doi:10.3723/ut.30.123 International Journal of the Society for Underwater Technology, Vol 30, No 3, pp 123–133, 2012

Technology requirements to investigate the effects of sound on marine wildlife

Ian L Boyd

Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews KY16 8LB, UK

Abstract

There is little information about the effects of sound on marine life. In spite of this high uncertainty, several new legal limits to sound levels in the marine environment are being introduced. The present paper summarises the conclusions drawn at a workshop that took a prospective view of the technological developments necessary in order to make significant progress with reducing these uncertainties. These developments would mainly aim to further the understanding of how sound may affect some of the most vulnerable marine species. The most important methods available to examine the effects of sound will involve the development of instruments that measure the received levels of sound at the animal and its behavioural response. The availability of power to operate instruments used in remote sensing is the main factor that limits most aspects of technology capability. Alternatives need to be developed to using sparse data (from a few instruments that are attached to animals or that are widely spaced), and a coordinated approach is required between commercial suppliers and academics to overcome the current constraints, foster innovation and turn new approaches into operational tools. There is also a need to improve the technology used to attach instruments to animals, particularly in the case of small cetaceans. Improved bandwidth for data communication, recovery or retrieval is likely to develop alongside other innovations as a result of improvements in large-scale infrastructure such as satellite systems. There is scope for innovation of sensors to improve the ability to measure behavioural/physiological response variables such as heart and/or respiration rate.

Keywords: noise, impacts, marine mammals, measurement, animal-borne instruments

1. Introduction

The effect of sound on marine life is one of the big unknowns of current marine science (Boyd et al., 2011). Rising anthropogenic sound levels from many sources, though mainly from shipping (Andrew et al., 2002; McDonald et al., 2008; Hildebrand, 2009), are suggested to be an emerging problem for ocean conservation (Ausubel, 2009). Since sound is an important factor in the lives of many marine organisms and there is considerable evidence that anthropogenic sound has increased in the ocean in recent decades (National Research Council (NRC), 2003; NRC, 2005), there is a need to develop new and better ways of studying and monitoring the effects of sound on marine wildlife.

New legislation, such as the Marine Strategy Framework Directive within the European Union, is establishing limits for the amount of sound entering the marine environment. This is likely to affect future industrial developments in the ocean as they are challenged by the need to comply with legal limits. It may help drive innovation that reduces the sound profiles of ships and the use of sonar and other sound sources, such as pile driving and seismic surveying. However, the high uncertainty around the effects that the sound produced by this combination of sound sources has on marine life is a barrier to ensuring that legislative constraints are set using rational criteria. A principal reason why so little is known about the effects of sound on marine life is because of limitations with current technology.

It is important to prioritise the technology required against the need to reduce uncertainty. Previous exercises to develop models of the underlying rationale for studying the effect of underwater sound on marine wildlife (NRC, 2003; NRC, 2005; Southall et al., 2007; Boyd et al., 2008) have done much to define the major research questions to be addressed. These analyses have identified the need to measure the received levels of sound and the response of individual animals to these levels as a priority. They also identified the need not only for risk-based management of the effects of sound but also to prioritise research.

The capacity to titrate the effects of sound by measuring the sound received by marine life and their response to it was deemed important. However, current capability to study the effects of sound using basic physiological measurements (e.g. auditory brainstem response providing audiograms for different species, e.g. Houser et al., 2008) is restricted to unnatural circumstances.

Email address: ilb@st-andrews.ac.uk

Behavioural and peripheral physiological responses to sound are likely to be of greater biological importance than a simple measurement of what sounds an animal can hear. It is therefore important to have the capacity to titrate these biologically significant responses against received sound levels in a broad range of different species and circumstances.

Most current technologies focus upon telemetry and animal-borne instruments, and concentrate on marine mammals because they are often viewed as particularly sensitive species (Cox et al., 2006; Southall et al., 2007). This perception is, in part, because marine mammals are the focus of most of the conflicts between marine wildlife and industrial or military activities. Other modalities, including visual and acoustic methods for measuring behaviour, are also essential elements within the suite of methods that could be used to address the research questions. Fig 1 shows the relative importance of different types of technology to the major areas of biological activity that are relevant to the assessment of the effects of anthropogenic sound on marine wildlife.

While visual and photographic methods have an important part to play, most progress in the future will be made in the development of better technology based on micro-electronics to allow the remote observation of animals. This includes tagging and other electronic systems such as those used to provide information about vocalising animals using passive acoustics.

