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Marine Mammals *versus* Seismic and Other Acoustic Surveys: Introduction to the Noise Issues

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INTRODUCTION

Marine mammals rely strongly on underwater sound to communicate and to acquire information about their environment. Acoustic signals are of great importance to marine mammals for some of the same reasons that acoustic methods are of particular value to humans studying features of the watercolumn, bottom, and subbottom. Because marine mammals are sensitive to and depend on underwater sound, man-made sounds have the potential, in some circumstances, to cause several types of effects: behavioural disturbance and displacement, masking, temporary or perhaps permanent auditory impairment, and non-auditory physiological effects. Disturbance and (presumably) masking sometimes occur at much lower received levels, and thus longer distances, than hearing and acute physiological effects. Even at close distances, only the strongest sources of underwater sound are likely to cause physical injury. Also, the severity of effects from various types of sounds will depend on the type of marine mammal. Baleen whales are most sensitive to relatively low frequencies, and pinnipeds to moderate frequencies. Dolphins, porpoises, and most of the other toothed whales are sensitive to high frequencies, extending far into the ultrasonic (to humans) range. It is inappropriate to assume that different types of sound have the same effect, or that a given type of sound affects all marine mammals in a similar manner.

The presentation summarized here introduced the known and suspected types of noise effects on marine mammals. It also provided some introductory information on characteristics of underwater sounds from various sound sources used for seismic and other acoustic surveys. Then it reviewed what is known and suspected about the effects of various survey sounds on three groups of marine mammals: baleen whales, toothed whales, and pinnipeds. Emphasis was given to disturbance, but other types of known or potential effects were also mentioned. This review showed that, although disturbance effects have often been demonstrated, there are also many situations where marine mammals tolerate rather strong pulsed sounds without showing much overt disturbance. The review included comments on the main data gaps that impair our ability to assess and predict impacts of acoustic survey equipment on marine mammals. Later speakers provided more details on some of the topics touched on in this introduction, especially the relevant sound sources, hearing sensitivities of different marine mammals, and auditory effects of exposure to strong sounds.

The types, levels and directionality of sounds used for various types of seismic and acoustic surveys vary tremendously. These variations have a large influence on the types of effects to be expected in marine mammals. Important parameters of the source include the following: frequency or frequencies (and thus bandwidth), pulse duration and pulse repetition rate (together defining the duty cycle), nominal source level, directionality and beam-width, orientation of the beam, and whether the source is a point source or distributed (such as an airgun array).

Different workers describe the source and received levels from various pulsed sources in different ways, and often do not make clear which of several possible measures they are using. Commonly used measures include peak-to-peak levels, peak levels, average levels over the duration of the pulse or some other interval (often quoted as root-mean-square or rms levels), and energy content. Depending on which measure was used, the resulting dB value for a given pulse will vary widely, even if all are expressed in dB re 1 μPa@1 m or dB re 1 μPa^2 s. In predicting and interpreting such values, it is essential to know the specific basis of the measurement.

Regarding effects of seismic surveys, usually involving arrays of airguns, disturbance of baleen whales by the resulting strong and predominantly low-frequency sounds has been studied rather extensively. Less detailed data are available on disturbance to toothed whales and pinnipeds from seismic surveys. Because airgun sounds are pulsed, with several second gaps between pulses, masking may not be a major issue. Close to the source these sounds are strong enough for there to be concern about auditory effects (temporary or perhaps permanent hearing impairment). However, to date the available data on auditory effects of seismic surveys are very limited.

Regarding effects of medium- and high-frequency pulsed sources, less study has been given to the disturbance effects. Some information about the masking and auditory effects of such sounds is available from studies of captive toothed whales, although usually for exposure to single pulses, not repeated pulses. Little or no information of these types is available for baleen whales or pinnipeds. A very wide variety of sonars and other sources use medium- or high-frequency sound. It is not appropriate to assume that effects of one such source (e.g., mid-frequency naval sonars) apply to other sources with very different properties.

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BALEEN WHALES

Seismic Surveys

Reactions of several species of baleen whales to low-frequency sound pulses from seismic surveys have been reported. Early work on Bowhead, Grey and Humpback Whales was summarised in the book Marine Mammals and Noise (RICHARDSON et al. 1995). Since 1995, considerable additional information about reactions of each of those three species to seismic surveys has been obtained. Also, monitoring studies in U.K. waters have provided data on responses (or lack thereof) of various other species of baleen whales. Most of the post 1995 results are, to date, available only in limited circulation reports. For Grey Whales, recent results concerning the small western Pacific stock (JOHNSON 2002, WELLER et al. 2002) are generally consistent with eastern Pacific data from the 1980s (MALME & MILES 1985) in showing that exposure to high received levels causes localised avoidance. However, Grey Whales commonly tolerate moderately strong airgun pulses without interrupting their activities.

