PAPER

A Review of the Effects of Seismic Survey on Marine Mammals

AUTHORS

Jonathan C.D. Gordon
Sea Mammal Research Unit, Gatty Marine Laboratory, University of St Andrews

Douglas Gillespie
Song of the Whale Research Team, International Fund for Animal Welfare

John Potter
Acoustic Research Laboratory, National University of Singapore

Alexandros Frantzis
Pelagos Cetacean Research Institute

Mark P. Simmonds
Natural Resources Institute, University of Greenwich

René Swift
Aberdeen University

David Thompson
Sea Mammal Research Unit, Gatty Marine Laboratory, University of St Andrews

ABSTRACT

This review highlights significant gaps in our knowledge of the effects of seismic air gun noise on marine mammals. Although the characteristics of the seismic signal at different ranges and depths and at higher frequencies are poorly understood, and there are often insufficient data to identify the appropriate acoustic propagation models to apply in particular conditions, these uncertainties are modest compared with those associated with biological factors. Potential biological effects of air gun noise include physical/physiological effects, behavioral disruption, and indirect effects associated with altered prey availability. Physical/physiological effects could include hearing threshold shifts and auditory damage as well as non-auditory disruption, and can be directly caused by sound exposure or the result of behavioral changes in response to sounds, e.g. recent observations suggesting that exposure to loud noise may result in decompression sickness. Direct information on the extent to which seismic pulses could damage hearing are difficult to obtain and as a consequence the impacts on hearing remain poorly known. Behavioral data have been collected for a few species in a limited range of conditions. Responses, including startle and fright, avoidance, and changes in behavior and vocalization patterns, have been observed in baleen whales, odontocetes, and pinnipeds and in some case these have occurred at ranges of tens or hundreds of kilometers. However, behavioral observations are typically variable, some findings are contradictory, and the biological significance of these effects has not been measured. Where feeding, orientation, hazard avoidance, migration or social behavior are altered, it is possible that populations could be adversely affected. There may also be serious long-term consequences due to chronic exposure, and sound could affect marine mammals indirectly by changing the accessibility of their prey species.

A precautionary approach to management and regulation must be recommended. While such large degrees of uncertainty remain, this may result in restrictions to operational practices but these could be relaxed if key uncertainties are clarified by appropriate research.

INTRODUCTION

Marine seismic surveys produce some of the most intense manmade noises in the oceans and these surveys often operate over extensive areas for extended periods of time. The juxtaposition of intense sound sources and acoustically sensitive marine mammals must give rise to concerns about possible adverse impacts. Intense sounds can potentially have a number of effects on marine mammals. In this review, we divide possible effects into four categories: physical (including physiological) effects, perceptual effects, behavioral effects, and indirect effects. Possible physical and physiological effects include damage to body tissues, gross damage to ears, permanent threshold shift (PTS. i.e. permanent reduction in auditory sensitivity), temporary threshold shift (TTS. i.e. reduction in auditory sensitivity with eventual recovery), and chronic stress effects that may lead to reduced viability. The most likely perceptual effects would be masking of biologically significant sounds (e.g. communication signals, echolocation, and sounds associated with orientation, finding prey or avoiding natural or manmade threats) while behavioral effects could include disruption of foraging, avoidance of particular areas, altered dive and respiratory patterns, and disruption of mating systems. Indirect effects might include reduced prey availability resulting in reduced feeding rates.

There are a number of existing reviews of this topic. The comprehensive book on marine mammals and noise by Richardson and colleagues (Richardson et al., 1995) summarized most of the relevant work up to that date. Since then a number of reviews have focused on air gun noise and marine mammals, including Evans and Nice (1996), Richardson and Würsig (1997), and Gausland (2000). Harwood and Wilson (2001) consider the issue in a risk assessment framework, while an expert panel have provided recommendations on levels of exposure and mitigation procedures likely to minimize risk to marine mammals (HESS, 1997). A series of reports by the National Academy of Sciences have reviewed and summarized information relating underwater noise and marine mammals and made recommendations for future research. Relevant chapters from the latest of these are summarized elsewhere in this volume (Wartzok et al., 2004). Here our intention is to summarize the existing information including recent findings, make it available to an audience that includes non-biologists, and comment on some of the implications for regulation and management.

Methods for Investigating the Effects of Manmade Noise on Marine Mammals

Marine mammals, which spend most or all of their lives at sea and much of that time submerged, must rank amongst the most difficult of research subjects. We believe that, especially for a non-biological readership, a brief overview of research approaches that might be used to study these animals will help to set the context for a review of the potential effects themselves. If nothing else, this might explain why so many uncertainties still exist in this field.

Captive Studies

Studies on trained captive animals allow detailed observations and measurements of psychometric parameters. In this case, measurements of auditory sensitivity, auditory function, and the effects of noise exposure are extremely relevant. There are significant shortcomings, however. Only a limited range of species is routinely kept in captivity, and it is unlikely that some groups, offshore species and the great whales for example, ever will be. Sample sizes are usually small; typically data come from only one or two individuals, which may not be representative of animals in the wild. Captive studies can provide examples of responses (often dramatic) to high levels of exposure but they do little to elucidate disruption of natural patterns of behavior and extrapolating from the behavior of trained animals in small enclosures to the real world is problematical.

Extrapolation and Modeling

Approaches involving physical and physiological modeling and extrapolation from other species have some scope for predicting the occurrence of physical phenomena such as trauma and threshold shift but they are of limited value in predicting disturbance reactions, which are likely to vary greatly and will depend on species and context.

Observing Behavior in the Field

Measuring behavioral responses requires data to be collected from unrestrained animals at sea. Different approaches have their own strengths and weaknesses.

- **Visual observation**: Observation from ships has often been used to study the behavior of cetaceans. Unfortunately, even large whales are difficult to observe at sea. They are visible for only brief periods at the surface where they perform a small subset of their behaviors that may be poor indicators of disturbance. Further, the presence of a vessel close enough to allow visual observation can influence the behavior of the subjects. This approach is of little value for studying pinnipeds, which are particularly difficult to observe at sea.

Aircraft have the advantages of providing higher vantage points and can be less likely to affect behavior than ships (Richardson et al., 1995). However, air surveys are expensive and observation time will be limited by restricted range and endurance.

Observations from coastal vantage points do not rely on expensive platforms and do not affect the behavior of the target animals. Theodolites can be used to accurately locate and track animals seen at the surface. Inevitably though, observations are restricted to inshore waters with adjacent high vantage points, and even then it can be difficult to follow the behavior of individual animals.

- **Passive acoustic monitoring:** For the more vocal species, acoustic monitoring can provide researchers with a variety of behavioral cues. Acoustic monitoring can be carried out using remote hydrophones or receivers (Clark & Fristrup 1997; Clark & Charif 1998; Culik et al., 2001) or from relatively inexpensive small vessels that are quiet and are unlikely to affect the behavior of the study animals. Acoustic monitoring has several advantages compared to visual methods: 1) the range for acoustic detection is often greater than visual range; 2) many species are audible for a greater proportion of time than they are visible at the surface; 3) monitoring can continue through the night and in poor weather conditions (although background noise does increase in rough weather, which reduces acoustic range, this is typically less pronounced than the effect of the same weather on visual detectabilty); and 4) data collection and analysis can be readily automated. However, not all marine mammal species are vocal, and the significance of changes in vocal behavior can be hard to interpret. Acoustic monitoring can be readily combined with visual observations and the two approaches should be seen as complementary.

- **Telemetry:** Both direct real-time tracking using acoustic and VHF telemetry and remote tracking using satellite transmitters have been widely applied to study pinnipeds and, more recently, cetaceans. Telemetry techniques, particularly satellite-linked tracking systems, can provide large quantities of reliable data, including information on underwater behavior (Martin et al., 1998; Fedak et al., 2001), on physiological responses such as heart rate (e.g. Thompson *e*t al., 1991; Thompson et al., 1998), and on the physical environment (Lydersen et al., 2002). Tags incorporating hydrophones and sound recording devices have recently been developed (Fletcher et al., 1996). Because they provide both detailed data on animal movements and record received sound and the subject's vocalizations, they are well suited for noise effects studies. Indeed such tags are already being used to measure responses of sperm whales to seismic air guns (Johnson & Tyack, 2003).

Pinnipeds can be captured on or close to land and good results have been obtained by gluing transmitters to their fur (Fedak et al., 1983). However, the lack of an effective method for attaching tags remains a major constraint for cetacean telemetry. Long-term cetacean attachments have been achieved with implantable tags (e.g. Watkins et al., 1999; Mate et al., 1999), however, these methods are invasive and space constraints within the dart limit the sophistication of the telemetry packages. A better approach for cetacean effects studies may be short-term attachments of archival tags using suction cups (e.g. Baird, 1998; Johnson and Tyack 2003).

Tag costs and problems of attachment mean that marine mammal telemetry studies usually have small sample sizes and the use of tags also requires ethical evaluation.

■ **Experimental control:** Ideally researchers should have full control over when and where a seismic source is active during field trials. If correctly designed, the resulting Controlled Exposure Experiments (CEEs) provide a powerful method for demonstrating cause and effect (see Tyack et al. this volume). Financial constraints may dictate that this approach is only possible with small-scale sources and in a limited set of conditions. Investigations of responses to full-scale seismic arrays will usually have to be conducted around ongoing surveys. Long-term effects will be almost impossible to investigate using CEE.