The aim of the present study was to prioritise requirements for technology development associated with data collection for measurements of the behaviour of marine wildlife in response to sound. The study emerged from a workshop sponsored by

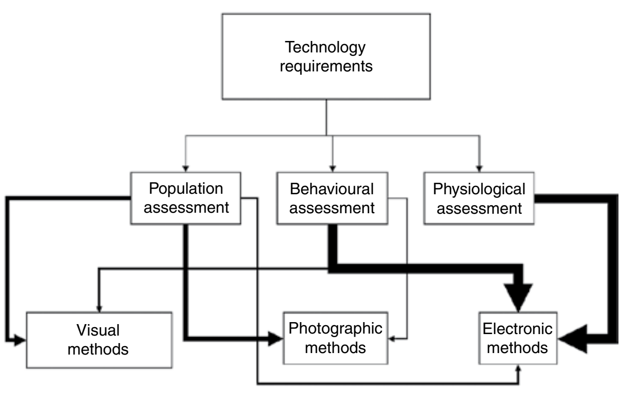

Fig 1: A flow diagram that summarises the relationship between the need for technology to support research on the effects of underwater sound on marine life, the types of biological assessment that will be required and the types of technology that are likely to be used to support those assessments. The relative width of the lines is used as a guide to the importance of the linkage

the joint industry programme (JIP) on the effects of sound on marine life. In so doing, the paper does not review the current state of technology, some of which is summarised elsewhere (e.g. see various chapters in Boyd et al., 2010). The paper focuses principally on the challenges present for technology development and concludes by suggesting where the priorities for such development might lie.

2. Background

The source-pathway-receiver (SPR) model (Fig 2) is an heuristic way of defining the relative importance of different parts of the process. The significance of each element needs be understood in order to constrain the uncertainty surrounding the possible effects of sound on marine wildlife (for this purpose, most of the discussion will concern marine mammals). It is a slightly simplified version of the model known as the Population Consequences of Acoustic Disturbance (PCAD; NRC, 2003). It shows marine wildlife as complex transducers that receive sound by particular pathways from a known anthropogenic source.

The response to the sound may be manifest as a physiological, anatomical or behavioural change. In any particular case this could be damaging to the individual animals involved. However, for this damage to be biologically significant the change must be sufficient, either on its own or as part of a cumulative process, to alter the trajectory of marine wildlife populations (Wartzok et al., 2005). In other words, this defines the difference between the effects of transient or rare disturbances that affect relatively small numbers of individuals in populations, and disturbances that are sufficiently frequent or sustained to an extent that they reduce the viability of marine wildlife populations.

Within the context of SPR and PCAD models, there is a need to frame the issues of marine sound and its effects upon wildlife in the context of a high-level environmental risk management procedure (Boyd et al., 2008). This procedure should be developed so that it can be integrated with other risk assessment activities undertaken by marine industries, such as defence, offshore oil and gas, and shipping.

Improving the knowledge of behaviour and physiology in marine wildlife species is challenging for three main reasons. Firstly, access to animals in their natural, undisturbed state is particularly difficult and varies between species and taxonomic group. It can also vary depending upon the sex and stage of the life cycle of the species concerned. Secondly, there is the challenge of building

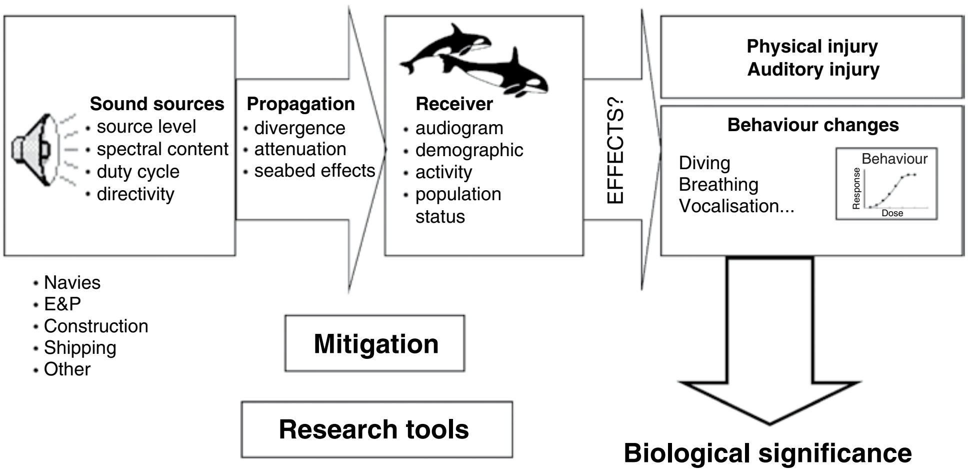

Fig 2: The source-pathway-receiver model, which shows the basic features of the problem to investigate. Sound sources produced by different marine users propagate sound that is dependent upon characteristics of its source and the environmental condition. The biological features of the receiving marine mammal could determine if and how the animal receives this sound, as well as the latter's distribution and abundance. This may elicit behavioural changes or could cause injury. A major question being addressed is the extent to which these effects are biologically significant

baseline datasets that encompass most of the natural variability of a species. To achieve this, a sufficient sample size is required to allow appropriate statistical inference about the presence of abnormal behaviour or physiology in response to a sound stimulus. Thirdly, the context of exposure is critical to understanding the biological effects. These challenges can be met to some extent by the application of technological advancements within a valid environmental risk management framework.