For Humpback Whales, recent Western Australian results (MCCAULEY et al. 1998, 2000) indicate that avoidance responses may begin at somewhat lower received levels than had been evident from limited work in the 1980s (MALME et al. 1985).

For Bowhead Whales, a recent LGL Ltd. study of migrating animals showed that deflection began at lower received levels than had been previously documented, with most individuals remaining >20 km from the airguns. However, recent LGL data on summering bowheads are consistent with early 1980s results suggesting that bowheads are more tolerant of airgun pulses when feeding in summer than when migrating in autumn.

For other baleen whale species, sighting rates by observers aboard the seismic vessels in U.K. waters are similar during periods with and without airgun operations. However, sighting distances, relative to the seismic vessel, tend to be greater when the airguns are operating (STONE 2003).

Proximity to a single seismic vessel probably causes little masking effect on natural sounds relevant to baleen whales, including calls from baleen whales themselves. The several-second gaps between seismic pulses provide an opportunity for whales to hear natural sounds between the pulses. Bowhead Whales, in particular, have been shown to continue calling in a typical manner when exposed to seismic pulses. Masking might be an issue if whales receive pulses from several distant seismic vessels operating simultaneously, but this has not been studied.

There are no direct data concerning the hearing sensitivity of any baleen whale, although baleen whales clearly are adapted for low-frequency hearing, and airgun pulses must be very prominent to baleen whales. There are no data on the possibility that exposure to strong low-frequency pulses from a nearby airgun array might cause temporary or even permanent hearing impairment, or other physiological effects, in baleen whales.

A considerable amount is known about the behavioural effects of seismic surveys on baleen whales, but there are gaps in that knowledge. It is unclear whether Bowhead Whales (at least during migration) are more responsive than other baleen whales, or whether some other species would, with more detailed study, prove to be more responsive than now known, at least under certain circumstances. There have been no direct studies of the effects of airgun pulses on the underwater behaviour of any baleen whales, aside from calling behaviour; with that exception, all available data are based on surface observations. The extent to which observers based on seismic vessels can provide reliable data on avoidance and other behavioural effects is unclear; such data may be biased by the limited visual range of the observers. Longterm effects on baleen whales of occasional exposure to seismic survey sounds are not well documented, although in some areas it has been noted that baleen whales continue to occur year after year despite periodic exposure to airgun pulses. For baleen whales, there is a near-total lack of knowledge concerning the auditory effects of exposure to high-level sounds from airguns.

Mid- and High-Frequency Pulsed Sources

Effects of other pulsed acoustic sources on baleen whales are little known. Various species show some avoidance of single airguns, which are often used in shallow-hazards surveys. Reaction distances are, as expected, less than those for the stronger sounds from arrays of airguns. A few reports of baleen whales avoiding sonars and pingers were reviewed in RICHARDSON et al. (1995). Baleen whales no doubt can hear mid-frequency sounds, but anatomical evidence (KETTEN 2000) suggests that they do not hear well (if at all) above about 22 kHz, with some variation among species.

TOOTHED WHALES

Seismic Surveys

Behavioural responses of toothed whales to seismic surveys have not been studied to the same degree as have the responses of baleen whales. Pre-1995 data were extremely limited (see RICHARDSON et al. 1995). Those early data suggested that dolphins might be relatively non-responsive, but that Sperm Whales might be highly responsive.

Monitoring studies since 1995 have shown that various small- and medium-sized odontocetes are sufficiently tolerant of airgun sounds to be readily seen by observers aboard seismic vessels. However, results from U.K. waters (STONE 2003) indicate that dolphins are more strongly affected by exposure to airgun operations than are some other cetaceans. Dolphins were sighted significantly less often while airguns fired and, when sighted, were significantly farther away than those sighted without airguns firing. Bowriding and other "positive" reactions were less frequent when airguns were firing.

