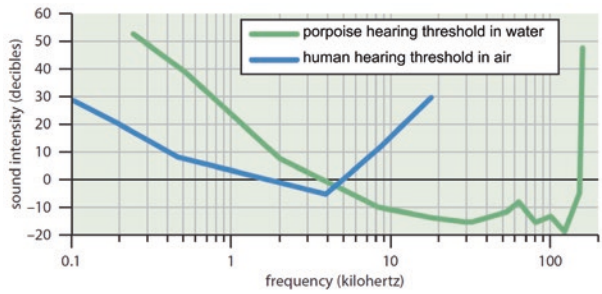


Fig. 3 Left: the human hearing threshold in blue, and threshold of pain shown in red. On the right, the audiogram of a harbour porpoise (green) is compared to a human audiogram (blue). The audiogram thresholds have been shifted so that the intensity level is the same for the underwater and in-air hearing thresholds. Left figure from Larsen and Wahlberg (2017), right figure from Wahlberg et al. (2015)

underwater than in air, as the wavelength is the ratio between speed of sound and frequency. Due to the longer wavelengths, and the similarity of flesh, bone and water density, the animal's head is less efficient in shielding signals underwater than in air. Therefore, intensity difference cues between the two ears to determine the direction of a sound source become less efficient in water. Terrestrially adapted animals, and humans, have a very hard time determining the direction of a sound source underwater. Marine mammals, however, have certain anatomical and physiological adaptations to tease out the direction of underwater sounds. Porpoises, for example, have acoustically decoupled inner ears: they are detached from the skull and surrounded by air compartments.

3 Hearing and sound production

Marine mammals use sound to communicate over short and long distances, to acoustically sense their surroundings and navigate underwater, locate prey and mating partners, and to avoid predators.

Depending on the species, the upper hearing limit differs tremendously. Seals can hear well up to about 20 kHz in air, whereas their underwater frequency range is more than doubled, up to 50 kHz. Their hearing is adapted to life both in air and water. Toothed whales hear well underwater but poorly in air. Many of them can hear even higher frequencies than seals. The record holder are small odontocetes such as the harbour porpoise, which can hear frequencies higher than 140 kHz. Porpoises hear best in the frequency range where they produce their echolocation signals (Fig. 4). Their hearing sensitivity at these frequencies is among the best sensitivities found in any aquatic mammal.

Marine mammals produce a large repertoire of different sounds. In most cases you can quite easily detect the difference between sounds from a seal, a dolphin and a baleen whale. Seals produce sounds both in air and underwater in the same frequency range as humans, mainly for communication and during mating activities. Dolphins produce clicks, burst-pulsed sounds and whistles. Some of these signals are produced in the frequency range audible to humans, but they often also contain higher, so-called *ultrasonic*, frequencies. Baleen whales produce extremely low-frequency sounds. Blue and fin whales regularly sing below 20 Hz, which is the lower frequency limit of human hearing; sounds below this limit are called *infrasound*.

Sound is one of the most useful ways of communication, above and especially underwater. Many marine animals have good eyesight, but even in the clearest tropical waters, visibility is restricted to a few tens of metres. Sound on the other hand travels much further. Many low-frequency sounds may be often heard over very large distances. Many