3. Analytical methods

The approach to analysing the options for new technology involved a detailed consultation with 45 experienced practitioners in the field of technology development and the application of technology in research. This included commercial companies that supply technology, representatives of the offshore oil and gas industry, as well as academic researchers, biologists and engineers. They represented a broad international community mainly from Europe and North America. The participants were brought together within a workshop and tasked to consider different aspects of the problem in a logical, structured sequence.

Technological solutions include: monitoring the acoustic environment and passive acoustic monitoring; locating and measuring the movement pattern in mobile species; measuring responses to sound and its biological effects; on-board sensors; power supplies; attachment techniques; communications; and user-supplier interactions. Within each of these subject areas the analysis undertaken by the participants included the current state of the technology, an assessment of the challenges, and the solutions and approaches to implementation of the solutions. The present paper is a summary of the conclusions resulting from this process.

The rationale was also developed for identifying technology gaps: first, by defining the functions needed to address the main research questions; and second, by assessing the sensor technology needed to meet current requirements. The differences between the assessment of the 'functions' and the 'sensors' were used to define the gap between current capability and the requirements of the research field.

The principal research questions, as defined in Boyd et al. (2008), were structured to address the problem of sound and its effects upon marine mammals within a risk assessment framework. Although marine wildlife includes a broad range of species from fish to reptiles, the present paper remains biased towards the effects upon marine mammals because this is seen to be the most pressing issue (Cox et al., 2006; Southall et al., 2007). The analysis conducted by Boyd et al. (2008) showed that some research questions have a higher priority. This important subset included the following questions: Where are the animals? What are the received sound characteristics? What is the response of the animal? Answering these questions was a prerequisite before attempting to answer other questions and was used as a guide to priorities for technology development.

4. Results and discussion

4.1. Technology gap analysis

Table 1 summarises the gap analysis of the current capacity to measure important types of variables and shows that gaps in capability occur where there is a high demand but low current capacity. Those variables that match these criteria and have a high likelihood of success are highlighted.

Table 1 is constructed specifically around marine mammals, and there are differences among different groups in terms of priorities. Some areas where technology already exists (e.g. for pinniped heart rate) are not highlighted. In general, this table illustrates the existence of a gap in technology that can measure both the specific physiological variables in small odontocete and mysticete cetaceans, and the variables that reflect important behavioural activities that can be used to construct time budgets in small cetaceans.

The gap analysis suggested that there is a need to focus attention on improving methods to enable on-board data processing within instruments during deployment. However, passive acoustics for detecting and studying cetacean behaviour would also benefit from technology development, and the same could be said for visual surveys.

Recent developments in visual surveys using high-definition video have mainly been applied to seabird surveys, but much work is required to validate the use of this method with other marine life, especially marine mammals. A recent tendency (especially by offshore industry) to combine survey designs for different groups of marine species has shown that it is often not possible to optimise surveys for all species groups (e.g. seabirds combined with cetaceans). In these circumstances, the design that caters to the groups with the highest underlying variance in the results would be most appropriate.

4.2. Researcher and supplier requirements

An additional analysis of technology gaps was carried out by asking specialists to provide a list of their five top technology issues that required further development specifically to address the needs of the offshore industry. This was done in an attempt to provide an alternative integration of the technology needs.

The attachment of instruments was identified as the greatest priority in this analysis (Table 2). However, this analysis also included an acknowledgement that the challenges with instrument attachment varied depending on the species, for example it was in particular most challenging in cetaceans and in small/medium-sized species.

The analysis also indicated the need to have improved release systems for attachments and the

Table 1: Summary of the gap analysis conducted. Low (L) in 'present status' means that the measurements have not been made in free-ranging individuals or that the circumstances under which measurement are possible are very constrained. Medium (M) means that there has been some limited success, while high (H) means that the method has been used extensively. N means the success of the method is not known. Shaded boxes highlight those variables where the present capability is poor, the development need is high and the probability of success is high. These could be seen as important gaps in essential capability with high priority for future investment

	Demand			Current capacity								
Variable	**Duration**	**Temporal resolution**	**Priority**	**Present status**			**Development needed**			**Probability of success**		
				Odontocete	**Mysticete**	**Pinniped**	**Odontocete**	**Mysticete**	**Pinniped**	**Odontocete**	**Mysticete**	**Pinniped**
Physiology												
Heart rate	Weeks-months	Seconds-minutes	High	L	N	M	H	H	M	H	H	H
Temperature (body)	Weeks-months	Hours	Medium	L	L	M	M	M	M	L	L	H
Energy consumption	Weeks-months	Minutes-days	High	L	L	M	H	H	H	L	L	M

(continued)

