COMING TO TERMS WITH THE EFFECTS OF OCEAN NOISE ON MARINE ANIMALS

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"The challenge is to balance our sound producing activities so they do not impact the health and safety of creatures, large and small, that live in the sea."

From the sound that threatened "to deafen whales" with a low frequency hum throughout the world's oceans (Anderson, 1991) to present day military exercises using active sonar, controversy about the effects of sound on the marine environment has continued for over two decades. Marine animals use sound for communication, navigation, detection of predators and prey, and identification of their habitats. But the ocean is filled with many interfering sounds, some naturally occurring such as earthquakes and volcanic eruptions, and others resulting from human activity. The largest contributor to anthropogenic (human-caused) sound in the ocean is commercial shipping, which accounts for over 90% of international commerce. But other contributors, such as active sonar and seismic air guns, have very high source levels even though they affect smaller defined areas. Active sonar is used not only by the world's navies to detect and track potentially hostile underwater intruders, but also by scientific researchers to study the ocean environment and the animals that live there. Likewise sound pulses created by arrays of seismic air guns are used for geophysical research to understand structures and processes beneath the seafloor as well as by oil and gas companies to locate and quantify reserves of hydrocarbon fuels. The challenge is to balance these activities so they do not impact the health and safety of creatures, large and small, that live in the sea.

The public is acutely aware of potentially harmful interactions between marine animals and anthropogenic sound (Simmonds *et al.*, 2003; Wartzok *et al.*, 2003/04; Jasny *et al.*, 2005). As this article goes to press, the U.S. Navy finds itself in a 30-day period during which it can file an appeal to the U.S. Supreme Court for exemption from environmental laws[1] that protect whales and other marine mammals so that it can fully conduct sonar training exercises off the coast of California. President Bush had exempted the Navy from applicable environmental laws on the basis of national security so that sonar training activities could continue without restrictions. But on February 29th of this year the U.S. Court of Appeals for the 9th Circuit upheld a lower court ruling that requires the Navy to limit sonar training off the California coast to minimize harm to marine life (*The Washington Post*, 2008). Now for the first time, it appears that the debate over effects of sound on marine mammals could be headed to the highest court in the land.

How did it begin?

Concern about potential adverse effects of anthropogenic sound on marine life accelerated in the early 1980's when endangered gray whales off the coast of California and bowhead whales in the Beaufort Sea displayed avoidance responses when exposed to playbacks of noise from drillships and dredges (Richardson *et al.*, 1990). But beginning in 1990, considerable public awareness about the effects of anthropogenic sound on marine animals materialized when plans for the Heard Island Feasibility Test (HIFT) coincided with advanced development of the U.S. Navy's Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar. Because sound at low frequencies can travel further underwater than sound produced at higher frequencies, SURTASS LFA was designed to emit signals at frequencies between 100 and 500 Hz using an array of 8 transducers, each with a source level of 215 dB re 1 μPa at 1 m (DoN, 2001), which could propagate from tens to hundreds of nautical miles (nm), effectively covering an ocean basin, to provide longer detection ranges for small, relatively quiet diesel-electric submarines and thus more time for defensive action.[2]

At the same time, the Office of Naval Research (ONR), the National Science Foundation (NSF), the Department of Energy (DOE), and the National Oceanic and Atmospheric Administration (NOAA) were sponsoring researchers led by Walter Munk at the Scripps Institution of Oceanography to plan and conduct the HIFT in attempt to demonstrate a method to monitor climate changes on a global scale. Taking advantage of known, long distance sound wave paths often referred to as the "deep sound channel," the Heard Island experiment was designed to show that measuring sound speed in the world's oceans could be used to monitor global warming (Cohen, 1991). The experiment consisted of transmitting acoustic signals at a frequency of 57 Hz (sometimes described by the press as a "low frequency hum") from Heard Island in the southern Indian Ocean and then measuring their time of arrival at various points around the world. The speed of sound in water increases with increasing temperature, so small changes in temperature of the ocean basins could be determined by measuring the amount of time it took for these sounds to travel from one point to another (Baggeroer and Munk, 1992; Munk *et al.*, 1994). This experiment created an outcry from several environmental groups, whose members feared that the HIFT sound transmissions would interfere with low frequency communications among large baleen whales (mysticetes)[3] or even physically harm these animals. The experiment began in January 1991, but with scientists onboard ships to monitor marine mammal activities in the vicinity of the sound source. No adverse reactions were observed (Bowles *et al.*, 1994).