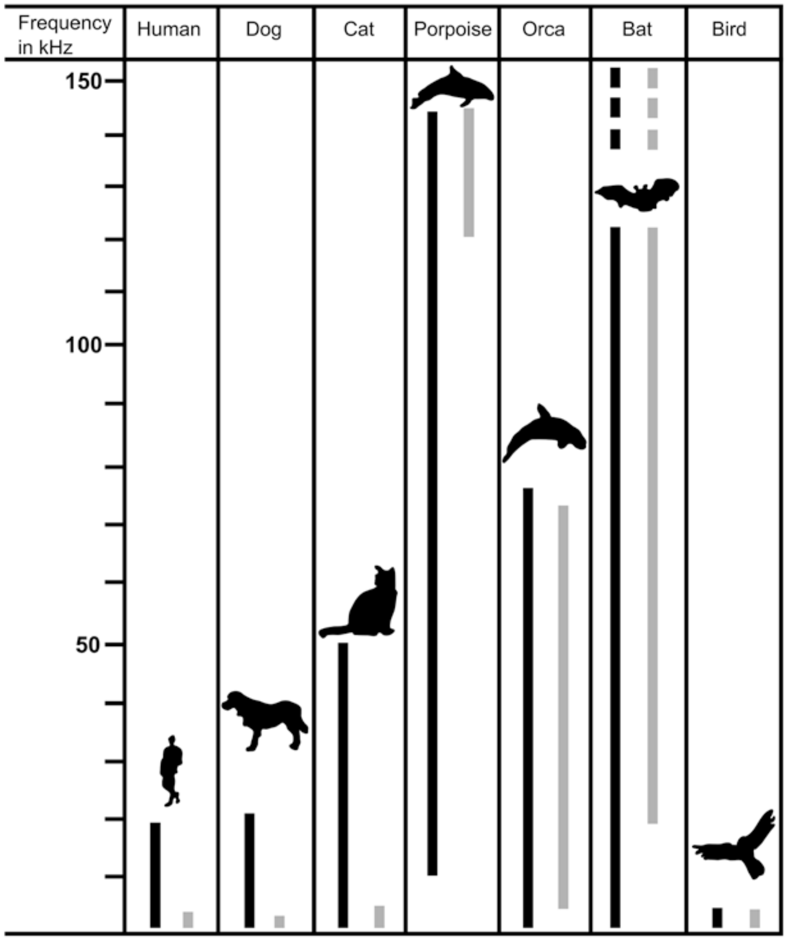


Fig. 4 Hearing (in black) and sound production (in grey) ranges in a selection of animals

marine organisms have developed ways to produce and detect sound. Whales, for instance, have developed distinct communication strategies and orientation systems, which allow them to find prey and communicate with conspecifics over great distances. For example, blue whale calls have been heard at ranges of tens or even hundreds of kilometres.

Toothed whales (odontocetes) use echolocation. They produce very high-frequency sound waves by forcing air past so-called *phonic lips* into the air sacs of their nasal passages. The clicks are transmitted through sound conducting acoustic fat of different densities in the front of their head (the *melon*), directing the sound in to a narrow beam. The emitted sound waves travel through the water until they reach an object, such as a prey item or an underwater obstacle. The object reflects some of the sound energy, creating an echo. The returning echoes are mainly received through the whale's lower jaw, containing fat which channels the perceived sound towards their inner ear complex (Fig. 5). Thus, by emitting ultrasonic sound pulses, odontocetes listen for echoes and can detect objects underwater. They can basically 'see' their environment through the sound waves they produce, in some ways similar to the echo sounder on board a ship.

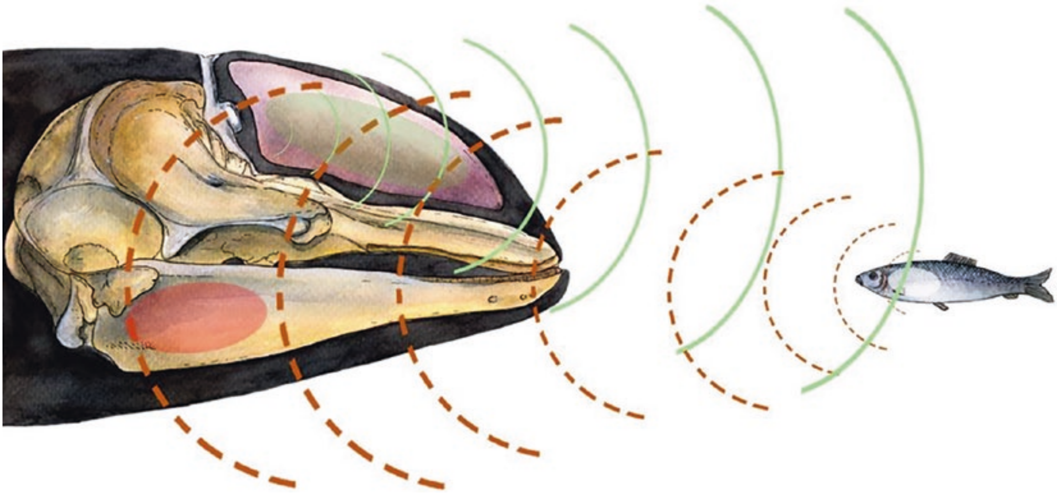


Fig. 5 Sound production and reception in a harbour porpoise. The purple structure in the forehead is the acoustic fat of the melon, which channels the emitted clicks (green). The sound is reflected by the fish (orange dashed line) and mainly received through the lower jaw. The red shading indicates the mandibular acoustic fat close to the ear bone. © Annika Toth

Baleen whales and seals do not use echolocation, but they still rely on sound and hearing for survival. Seals, and probably also baleen whales, produce sounds with their larynx and some additional air sacs, similar to terrestrial mammals. Besides good underwater and in-air hearing abilities, pinnipeds (true seals, walrus and eared seals) can perceive water disturbances with their whiskers to detect water movements generated by swimming fish.