Effects of Air Gun Noise

Physical Damage

Underwater explosions cause tissue damage and can be lethal. The effects of shock waves from explosions have been explored using submerged terrestrial animals (Goertner 1982; Richmond et al. 1973; Yelverton et al. 1973), and dolphin carcasses (Myrick et al. 1990). However, pressure pulses from air guns have longer rise times and are therefore less likely to cause damage than pressure waves from high explosives. To date there is no evidence that seismic pulses cause acute physical damage to marine mammals.

Human divers exposed to pulses of very intense low frequency sound have experienced non-auditory physiological effects, including resonance of the lungs and other cavities and symptoms of dizziness, nausea and visual disruption. Possible sources of such pulses include a new generation of Low Frequency Active Sonar Systems (Cudahy & Ellison, 2002). The potential for relatively short seismic pulses to cause similar effects has not yet been investigated.

Another potential mechanism by which powerful sounds could cause tissue damage is by sound-induced growth (rectified diffusion) of gas bubbles in super-saturated tissues of diving mammals. Although marine mammals are breath-hold divers and are thus less likely to suffer the bends than human divers breathing compressed air, it is believed that during long sequences of dives, their body tissues could become super-saturated (Ridgway & Howard 1982). Crum & Mayo (1996) calculated that exposure to 500 Hz sounds at SPLs of 210 dB re:1ìPa could cause bubble growth that could induce the 'bends' in marine mammals. They considered that this effect was unlikely at SPLs below 190 dB re:1ìPa. However, as bubbles get larger the so-called "Laplace pressure" resulting from surface tension in the bubble wall, which serves to limit the expansion of small bubbles, will reduce and passive diffusion from saturated tissue into bubbles may then be sufficient to maintain bubble growth. The potential for noise from seismic air guns to cause such effects has not been investigated.

Behaviorally-Mediated Damage and Stranding

A series of incidents in Greece, the Bahamas, Madeira, and the Canary Islands (Frantzis, 1998; Balcomb & Claridge, 2001; Jepson et al., 2003) have served to establish that military sonar can cause cetaceans, in most cases beaked whales, to strand. Autopsies of some of these animals reveal signs of physical damage including hemorrhages in the acoustic fats, sub-arachnoid bleeding and gas and fat emboli in certain tissues (Evans and England, 2001; Jepson et al., 2003). The extent to which these are a direct result of sound energy or are a secondary behaviorally-mediated effect is not clear. For example, panic could lead to high levels of stress resulting in internal bleeding and/or could cause rapid surfacing or changes in patterns of diving behavior that might trigger decompression sickness.

Two incidents hint at the possibility of similar links between air guns and beaked whale strandings. In 2002 two beaked whales were found stranded in the Gulf of California close to an area in which a scientific survey, using a powerful air gun array, was being conducted by the RV *Maurice Ewing* (Malakoff, 2002). The same vessel had been potentially linked to a beaked whale stranding event in the Galapagos in 2000 (Gentry, 2002) . It should be stressed that a causal link was not established in either case, but concern was sufficient for U.S. courts to agree to a restraining order until a more complete investigation could be completed. This is perhaps the strongest indication that air guns could lead directly to stranding and cetacean mortality.

If, as these incidents suggest, changes in animals' behavior can lead to physical damage, the zones of influence models typically used for regulation, in which it is assumed that physical damage will be restricted to limited areas very close to powerful sound sources, may have to be revised. As we will see, behavioral responses can occur at extended ranges and are often highly variable.

Auditory Damage

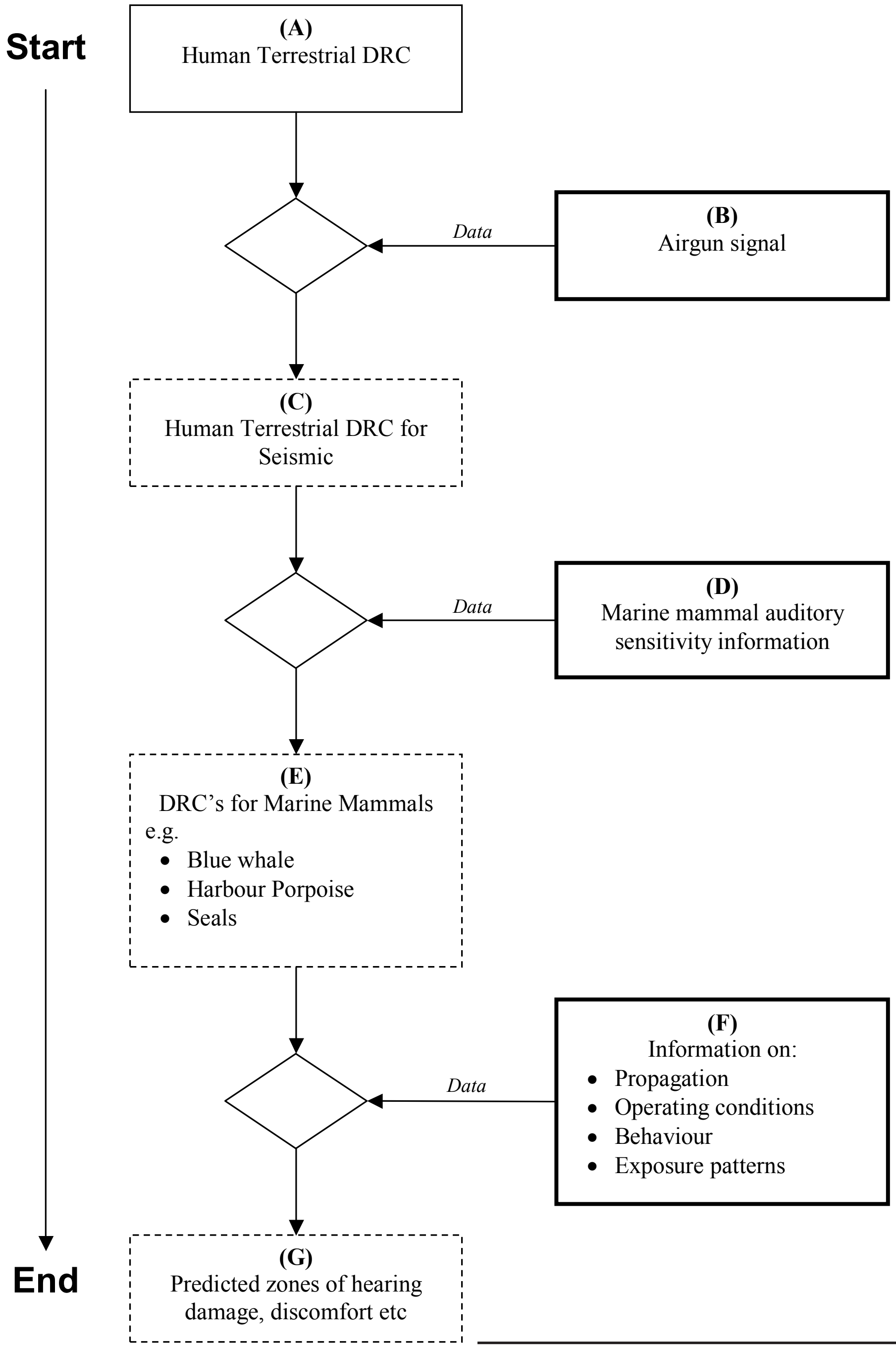
It is hardly surprising that ears, which have been adapted to be exquisitely sensitive to sound, are also vulnerable to being damaged by it. Underwater explosions can result in gross tissue damage in ears. For example, half of a sample of 10 Weddell seals (*Leptonychotes weddellii*) collected in McMurdo Sound after a series of dynamite explosions, had tissue damage in their ears (Bohne et al. 1985; 1986). Similarly, Ketten et al. (1993) found damage consistent with blast injury in the ears of humpback whales (*Megaptera novaeangliae*) trapped in fishing gear off Newfoundland after blasting operations in the area. To date there is no direct evidence of damage to the ears of marine mammals resulting from seismic sound sources.

■ **Noise-induced hearing loss; temporary and permanent threshold shifts:** Exposure to noise of sufficiently high intensity causes a reduction in hearing sensitivity (revealed as an upward shift in the hearing threshold). This can be a temporary threshold shift (TTS), with recovery after minutes or hours, or a permanent threshold shift (PTS) with no recovery. PTS may result from chronic exposure, and sounds that can cause TTS usually cause PTS if the subjects are exposed to them repeatedly and for a sufficient length of time. Very intense sounds, however, can cause irreversible cellular damage and instantaneous PTS.

TTS appears to be associated with metabolic exhaustion of sensory cells and certain anatomical changes and damage at a cellular level. Excessive metabolic and electromechanical response activity also leads to swelling in the hair cells, in neural connections, and in the vascular system of the cochlea. PTS may be accompanied by more dramatic anatomical changes in the cochlea including the disappearance of outer hair cell bodies and, in very severe cases, a loss of differentiation within the cochlea and degeneration of the auditory nerve.

As no direct investigations of threshold shifts induced by air guns have been made in marine mammals, any consideration of safe levels of exposure must depend to a greater or lesser extent, on inference and extrapolation. A schematic representation of this process is shown in Figure 1. This chain of inference requires the input of usually uncertain data and the making of assumptions at each step. The conclusions arising from such a process must be treated with caution as the errors introduced at each stage may become

FIGURE 1 **Schematic representation of routes of extrapolation and data needs (bold boxes on the right) to estimate safe levels of exposure to seismic pulses for marine mammals.**



(A) + (B) → (C)
(A) Existing information on safe levels of exposure to particular sounds in terrestrial mammals and humans combined with (B) our existing knowledge/data on the characteristics of seismic sources received at marine mammal ears is used to derive (C) acceptable levels of exposure (DRC) to marine seismic sources for humans and terrestrial mammals.

