POTENTIAL EFFECTS OF NOISE FROM HUMAN ACTIVITIES ON MARINE ANIMALS

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Abstract

There is considerable interest in the effects of noise from human activities on marine animals but our knowledge is limited. This makes it difficult to demonstrate compliance with environmental protection requirements in the conduct of ocean activities. Consequently, a significant amount of research is being conducted in Australia and world wide. This paper discusses the areas of potential impact and what is known. Potential levels of impact include disturbance, masking of sounds of interest and hearing damage. Studies of behavioural reactions to noise exposure have demonstrated that disturbance does occur, but it is more difficult to determine the consequence of the disturbance. The potential for masking and hearing loss can be inferred from what is known about effects on humans and terrestrial animals and the limited data available for marine animals, but depends on the validity of modelling the differences in animal hearing mechanisms in air and water.

INTRODUCTION.

Noise has long been recognised as causing problems to humans ranging from disturbance to hearing damage. In the last 10 years or so there has been increasing concern that noise from human activities may cause similar problems to marine animals. This has been heightened by the recognition of the importance of acoustic communication to marine animals in an environment where light has far less penetration than sound. Australia, like many other nations, has legislation that, among other things, protects the ocean environment and marine animals. The Australian Environmental Protection and Biodiversity Conservation Act (1999) covers Australian activities anywhere and provides a high level of environmental protection. The Act gives special protection to listed species and communities (this includes listed threatened species and ecological communities, listed migratory species and listed marine species) as well as providing strong protection for cetaceans (whales, including dolphins and porpoises). Public attention tends to focus on whales, and the subject of noise and whales has become very controversial in the USA, much of this fuelled by misunderstanding of the acoustics, leading to misinterpretation of the potential effects of noise.

A difficulty both in complying with the requirements of the Act and in demonstrating compliance, is the lack of knowledge of the impact of noise on marine animals. This paper considers the potential effects of noise in terms of the current knowledge and research in progress. The effects of explosions are not discussed in detail, since much more is known about these effects (see Richardson et al., 1995).

TYPES OF NOISE IMPACT.

Generally, the expectation is that lower noise levels result in disturbance or masking while higher levels are required to cause actual damage to hearing and higher levels still to cause other tissue damage. Explosions can cause substantially greater damage than sound generated by vibrating transducers such as those used in most underwater sound sources or noise incidental to most human activities (e.g. ship noise). The effects of noise on marine animals can be graded, generally in order from the least to greatest impact as follows:

- Disturbance: inconsequential, with positive effect, with negative effect
- Masking of sounds of interest to the animal
- Hearing damage – through long term exposure
- Hearing damage through high level short term exposure
- Tissue damage other than hearing
- For explosions: substantial damage or death

DISTURBANCE AND BEHAVIOURAL EFFECTS.

Disturbance may be detectable from observable changes in behaviour. It may be inconsequential (the animal resumes normal activities soon after exposure) but whether it is or has more significant effect may be difficult to determine. Examples are reactions to the passage of vessels or short term sounds.

Disturbance may be beneficial as in the case of an animal moving out of the path of a vessel and thus avoiding collision, or where a pinger on a net warns of the presence of the net so that the animal avoids entanglement. There is considerable interest in developing sound sources that are effective in warning of the presence of danger to marine mammals, such as fishing nets, shark nets, and the approach of fast vessels. The impact of ship strikes on the right whale population off NE USA is causing a reduction in the population that is considered to be not sustainable in the long term. There are similar problems with the manatees in Florida. Acoustic methods of warning marine mammals of the presence of nets in Australian waters are being trialled (see McPherson et al. 2004 for example).

Disturbance may cause changes that are negative in that they have long term effects. There may or may not be an observable behavioural reaction. Denial of habitat results when animals cease to use a habitat because of noise and are forced to use a less favourable habitat such as one where food supplies are poorer. For stocks of species that are in historically low numbers, this could affect the survival of the stock.