► Example

Marine mammals have evolved adaptations that allow them to use sounds both to detect prey and to avoid predators. An interesting example is the frequency range of sounds and hearing of harbour porpoises compared to one of their predators, orcas. Orca sounds consist of a wide range of whistles and pulsed calls, with fundamental frequencies as low as a few kHz and harmonics beyond 100 kHz. Their best hearing is around 40 kHz. Harbour porpoises hear best between 120 and 140 kHz but can also hear sounds as low as a few kHz. Harbour porpoise signals, on the other hand, do not contain much energy at frequencies below 100 kHz and are centred around 120–140 kHz, where they hear best. It is believed that porpoises have adapted their sound production to higher frequencies, which are out of the hearing range of orcas. This prevents orcas from hearing sounds from their potential prey. Porpoises, on the other hand, can hear the sounds from nearby orcas and may therefore be able to avoid being captured. However, orcas have highly specialised hunting strategies and often stop making sounds before starting a hunt, making it more difficult for their prey to evade the attack.

Some of the strongest reactions to sounds played to marine mammals occur when a playback signal sounds like a natural predator. Again, orcas are an interesting example. There are different types of orcas: some feed on marine mammals, while others only eat fish. The different orca types also have different sound repertoires. Orca sounds were played back to Canadian harbour seals, which are regularly preyed upon by orcas. The seals responded aversively to sounds from mammal-eating orcas, but they did not respond to calls of fish-eating orcas. ◄

4 Impact of noise pollution on marine mammals

There are many ways humans utilise the oceans, and many of these activities introduce sound into the natural environment. Underwater noise pollution is caused by, for example, recreational boats, commercial shipping, windfarms, oil rigs, underwater exploration for oil and gas, and military activities. Highly utilised areas often have particularly high levels of underwater sound. Noise pollution may however be just as bad or even worse in quieter areas due to a smaller degree of *habituation* (become accustomed to a behaviour or condition) in animals living in such environments.

Because many marine mammals use acoustics as an important way to detect prey, to communicate or to orient themselves, a functional hearing system is of uttermost importance to them. To a certain degree, marine animals can increase the sound level or frequency range of their communication signals to make them more audible under noisy conditions. If communication sounds are masked by anthropogenic noise, they may not be able to hear calls of conspecifics to find mating opportunities or food. This can potentially play a major role in individual or species survival.

Noise can also disturb the animals' natural behaviour, make them leave their known habitat to find more silent locations, interrupt feeding, change diving behaviour, maybe even cause reproductive impairment through acute and chronic stress, and lead to temporal or permanent changes in distribution. Loud continuous or impulsive noise can damage hearing at certain frequencies, temporarily or permanently, which can result in failure to hear important signals, such as an approaching ship or a certain frequency component of mating calls. Additionally, certain types of anthropogenic noise, like military sonar, can lead to death when deep-diving whales attempt to escape or evade the sound by ascending too quickly.

Hearing impairment is caused by exposure to loud sounds, also to less intense but continuous noise over longer periods. If temporary hearing impairment occurs, it is called temporary threshold shift (TTS). A TTS is a passing increase in the auditory threshold resulting in momentary hearing impairment. We humans know this phenomenon as the 'discotheque effect', as our hearing is temporarily reduced after exposure to loud music. A permanent hearing threshold shift can occur as a result of repeated TTS events or from a single exposure to an intense sound. Both humans and marine mammals can become permanently less sensitive or even deaf to sounds of certain frequencies after loud or long exposure of sound.

► Example

Another problem that can be investigated with bioacoustics is collisions between ships and whales. The *International Whaling Commission* runs a global ship strike database (► http://iwc.int/ship-strikes), and it shows an increasing number of records over the last years. Why do whales and manatees get hit by vessels instead of avoiding them?