	Demand			Current capacity								
Variable	Duration	Temporal resolution	Priority	Present status			Development needed			Probability of success		
				Odontocete	Mysticete	Pinniped	Odontocete	Mysticete	Pinniped	Odontocete	Mysticete	Pinniped
Heat flux	Hours-weeks	Minutes	Low	M	N	M	H	H	H	L	L	L
Respiration	Minutes-months	Seconds-minutes	High	L	L	L	H	H	H	H	H	H
Condition/growth	Months-years	Days-weeks	High	L	L	M	H	H	H	H	H	H
Behaviour												
Location and movement	Months-years	Minutes-days	High	M	M	H	H	H	M	H	H	H
Diving	Weeks-months	Minutes-hours	High	M	M	H	H	M	L	H	H	H
Feeding	Hours-weeks	Minutes-hours	High	L	M	M	H	H	H	H	H	H
Speed	Hours-weeks	Minutes-hours	High	M	M	M	H	H	H	H	H	H
Stroking	Hours-weeks	Seconds-minutes	High	M	M	M	H	H	H	H	H	H
Acceleration	Hours-weeks	Seconds-minutes	High	M	M	M	H	H	H	H	H	H
Orientation	Hours-weeks	Seconds-minutes	High	M	M	M	H	H	H	H	H	H
Vocalisation	Weeks-years	Seconds-minutes	High	H	H	H	M	M	M	M	M	M
Haul-out	Hours-weeks	Minutes-days	Medium	–	–	H	–	–	L	–	–	H
Social	Minutes-weeks	Minutes-hours	High	M	M	L	H	H	H	M	M	M
Sleep	Days-weeks	Minutes	Low	N	N	L	H	H	H	L	L	L
Population												
Survival	Years	Months	High	L	L	L	H	H	H	L	L	L
Reproduction	Years	Months	High	L	L	L	H	H	H	L	L	L
Environment												
Ambient sound	Weeks-years	Days-weeks	High	M	M	M	H	H	H	H	H	H
Received sound level	Days-weeks	Minutes-hours	High	M	M	H	H	H	M	H	H	H
Prey field	Days-weeks	Minutes-hours	High	N	N	M	H	H	H	L	L	H
Bio Oceanog (e.g. ocean colour)[1]	Days	Minutes	Medium	N	N	M	M	M	M	H	H	H
Phys Oceanog (e.g. conductivity, salinity)[1]	Days	Minutes	High	N	N	M	H	H	H	H	H	H

[1]Consideration was only given to the measurements that could be made using instruments developed for studying marine animal biology. This excluded the technology normally associated with standard oceanography.

Table 2: Listing of the main technology issues identified by specialists in the field, together with the frequency with which each issue was mentioned. The frequency represents the relative priority by the respondents

Technology issue	Frequency
Instrument attachment	33
Communications	23
Sensors	21
Availability of access	11
Data analysis (on-board)	10
Power	8
Multifunctional, multimodal tag	8
Size	7
Cost	5
Data analysis (post-hoc)	3
Species-specific designs	2
Long-term, low-cost tags	2
Additional, unclassified comments	28

need for control over the deployment duration, so that short/medium-term deployments can take place on the same duration as key activities. Although some respondents suggested that longer durability of instruments was desirable, this was generally interpreted as an issue concerning attachment rather than the memory or battery life of an instrument.

There was a high level of co-variation between several of the technology issues. In particular, instrument 'attachment', 'size' and 'power' involve several trade-offs. There tends to be a set of dependencies that leads, respectively, to power affecting size, attachment and longevity. Power supply is limited by battery technology, which ultimately limits the size of attached instruments as well as the sampling by sensors, memory storage capacity, on-board processing capacity and the bandwidth of communication. All these elements affect longevity and result in the general trade-off between longevity and functionality. The limits that this imposes can possibly be overcome to an extent by better on-board data compression and processing, or by considering the distinctive needs of the different taxonomic groups and designing tags specific to each of those groups.

A balance needs to be found between instruments that are closely aligned with the needs of researchers, which are more likely to be costly, bulky and less reliable, and those that are mass-produced to a standard design at comparatively low cost, but may not be tailored to support researchers' specific needs. For example, some researchers needed a modular instrument for tagging marine wildlife that has, at its core, a specific control and power unit that could then be used to carry a wide variety of sensors and communications devices. Others needed a low-cost, low-capability instrument for tagging marine wildlife that could be deployed in large numbers.

Matching the researcher needs for both ends of this spectrum is perhaps the greatest challenge for technology developers and commercial technology suppliers. They also need to ensure that systems will maximise flexibility in terms of what an instrument is able to do while minimising cost and size. There will always be a tension between the commercial suppliers of instruments who need to reduce costs and increase production volume, and the researchers, who prefer to have custom-made instruments that have been tailored to address specific research questions.

4.3. Measuring the response to sound

Important responses to sound are those that have ultimate consequences on the population and/or species. These responses include avoidance, changes in feeding success, reproductive success and survival. The lack of any observable behavioural avoidance to sound does not eliminate the presence of physiological responses that could be adaptive or non-adaptive.