Recent data for Sperm Whales suggest that they are less responsive to airgun pulses than had been suspected based on the limited early data. Off the U.K., sighting rates and distances are similar with and without airgun activity, although there did seem to be some behavioural effects (STONE 2003). Off

Norway, male Sperm Whales seemed to tolerate exposure to moderately high levels of airgun sounds, and continued to produce their usual click sounds (MADSEN et al. 2002). A major experimental study of Sperm Whale reactions to airgun sounds is presently underway in the Gulf of Mexico. The U.K. data also suggest that Pilot Whales are relatively non-responsive to airgun signals.

Intermittent seismic pulses probably have relatively little masking effect on sounds relevant to odontocetes. As for baleen whales, the gaps between the pulses provide "windows" through which natural sounds can be heard. Sperm Whales and some dolphins continue calling during exposure to airgun pulses. Also, the odontocetes whose hearing has been studied are most sensitive to mid- and high-frequencies; they are relatively insensitive to the low-frequencies that are the primary components of airgun sounds. Nonetheless, seismic pulses are sufficiently strong, and include sufficient mid-frequency energy, that their received levels remain above the auditory thresholds of odontocetes as much as several tens of kilometres away (RICHARDSON & WÜRSIG 1997).

For small odontocetes (unlike baleen whales), there are now rather extensive data on hearing thresholds as a function of frequency, and some data on the levels and durations of sounds that elicit temporary hearing impairment (TTS, temporary threshold shift). One study has investigated the onset of TTS in two odontocetes species exposed to single pulses of water-gun sound (FINNERAN et al. 2002). For a single water-gun pulse, the TTS threshold is apparently at or above 226 dB re 1 μPa or 186 dB re 1 μPa^2 s. The equivalent rms level would be somewhat over 200 dB re 1 μPa. There are no data concerning the TTS threshold for exposure to repeated water-gun or airgun pulses. However, it is probably well above the precautionary 180 dB re 1 μPa (rms) value that the U.S. regulatory authority has set as an interim "do not exceed" criterion for cetaceans exposed to pulsed sounds. The levels necessary to cause permanent hearing damage would be higher than the TTS threshold.

Given the number of seismic surveys and the opportunities to study odontocetes nearby, there are still surprisingly few quantitative data concerning odontocete reactions to airgun sounds. Relationships between received levels of airgun sounds and the behavioural reactions of the animals have received little study (less than in baleen whales). As for baleen whales, there is little direct information on the underwater behaviour of odontocetes exposed to airgun sounds (although this is now being studied in Sperm Whales). The potential biases in response data collected by observers aboard a seismic vessel are even less well known than for baleen whales. Long-term effects of seismic surveys (single or repeated) on odontocetes are unstudied. Auditory physiology of some of the smaller odontocetes is comparatively well studied, and some recent data on TTS thresholds are available, but effects of multiple pulses on odontocete hearing have not been studied. There are almost no direct auditory data for Sperm or Beaked Whales.

Mid- and High-Frequency Pulsed Sources

Data on behavioural actions of free-ranging odontocetes to mid- and high-frequency pulsed sounds are limited (see RICHARDSON et al. 1995, for review). Some data concerning dolphins exposed to sounds from "site surveys" are available. Studies on captive animals indicate that behavioural aversion to single sound pulses becomes evident at received levels several dB below the TTS threshold (SCHLUNDT et al. 2000). However, the applicability of these captive data to the field situation is uncertain. Studies of acoustic alarms on fishing gear indicate that harbour porpoises tend to show avoidance responses to mid-frequency pulsed sounds received at much lower levels.

Recent TTS data are helpful in understanding potential auditory effects of sonars and related sources on odontocetes, but there is a need for data concerning auditory effects of multiple pulses. The much-publicised strandings of Beaked Whales in proximity to naval operations are also relevant, but need to be interpreted carefully. The characteristics of the sonar signals involved in the Bahamas incident were very different from those associated with, for example, a multibeam bathymetric sonar. In the Bahamas case, the Beaked Whales were apparently exposed to prolonged sequences of pulses from horizontally-directed sonars. In contrast, a bathymetric sonar has much shorter pulses, directed generally downward in narrow beams. A given mammal is unlikely to be within such a beam for more than one or a very few (brief) pulses, and the total energy received by any given animal would be far less than occurred in the Bahamas incident.

PINNIPEDS

Seismic Surveys

Early studies showed that pinnipeds are often quite tolerant of exposure to strong underwater sounds, especially in areas where they are attracted to a concentrated source of food, and in situations where habituation has occurred. However, before 1995, there were essentially no data on reactions of pinnipeds to seismic surveys.