One of the reasons may be that the main noise source of a boat is the engine, which is situated in the stern of the boat. The hull is shielding the engine noise towards the front, so straight ahead of the boat the noise level is substantially reduced. If the animal approaches the boat sideways, the noise level drastically increases, making it aware of the approaching danger. If an animal forages or sleeps straight ahead in the ship's pathway, it may not perceive the sound of the engine and propellers, making it more vulnerable to collide with the ship, while whales startled by noise tend to surface rapidly, putting themselves in greater danger for collisions at the surface. The animal may even seek out a location straight ahead of the boat, to avoid too much noise from the approaching vessel. Additionally, underestimation of vessel speed, and maybe also hearing impairment, could also explain why animals are increasingly colliding with boats. Also, the number of fast-moving boats in waters frequented by cetaceans and manatees are constantly increasing. ◄

Continuous stress through noise pollution can supress the immune system and make marine life more vulnerable to infectious diseases and parasitic infections. Many marine mammals hear and communicate at frequencies different from the ones used by humans. They may therefore be affected by sounds that we cannot hear. Thus, when evaluating noise effects on marine mammals, it is important to use broadband recordings and analysis systems that can detect sounds also outside the hearing range of humans.

We need more research on the current levels of noise in the oceans, and how noise affect marine fauna. Politicians and decision makers need to take the results from such research into account when judging if mitigation measures are needed. The environmental impact assessment of new marine activities should include potential effects of noise emission. When needed, successfully tested sound mitigation measures should be implemented. Such measures could include effective animal warning devices used prior to military sonar, or so-called 'bubble curtains' used during construction work (see Exercise 5). One could also envision the development of quieter ship engines, changing shipping routes and harbour entry lanes, or speed reduction zones.

Tip

Buying more local goods instead of having everything shipped from abroad is another way to improve the current situation of extensive shipping (if you want to learn more about the marine traffic density in your area, you can search on the internet for links displaying marine traffic in your country's coastal zones or exclusive economic zone). Thus, by adjusting our personal behaviour we may improve the situation not only for marine mammals but also for the marine environment in general.

Current topics of acoustic and noise pollution research on marine mammals

How can we use acoustic research to protect marine mammals and to learn more about them?

We still do not know much about how marine mammals communicate and orientate themselves underwater with sound. Researchers work with trained animals, sometimes blindfolded to ascertain they only make use of auditory cues during the experiments. In this way, it can be shown that, for example, blindfolded toothed whales are able to find their way through a maze or detect and catch prey. This is considered the classical evidence of their ability to echolocate.

We can also investigate the hearing abilities of trained animals by hearing tests. This can be done in the same way as with humans: When a sound is played during an experiment, the animal is trained to indicate if it heard the sound by putting its snout on a certain *response symbol*. The hearing abilities of stranded individuals can be checked through measurements of their *auditory brainstem response* (ABR), small electrical potentials originating from the brain in response to auditory stimuli. The electrical potentials are recorded from the skin of the animal with electrodes embedded in suction cups, which are attached to the head. In this way we can measure if animals can hear a certain sound without being trained for a hearing test. The same methodology is used to detect hearing problems in newborn human babies. In stranded marine mammals, ABR measurements are sometimes used as a health parameter: The animal needs to be able to hear the species-specific frequencies to be released back into the wild.

Another approach to study the impact of noise pollution on marine mammals is using acoustic data loggers that can be deployed in critical habitats or along shipping channels. The data loggers record calls of the target species and ambient noise. In this way, scientists can better understand species distribution and habitat use without having to be continuously present on a boat for observations. Real-time passive acoustic sensors can transmit the sounds of seals and whales via satellite or radio links to a unit, which informs captains that animals are present, and that caution has to be practiced once an alert has been sent.

If you want to learn more, *Discovery of Sound in the Sea* offers great further learning materials and updated information on their web page ► https://dosits.org/ (only in English).

5 Teaching materials

Exercise 2.1: The frequencer

Have you ever wondered why some people hear sounds that others cannot hear? What are the frequency limits of your hearing, and are both of your ears equally sensitive to sound?

By listening to sounds of different frequency and intensity, you can register the frequency limits of your hearing. You can then compare your hearing limits with the ones of other animals (such as marine mammals; see an example in Fig. 3) to better understand in what ways our hearing differs from theirs.

Required materials

- Frequency sheet, available as online Supplementary file S2.
- Sound files, available as online Supplementary file S3.
- Loudspeaker and device to play sound files
- Headphones

Tasks

1. Listen to the sound files (always use the same volume); start with the lowest frequency (20 Hz).
2. Mark down when you hear the sound on the spreadsheet and leave the spot blank if you do not hear it.
3. After filling out your audiogram, you can repeat the exercise using each side of your headphones separately. This way you can create audiograms for both your right and your left ear and compare them.

Results

The result will be your own, personal frequency limits of your hearing.

Compare your results to other students and repeat the experiment with people of different age classes, like your parents and grandparents. Can you see differences in the hearing limits?

The results will not be as accurate as an audiogram measured by professional audiologists, as the played back sound level will depend on the type of loudspeaker.