Conditioning to sound, through processes of habituation or sensitisation, is recognised as an important variable that is difficult to measure yet will contribute to the variance in any response to sound that may be used to titrate an effect (e.g. Tyack, 2008; Slabberkoorn et al., 2010). Moreover, sound may have a cumulative effect, so the measurement of sound exposure histories of animals is important but is technologically challenging. However, measuring exposure histories directly in marine wildlife is probably not currently technically feasible, at least over timescales of years to lifetimes. This points to a need for more proficient statistical modelling of likely sound exposure histories.

Large sample sizes will be required to overcome the challenge of the relatively high variance in the types of responses the marine wildlife will have to different sound stimuli. Factors contributing to this variance that could potentially be controlled include the effects of disturbance from making measurements and recording exposure history.

Responses to sound were considered under several categories that relate to providing information of relevance to modelling or assessing the biological significance (see Fig 1) of effects. The types of variables were: avoidance; behavioural change; life function; and vital rates.

4.3.1. Avoidance

Avoidance may occur on short and long timescales, but over short timescales avoidance may represent a behavioural change (see section 4.3.2). Over the long term (months to years) tracking individuals using either instruments attached to animals or photographic identification is the most appropriate technological solution.

Changes in distribution as an indication of avoidance can probably be tracked most effectively at the regional and population levels using visual surveys of populations through distance sampling (e.g. Buckland et al., 2000), although passive acoustic methods are increasing in importance. Technological innovations for distance sampling could involve the use of non-visual methods to detect the presence of animals including passive acoustics, active acoustics involving sonars, high-frequency (HF) radar to detect surfacing or infrared visualisation and the use of high-definition video.

4.3.2. Behavioural change

Behaviour changes including those associated with orientation, movement, location and startle responses may be measured using accelerometry. However, the data volumes produced may require on-board processing for data reduction if there is a need to transmit the data. Specific behavioural changes include:

- breathing frequency and vocalisation, measured using a hydrophone and passive acoustics;
- diving behaviour, measured using accelerometry and pressure transducers;
- foraging behaviour, measured using accelerometry or passive acoustics;
- mother-infant associations, measured using visual, passive acoustic and double tagging methods; and
- heart rate measured using electrocardiography (ECG) in pinnipeds.

ECG, however, is a difficult technique to apply to free-ranging animals. It may be possible to develop a 'stethoscope tag' to measure heart rate (Miksis et al., 2001), but this is also difficult to implement with unrestrained animals and may require complex signal processing to subtract ambient sound that could mask heart rate.

4.3.3. Life function

A life function assessment involves measuring the significance of changes in migration patterns and the rate of food consumption. Proxies for feeding include defecation rates, the use of specific echolocation signals by animals, changes in buoyancy and stomach temperature measurement. The utility of these varies greatly between species.

4.3.4. Vital rates

Vital rates include survival, growth and reproductive rates, and can be estimated for some species using visual/photographic methods combined with demographic modelling. Direct measurement of survival rates may be possible using survival/mortality tags. Life-long implantable loggers that are released on the death of the animal are a focus of activity. Long-term mark-recapture studies are likely to be at least as useful, however, ethically appropriate and reliable marking methods, such as implantable passive integrated transponder (PIT) tags, are needed. Mass changes may be estimated using buoyancy and acceleration changes, passive acoustics (e.g. size measurement of some cetaceans) or ultrasound measurement (e.g. blubber depth in some marine mammals) (Biuw et al., 2003).

There are already suitable, well-developed methods for measuring breeding success in some species using visual/photographic survey (Hiby and Hammond, 1989), but there is potential for developing new methods using sensors to assess reproductive hormones assays. Chorionic gonadotrophins are present in pinnipeds and some cetaceans, thus making detection of pregnancy more reliable (Hobson and Boyd, 1984).

4.3.5. Exclusion of auditory brainstem response

Titration of short-term behavioural/physiological responses that does not have to rely upon the use of auditory brainstem response (ABR; Houser et al., 2008) is necessary in order to assess whether animals are affected by sound exposures. ABR cannot be used in free-ranging animals.

It may be possible, for example, to replace ABR with a behavioural or physiological response variable such as heart rate. Although still difficult to measure, heart rate has several advantages over many other potential variables. For one, it has already been used as a proxy for energy consumption in a range of higher vertebrates (Butler et al., 1995). Since changes in energy consumption are likely to have direct effects on vital rates, it has value as a proxy for responses that may affect vital rates.

In addition, heart rate in its own right is a physiological response. In marine mammals, where there appears to be a high level of autonomic control of the heart, it may even be used as a behavioural variable (Boyd et al., 1999). Finally, it can be used as an autonomic stress response in vertebrates. Breathing rate also has many of these qualities and could be measured alongside heart rate.