Habituation, where animals become used to a stimulus (such as noise) and cease to display behavioural responses, may be detrimental if the stimulus is harmful in some way. For example, animals may remain in an area affected by human activity because the resources in the area are worth the trade off, e.g. food, suitable nursing habitat, etc. An example is tolerating high levels of noise that over a long period cause hearing loss – humans show this type of behaviour. In these cases the lack of behavioural response or displacement makes assessment of disturbance very difficult.

Animal behaviour is complex and separation of behavioural reactions due to noise from all other behavioural reactions is difficult. It requires a good knowledge of the normal behaviour to provide baseline data, then extensive series of observations with and without noise exposure to provide a statistically significant result. Many studies end up being inconclusive. There is currently a considerable amount of research being conducted on effects of noise on behaviour in order to obtain the level of knowledge required to make valid assessments of the effects of noise. An example is the experimental work off the Queensland coast as part of the Humpback Whale Research Collaboration (Noad et al., 2004).

Some regulations specify observable behavioural changes as indicators of "significant" effects because these are indicators that can be used in management and mitigation. The difficulty in dealing with disturbance is that there may or may not be an observable behavioural change in the animal, and the disturbance may or may not be of consequence in the sense of causing long term effects.

It would be convenient for environmental management and mitigation if each of these effects could be associated simply with a particular sound level, and there is a tendency for people to quote particular sound levels as the maximum acceptable exposure. However, it is not just the level of the sound but also the acoustical characteristics (such as spectral content), the sound duration, the repetition rate, the total exposure dose, and the rate of change in level that are important. In the case of disturbance, other factors sensed by the animal (e.g. visual) may also be important and the response dependent of the information from senses other than auditory. Noise may cause a reaction because of what it implies, rather than a direct effect of the noise itself. For example, an increase in the level of noise from a vessel indicates that the vessel is approaching and that there is the threat of collision. In this case the animal is more likely reacting to avoid being struck by the vessel than because of an aversion to the noise itself. It has been observed that a rapidly increasing noise level from a vessel has more effect than a steady noise level (Watkins, 1986; McCauley et al., 1996).

The behavioural context (how the animals are interacting with each other and with the source of noise) is also important. There is also significant variation in effects with species. The complexity of the effects of noise exposure make it difficult to understand scientifically, to develop suitable regulations and to develop suitable measures of impact that are useable in management and mitigation. Such difficulty is not unusual in dealing with complex environmental issues.

Studies reporting observations of behavioural changes in marine mammals in response to noise vary widely in the noise levels at which responses were observed. The median responses of studies reported by Richardson et al. (1995) vary from 115 to 170 dB re 1 μPa. There are also reports of higher exposure levels without observable reaction (e.g. 180 dB re 1μPa, Madsen and Møhl, 2000). This wide variation illustrates the point that noise level alone is a very poor indicator of likely impact on behaviour. It becomes a much better indicator if different levels are established for each combination of source type, effect, species exposed, category (male, female, calf), behavioural context and current activity (migrating, resting, breeding, feeding). The duration of exposure and the frequency content of the noise are as important and need to be included. The lowest levels of median response given above are lower than the upper limits of natural ambient background noise (about 120 dB re 1μPa, around Australia – Cato and McCauley, 2002, 2003), levels that the animals would naturally experience, and much lower than sounds from many marine mammals themselves. This is further indication that noise level itself is a poor indicator of response.

HEARING EFFECTS

There have been a number of studies of fish hearing and of hearing in smaller marine mammals such as seals and toothed whales (e.g, dolphins) which are readily trained in captivity. There have been no studies of hearing in the larger whales which are too large to handle in captivity and none for any of the baleen whales, most of which are large whales such as the blue, right and humpback whale. Significantly, these baleen whales were the species most depleted by whaling in the Australian region. Most of our knowledge of the effects on noise on hearing, such masking and noise induced hearing loss is based on studies of humans and laboratory animals, so it is important to be able to apply this substantial amount of knowledge to marine animals.