Exercise 2.2: Human echolocation

Imagine you are trapped in a dark room you are unfamiliar with. How could you orientate yourself? Do you think you could teach yourself *human echolocation*?

Not only bats and toothed whales use echolocation—humans can also learn to echolocate, and some can become quite good at it. Visually impaired humans sometimes spontaneously learn to echolocate to compensate for their lack of vision. This phenomenon was formerly called 'facial vision' but is now known to be echolocation. Interestingly, one of the best human echolocators known, Daniel Kish from California, remembers learning this skill while being only a few years old. He only understood that he was using a method comparable to bats and dolphins when 20 years old. If you want to know more about this technique, check out ► https://visioneers.org/.

■ **Required materials**

- Several large wooden
- Plastic or cardboard panels (A0 or similar sizes)

■ **Tasks**

1. All students should try to practice emitting click sounds with their tongues prior to the experiment by using their own hand as a barrier to see if the clicks they emit are effective. It might take some time to produce efficient sounds, but it is a fun group exercise.
2. The students need to stand in a circle, facing the middle, shielding themselves with the panel 'walls'. During the experiment, all students should be silent to get the best experimental effect.
3. Position a blindfolded student inside the circle. The blindfolded student needs to emit click sounds while slowly walking towards the classmates, without stretched out arms, just relying on the sound of the returning echoes (◘ Fig. 6).

■ **Results**

When approaching a wall, the blindfolded student will notice a change in the returning echo of the emitted click sound. This should cause the student to stop or to turn, instead of walking into the wall. When stopped in front of a wall, the student should slowly reach out for them to appreciate the actual distance. You can also leave an opening in the shielded circle, that has to be found by echolocation. Afterwards, the students can disperse in the room and the blindfolded one can try to locate them by echolocation and find a way to navigate around them. Additionally, if the students are trained to echolocate, different materials can be tested, since harder surfaces (e.g. a white board) reflect sound in a different way than softer ones (e.g. cardboard) do.

Exercise 2.3: Name the sound

How much do you know about animal, environmental and anthropogenic sounds? And how much do you know about underwater sounds? Do you think you can discern natural from man-made underwater sounds

◘ **Fig. 6** Human echolocation (▶ Exercise 2.2). The students stand in a circle, shielding themselves with panel 'walls', while a blindfolded student is standing inside the circle. The blindfolded emits click sounds while slowly walking around, trying to figure out where the 'walls' are by listening for returning echoes easily? You have surely listened to songbirds, and you may have tried to identify them by their song. There are many more natural sounds to explore. In this exercise, we focus on some underwater sound examples that are completely unknown to most people. Can you guess the origin of those sounds?

Required materials

- Game file -loudspeaker
- *Name the sound* game, available as online Supplementary file S4

Tasks

1: Listen to the automatically played sound and repeat it by clicking on the small speaker symbol.

Guess its origin before continuing to reveal the four provided possible answers.

Was your first guess represented in the four answer options?

If not, choose A, B, C or D as your answer.
If so, was your answer correct?

Results

You will see how easy or difficult it is to discern natural and man-made sounds from each other. Probably animals often have the same difficulties as we do.

Exercise 2.4: Build your own hydrophone

Do you think that there is a simple technological way for us to hear sounds inside natural bodies of water? If so, what do you think you will hear down there?

Hydrophones are underwater microphones that can be easily built from a few components. With a hydrophone, you can listen for animals, such as whales and seals communicating with one another, or just the general underwater soundscape, sounding so eerie and unfamiliar to most of us ‘land dwellers’. And with the right materials, it only takes 30 min to build your own hydrophone.

Required materials (Fig. 7a)

- This exercise includes soldering, so proper safety precautions need to be in place and care is advised. A fume hood or other ventilation system is needed, students have to be extra cautious while the soldering iron is connected and accordingly need supervision for the soldering part of the task. If soldering is considered too dangerous or unfeasible during a class exercise, this part can also be prepared prior to the experiment.
- Piezoelectric crystal (they come in very different sizes and shapes, depending on the desired frequency response and sensitivity. For example, guitar piezos are fairly cheap and appropriate for the experiment. Crystals can be ordered online, or contact a company directly and ask for a crystal that can be used in the audible frequency range, since product types change over time and vary among companies).
- Solder with low melting point (e.g. solder containing silver) and soldering iron (preferably with the possibility to regulate the temperature manually).
- A shielded cable with two exposed final strands (long enough to be lowered into the study waterbody).
- A small plastic bottle (about 3 ml) with a plastic lid.
- Vegetable oil (olive, sunflower, or similar).
- A high-impedance amplifier (this can be bought relatively cheap online).
- A pair of headphones or a small loudspeaker.
- A connector to attach to the hydrophone cable (e.g. a so-called BNC connector that can be bought online).
- Sinking weight.