4.4. Attachment of instruments to animals

Instruments are attached or glued to the hair of pinnipeds (seals), meaning that longevity is dependent on the period of time until the next moult. Improvement in attachment duration in pinnipeds may be achieved with new forms of glue for attaching to fur. Current glues tend to heat the hair on curing and can cause the hair to become brittle. Longer-term attachment can be achieved by clipping to flippers and tusks (walrus). Short-term (hours to days) attachment to cetaceans can be achieved using suction cups by remotely operated methods.

Longer-term attachment of tags requires implantation or clipping to the dorsal fin or ridge, but both these methods require capture. Remote attachment can be achieved with trans-dermal barbs and, in larger species, may be implanted in the blubber or muscle using a projectile fired into the animal. Harnesses can be used on small cetaceans. Several attempts have been made to develop methods that will allow the surgical implantation of tags (e.g. Green et al., 2009), but there are ethical complications associated with using some of the more invasive methods of attachment (see Gales et al., 2010).

Instrument size should be as small as possible to reduce drag, thereby reducing the effects on animal behaviour and most likely increasing the period of attachment. However, there is a trade-off between instrument size and the level of functionality of the instrument and the invasiveness of the attachment.

There is a lack of methods providing attachment over intermediate durations. Improving suction-cup capabilities may be a viable solution, since current suction cups have been borrowed from off-the-shelf products and not developed specifically for attachment to marine mammals. Problems with suction cups being used for deployments of more than a few days come from the restriction of blood circulation in the area under the suction cup. A possible solution is an attachment system with multiple suction cups, each one of which could then be loosened and moved to a new patch of skin while other cups remain attached. Such a system would be an engineering challenge, but it could help overcome ethical concerns with the use of suction cups and how they affect the animal's skin. This could possibly be co-developed with controlled remote-release instruments.

4.5. Monitoring acoustic environments

Monitoring acoustic environments is a complex problem with many different approaches and applications beyond those being considered in the present paper. It can also conflict in some places with national security issues, which can prove to be an insurmountable bureaucratic obstacle, depending upon circumstances and jurisdictions.

Present methods for characterising the acoustic environment are built around physical sound propagation models. These rely heavily upon data on the water column structure and bottom type and topography, and do not work well in regions with a complex bathymetry and coastal areas. Current techniques focusing on marine wildlife mainly include passive acoustics using moored bottom-mounted or ship-based hydrophones or arrays. Passive acoustics can include bottom-mounted localisation, periodic acoustic surveys with towed arrays from mobile platform and tags (long-term acoustics). All have the potential to integrate background broadband sound levels, as well as sound in the bands used for social interaction by marine wildlife.

There are examples of systems currently monitoring the acoustic environment in the long term (years to decades), such as the system established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). Long-term background monitoring is important to answer questions about avoidance and short-term effects, because it provides a context within which to assess the statistical significance of an effect against background variation in sound levels. Relevant questions emerging from this include how acoustic 'budgets' could be measured and in what currency, and what parts of the acoustic spectrum are likely to be relevant.

While there remain technical challenges with passive acoustic monitoring systems, which can be overcome, the development of long-term sound-recording tags for attachment to marine wildlife is a priority. Past reviews (e.g. Boyd et al., 2008) have shown that measuring the sound exposure of animals is perhaps the most important variable that needs to be measured when titrating the response to sound in an animal's environment.

4.6 Acoustic tag technology

There are two biological goals of acoustic tags: to measure external stimuli; and to measure the animals' vocal behaviour. In general, there is a trade-off in acoustic tags between bandwidth and recording life caused by the limitations of memory capacity. Different tags have been designed to exploit different parts of this constraint, which determines how useful they are for different applications.

There is a possible evolutionary path from the broadband general acoustic tags available at present, to hybrid tags with compressed data and decision criteria (about what should be recorded), and ultimately to special purpose tags in the future. Currently, acoustic tags generate large volumes of data, making it impractical to download the data remotely with current bandwidth capability for data transmission. As a result the tags must be retrieved in order to obtain the data, or the tag itself needs to undertake most data processing

Table 3: A list of recommendations for the progress of technology development to support the investigation of the effects of sound on marine wildlife, together with a justification, priority rating and an assessment of the likelihood of success for each recommendation