The U.S. Navy's response to public outcry in the 1990's was twofold. First was initiation of environmental risk assessments and preparation of documents and requests for permits needed for HIFT and SURTASS LFA in compliance with national environmental laws. Second was funding for scientific research to understand the interactions between marine animals and sound. ONR funded the National Research Council (NRC) in 1992 to establish a Committee on Low-Frequency Sound and Marine Mammals, and produce a report on the state-of-knowledge and recommendations for changes in the regulatory process[4] to facilitate scientific studies as well as research needed to evaluate effects of low-frequency sounds on marine mammals and their major prey (NRC, 1994). ONR also began to sponsor research on the effects of low frequency sound on marine mammals and fish. Initially the primary concern was hearing and communication. So experimental studies to determine the effects of underwater sound on hearing in odontocetes (toothed whales) and pinnipeds (seals, sea lions and walrus) were initiated with captive animals—and continue today—at the Space and Naval Warfare Systems Center San Diego (SSC San Diego), the Hawaii Institute of Marine Biology (HIMB) at the University of Hawaii, and Long Marine Laboratory at the University of California, Santa Cruz (UCSC). In addition a SURTASS LFA Scientific Research Program (SRP) began in 1997 to quantify the reactions of large whales to low frequency broadcasts (Croll *et al.*, 2001).

The debate continued as plans were made for the offspring of the HIFT—a long term monitoring project, acoustic thermometry of the ocean climate (ATOC), using a lower power source operating at 75 Hz over a smaller region of the Pacific Ocean. Even though the ATOC sound projectors had lower source levels than those used for the HIFT (195 dB vs. 221 dB re 1 µPa at 1 m), public outcry caused the final project to be significantly delayed and scaled back. The final environmental impact statement set aside about $3 million of funding to study the effects of ATOC sound transmissions on marine mammals—the first two years of the project—so that it could be stopped if any adverse effects were observed. This ATOC Marine Mammal Research Program (MMRP) was reviewed by a new NRC study panel to update the 1994 NRC report with MMRP data and results of any other relevant research, and to identify continuing knowledge gaps. The review (NRC, 2000) indicated that results of the MMRP were inconclusive as to whether or not ATOC sound transmissions had any effect on marine mammals (Au *et al.*, 1997; Frankel and Clark, 2000; Frankel and Clark, 2002).

Attention turns to mid-frequency sonar, seismic air guns, and impact pile driving

Mid-frequency active sonar has been in operation since the 1940's and is the standard modality for localizing submarines. But in 1996 exposure to military sonar during a North Atlantic Treaty Organization (NATO) Undersea Research Centre exercise was postulated as the cause of a mass stranding of 12 beaked whales in Greece (Frantzis, 1998).[5] Similar mass stranding events during military exercises in the Bahamas and Madeira in 2000 (Evans and England, 2001; Cox *et al.*, 2006), and the Canary Islands in 2002 (Evans and Miller, 2004), each involving between 4 and 18 whales within two days, confirmed that beaked whales, and in particular Cuvier's beaked whale (*Ziphius cavirostris*), are sensitive to mid-frequency sonar, which operates in the 1 – 10 kHz bandwidth with source levels as high as 235 dB re 1 µPa at 1 m (Evans and England, 2001). In these four events about half of the stranded animals died, but the mechanisms that caused the animals to strand and contributed to pathological traumas revealed during necropsies are unknown (Ketten, 2005).

Subsequent mass stranding events coincident with the use of mid-frequency sonar in the Haro Strait near the state of Washington in 2003 (Norman *et al.*, 2004; National Marine Fisheries Service, 2005), and off the coasts of Hawaii in 2004 (Southall *et al.*, 2006) and North Carolina in 2005 (Hohn *et al.*, 2006) involved other species, including harbor porpoises, melon-headed whales and short-finned pilot whales, respectively. Medical examinations and necropsies of animals affected in these events, however, indicated that beaked whales are most susceptible to acoustic trauma when exposed to mid-frequency sonar transmissions (Freitas, 2004; Ketten, 2005; Fernández *et al.*, 2005).