Tasks

1. Pierce a small hole into the lid of the plastic bottle, run the cable with its exposed final strands through it and attach a connector to the other cable end (outside the lid).
2. Solder one of the cable’s two strands on the inside and the other on the outside of the piezoelectric crystal under a fume hood. It is best to use solder with a low melting point. Ideally, the soldering iron temperature should be kept below 250°C to avoid damaging the

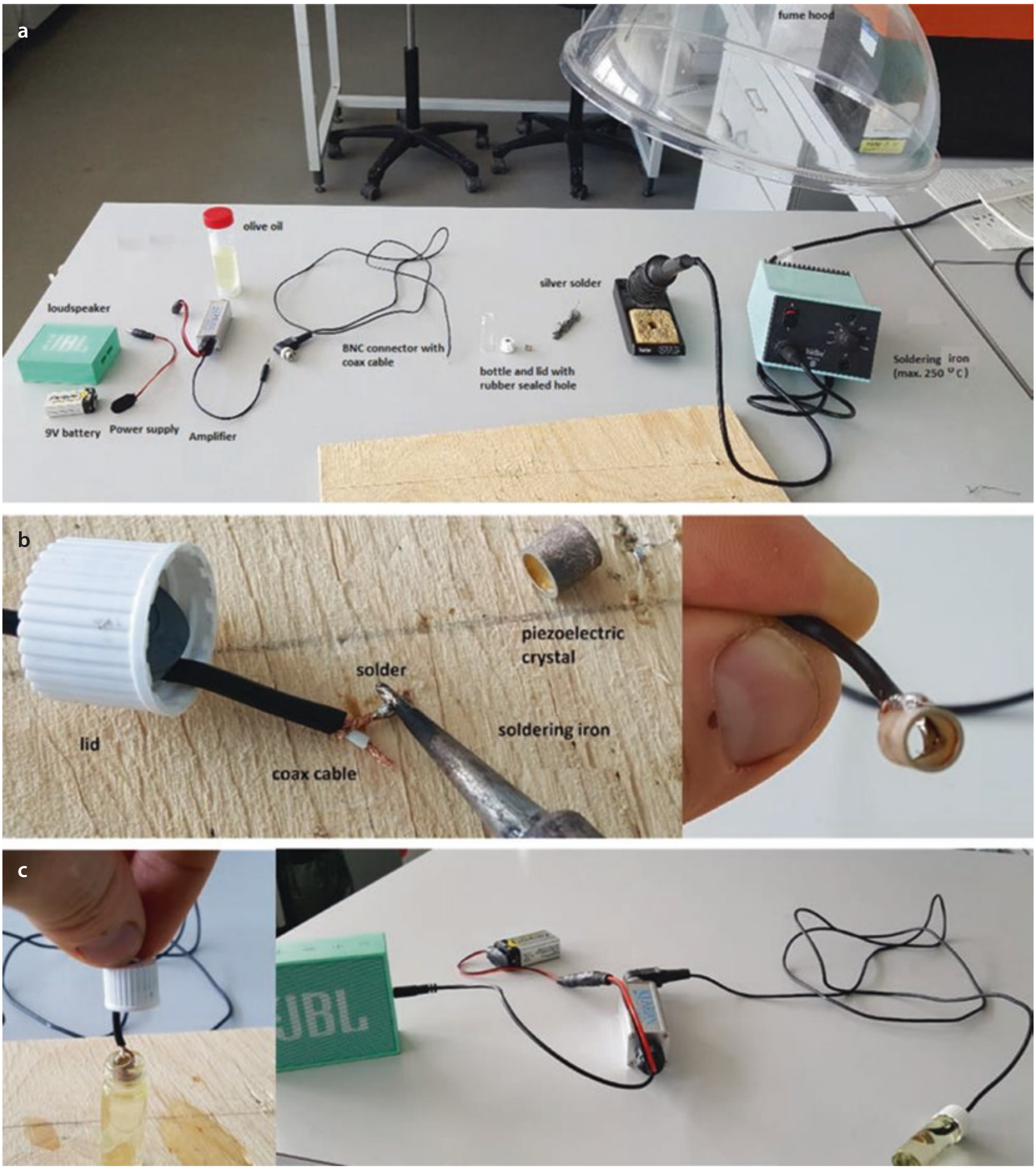


Fig. 7 Build your own hydrophone (▶ Exercise 2.4). **a** All necessary materials laid out on the working desk. **b** Soldering the cable, one strand on each side of the piezoelectric crystal. **c** After placing the crystal in the oil filled container, everything is connected and tested

sound-sensitive crystal. Always take caution not to inhale solder fumes (Fig. 7b).