Recommendation	Justification	Priority	Likelihood of success
Develop a method for power generation on animal-borne instrumentation	The ultimate constraint on almost all aspects of remote data acquisition involves the management of scarce power resources. A solution will probably require consideration of new and perhaps novel technologies used to generate power from the environment.	High (1)	High
Improve communication and high bandwidth data transfer	Current systems cannot cope with high data volumes, especially from sensors that sample at high frequency and for sound levels and acceleration, both of which are highly relevant.	High (2)	Medium
Continue development of wider-scale ocean sound observation technologies that can be deployed into focused regions where industrial activities are planned	This development is important as a means of providing data for statistical algorithms that build exposure budgets for animals following particular distributions and migration tracks, which could themselves be carrying tracking tags. This measure is essential to estimating received levels of sound given that the developments required to monitor received levels from tags on the animals themselves are probably not feasible in the short to medium term. The method also has potential to collect dose-response data from certain species for which tagging is not a feasible option, or where tagging will not produce the required, statistically-robust result.	High (3)	High
Develop systems that allow long-range (>1km) remote-controlled release of instrument packages attached to animals	Part of the process of data recovery needs to involve the use of archival tags that can be released on command. Since archival tags are probably at the most advanced state of development and are comparatively easy to build, this could lead to a rapid improvement in capability.	High (4)	Medium/ Low
Make better use of the data collected from instruments by developing statistical and mechanistic frameworks for analysing data in the context of broader-scale, lower-resolution data	Even a step-change in technology may not lead to an equivalent change in the ability to obtain appropriate sample sizes that have enough statistical power to draw robust conclusions about effects. It is important to develop a strong understanding of the statistical power that can be developed by combining low volume, highly detailed data with high volume data of lower quality.	High (5)	High
Develop new methods of instrument attachment to mobile species	Remote observation is impossible without appropriate attachment methods, but these are not well developed for many species. Likelihood of success in this case has been classed as 'low' because this has received a lot of attention to date and approaches not yet attempted are highly speculative.	High (6)	Low
Develop sensors for heart rate that can be used reliably in systems involving remote attachment	Heart rate was identified as an appropriate response variable for titrating the effects of received sound. It has the important property in marine mammals of being both a physiological and behavioural variable.	High (7)	Medium
Real-time (or near real-time) data transmission from tags	Any dose-response experiment or *in situ* monitoring of responses to real surveys will require rapid feedback from instrumented animals as part of the risk assessment process so that an adaptive approach could be taken.	High (8)	Medium
Develop a sensor for breathing rate that can be used reliably in systems involving remote attachment	Breathing rate will probably not be as useful as heart rate, but it can be measured for the same reasons.	Medium (9)	Medium

on-board with pre-programmed algorithms. Therefore, retrieval techniques and on-board data compression are important factors. Progress in data compression can possibly be achieved by spectral averaging, event/peak detection and recording triggers based on sound, depth, proximity, time, orientation, acceleration/startle, temperature and position.

4.7. Communications

The rate and manner of data transmission from instruments carried on animals are important constraints on how useful various types of technology are in different circumstances. The effectiveness of different types of communication depends on the data transfer rate, range, energy cost, financial cost, instrument size and the power required.

The most widely used system for communication of data is the Advanced Research and Global Observation Satellite (ARGOS) system, which is being augmented by the capacity for much higher data transfer rates at lower power using cell phone networks when available and the Iridium network. However, there are a limited number of modalities for the communication of data, and these are often constrained by physics and practicality, e.g. attenuation of radio waves within salt water, poor transmission of acoustics in air. In addition, there are sometimes licensing and bureaucratic issues concerning different forms of radio communications that are also barriers.

The main challenges for developments in this area are those associated with increasing data transfer rates, achieving timely two-way communication, and developing automated frequency selection to achieve the maximum baud rate.

5. Conclusions

Table 3 provides a set of overall conclusions in the form of recommendations for the future technology required to develop a better understanding of the effects of sound on marine wildlife. Priority levels are notional but are assessed upon a set of criteria including the likelihood of success, the extent to which outputs are likely to make a step-change in capability and the relevance to the ocean users.

Acknowledgements

This study emerged from a workshop on technology requirements to investigate the effects of sound on marine wildlife, which was initiated and sponsored by the International Association of Oil and Gas Producers Joint Industry Program (OGP-JIP) on Sound and Marine Life. It took place in St Andrews on 20–22 March 2007. The author wishes to thank all 45 participants in the workshop, who were from a wide range of institutions. Attendees were representative of a much larger community than could be hosted at the workshop and were asked wherever possible to represent their community rather than their own interests. Delegates were drawn from across the research and technology development sector to include those who used and applied technology, those who both used and built technology, and those who designed and supplied technology on a commercial basis to the researchers working in the field. This included representation from the OGP-JIP.

References

Andrew RK, Howe BM, Mercer JA and Dzieciuch MA. (2002). Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustic Research Letters Online* **3**: 65–70.

Ausubel J. (2009). Rethinking sound and light. *Seed Magazine*, 23 November, http://seedmagazine.com/content/article/rethinking_light_and_sound.

Biuw M, McConnell B, Bradshaw CJA, Burton H and Fedak M. (2003). Blubber and buoyancy: monitoring the body condition of free-ranging seals using simple dive characteristics. *Journal of Experimental Biology* **206**: 3405–3423.

Boyd IL, Bevan RM, Butler PJ and Woakes AJ. (1999). Heart rate and behavior of fur seals: implications for the measurement of field energetics. *American Journal of Physiology – Heart and Circulatory Physiology* **276**: H844–H857.