(C) + (D) → (E)
(C) Estimated acceptable levels of exposure to marine seismic surveys for humans and terrestrial models combined with (D) our current knowledge of auditory sensitivity in a range of marine mammal species would be used to estimate (E) safe levels of exposure (DRC) to marine seismic surveys for different marine mammal species.

(E) + (F) → (G)
(E) Estimates of safe levels of exposure combined with (F) estimates of exposure (based on our knowledge of source levels, propagation conditions, seismic vessel working procedures, and animal behavior) would be used to draw up (G) guidelines and practical codes of conduct to minimize the risk of hearing damage .

compounded. In the following sections we examine some of the steps in this process in greater detail.

■ **Hearing loss in terrestrial mammals (A):** Threshold shifts in man, including those caused by chronic exposure to industrial noise, have been an area of intense research. Extensive reviews are provided by Kryter (1985, 1994). Typically, and especially when human experimental subjects are involved, measurements of TTS are made in controlled conditions and these are used to infer the risk of PTS from higher levels of exposure. Often the goal is to calculate Damage Risk Criteria: levels of exposure that should not be exceeded without risking hearing damage.

Ward (1968) (cited in Richardson et al., 1995) investigated human damage risk criteria (DRC) for impulse noise in air, based on empirical observations of TTS, and derived a predictive formula for PTS using peak pressure levels, pulse duration, and number of pulses as parameters. Risk was found to increase with both the number of pulses and with their duration. The threshold for damage diminishes by 2 dB for each doubling of pulse length, up to a pulse length of 200 ms, beyond which there was no further decrease. Thus, for 'safe' exposure to 100 pulses the peak pressure level is 164 dB re: 20ìPa when pulses were 25 ms long, and 138dB re: 20ìPa for prolonged (>200 ms) pulses. As the number of pulses is reduced, the DRC is adjusted upward, by 5 dB per 10-fold reduction in pulse number. Thus for a single 200 ms pulse, the DRC is 148 dB re: 20ìPa. Exposure to a single pulse at this level might be expected to cause damage.

There are indications that DRC for impulsive noise currently applied to humans may underestimate the risk of hearing damage from impulsive noises. Procedures for predicting TTS and PTS are based on the equal energy hypothesis, i.e. that threshold shift should be proportional to the product of intensity and time. Thus, impulsive noises are assumed to have a much-reduced potential to cause threshold shifts because of their short duration. However, the relationship of TTS to the characteristics of pulsed sound is complex (Melnick, 1991). In humans, the levels of TTS resulting from prolonged exposure reached an asymptote (indicative of PTS) 16 times faster for impulsive (impact) noise than for continuous noises (Laroche et al. 1989). This may be because pulses cause greater displacement of the basilar membrane (increasing the potential for sensory cell damage) than exposure to continuous noise.

■ **Nature of the seismic signals received at marine mammal ears (B):** Seismic gun arrays are designed to deliver a very well defined and uniform sound pulse in the desired direction—downwards. However, the characteristics of sounds projected in other directions are very different. Marine mammals will be distributed in a variety of positions relative to a seismic array and the signal they receive may have a complicated and variable nature. In deep water for example, it may include both components with a sharp onset and short duration received directly and longer pulses with slower rise times received by reflection from the seabed. These components may be separated by different time intervals, depending on water depth and the position of the marine mammal receiver within the water column. Measurements by Goold and Fish (1998) have shown that air gun arrays can produce significant sound energy up to, and probably beyond, 22kHz. Well above the lower (~200Hz) frequencies at which air guns are designed to provide most energy. In addition, many other sound sources are associated with a seismic survey, including networks of high frequency transponders used to track the positions of arrays of hydrophone streamer. All small cetaceans and pinnipeds for which audiograms have been measured are much more sensitive to sound at these higher frequencies than at 200Hz.

It is unclear which measurements of a seismic pulse provide the most reliable indications of its potential to impact the hearing sensitivity of different species of marine mammal, but at short ranges, where hearing damage may occur, the peak broad band pressure and pulse rise time and duration seem to be the most relevant measures (see section A, above). It should be emphasized, however, that the effects of noise with the characteristics of air gun pulses on hearing sensitivity have not been measured, even in easily studied terrestrial mammals and man, and extrapolation from existing data on the effects caused by generic 'impulsive noise' may be misleading.

■ **Marine Mammal Auditory Sensitivity (D):** A basic measure of auditory sensitivity is the audiogram: a plot of auditory threshold against frequency. Audiograms have been measured for many small cetaceans and pinnipeds that can be kept and trained in captivity, although for most species only a few individuals have been measured (Moore, 1997). The use of electrophysiological techniques to measure evoked auditory potentials allows thresholds to be measured much more quickly, at least for the smaller species and at higher frequencies (Dolphin, 1997). No equivalent measurements have been made of the hearing sensitivities of the great whales. Instead auditory parameters are inferred from the frequency range of their vocalizations, from levels of background noise, from field observations of responses to biologically significant sounds (Frankel et al., 1995), and from models of the physical characteristics of the inner ear (Helweg, 1999). If auditory systems of different species are assumed to have similar dynamic ranges then audiogram data, combined with threshold shift data from other species, might indicate the levels of sound at particular frequencies that could cause threshold shifts in marine mammals. It is almost certain that dynamic range of marine mammal auditory systems varies considerably. However, given the current lack of direct observations, extrapolations like this, with appropriate caveats, may often be the best that can be attempted.

■ **Direct measurements of noise-induced TS in marine mammals:** Only recently have experiments to measure threshold shifts directly been conducted with marine mammals. Initial work with odontocetes has been driven by concerns about effects of military sonar and explosions. Schlundt et al. (2000) measured masked hearing thresholds of bottlenose dolphins and belugas before and after exposure to 1 sec tones at 0.4, 3, 10, 20, and 75 kHz. Levels between 192 and 201 dB caused a 6 dB reduction in sensitivity except at 400 Hz, where no animals showed evidence of threshold shifts. There was evidence of some inter-individual variation in sensitivity: one dolphin showed a threshold shift at 75 kHz at 182 dB re:1ìPa while another showed no shift at a maximum exposure of 193 dB re:1ìPa. Threshold shifts described in this work are termed "masked threshold shifts" because background noise was broadcast during the experiment to provide a consistent noise floor in the test facility. Masked TTS are generally smaller than the non-masked TTS that would be induced by the same level of fatiguing noise. Finneran et al. (2000a) measured masked underwater hearing thresholds of dolphins after they had been exposed to sounds resembling distant explosions. No threshold shifts were evident after exposure to single pulses. This group is continuing this investigation of responses to powerful single pulses using a seismic water gun as a sound source (Finneran et al. 2000b). So far, however, no results have been published. (Water guns are not routinely used as sound sources by the seismic industry nowadays.) Au et al. (1999) explored the effects on bottlenose dolphins of longer exposures to broader band noise. They subjected individuals to a 5-10kHz (octave band) fatiguing source for at least 30 minutes over a one hour period. No TTS was evident at a received level of 171dB. However, a fairly substantial threshold shift of 12-18dB occurred at 179dB re: 1mPa.

There have been no direct observations of noise-induced PTS in cetaceans. However, Andre et al. (1997) reported patterns of cell damage, consistent with PTS effects, within the cochlea of a mother and calf sperm whale (*Physeter catodon*) that died after being struck by a high-speed ferry. They proposed that this might have been caused by long-term exposure to noise from the relatively high level of shipping in the Canaries.

Similar noise exposure experiments have been conducted with pinnipeds (Kastak et al., 1999). Detection threshold increases of 4.8 dB (harbor seal), 4.9 dB (sea lion), and 4.6 dB (elephant seal) were recorded in harbor seals, elephant seals, and California sea lions respectively exposed to 20-25 min. of octave band noise with mid frequencies ranging from 100 Hz to 2 kHz, at octave band sound levels of 60-75 dB above the threshold level at the central frequency. All animals showed full recovery after 24 hrs (Kastak et al., 1999). Responses of California sea lions to single impulses from an arc gap transducer (a device designed to frighten pinnipeds away from fishing gear) were investigated by Finneran et al. (2003). Exposure levels were equivalent to 178-183 dB re:1ìPa. While the two test animals showed avoidance responses, no TTS was observed.

It is clear that threshold changes can be induced in both odontocetes and pinnipeds by exposure to intense short tones and sounds of moderate intensity for extended periods. Exposures to single short pulses have not induced threshold shifts. However, it is difficult to extrapolate from these findings to the situation typical of a seismic survey, where animals will receive many pulses over the course of an exposure.

■ **Relative sensitivity of marine mammals to hearing damage:** It has been suggested that cetacean ears may be less vulnerable to acoustic damage than those of terrestrial mammals. However, there is no direct evidence to support this contention. The middle and inner ears of cetaceans are located outside the cranium and are enclosed in two fused, dense, bony capsules. The middle ear is enclosed by the tympanic bulla while the inner ear is within the periotic bulla. These bones are massive by comparison to homologous structures in terrestrial mammals, and this may be an adaptation to withstand pressure changes during diving. However, noise-induced threshold shifts result from damage to sensory cells of the organ of Corti, which sits on top of the basilar membrane within the cochlea. These structures are as delicate and vulnerable in cetaceans as in terrestrial mammals. In odontocetes, the organ of Corti is very well developed and exhibits conspicuous hypercelluarity. The stria vascularis—a well vascularised region that runs through the cochlea and maintains the high potassium concentration within the scala media, which is essential for the triggering of the ear's sensory hair cells—is also very well developed. It might be argued that this would make the ear less vulnerable to metabolic exhaustion but it could not protect the stereocilia of the hair cells from the physical damage that often underlies PTS, particularly that caused by relatively short exposure to intense impulsive sounds.