3. Attach the amplifier to the connector, connect the output of the amplifier to the loudspeaker or headphones and switch it on. Now perform a ‘tap test’: tap gently on the crystal—you should hear a sharp noise through the loudspeaker.
4. Waterproof the crystal by pouring vegetable oil into the small plastic bottle and placing the crystal attached to the cable inside. Then, tightly seal the lid and attach the sinking weight to the hydrophone so it does not float.
5. Now the hydrophone is ready for use (Fig. 7c).

Results

The vegetable oil does not conduct electricity, but it conducts sound waves: therefore, the underwater sound waves can reach the piezoelectric crystal. The crystal transforms the pressure into voltage. The voltage is picked up by the cable strands and gets amplified before being transmitted to the loudspeaker. Thus, sound can be transmitted to the speaker without short-circuiting the crystal.

Tip

Bring the hydrophone out to a dock by a lake or by the sea and sink it into the water. Take caution to keep the rest of the electronics dry. Now, listen to the sounds. You can also splash the water surface with your fingers or throw a small stone into the water. You can hear if you can detect fish or other natural sounds, or perhaps you can hear a passing boat?

Exercise 2.5: Build a bubble curtain

Imagine you want to build an offshore wind farm, to generate renewable, clean energy. How would that effect aquatic life in the area? What can be done to protect them from harmful noise impacts?

Bubble curtains are noise mitigation measures that are used to dampen and absorb sounds of underwater constructions to prevent extensive hearing loss and noise harassment of marine mammals close to the construction location. Sometimes, huge bubble curtain systems are built around construction sites and activated when necessary. If you are interested in more information and pictures regarding this topic, search the internet for, for example, *The Big Bubble Curtain* by BBC.

In this experiment, we will build a miniature bubble curtain to show the effectiveness of such a mitigation device.

Required materials

- Air compressor (it can be a very simple, cheap aquarium pump, but the stronger the compressor, the better the result).
- Air bubble tube (use a commercially available bubble tube for aquaria).
- A 1.5 m hose to connect the pump with the air bubble tube.
- A waterproof sound device (e.g. a panic alarm or similar).
- An aquarium, a container or a bucket full of water.
- *Suction cup* tube holders or weights to prevent the air bubble tube from floating in the aquarium.

Tasks

1. Flex the bubble tube in tight loops, so that it results in almost two full rings. Make sure the end of the bubble tube is blocked (clamped or glued), so no air can escape that way (Fig. 8a). All air needs to flow through the holes along the tube for the bubble curtain to function properly. Then, mount the coiled tube with the *suction* tube holders or weights inside the aquarium, so that it stays at the bottom.
2. Connect the bubble tube with the compressor or aquarium pump by using the extra hose (Fig. 8b). The hose needs to be long enough to ensure that the bubble tube is fully submerged on the aquarium bottom, while the pump can safely be stored outside and connected to a power circuit. Then, fill the aquarium with water.
3. Place the sound-producing device in the middle of the air bubble tube rings, freely floating in the water column. If the device is in contact with the walls of the aquarium/bucket, they may function as sound transmitters and the experiment will not work, as the produced noise will be dispersed equally by all container walls.

   The students should be silent during the entire experiment.
4. Begin the experiment: start the sound device underwater and let the students listen to the sound of the freely submerged device for a moment.
5. Start the aquarium pump to initiate the bubble curtain and listen for changes (Fig. 8c). Do not let the experiment run for too long, since our ears adapt to the volume of the sounds and after some time noises appear louder to us again.