The few recent seismic surveys on the west coast of the U.S.A. have included visual monitoring and mitigation programs. Although Harbour Seals and California Sea Lions have occasionally been reported to show some avoidance of the operating airguns, other individuals have apparently tolerated the noise exposure with little or no obvious reaction.

More specific data have been collected on behaviour of Ringed Seals exposed to airgun operations in Arctic Alaska, based on observations from the seismic vessels (HARRIS et al. 2001, MOULTON & LAWSON 2002). Average sighting distances tended to be slightly greater when the airguns were operating then when they were not. However, many seals remained within 100-200 m of the operating airguns, which is often within the radius where received sound levels are >190 dB re 1 μPa (rms). Avoidance reactions appeared to be quite limited, and the observable behaviour of seals close to the operating airguns was not much different from that when airguns were silent.

In contrast, a telemetry-based study of Common (= Harbour) and Grey Seals exposed to pulses from a small airgun source suggested that seal behaviour was strongly affected by the sound exposure (THOMPSON et al. 1998). Upon exposure to airgun sounds, seals interrupted feeding and often showed avoidance until the airgun pulses ceased.

The levels of underwater sound necessary to elicit TTS in three species of pinnipeds have been studied (KASTAK et al. 1999), but this work has involved exposures to relatively prolonged, steady sounds – not pulsed sounds. Available results indicate that TTS thresholds depend on duration of exposure, as expected. However, those results concern prolonged sounds differing greatly from airgun sounds. There are no data showing how much airgun sound pinnipeds can tolerate before TTS (or perhaps PTS) starts to occur.

In summary, there have been few specific studies of pinniped responses to marine seismic surveys. Vessel-based monitoring has demonstrated only slight avoidance and behavioural responses by pinnipeds. In contrast, initial telemetry-based work (on different species) indicates that disturbance effects sometimes are stronger. This discrepancy needs to be resolved. Available TTS data are for prolonged exposures, and the levels of pulsed low-frequency sounds necessary to cause the onset of TTS (and possibly PTS) are unknown. This data gap is of particular concern for pinnipeds given that their avoidance responses are weak and they cannot be relied upon to avoid the area close to an operating airgun array.

Mid- and High-Frequency Pulsed Sources

There are few specific data about the effects on pinnipeds of bottom and hydro-acoustic surveys. However, as noted above, there are seemingly inconsistent results concerning reactions of seals to small airgun sources. Pinnipeds often tolerate exposure to Acoustic Harassment Devices (AHDs) producing high levels intermittent sound, sometimes resembling sounds used for sub-bottom surveys. Pinnipeds may show initial startle and/or avoidance responses to such sounds, but typically habituate rapidly. Harp Seals have been reported to alter their swimming pattern when in an echo-sounder beam (TERHUNE 1976). However, in other studies seals have apparently not been affected by sound from ultrasonic (60-69 kHz) acoustic tags attached directly to the seals (WARTZOK et al. 1992). There are no data on the levels of pulsed mid- and high-frequency sound necessary to elicit hearing impairment in pinnipeds.

DISCUSSION

Monitoring and mitigation measures aimed at protecting marine mammals from exposure to strong acoustic sources are commonly applied during seismic and some other acoustic surveys. Some mitigation measures undoubtedly benefit marine mammals. However, there are many problems in deciding on mitigation objectives (e.g., to avoid hearing impairment, or to minimize disturbance as well?), when mitigation measures are needed, optimum mitigation methods, and their effectiveness. Some common approaches are not very effecttive or adequate. Conversely, some mitigation measures significantly restrict human activities with little evidence of benefit to marine mammals. In order to make defensible decisions about appropriate mitigation strategies, additional data are needed on the effects of various types of acoustic signals on different types of marine mammals.

A considerable amount has been learned about short-term disturbance effects and auditory effects of various underwater sounds to which marine mammals are exposed. However, each issue has been studied in detail for only a few species of marine mammals. For many questions, the available empirical data apply to only one or two of the major groups of marine mammals; effects may differ widely among the major groups. Also, long-term effects on individual marine mammals, and especially on their populations, remain poorly known. Ongoing types of research and monitoring, and recently developed research techniques, can help address some of the data gaps. However, additional new approaches are needed to resolve the more intractable questions about effects and appropriate mitigation measures. In the meantime, practical decisions about regulatory and mitigation issues must be made based on incomplete knowledge.

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