In terrestrial mammals, the ear can be protected from intense noise by the operation of the 'stapedius reflex'. This involves the contraction of small muscles that run between the walls of the middle ear chamber and the ossicles. In terrestrial mammals, the ossicles act as a series of levers matching the low impedance of the external medium (air) to the high impedance of fluid filled cochlea. Contraction of these muscles stiffens the ossicular chain and reduces the transmission of sound. In marine mammals, the internal and external media are both liquid and thus there is not the same requirement for impedance matching. The ossicles are relatively massive and in odontocetes the ossicular chain is stiffened. Thus, although the stapedius muscles are present, it can be argued that their contraction would be less effective in disrupting the transmission of acoustic signals to the cochlea. In addition, there is an unavoidable delay between sensing an intense sound and implementing the auditory reflex—in humans this is of the order of 50-100 ms. Consequently, even in terrestrial mammals, the stapedius reflex has only a limited potential for protecting the inner ear from short rapid onset sounds such as seismic pulses.

There is currently no firm evidence to suggest that cetacean ears are less vulnerable to the effects of intense noise than terrestrial mammals and man, or that applying damage risk criteria developed for humans will necessarily lead to particularly conservative conclusions for cetaceans.

■ **Extrapolations from human criteria to assess risks of threshold shifts in marine mammals (E):** It is not clear which measures best describe a transient sound's ability to cause threshold shifts. Some evidence suggests that peak pressure may be a more appropriate measure than total energy for predicting instantaneous damage. For any sound type, there is an intensity threshold above which damage occurs and below which threshold shifts are the result of metabolic processes. Most human research and noise regulation criteria address long-term exposure to moderate noise sources. However, animals close to an operating air gun array would receive very high levels for a relatively short period. Thus, when considering the potential for seismic guns to cause TTS or PTS in marine mammals, it may be that the risks associated with short exposures to very high levels are of greatest concern. As already noted, long-term exposure to moderate levels may not adequately predict the effects of shorter exposure to more intense sounds.

Richardson et al. (1995) considered the application of the human damage risk criteria (derived by Ward 1968) to marine mammals. They allowed for differences in hearing thresholds between man and various marine mammals by expressing critical sound levels in DRCs relative to the likely best hearing thresholds for the species under consideration. (An implicit assumption here is that the dynamic range of all marine mammals is the same, and is similar to that of humans. The added uncertainty due to this simplification must be born in mind when considering the results.) They considered that, for the purposes of this exercise, marine mammals could be considered in two groups: sensitive species, with lowest hearing thresholds of around 40 dB re:1ìPa, and less sensitive species, with best hearing thresholds at 70 dB re:1ìPa. Comparisons between different species are then made as dBs over threshold level. Threshold levels for humans at frequencies of best sensitivity are 0 dB re: 20 ìPa, so it is necessary to add to that 40 dB or 70 dB (depending on the assumed sensitivity of the species) to any human criteria when applying them to marine mammals. Based on these assumptions, Richardson et al. (1995) derived a table of DRCs for exposure to different numbers of 'long' (200 ms or more) or 'short' (25 ms) pulses, and these data are presented here as Table 1. This suggests that sensitive marine mammals might exceed DRC from a single 200 ms pulse with a peak received level of 188 or 218 dB re:1ìPa, for more or less sensitive marine mammals respectively (=148 dB single pulse DRC for humans + 40 or 70 dB).

Further extrapolations can be made to explore DRC for exposures to different pulse lengths and numbers of pulses. For examples consider a typical 10msec air gun pulse.

(152 dB re: 20 ìPa is given as a threshold level for 100-1.5 ms pulses in humans For 10 msec pulses subtract 6 dB = 146 dB (Ward 1968). For a single pulse add 10 dB = 156 dB, then add 40 dB or 70 dB = 196 dB and 226 dB dB re:1ìPa as DRCs for more sensitive or less sensitive marine mammals respectively)

For a 260 dB re: 1 m Pa peak-to-peak source, and assuming spherical spreading, these levels would be exceeded out to ranges of 1,585 m and 50 m respectively. It should also be appreciated, though, that an animal might receive several loud pulses from an operating array.

For an animal to the side of the array, pulse length is greater than 200 ms and DRCs from Table 1 would apply directly. DRCs are 188 dB or 218 dB for more or less sensitive marine mammals. Assuming spherical spreading, these levels would be exceeded out to ranges of 1,260 m and 40 m.

If exposure to 100 pulses is considered, then DRCs from Table 1 would be 178 dB or 208 dB and, for spherical spreading, these levels would be exceeded out to ranges of c.4,000 m and 130 m.

A seismic survey vessel making 5.5 knots and emitting one shot every 10 secs will travel 2.8 km in the 1,000 secs required for 100 shots. Exposure of stationary sensitive marine mammals with a 40 db threshold would then exceed the levels prohibited by these DRCs out to a range of ~3,700 m. (An assumption of spherical spreading at such ranges may overestimate attenuation and if so then effects at even greater ranges would be anticipated.)

Davis et al. (1998) considered the implications of Ridgway et al.'s (1997) finding of a 192 dB threshold for TTS from a 1 sec pulse. They suggested that, because of the shorter duration, seismic pulses would have to have to be 10 dB louder, 202 dB re:1ìPa, to achieve the same sound exposure levels. (This 10 dB increment assumes the seismic pulse is only 0.1 sec in duration. However, in deep water, the primary pulse and echo can last for 0.4 secs, in which case only around 4 dB should be added to Ridgway et al.'s (1997) threshold for TTS.) More importantly, these calculations make the assumption that the damaging effect of a pulse is directly proportional to its energy. This may not be the case with transients for which peak pressure seems to be the most important factor. For example, as mentioned above, Ward (1968) found that in humans there was no additional damage from impulse noises once pulse length exceeded 200 ms. This then would seem to be the most appropriate integration time to apply, suggesting a possible addition of 3 dB to Ridgway et al.'s (1997) value to allow for a 0.1 sec pulse length and giving a threshold for TTS of 195 dB re:1ìPa. This is at least within the range of values suggested by Richardson et al's (1995) extrapolation from human DRCs

Clearly, extrapolations such as these, between different species, different media and noise types, are highly speculative. They could be either significantly over- or under-estimating the real risks. Given the current state of knowledge, it is not possible to reach firm conclusions on the potential for seismic pulses to cause threshold shifts or hearing damage in marine mammals. However, extrapolations made here and elsewhere do serve to indicate that the risk of seismic sources causing hearing damage to marine mammals cannot be dismissed as negligible.

TABLE 1 Inferred Auditory Damage Risk Criteria for humans and marine mammals exposed to noise pulses underwater. After Richardson et al (1995).

Number of Pulses	DRC for human in air (dB re. 20 m Pa)	Speculative DRC (in dB re. m Pa) for marine mammal listening in water with hearing threshold of 40 and 70 dB re. 1 m Pa	
		40dB re. 1 m Pa	*70 dB re. 1 m Pa*
100 long (>200 ms)	138	178	208
10 long (>200 ms)	143	183	213
1 long (>200 ms)	148	188	218
1 short (25 ms)	174	214	244

Perceptual Effects: Auditory Masking

Background noise can reduce an animal's ability to detect certain other sounds by masking. Generally, noise will only mask a signal if it is sufficiently close to it in frequency, i.e. within that signal's 'critical band'. At low frequencies, critical bands are broad and have a constant bandwidth. At higher frequencies, bandwidths are narrower and their width scales with frequency. Johnson et al. (1989) found that in beluga whales bandwidths were fairly constant below 2 kHz, while data for pinnipeds (summarized by Richardson et al. 1995) suggest broad critical bands below ~200 Hz. Thus, marine mammals might be expected to be most susceptible to masking of low frequency sounds by low frequency noise, such as seismic. A masking bandwidth of 1/3 octave at higher frequencies has often been assumed. However, in their review of this topic, Richardson et al. (1995) found masking bandwidths are typically narrower than this and often >1/6 octave, at higher frequencies. Studies of masking have usually considered the masking of a pure tone by other tones or by noise in a frequency band around it. The situation is more complex when, as would be the case for masking most biologically significant sounds by seismic sources, both the noise and the signal are broadband and the noise is intermittent rather than continuous. Signals that are structured, stereotyped, and repeated will be less susceptible to masking because they have in-built redundancy. The effects of masking can also be reduced when the noise and the signal come from different directions and the receiver is able to determine the direction of one or both. In effect, the signal-to-noise ratio is reduced in the direction from which the signal is coming. Directional hearing, however, has not been investigated in marine mammals at the low frequencies where most seismic source energy is centered.

There is no direct information on the extent to which seismic pulses mask biologically significant sounds for marine mammals. At greater ranges from the source the main potential for masking will be at the lower frequencies where masking bands are wider and susceptibility to masking may thus be greater. Baleen whales that are believed to be low frequency specialists might thus be most vulnerable. Most of their vocalizations are below 1 kHz and some, such as blue (*Balaenoptera musculus*) and fin (*B. physalus*) whales make predominantly low frequency calls (Clark 1990). It has been suggested that baleen whales could use low frequency sound to communicate over great distances (Payne & Webb 1971), and monitoring of whale calls using the military SOSUS hydrophone arrays (Clark & Fristrup 1997), which listen within the deep water (~1000m) SOFAR channel, lends some support to this suggestion. Recent attempts to monitor baleen whales off the west coast of the British Isles using SOSUS array hydrophones (Clark & Charif, 1998) were hampered for long periods by interference from oil-related seismic surveying. This suggests that the ability of baleen whales to monitor their acoustic environment in oceanic waters could be similarly compromised by seismic surveys. The intermittent nature of seismic pulses might be expected to reduce their potential for masking. However, the length of a seismic pulse increases with range from the source so that at range it may approach the 1-sec duration of the 20 Hz pulses produced by fin whales, possibly increasing the potential for masking. Phocids, especially elephant seals, are another group with good low frequency hearing that would be expected to be more susceptible to low frequency masking.