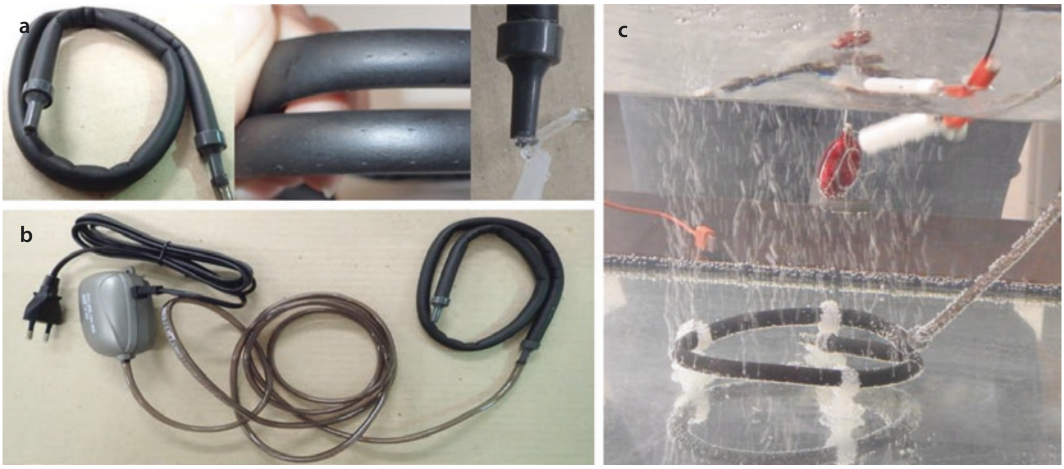


Fig. 8 Build a bubble curtain (▶ Exercise 2.5). **a** Air bubble tube for aquaria, the air holes are clearly visible. The end needs to be sealed; here we use glue. **b** Complete bubble curtain setup with aquarium pump, connective hose and air bubble tube. **c** Running bubble curtain experiment. The red alarm functions as free-floating underwater sound source. The white, self-built hydrophone is used to measure sound levels inside and outside the curtain for comparison

6. Think about the implementation of a bubble curtain on a large scale. Which materials are needed to make it work? Are there other problems that could be caused by using a bubble curtain?

Results

When the bubble curtain appears, there should be a clearly detectable drop in the sound level. Due to the limited amount of air holes in the commercially available tubes or depending on the strength of the used compressor, the effectiveness of this experiment is often not huge, but the students can get a good feeling for how effective it can be if more air bubbles and dual or triple layers are used.

For Task 6, additional ship traffic around the construction site, electricity supply to the construction site and running of loud generators should be considered, as well as huge hoses on the sea floor, likely damaging plants and microhabitats. Still, the impact of pile-driving is usually considered more dangerous and needs mitigation measures, even if they come at additional environmental costs.

Tip

By submerging the active sound device in the water, you can try to explain a hard sound barrier and sound reflection. The density difference between the two media (air and water) is several hundredfold; therefore, the two media form a *boundary* and we cannot hear what is happening underwater while we listen in air. This is why bodies of water usually appear silent to us. In this case, we still hear the sound of the panic alarm, because it is loud and the container walls transmit the sound back into the air. To prove this, let the alarm sink to the bottom, and the transmission of the sound will appear louder. Try the bubble curtain again with the sound device lying on the bottom. It will not work well, due to sound being transmitted by the container walls. You can also use a stethoscope to listen to the sound from inside the aquarium and better avoid the effects of the walls.

If the device would be submerged in the ocean where the sound is not redirected and transmitted, we would not hear it at the water surface. If we are submerged, we can hear more of the sounds present underwater. However, the air-water sound barrier still exists inside our ears, so we do not hear underwater sounds as good as in-air sounds. Many underwater sounds are outside the human hearing range but within the hearing range of marine life. Often, we may not think enough about the potential damage caused by underwater noise because we do not hear the noise that well.

Home Page

All animated graphics by Dan Russell are available under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License. ► https://www.acs.psu.edu/drussell/

Suggested reading

1. Tyack PL 1998. Acoustic communication under the sea. In: Hopp SL, Owren MJ, Evans CS, editors. Animal acoustic communication. New York: Springer-Verlag p. 163–220.
2. Wahlberg M, Linnenschmidt M, Madsen PT, Wisniewska D, Miller LA 2015. The acoustic world of harbour porpoises. American Scientist; 103:46–53. https://doi.org/10.1511/2015.112.46.
3. Au WWL 2018. Echolocation. In: Würsig B, Thewissen JGM, Kovacs K, editors. Encyclopedia of marine mammals. New York: Academic Press.
4. Nummela S, Yamato M 2018. Hearing. In: Würsig B, Thewissen JGM, Kovacs K, editors. Encyclopedia of marine mammals. New York: Academic Press.
5. Mann D, Hill-Cook M, Manire C, Greenhow D, Montie E, et al 2010. Hearing loss in stranded odontocete dolphins and whales. PLoS ONE 5(11):e13824. https://doi.org/10.1371/journal.pone.0013824.