To apply what is known from studies of terrestrial mammals to marine mammals requires an understanding of how the hearing mechanisms compare. The large impedance difference (about 36 dB) between air and sea water has lead to different adaptations between marine and terrestrial hearing. Generally the differences are greatest in the outer and middle ears and least in the cochlear. The outer and middle ear of terrestrial mammals, particularly the middle ear, are generally interpreted as providing an impedance match between air and the fluid of the cochlear which has an impedance close to water (Yost, 1994). The effect is also to provide pressure amplification. A consequence of the impedance differences is that for the same sound intensity in air and water, the sound pressure in water is about 36 dB higher and the particle velocity about 36 dB lower than in air.

Since we usually measure pressures and express results as pressure levels, a mistake that is commonly made by non acousticians is to directly compare pressure levels in air and water for the purpose of comparing noise exposure of terrestrial and marine mammals. A more realistic approach would be to compare acoustic intensities. Audiograms for fish (Platt and Popper, 1981) and marine mammals (Richardson et al. 1995) show sensitivities match that of humans much more closely if intensities rather than pressures are compared.

Critical ratios have been measured for some species of seals and toothed whales (Richardson et al., 1995), and are broadly similar to that of humans at similar frequencies. The critical ratio is the difference in level between a tone at the threshold of aural detection and the spectrum level of masking noise at the same frequency. Small temporary threshold shifts due to short term noise exposure have been measured for some toothed whales ((Finneran et al., 2002; Nachtigall et al., 2003 and Schlundt et al., 2000). Effects of masking have also been studied. These measurements provide some confidence in applying knowledge of effects on hearing and from terrestrial mammals to the marine animals and allow some predictions of effects for which little information is available, such as potential hearing damage from noise exposure underwater.

The biggest unknown, however, is the hearing of the baleen whales for which no measurements are available. The impedance matching of the terrestrial ear is not needed for marine animals, but since the marine mammals evolved from terrestrial mammals, they retain a form of the ossicular chain. Just how this functions in baleen whales is not well understood, nor is the general mechanism of the middle ear (Ketten, 1997). This leaves a significant uncertainty in predicting effects on baleen whales.

Masking

If the critical bands (the bandwidths over which noise contributes to the masking a tonal signal) or the critical ratios are known for a marine mammal, the noise levels that would mask signals of interest can be calculated (Erbe and Farmer, 1994, reports examples of this). Critical bands and critical ratios have been measured for some species of marine mammal and the results are generally similar across species, and similar to values for terrestrial mammals. It seems that the cochlea is the part of the ear that shows the least difference between species, whether terrestrial or marine. For those marine mammals for which there is no information available (notably the baleen whales), the best we can do is to estimate the upper and lower limits on masking using the range of critical bands and ratios known for other species.

Estimates of masking need to be interpreted in the context of masking from the ambient background noise since this varies by more than 20 dB and high levels arise from animal vocalisations such as chorusing (Cato and McCauley, 2002, 2003).

Potential for hearing damage

Small temporary threshold shifts have been measured in some smaller toothed whales from short term noise exposure to levels from 179 to 201 dB re 1 μPa, the higher levels tending to be shorter duration, though with significant variation (Finneran et al., 2002; Nachtigall et al., 2003 and Schlundt et al., 2000). The same intensities in air would have pressure levels of 117 to 139 dB re 20 μPa. No data exist on levels of short term noise exposure that would cause permanent hearing damage in marine mammals, but there have been measurements of damage to fish hearing from short term exposure to intense sounds from seismic airguns (McCauley et al., 2003).

The levels causing temporary threshold shifts described above may be compared with the exposure from higher level anthropogenic and natural sources in the ocean. To determine the likely exposure from the following examples of source levels, it is reasonable to allow for propagation loss according to spherical spreading over short distances, so that a reduction of 20 dB at 10 m and 40 dB at 100 m would be expected. Sonar source (mean square) levels are mostly in the range 180 – 230 dB re 1 μPa and transmit over a narrow frequency band (Richardson et al., 1995). All ships have sonars and are used for wide variety of purposes. They are usually highly directional and transmit intermittently on narrow beams so that exposure would decrease substantially away from the beam direction. The higher source levels are obtained by summing the contributions of an array of separated sources, so that the actual noise levels are significantly less than the nominal level at 1 m. The noise of vessels (apart from the sonar) is predominantly from engines, gearing and propeller cavitation and is broad band, continuous and has limited directionality compared with sonar. Large vessels have (broad band mean square) source levels typically around 185 dB re 1 μPa (Richardson et al., 1995).