It is not possible, given the current state of knowledge, to properly assess the potential for biologically significant masking by noise from seismic sources. On the one hand, mammals show a number of adaptations to enable them to minimize the effects of masking. On the other, it is likely that being able to detect a variety of sounds at very low levels is important for their well-being and survival. Indeed, the fact that such sensitive hearing and sophisticated mechanisms for minimizing the masking effects of noise have evolved is one indication of the importance of this for their biological success. If this is the case, then any reduction in a marine mammal's ability to detect biologically significant signals could reduce its viability and the noise from seismic surveys could be having deleterious effects on marine mammals over very substantial ranges.

Behavioral Effects

Many studies have measured changes in behavior in response to exposure to seismic noise. Table 2 summarizes the findings from some of those that provide data on received noise levels and/or ranges from sources for behavioral responses.

Baleen Whales

- **Bowhead whales (*Balaena mysticetus*):** Oil exploration in the Bering, Chuckchi, and Beaufort Seas has prompted considerable research to investigate possible disruption of the behavior of endangered bowhead whales. Research has included both opportunistic observations made during seismic surveys (e.g. Reeves et al. 1984; Richardson et al. 1986, Richardson et al., 1999), and experimental exposure to air guns (Richardson et al. 1986; Ljungblad et al. 1988; Richardson & Malme 1993). Richardson et al. (1991, 1995) provide comprehensive reviews of much of the earlier work.

Initial studies in the 1980s indicated that bowheads typically exhibited overt avoidance behavior at ranges as great as 6-8 km, corresponding to received noise levels of 150-180 dB re:1ìPa, though some observations hinted at avoidance at greater ranges, e.g. >20 km by Koski & Johnson (1987). However, observations of migrating animals made between 1996-9, which were able to look for reactions at greater ranges, revealed a higher sensitivity (Richardson et al., 1999). Bowheads avoided the area with 20km of seismic sources ranging in size from 560-1500 in^3, which at this range received levels were typically 120-130 dB re:1ìPa rms. In 1998 numbers were also lower at ranges between 20 and 30km. Beyond the avoidance zone, densities were higher, providing strong support for the existence of long-range avoidance. Changes in behavior characteristic of disturbance, including reduced surface interval and dive duration and lower numbers of blows per surfacing, have been recorded at ranges of up to 73 km from seismic vessels (Malme et al. 1988) where received levels were between 125 and 133 dB re:1ìPa.

- **Gray whales (*Eschrichtius robustus*):** Eastern gray whales migrate annually along the western seaboard of the United States. The regular and predictable movement of thousands of animals close to land-based observation points provides ideal opportunities for conducting controlled and replicated experiments. Reactions of gray whales to air guns were monitored as they moved along the Californian coast by Malme et al. (1984). Observation teams on the shore tracked individual whales as they swam past a moored source-vessel during periods when an air gun was firing and periods when it was silent. Animals that responded to the guns slowed and turned away from them and some moved into areas where the topography shielded them from the noise of the guns. Received levels for avoidance reactions by 10%, 50% and 90% of the animals were 164, 170 and 190 dB re:1ìPa. A smaller-scale experiment with gray whales summering in the Bering Sea yielded similar results with 10% and 50% avoidance at 163 and 173 dB re:1ìPa, respectively. Würsig et al., (1999) made observations of the behavior of western gray whales while seismic surveys were being conducted in their summer foraging grounds off Sakhalin Island. They found indications of avoidance at ranges up to 24km and altered behavior (faster and straighter swimming and shorter blow intervals during seismic noise) at ranges of over 30 km. During a seismic survey in the same region in 2001, 3-5 gray whales were apparently displaced from the seismic survey area to the main known feeding area for the Sakhalin Island population (Johnson, 2002). Mitigation measures should have ensured that animals were not exposed to levels above 163dB (the level causing 10% avoidance during experiments described above). Thus, this observation may indicate greater levels of disturbance from more extended exposures.
- **Humpback whales:** McCauley et al. (1998) reported observations of humpback whales, migrating off Western Australia, made during both full-scale seismic surveys and experimental exposures to a single air gun. Observations were made from three different platforms: aircraft, the seismic survey vessel, and an independent tracking vessel.

Comparison of the onshore-offshore distribution of sightings made during pre-seismic aerial surveys and the distribution of sightings from the seismic survey vessel did not indicate any gross disruption of the

TABLE 2 Summary of observations of behavioural change in marine mammals in response to air guns and seismic surveys

Species Location Observation Source Received level Range Behaviour Water depth Prop.Model Reference

Common dolphin Irish Sea Operating seismic 2D Seismic2,120 cu. In. >1 km Reduced vocalisation rate within vocal range and/or exclusion within 1 km. 50-100 m Goold (1996)

Bottlenose dolphin Captivity 1 sec 20 kHz pulse · 178 (75 kHz) dB-186 (3 kHz dB Behavioural avoidance responses at 178 dB Ridgeway et al. (1996)

Sperm whales Southern Ocean Opportunistic Seismic 8x16l (263 dB re. 1 mPa –m) · 112 dB >300 km Cessation of vocalisation in response to some instances of air gun activity >500 m Bowles et al. (1994)

Gray whales California Experimental playback Seismic array · 180 dB· 170 dB· 164 dB 1.2 km2.5 kmc.3.6 km 90% avoidance50% avoidance10 % avoidance by migrating whales 50-100 m Malme et al. (1983, 1984)

Gray whales Bering Sea Experimental playback Seismic array1.64l, 226 dB · 173 dB· 163 dB 50% avoidance10% avoidance by summering whales Malme et al. (1986, 1988)

Gray whales(western) Sakhalin Island, Russia Operating seismic · <163db Whales abandoned foraging site close to survey area and moved to main foraging area Johnson (2002)

Bowhead whale Beaufort Sea Operating seismic Seismic array · 142-157 8.2 km Behavioural changes. Changes in blow rates and dive patterns. Various studies in Richardson et al. (1995)

Bowhead whale Beaufort Sea Operating seismic · 152-178 Active avoidance. Swimming away from the guns and behaviour disrupted for 1-2 hrs. 30-60 m “

Bowhead whale Beaufort Sea Operating seismic · 125-133 dB 54-73 km No avoidance behaviour but significantly shorter dives and surfacing periods. “

Bowhead whale Beaufort Sea Operating seismic 560-1500 cu. in · 120-130db 20-30km Avoidance

Humpback whale S.E. Alaska Experimental playback Seismic gun1.64L (226 dB) · 150-169 <3.2 km Short-term startle response. No clear avoidance at levels up to 172 dB re. 1m Pa effective pulse pressure level. Malme et al. (1985)

Humpback whale North West Cape, W. Australia Operating seismic Seismic array 44l (258 dB re. 1 mPa^2-m p-p) · 170 dB P-P· 162 dB P-P· 157 dB P-P3- 4 km5 km8 km Stand-off (General avoidance)Avoidance manoeuvresAvoidance manoeuvres 100-120 m 25 logR McCauley et al. (1998)

Humpback whale Exmouth Gulf, W. Australia Experimental playback Seismic gun0.33L, (227 dB re. 1 m Pa^2-m p-p)· 168 dB P-P· 159 dB P-P 1 km2 km General avoidanceCourse alterations begin 10-20 m McCauley et al. (1998)

Blue whale North Pacific Ocean Operating seismic Seismic source1,600 cu. in.(215 dB re. 1 mPa 1-m p-p). · 143 dB P-P10 km Closest approach 10 km?Cessation of vocalisations for c.1 hr.Resumption of vocalisations and movement away from source. 2,400 m Macdonald et al. (1995)

Grey seal Scotland and Sweden Experimental playback.1 hr exposure Single gun or small array(215-224 dB re. 1 mPa-1 m) Avoidance. Change from feeding to transiting behaviour. Haulout.Apparent recovery c 20 mins after trial. 20-100 m Thompson et al. (1998)

Common seal Scotland and Norway Experimental playback1 hr exposure Single gun or small array(215-224 dB re. 1 mPa-1 m) Initial fright reaction. Bradycardia. Strong avoidance behaviourCessation of feeding 20-100 m Thompson et al. (1998)

Ringed Seal Prudhoe Bay,Alaska Operating Seismic Array, 21.6L(236 dB re. 1 mPa-1 m p-p horizontal) 200 dB rms190 dB rms180 dB rms160 dB rms .03 km.24 km.96 km3.6 km Partial avoidance at <150mMore seals seen swimming away while guns firing 3-17m Harris et al. (2001)

whale's migration route. However, all pods followed by the independent tracking vessel were observed to respond to the seismic vessel. One whale showed a dramatic alteration of behavior, swimming at high speed (10-15 knots) very close to the surface before passing 1,500 m ahead of the seismic vessel. It eventually slowed when some 3 km beyond the seismic vessel and resumed its previous course when 6 km south of it. Two other pods showed less dramatic course changes at ranges of 5-8 km, passing 3-4 km behind the survey vessel. The fourth pod followed an erratic zigzag course and eventually passed 3 km behind the survey vessel. On two occasions, animals spent an unusually high proportion of time at the surface. The authors speculated that this could be due to reduced sound level in surface waters.