Boyd IL, Brownell R, Cato D, Clarke C, Costa D, Evans P, Gedamke J, Gentry R, Gisiner R, Gordon J, Jepson P, Miller P, Rendell L, Tasker M, Tyack P, Vos E, Whitehead H, Wartzok D and Zimmer W. (2008). The effects of anthropogenic sound on marine mammals – a draft research strategy. European Science Foundation Marine Board Position Paper 13, June 2008.

Boyd IL, Bowen WD and Iverson SJ. (2010). *Marine Mammal Ecology and Conservation: A Handbook of Techniques*. Oxford: Oxford University Press, 450pp.

Boyd IL, Frisk G, Urban E, Tyack P, Ausubel J, Seeyave S, Cato D, Southall B, Weise M, Andrew R, Akamatsu T, Dekeling R, Erbe C, Farmer D, Gentry R, Goss T, Hawkins A, Li F, Metcalf K, Miller JH, Moretti D, Rodrigo C and Shinke T. (2011). An international quiet oceans experiment. *Oceanography* **24**: 78–85.

Buckland ST, Goudie IBJ and Borchers DL. (2000). Wildlife population assessment: past developments and future directions. *Biometrics* **56**: 1–12.

Butler PJ, Bevan RM, Woakes AJ, Croxall JP and Boyd IL. (1995). The use of data loggers to determine the energetics and physiology of aquatic birds and mammals. *Brazilian Journal of Medical and Biological Research* **28**: 1307–1317.

Cox TM, Ragen TJ, Read AJ, Vos E, Baird RW, Balcomb K, Barlow J, Caldwell J, Cranford T, Crum L, DAmico A, D'Spain G, Fernández A, Finneran J, Gentry R, Gerth W, Gulland F, Hildebrand J, Houser D, Hullar T, Jepson PD, Ketten D, Macleod CD, Miller P, Moore S, Mountain DC, Palka D, Ponganis P, Rommel S, Rowles T, Taylor B, Tyack P, Wartzok D, Gisiner R, Mead J and Benner L. (2006). Understanding the impacts of anthropogenic sound on beaked whales. *Journal of Cetacean Research and Management* **7**: 177–187.

Gales NJ, Johnston D, Littnan C and Boyd IL. (2010). Ethics in marine mammal science. In: Boyd IL, Bowen WD and Iverson SJ (eds.). *Marine Mammal Ecology and Conservation: A Handbook of Techniques*. Oxford: Oxford University Press, 1–15.

Green JA, Haulena M, Boyd IL, Calkins D, Gulland F, Anthony J, Woakes AJ and Butler PJ. (2009). Trial implantation of heart rate data loggers in pinnipeds. *Journal of Wildlife Management* **73**: 115–121.

Hiby AR and Hammond PS. (1989). Survey techniques for estimating abundance of cetaceans. In: Donovan GP (ed.). *The Comprehensive Assessment of Whale Stocks: the early years*. Reports of the International Whaling Commission, Special Issue 11. Cambridge: International Whaling Commission, 47–80.

Hildebrand JA. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series* **395**: 5–20.

Hobson BM and Boyd, IL. (1984). Gonadotrophin and progesterone concentrations in placentae of grey seals (*Halichoerus grypus*). *Journal of Reproduction and Fertility* **72**: 521–528.

Houser DS, Gomez-Rubio A and Finneran JJ. (2008). Evoked potential audiometry of 13 Pacific bottlenose dolphins (*Tursiops truncatus gilli*). *Marine Mammal Science* **24**: 28–41.

McDonald MA, Hildebrand JA, Wiggins SM and Ross D. (2008). A 50 year comparison of ambient ocean noise near San Clemente Island: A bathymetrically complex coastal region off Southern California. *Journal of the Acoustical Society of America* **124**: 1985–1992.

Miksis JL, Grund MD, Nowacek DP, Solow AR, Connor RC and Tyack PL. (2001). Cardiac responses to acoustic playback experiments in the captive bottlenose dolphin (*Tursiops truncatus*). *Journal of Comparative Psychology* **115**: 227–232.

National Research Council (NRC). (2003). *Ocean Noise and Marine Mammals*. Washington, DC: National Academy Press, 204pp.

NRC. (2005). *Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects*. Washington, DC: National Academy Press, 142pp.

Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C and Popper AN. (2010). A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology & Evolution* **25**: 419–427, doi: 10.1016/j.tree.2010.04.005.

Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene CR, Kastak D, Ketten DR, Miller JH, Nachtigall PE, Richardson WJ, Thomas JA and Tyack PL. (2007). Marine mammal noise exposure criteria: initial scientific recommendations. *Aquatic Mammals* **33**: 411–522.

Tyack PL. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy* **89**: 549–558.

Wartzok D, Altmann J, Au W, Ralls K, Starfield A and Tyack PL. (2005). *Marine mammal populations and ocean noise: determining when noise causes biologically significant effects* (Tech. Report No. 0-309-09449-6). Washington DC: National Academies Press, 142pp.