Air guns used in seismic surveying are usually used in arrays with combined (broad band mean square) source levels up to about 235 dB re 1 μPa at 1 m (radiated horizontally). Air guns are also quite directional, higher levels being directed vertically downwards than horizontally, since the purpose is to probe the underlying sea floor. The sounds are impulsive and sufficiently short in duration that the peak to peak or energy flux values are more appropriate than mean square measurements (used in all other examples given here). As with sonars, actual noise levels are less than the nominal value at 1 m.

Mean square broad band source levels of larger baleen whales are mostly in the range 160 – 188 dB re 1 μPa at 1 m (Richardson et al., 1995), while some sperm whale clicks have been measured as high as 236 dB re 1 μPa at 1 m (Møhl et al., 2003). The sperm whale clicks are very short duration (100 μs) and highly directional, accounting for the higher source levels compared with the lower frequency baleen whale sounds which have little directionality and long duration (order seconds). By concentrating the energy into a short duration pulse and narrow beam, sperm whales can achieve very high mean square source levels.

We can only speculate on the likelihood of hearing damage from long term exposure to anthropogenic noise, analogous to hearing loss in humans from industrial noise in the work place. Exposure to noise from the sources listed above would be intermittent and infrequent when compared, say, with the day by day exposure of a worker in a noisy factory. An exception might be the case of animals resident in a very busy port where there are shipping movements for much of the day throughout the year. No Australian port has traffic of this magnitude.

Sustained background noise in the ocean from human activities is mainly due to distant shipping, and known as "traffic noise" (Wenz, 1962). The good propagation in ocean basins allows ships to contribute to the background noise at great distances, and even though the contribution from an individual ship is negligible, high noise levels can result where there are many ships in an ocean basin. Even so, traffic noise would rarely reach broad band levels of 110 dB re 1 μPa and even these levels are less than the highest levels of naturally occurring ambient noise. Noise levels from natural ambient noise averages about 100 dB re 1 μPa and reaches levels of 120 dB re 1 μPa (Cato and McCauley, 2002, 2003). Traffic noise is most significant at frequencies below 200 Hz and is the dominant component at those frequencies around North America and Europe. This has lead to concern that at these frequencies sustained background noise is now higher due to human activities than it would be naturally. Australian measurements, where traffic noise is much less and in some places negligible (Cato, 1976), show that natural noise often reaches levels comparable to the higher levels of traffic noise during high winds and heavy seas or during biological choruses (Cato and McCauley, 2002, 2003).

Richardson et al. (1995) hypothesise that hearing damage to marine mammals as a result of prolonged noise exposure to continuous man made noise is not likely to occur in marine mammals, at least for source levels up to about 200 dB re 1 μPa at 1 m. Exposure to noise from sources with source levels higher than this will generally be infrequent and limited in duration, not the circumstances to provide permanent hearing loss from long termed sustained exposure. The most likely threat from prolonged exposure seems to be the busy ports where shipping movements and other industrial activities are sustained for long periods.

EFFECTS OF VERY HIGH LEVELS OF NOISE

While there is concern that very high noise levels may cause trauma such as tissue damage, there is little evidence to show that this can occur from other than explosions. The shock wave from an explosion can cause such damage and death, but there is a limit to noise level that can be produced in water by vibration of a solid object like a sonar transducer or part of a ship. This results when the pressure fluctuation becomes comparable to the static pressure, so that the negative acoustic pressure cancels the static pressure and the total pressure goes to zero. As the pressure in water becomes very small, cavities are formed from small inhomogeneities resulting in cavitation. This most frequently occurs when an object moves very rapidly through water leaving a very low pressure region behind it (e.g. a propeller). The cavitation disrupts the process of sound generation by limiting the efficient transfer of energy to the water as sound and the surrounding bubbles absorb and scatter the sound. The point at which this occurs is about 220 dB re 1 μPa for a single sound projector surface at a depth of less than about 10 m (Urick, 1983). The threshold increases with depth but most sources of interest will be at depths of less than 10 m. It is for this reason that high source levels require a number of separated transducers so that the combined output at some distance reaches a level above the limit from one transducer. The actual sound level generated will at no point reach the source level, but the level received at distance will be the same as if a single source generated such a level. The cavitation limit of a transducer increases with depth as the static pressure increases, though the effect is very small for the shallow depths of most transducers. Explosive shock waves can produce much higher peak pressures above the static pressure because of the extremely fast rise time relative to a vibrating transducer.