Observers on the seismic vessel made proportionally more sightings within 3 km and relatively fewer at ranges of greater than 3 km during periods when guns were off. Sighting rates at ranges >3 km were some 3 times higher during "guns on" than "guns off" periods. This is consistent with whales avoiding the survey vessel out to ranges of >3 km. Total sightings rates were highest during 'transition periods': the periods when guns were turned on and when they were turned off. It was suggested that this could be a startle effect or curiosity, causing whales to come to the surface.

Controlled exposure experiments using a small air gun array were conducted in an adjoining bay. The source vessel approached groups of humpback whales while a dedicated observation vessel tracked their movements. Whales generally showed speed and course changes to avoid coming closer than 1-2 km to the air gun vessel. However, on several occasions whales were observed to approach and circle the seismic vessel at ranges within 100-400 m (expected exposures 192-177 dB re:1ìPa^2 peak-to-peak).

In summary, humpback whales showed avoidance behavior at a range of 5-8 km from a full-scale array and maintained a stand-off range of 3-4 km. Typical received levels at 5 km were measured as 162 dB re:1ìPa^2 peak-to-peak. During the trials with a smaller air gun, avoidance was usually evident at 2 km at which received levels were 159 dB re:1ìPa^2 peak-to-peak.

McCauley et al. (1998) suggested that different classes of humpback whales might exhibit different levels of sensitivity. For example, adult males seeking mates might be least likely to alter their behavior in response to seismic surveys. The authors also suggested that males might even confuse seismic pulses with the noise made by the flipper slaps and lob-tails of competitors.

This comprehensive study demonstrates how valuable it can be to integrate CEE and observational approaches and how detailed behavioral observations from a few individuals can assist with the interpretation of more general observations.

■ **Blue whales:** McDonald et al. (1995) tracked the locations, and from these, inferred the movements of blue whales by analyzing data from an array of seismometers mounted on the seafloor. One blue whale was tracked while an active seismic survey vessel was moving through the area. The source was a relatively low-powered four-air gun array with a total capacity of 1,600 in^3 and a source level of 215 dB re:1 ìPa peak-to-peak @ 1 m over a 10-60 Hz band. Initially, the whale was tracked moving at a speed of about 10 km/hr on a course converging with that of the vessel. At a range of 10 km from the seismic vessel (estimated received level of 143 dB re:1 ìPa peak-to-peak in the 10-60 Hz band) the whale stopped vocalizing and remained silent for an hour before resuming calling at a range of 10 km. Its track then diverged from that of the seismic vessel by about 80° and from its original course by c.120^{o}. This apparent long-range avoidance of the seismic vessel may indicate that blue whales are rather more sensitive to air gun noise than humpbacks, bowheads, or gray whales.

■ **Other rorquals:** Stone (2003) summarized reports from observers on seismic vessels operating in UK waters between 1998 and 2003, collated by the UK Joint Nature Conservation Committee. When sightings of minke whales (*Balaenoptera acutorostrata*), sei whales (*B. borealis*), and fin whales were combined, ranges to animals were higher for sightings made during surveys than those made at other times—suggesting avoidance.

Toothed Whales and Dolphins

The effects of seismic surveys on odontocetes have generally been less thoroughly investigated than effects on baleen whales.

■ **Dolphins and porpoises:** Goold (1996) monitored acoustic activity of common dolphin (*Delphinus delphis*) before, during, and after seismic surveys off the coast of Wales. Acoustic contact with dolphins was lower during the seismic survey than before it, and was lowest during periods when the guns were actually firing. In addition, fewer dolphins were observed bow riding during seismic surveys. These results were taken to indicate that within 1 km dolphins found the signals from a seismic source aversive.

Gordon et al. (1998) reported on both experimental exposures to harbor porpoises in inshore waters around Orkney, UK, using a small source (3 x 40 cu. in. air guns; source level approx 228 dB re: 1 ì Pa zero-to-peak @ 1 m), and on harbor porpoise detection rates made during commercial seismic surveys. In both cases, porpoise groups were detected acoustically using semi-automated detection equipment (Chappell et al. 1996). During experiments in inshore waters the sound source was slowly brought into a bay while a small boat conducted continuous acoustic survey lines within the bay. No changes in the rate of acoustic contact were observed during two hour periods before, during, and after the controlled exposure. Harbor porpoises were not excluded from an area of preferred habitat by short-term exposure to this modest source. The authors caution, however, that these results can only be applied to the very precautionary experimental approach that they employed which involved using a small source and short exposure periods.

Detections of porpoises were also made during full-scale seismic surveys to the north of Shetland. The same acoustic detection equipment was deployed from a guard vessel that kept station about one mile ahead of the seismic vessel. At this range, there were no significant differences in acoustic detection rates for porpoises during periods when the guns were firing and when they were off (during turns between lines for example). This might be taken as lack of evidence for avoidance by harbor porpoises at ranges of a mile and more, though it is of course possible that avoidance could have occurred at shorter ranges than this.

Probable avoidance of active seismic sources by odontocetes is suggested by analysis of the reports of observers on seismic vessels off the UK collated by the UK Joint Nature Conservation Committee (Stone 2003). Encounter rates for both white-beaked (*Lagenorhynchus albirostris*) and Atlantic white-sided dolphins (*L. acutus*) were significantly lower during seismic surveys than at other times and distance to sightings was significantly higher for these two species and for killer whales, bottlenose dolphins, other dolphins, and porpoises when guns were firing.

■ **Sperm whales:** Sperm whales are the largest odontocetes and are thought to have better low frequency hearing than smaller odontocetes. They may therefore be more vulnerable to disturbance from seismic surveys. Observations of responses to seismic surveys are contradictory however. Some suggest a strong effect. For example, Mate et al. (1994) reported that sperm whale density in a preferred area in the Northern Gulf of Mexico decreased to approximately 1/3 of pre-survey levels for the two days after the seismic survey started and to zero for five days after that. The authors do point out that these observations were serendipitous and it would be wrong to assume that any causal relationship was demonstrated. Sperm whales were also reported to temporarily vacate the waters off Kaikoura, New Zealand, after a seismic survey (Liz Slooten, pers. comm. Cited in IFAW, 1996).

Indications that sperm whales in the Southern Ocean respond to seismic surveys at extreme ranges are provided by (Bowles et al., 1994). They observed that sperm whales ceased vocalizing during some, but not all, periods when a seismic survey vessel was heard firing at a range of 370 km. These were apparently not startle or curiosity responses to a novel stimulus, as the seismic source had been audible intermittently over the two weeks in which they had monitored acoustically in the area, and indeed had been surveying for some time before the start of their study. The sound source was later found to be an array of 8 x 16l Bolt air guns with an estimated source level of 263 dB re:1ìPa @ 1m. At these extreme ranges the seismic pulses had a duration of c. 3 secs, ranged in frequency from 30-500 Hz and received levels of 120 dB re:1ìPa were measured at a range of 1,070 km.

In contrast to these reports of extreme sensitivity, other observations suggest that sperm whales show little response and are not excluded from habitat by seismic surveys (e.g. Rankin & Evans 1998; Swift 1998). Swift (1998) used acoustic monitoring techniques to determine the relative abundance and distribution of sperm whales before, during, and after a three week seismic survey on the Rockall bank west of Scotland. Observations extended over seven weeks to include one week pre-survey, three weeks during the survey, and a week of post-survey monitoring. Acoustic detection rates were actually higher during the seismic survey period than the weeks before or after the survey. It is possible that whale density did actually increase in response to the seismic survey but perhaps more probable that changes in detection rates were the result of a seasonal change in sperm whale distribution

Swift (1998) also found no significant difference in detection rates between 'guns on' and 'guns off' periods during the seismic survey itself, suggesting a lack of short-term responses as well. However, it should be remembered that, using hydrophones, these researchers were able to detect sperm whales at ranges of c. 5 miles and this may have made changes in behavior and distributions at lesser ranges more difficult to detect.

■ **Pinnipeds:** There have been surprisingly few studies of the effects of air gun noise on pinnipeds, even though members of this group have good underwater hearing and their feeding grounds often overlap with seismic survey areas. When Richardson et al. (1995) reviewed the subject, they could only find two anecdotal reports, and both suggested that seals did not react strongly to seismic noise. Recently, detailed observations of the behavioral and physiological responses of harbor and grey seals (*Halichoerus grypus*), have been reported by Thompson et al. (1998). These researchers conducted 1 hr controlled exposure experiments with small air guns (source levels of the air guns used were 215-224 dB re: 1 m Pa peak-to-peak) to individual seals that had been fitted with telemetry devices. The telemetry packages allowed the movement, dive behavior, and swim speeds of the seals to be monitored and thus provided detailed data on their responses to seismic pulses. Two harbor seals equipped with heart rate tags showed evidence of a fright responses when playbacks started: their heart rates dropped dramatically from 35-45 beats/min to 5-10 beats/min. However, these responses were short-lived and following a typical surfacing tachycardia; there were no further dramatic drops in heart rate. In six out of eight trials with harbor seals, the animals exhibited strong avoidance behavior, swimming rapidly away from the source. Stomach temperature tags revealed that they ceased feeding during this time. Only one seal showed no detectable response to the guns and approached to within 300 m of them. The behavior of harbor seals seemed to return to normal soon after the end of each trial.

Similar avoidance responses were documented during all trials with grey seals: they changed from making foraging dives to v-shaped transiting dives and moved away from the source. Some seals hauled out (possibly to avoid the noise); those that remained in the water seemed to have returned to pre-trial behavior within two hours of the guns falling silent. The authors comment that responses to more powerful commercial arrays might be expected to be more extreme, longer lasting, and to occur at greater ranges. These represent some of the most detailed and dramatic short-term responses to air guns observed from any marine mammal.

By contrast, sightings rates of ringed seals (*Phoca hispida*) from a seismic vessel in shallow arctic waters showed no difference between periods with the full array, partial array, or no guns firing (Harris, 2001). Mean radial distance to sightings did increase during full array operations, however, suggesting some local avoidance.

Habituation, Sensitization, and Individual Variation in Responsiveness

It is clear from the above review that, even within species, the behavioral responses of marine mammals to seismic survey noises are quite variable. A range of factors may affect an animal's response to a particular stimulus including: 1) its previous experience of it; 2) any associations it may have made with that signal; 3) the individual's auditory sensitivity; 4) its biological and social status, including its age and sex; and 5) its behavioral state and activity at the time. Thus, by their very nature, behavioral responses are likely to be unpredictable. (See Wartzok et al.'s paper in this volume for a fuller exposition.)

Habituation occurs when an animal's response to a stimulus wanes with repeated exposure in the absence of unpleasant associated events. Animals are most likely to habituate to sounds that are predictable and unvarying. The opposite process is sensitization, when experience of a signal leads to an increased response. This may occur when an animal learns to associate a sound with a harmful or unpleasant event. Animals might be expected to respond to such signals when they are just audible. In the case of seismic sounds, an animal that had been exposed to levels of sound at a level high enough to cause discomfort might show avoidance responses at a lower level on subsequent exposures, while other animals, which had only been exposed to lower levels, might become habituated. Thus, quite different response behaviors could become established in different individuals.

Within a species, different classes of individuals might be expected to be differentially vulnerable and/or responsive. For example, a mother nursing a young calf might be expected to be more likely to show avoidance behavior than a male guarding a breeding territory. Finally, the animal's behavioral state might make it more or less likely to exhibit disturbance behavior: animals that are resting or engaged in some non-essential activity may show greater behavioral change than animals highly motivated to perform an important activity, such as feeding or mating.

Chronic Effects and Stress

Extended exposure to even quite low levels of sound can cause stress and lead to health problems in humans. Elevated levels of noise can impair both mental and psychomotor functions in man (Kryter, 1994). In mammals, stress is often associated with release of the hormones ATCH (adrenocorticotrophic hormone) and cortisol. This has been shown, for example, during transportation in pigs (Dalin et al. 1993; McGlone et al. 1993) and goats (Greenwood & Schutt 1992). Increases in hormone levels are typically also associated with changes in behavior, e.g. increased aggression, changes in respiration patterns or social behavior and may lead to a reduction in the effectiveness of the immune system.

Thomas et al. (1990) attempted to measure stress induced in four captive belugas by playback of recordings of drilling platform noise (source level 153 dB re:1ìPa@1m). Levels of catecholamines in blood samples did not increase during the experiment. However, the playbacks were relatively short and these captive animals may have already adapted to living in a noisy and stressful environment.

In spite of the potential difficulty of demonstrating cause and effect in marine mammals in the field, the potential for noise-induced stress to have effects on so many aspects of the health of individuals and populations makes it a matter of real concern.

Indirect Effects

Noise may indirectly impact cetaceans through its effects on prey abundance, behavior, and distribution. Bony fish may be particularly vulnerable to intense sound because most of them possess an air-filled swim bladder. Although marine fish typically have less acute hearing than marine mammals, many are more sensitive than odontocetes in the range 100-500 Hz where most seismic sound is produced. Effects of air gun pulses on fish range from serious injury at short ranges, to avoidance behavior, possibly at the range of many kilometers (Turnpenny & Nedwell 1994). Reduced catch rates have been reported for several species of fish in areas of seismic surveying activity (see review in McCauley, 1994). For example, catch per unit effort for rockfish (*Sebastes* spp.) declined by 50% during a series of controlled exposure experiments using air guns (Skalski et al., 1992). Acoustically estimated fish populations were reduced by 36% for demersal species, 54% for pelagic species, and 13% for small pelagic species during a 3-D survey in the North Sea compared with pre-shooting abundance (Bohne et al. 1985). Recorded cod and haddock catches were reduced by 50% within a 20 nm radius of an operating seismic vessel, and reduced by 70% within the 3 x 10 nm seismic shooting area (Engas et al. 1993). Long-line catches of both species were also reduced by 44% inside the seismic shooting area but were not affected at a range of 18 nm. Scanning electron microscopic examination of the ears of pink snapper (*Pagrus auratus)* after exposure to air gun pulses has revealed ablated hair cells and extensive damage to the sensory epithelia (McCauley et al., 2003).

These studies indicate a variety of effects from seismic pulses on potential marine mammal prey species. If seismic surveys cause fish (or other animals) that are the prey of marine mammals to become less accessible, either because they move out of an area or become more difficult to catch, then marine mammal distributions and feeding rates are likely to be affected. Conversely, it might be possible that damaged or disoriented prey could attract marine mammals to a seismic survey area, providing short term feeding opportunities but increasing levels of exposure. There have as yet been no attempts to investigate such indirect effects on marine mammals.

Effects of Seismic Disturbance on Human Utilization of Marine Mammals

In addition to strong ethical reasons for wishing to avoid disrupting marine mammal populations with seismic noise, there may also be immediate economic and political concerns when human utilization of a marine mammal is potentially affected. Marine mammals are exploited both consumptively (hunting of seals and whaling), and non-consumptively (nature tours and whale watching).

Marine mammals continue to be hunted by both commercial and aboriginal operations in many parts of the world. Changes in distribution, abundance, or behavior of marine mammals that make them less accessible to local hunters will reduce commercially valuable catches that in some cases are also considered to be of significant subsistence or cultural value. Avoiding the potential disruption of Inuit whaling and sealing operations is an important concern during oil exploration activities off Alaska, for example.

Whale watching is a significant and rapidly increasing sector of the tourist industry. Hoyt (1995) estimated worldwide revenues to be US$ 504 million, and the activity has continued to expand since then. The importance of seals as subjects for wildlife tourism has been less well appreciated, but Young (1998) estimated the gross annual value of seal watching in the UK and Ireland to be £38 million. Clearly, changes in a local populations, abundance, and distribution, or in the approachability of marine mammals could all affect the viability of specific marine mammal tourism operations.

Discussion and Comment

Marine Mammals in a Three-dimensional Environment: The Particular Vulnerability of Deep Divers

As seismic exploration increasingly moves into deeper offshore waters, the magnitude of the third dimension, depth, becomes more significant. All marine mammals dive, in fact many will spend the majority of their lives underwater, and some can spend significant times at very substantial depths. Sperm whales, for example, regularly make dives in excess of 1,000 m (Watkins et al. 1993) and have been recorded down to 2,500 m (Norris & Harvey, 1972). Beaked whales are also known to be impressive deep divers (Hooker & Baird, 1999), possibly exceeding the abilities of sperm whales. Seals may be even more accomplished divers than cetaceans. For example, elephant seals regularly dive to depths greater than 1,700 m (Delong and Stewart, 1991; McConnel et al. 1992), and most phocid seals spend >80% of their time submerged and most of that at depth.

Deep divers are worthy of special consideration for a number of reasons. Diving takes them into regions in which received sound levels are higher than those measured or predicted close to the surface, including the zones beneath air gun arrays in which most sound is focused. A diving animal is also committed to a strict energy budget, to ensure that the oxygen stores within its body are managed to allow it to dive to a certain depth for a particular length of time and return to the surface.

A diving mammal leaves the surface with stores of oxygen in its blood and muscles that must sustain it through its entire dive. During dives, energetic activities are minimized and movement will tend to take place at close to the most energy-efficient swimming speed. It is possible for muscles to respire for short periods without oxygen (anaerobically) but this incurs an 'oxygen debt' which is expensive to 'repay' both in terms of energetic and time budgets (Thompson & Fedak, 2001). From the perspective of an animal wishing to avoid loud noise sources, this may mean that strategies involving energetically costly activities, such as rapid swimming, may be precluded, particularly towards the end of dives when oxygen stores will be minimal. Their options for avoiding loud noise sources are tightly constrained and the consequences of their taking avoiding action may be more serious than they would at first seem. An air-breathing diver must ultimately return to the surface to have access to air. This may force the animals to swim towards the noise source.

Generally, of course, submerged divers are not visible at the surface, and some divers, such as elephant seals, hooded seals, sperm whales and beaked whales may routinely perform dives of between 30 mins and an hour. In such cases, the fact that observers have not seen them at the surface before starting a seismic line is no guarantee that they are not within the 'danger zone'. For some species, notably the sperm whale, which is highly vocal, acoustic monitoring can provide helpful information on the presence of submerged animals (Leaper et al., 1992; Lewis et al., 1999). Unfortunately, this is unlikely to be a reliable method for detecting the presence of beaked whales or seals.

Zones of influence

A concept widely used in regulation and management is that of zones of influence, within which different types of effects would be expected to occur. If a uniform field of propagation and attenuation is assumed (and ignoring the third dimension of depth), these can be represented as a series of concentric circles around a noise source, whose radii are the ranges at which the level of the sound might be expected to have fallen to a certain threshold level. Four zones suggested by Richardson et al. (1995) are:

1) the zone of audibility (the area within which the sound is both above the animal's hearing threshold and detectable above background noise)
2) the zone of responsiveness (the region within which behavioral reactions in re sponse to the sound occur)
3) the zone of masking (the zone within which the sound may mask biologically significant sounds)
4) the zone of hearing loss, discomfort, or injury (the area within which the sound level is sufficient to cause threshold shifts or hearing damage)

The radius of the circle defining each zone will depend on the characteristics of the sound itself, the susceptibility of the animals being considered, and the acoustic propagation characteristics in the survey area. In devising management guidelines and regulations that are appropriate for a particular survey, managers will often use threshold sound levels for certain effects (based perhaps on research in a different area) and calculate the ranges at which the sound level from the particular source being used will fall to this threshold in the survey area being considered. In these situations, the nature of propagation conditions in the survey area becomes critical. Propagation conditions can vary widely from location to location and depend on a variety of factors (Urick, 1983). Differing propagation conditions will have a magnified effect (squared if considering area, cubed if volume) on zones of influence since these represent areas which rapidly increase or decrease with even small changes in radius. For example, the radius of a zone of behavioral influence for an air gun array with a threshold of 140dB could vary by 4000 times between different likely propagation conditions, in which case the area and number of individuals affected would vary by a factor of 16 million. This highlights the importance of making empirical measurements of propagation loss and applying appropriate models informed by up-to-date oceanographic data when management involving a zones of influence model is used.