Marine animals would have to be extremely close to a source to experience levels near this 220 dB re 1 μPa limit. Tissue damage by sound waves has been studied in ultrasonic medicine, and sound pressure levels for thresholds of tissue damage observed in laboratory animals have been reported to be of the order of 240 dB re 1 μPa (Carstensen, 1997). The frequencies used are in the order of a few megahertz, so much higher than the frequencies of sound likely to be encountered in the ocean that it is doubtful whether these results have much applicability for exposure of marine animals. Megahertz frequencies suffer so much absorption in water that they are useable only over distances of a few metres and have very limited application in the ocean.

Modelling has indicated that high levels of sound can increase rates of diffusion of gas into micro bubbles in tissues of animals, leading to bubble growth with consequent potential risk to divers and marine mammals of pathology similar to decompression sickness (Crum and Mao, 1996). The results estimated that received levels above about 210 dB re 1 µPa may significantly increase the rate of diffusion. The extent of the effect also depends on the exposure time. Such levels would be encountered from sound sources such as sonars only within metres of the transducers, so close that collision with the ship would be the greater danger. Jepson et al. (2003) claims to have found evidence of decompression sickness in whales stranded on the Canary Is. and on the coasts of Britain. Since the Canary Is. strandings occurred at a time of naval operations with sonar, they suggest that exposure to the sonar signals may have caused bubble growth. This article was criticised by Piantadosi and Thalmann (2004) on the basis that the whales do not develop sufficient gas saturation in tissues for this effect to occur and that the pathology reported was not consistent with decompression sickness. Marine mammals have substantial adaptations against the occurrence of decompression sickness.

CONCLUSIONS

Australian legislation gives high protection to marine animals and there is considerable public interest on impact on whales of noise from human activities. There are a range of effects that noise can have on marine animals but our knowledge is quite limited in this respect. The lack of knowledge makes it difficult for users of the ocean to comply with the requirements of the EPBC Act and to demonstrate that their management and mitigation strategies are effective. Part of the problem is the difficulty in studying marine animals given the difficulties of working in the ocean. This is particularly difficult with the larger whales, since they cannot be studied in captivity and it is difficult to carry out controlled observations on them at sea.

Disturbance is difficult to distinguish from other behavioural reactions. While it would be convenient to relate onset of disturbance to particular noise levels, thus leading to criteria based on noise levels alone, many other factors play a part in the reactions and behaviour of animals, such as the characteristics of the noise, the behavioural context during exposure and the differences between species. As a consequence, measurements of noise levels associated with disturbance to whales vary over such a wide range as to be of very limited value in determining what exposure is acceptable or in establishing a criterion.

Little is known about the potential for hearing damage from short term exposure to very high levels of noise. There are, however, analogies that can be made between what is known of mechanisms of hearing damage for humans and laboratory animals and the marine animals. Measurements of values such as critical ratios and temporary threshold shifts in various species of fish and marine mammals are consistent with such inferences. These allow predictions of masking for example. They also suggest that it is unlikely that human induced sustained background noise would be sufficient to cause permanent hearing damage from long term exposure, except for animals resident in very busy ports.

Apart from hearing damage, the shock wave from an explosion can cause tissue damage or death. Similar effects have not been established for high intensity sound generated by transducers, though some theories of how such effects could arise have been presented.

There is currently a significant amount of research in progress world wide addressing the inadequacies in knowledge.

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