Biological Significance of Possible Effects of Seismic Pulses for Individuals and Populations

There are both ethical and legal reasons for being concerned about the welfare of individual animals. In addition to these, are concerns for the health and viability of populations and species. Much legislation is couched in conservation terms, while public opinion often responds strongly to animal welfare issues. As we have seen, research is beginning to provide evidence for and against the existence of short-term effects on individuals. When it comes to assessing the biological significance of these, we have to rely on biological interpretation, modeling, and extrapolation. One might expect serious effects to cause changes in the size of populations, but, given the poor precision with which the size of any marine mammal population can be measured, and the fact that in many parts of the world there are no reliable estimates for many populations, only very large changes in population size would be identified. As many marine mammal populations have very small rates of increase, biologically important changes in these rates would be especially difficult to identify, particularly in a timely fashion. Further, its not good practice to wait for such major impacts before taking management action.

■ **Hearing damage:** Hearing is the most important sensory modality for marine mammals underwater and the ability to hear well is vital for many important aspects of their lives such as finding food, navigating, locating mates and avoiding predators. It would seem indisputable, then, that any reduction in hearing ability would very seriously compromise the viability of individual animals. If a significant proportion of the population was affected in this way, there could be deleterious conservation consequences as well. Exposure to high levels of noise could also have animal welfare implications if, for example, it induced panic or caused pain.

■ **Perceptual and behavioral effects:** Masking of biologically significant sounds by background noise is equivalent to a temporary loss in hearing acuity, but little is known about the importance to marine mammals of hearing low-level sounds in background noise. The very fact that they have developed such sensitive hearing, and seem to be adept at detecting signals in background noise, suggests that this is an important ability for them.

The significance of disruption of behavior in part depends on the importance of the behavior affected. Small-scale course changes to avoid surveys during migrations, such as those measured for gray whales by Malme et al. (1986), might, in themselves, have few long-term consequences for individuals or populations. The consequences might be more serious in areas where many surveys are occurring simultaneously. In some cases, alterations in migration paths could move animals into dangerous areas. For example, Simmonds & Mayer (1997) suggested that seismic surveys being conducted to the west of the British Isles might have contributed to recent live multiple sperm whale strandings in the North Sea if they caused southward-moving animals to divert to the east of their normal course and into the shallow North Sea. As discussed above, information from recent mass strandings of beaked whales (e.g. Jepson et al., 2003) hints at the possibility that noise-induced changes in behavior could lead deep diving cetaceans to develop decompression sickness. Disturbance could also lead to disruption of feeding and deep diving animals could be particularly vulnerable. If sperm whales use their vocalizations to echolocate, as most believe they do, then the cessation of vocalizations observed by Bowles et al. (1994) in the Southern Ocean in response to seismic noise at ranges of hundreds of kilometers, would have stopped those animals feeding. In this case, the effects were evident at such extended ranges that hundreds or thousands of animals might have been affected. Seismic surveys could influence the availability of prey, especially fish. Reduced feeding by marine mammals may eventually reduce their reproductive rates and increase mortality. Most marine mammals are adaptable and opportunistic feeders, and the large whales, in particular, have evolved to survive for extended periods without feeding. However, certain classes e.g. newly weaned phocid seal pups may be particularly susceptible to reduced feeding rates.

Disruption of social organization could have severe consequences for those animals for which long-term social groupings seem to be important for survival, such as the toothed whales. Long-range communication is important in keeping cetacean groups together (Payne, 1995). Acoustic disturbance may disrupt social groups, while increased background noise could hamper the ability of members of dispersed groups to find each other and keep in contact using vocalizations.

Mothers and their dependent calves may be particularly vulnerable to disturbance. In some species of odontocetes calves remain with their mothers for several years. Disruption of this bond could prevent calves from suckling and may lead to increased threat of predation.

These potentially damaging or disturbing effects of seismic surveys cannot be considered in isolation. Marine mammals are subject to a range of natural and, to an increasing extent, anthropogenic threats. It is the combination of all of these that may lead to biologically significant effects. Some factors will interact and may act synergistically. For example, chronic effects due to disturbance, stress, or chemical contamination may weaken the immune systems of individuals making them more vulnerable to disease. With marine mammals becoming subject to an increasing number of new threats whose effects are likely to be cumulative, it is important to minimize the impacts of all and any of them wherever possible.

There is at present, little or no direct evidence for biologically significant effects of seismic surveys on marine mammals but it must be appreciated that none of the research projects that have been conducted so far have been capable of adequately testing for effects at this level. The fact that plausible cases can be made that observed or possible responses could result in biologically significant effects, is an indication that this is a potential problem that deserves to be taken seriously.

Spatial and Temporal Scales

The spatial and temporal scales at which the potential effects of seismic surveys should be investigated are daunting. Sound from air guns may be audible to marine mammals at ranges of several hundreds of kilometers. In some cases (e.g. bowhead whales, Richardson et al., 1999; Malme et al., 1988; and sperm whales, Bowles et al. 1994), behavioral responses have been measured at ranges of many tens, or even hundreds, of kilometers from the source. However, few studies have attempted to measure effects at these ranges. Studies tend to focus on smaller numbers of animals close to seismic surveys and it is possible that very substantial numbers of marine mammals are subject to unmeasured effects, perhaps inducing stress, over huge areas. In the temporal dimension, in some commercially promising regions, such as the Gulf of Mexico and the North Sea, many seismic surveys may be being conducted simultaneously throughout most of the summer months of each year for many years. The modern trend towards using 4-D seismic surveys to monitor patterns of oil field exploitation will mean that seismic surveys will become a regular occurrence in many oil fields. Long-term studies to assess impacts at these temporal and spatial scales have not been conducted, and in nearly all cases baseline data, from the time before surveys start, are completely lacking.

Making Better Use of Data Collected on Seismic Surveys.

In many regions regulators require seismic operators to carry trained marine mammal observers to keep watch for marine mammals for mitigation purposes. This resource can provide high quality visual (and in some cases acoustic) data collected systematically by trained observers and this can potentially be used to provide information on the offshore distribution of marine mammals and on behavioral responses to air gun pulses. The scheme run in the UK by JNCC provides a good example of how such data can be collated (e.g. Stone, 2003). However, it is likely that even more useful data could be collected if specific observation protocols were developed by experts with appropriate experience.

Implications for Management

Concerns about the conservation of marine mammals have usually focused on cases where animals suffer dramatic effects, such as mortality from hunting or fisheries bycatch. Management regimes have been established, with varying levels of success, to address such issues. It is possible that, at short ranges, seismic survey noise could cause similar acute problems. Of potentially greater concern is the possibility that alone, or in combination with other factors, air gun noise will have less dramatic chronic effects such as: excluding marine mammals from important areas at significant times, interfering with their migrations and movements, contribute to overall habitat degradation, disruption of biologically significant behaviors, and increased levels of stress. Although such effects appear less severe than direct mortality or injury, they affect many more individuals and extend over significant periods of time. Cumulative effects could result in the reduction of reproductive rates, which are generally very low in marine mammals, and increases in mortality. Chronic problems of this kind are a legitimate conservation concern but they are difficult to manage within existing frameworks.

This review has emphasized the paucity of knowledge and the high level of uncertainty surrounding potential effects of sound on marine mammals. This problem is common to many conservation issues and has led to the development and adoption of a precautionary approach in many national and international agreements (Hey, 1991a; Hey, 1991b provide reviews). Mayer & Simmonds (1996) considered the role of precaution in cetacean conservation and used, as one case study, an example of acoustic disturbance, the 'Heard Island Experiment'—an experiment designed to transmit loud, low frequency sound underwater from Heard Island (near Antarctica) to 18 detection sites around the world. The experiment raised concerns about the impacts of anthropogenic sounds on cetaceans. It highlighted the lack of information on the biology and population distribution of the marine mammals in the study area and the widely differing scientific opinions on the effects of noise on them.

While so many uncertainties surround the effects of air gun noise on marine mammals, it is important that their use should be managed in a precautionary way to safeguard both individuals and populations. The most immediate and effective method of reducing impacts would be to minimize the number of surveys and the power of the sources employed. Encouraging companies to share the results of past and future surveys would be one mechanism for achieving this. When surveys must be undertaken, they should be governed by appropriate regulations and codes of practice that are based on either good empirical observations or on precautionary assumptions about sound propagation and the auditory sensitivity, behavior, and vulnerabilities of marine mammals. Such an approach should stimulate all stakeholders to strive to expand and refine our knowledge about the effects of anthropogenic noise and can help to clarify how research resources can best be used to reduce overall uncertainty. When precautionary management is applied, new research to decrease uncertainty in our understanding of key parameters will usually lead to regulations that are less onerous and disruptive for industry while providing effective protection to marine mammals.

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