Seismic air gun surveys for hydrocarbon exploration or oceanographic research are similar to active sonar operations. An air gun array towed by a vessel emits acoustic pulses directed vertically downward that penetrate the seabed. Refracted and/or reflected waves from different sediment layers are recorded by sensors on streamers towed behind the air gun array and used to reconstruct a picture of the substrate below the seafloor. Most all the acoustic energy in an air gun pulse is below 1000 Hz; however, sound pressure level (SPL) and spectral content vary spatially depending on the local undersea environment. Peak-to-peak source levels of emissions from air gun arrays can exceed 250 dB re 1 µPa at 1 m. Although the Department of Fisheries and Oceans (DFO) Canada, the U.S. Department of the Interior Minerals Management Service (MMS), as well as oil and gas companies worldwide had investigated the effects of noise on marine life from offshore industrial activities and seismic exploration for many years (e.g., Falk and Lawrence, 1973; Pearson *et al.*, 1987 and 1992; Richardson *et al.*, 1990, Richardson *et al.*, 1995), two beaked whales stranded September 2002 in the Gulf of California in association with seismic air gun use (Cox *et al.*, 2006). This stranding occurred coincidentally with a seismic air gun survey by the NSF-supported oceanographic research vessel, *Maurice Ewing*; however, the *Ewing* was also operating mid-frequency active sonar at the time. Since 2003, legal challenges and risk assessments for documentation of environmental impact statements have significantly hampered oceanographic research funded by NSF.

In the autumn of 2000 while the U.S. Navy was still trying to understand conditions that contributed to the March 2000 stranding of beaked whales in the Bahamas, the California Department of Transportation (Caltrans) was responding to a fish kill that occurred during a pile installation demonstration project (PIDP) for the San Francisco-Oakland Bay Bridge (SFOBB) East Span Seismic Safety

Project (East Span Project), a major public works effort to make the SFOBB "earthquake proof" (Caltrans, 2001). In addition to marine mammals, the major issues were endangered salmon species and impact on commercial fisheries. During the PIDP three 2.4-m diameter steel pipe piles were driven into the seabed with two different sizes of hydraulic impact hammers in effort to identify potential problems and test effectiveness of sound attenuation equipment. The immediate mortality zone for fishes was estimated to be within 10-12 meters of a pile without attenuation devices, but the potential for significant acoustic impacts extended far beyond this range.

A global environmental issue

The beaked whale stranding events, an increasing number of seismic surveys to meet the worldwide demand for oil and natural gas, and continued offshore pile driving activities at the start of the 21st century pushed the issue of ocean noise and marine animals to new heights. In 2003 the U.S. Congress passed legislation that directed the Marine Mammal Commission (MMC) to "fund an international conference or series of conferences to share findings, survey acoustic threats to marine mammals, and develop means of reducing those threats while maintaining the oceans as a global highway of international commerce." In response, the MMC convened a Federal Advisory Committee on Acoustic Impacts on Marine Mammals (MM FACA), consisting of 28 representatives from various stakeholders, including non-governmental environmental organizations, the U.S. Navy, oil and gas companies, geophysical contractors, shipping industry, government agencies, and the scientific research community (MMC, 2007). The MM FACA met six times in plenary meetings from February 2004 through September 2005 (more information can be found at http://www.mmc.gov/sound/). In addition, the MMC convened two international workshops—the Beaked Whale Technical Workshop in Baltimore, April 2004, and the Policy on Sound and Marine Mammals: An International Workshop in London, September 2004. But at their last plenary meeting, the MM FACA still could not reach consensus on recommendations to address the marine mammals and noise issue, so the report to Congress included a findings report and recommendations from the MMC, plus seven individual statements from the various stakeholder groups (MMC, 2007).

In October 2004, the European Parliament called for a moratorium on deployment of all active naval sonar until a global assessment of its impact on marine life could be completed (European Parliament, 2004).[6] This was followed by the first Inter-Governmental Conference on Sonar and Marine Mammals, convened in Lerici, Italy, in May 2005 by ONR-Global and the NATO Undersea Research Center. In 2005 the International Council for the Exploration of the Sea (ICES) headquartered in Copenhagen, also issued a report on the impacts of sonar on cetaceans and fish (ICES, 2005).

Although global attention was focused primarily on sonar and beaked whales during this period, Caltrans continued to work on the pile driving and fish issue. The Bay Planning Coalition and Caltrans organized and sponsored a Pile Driving Educational Workshop in October 2003. At this time NOAA Fisheries was requiring acoustic monitoring of all pile driving operations along the California coast, no matter how large or small. The additional costs for monitoring were threatening to put small piling contractors out of business. In 2004 Caltrans formed the Fisheries Hydroacoustics Working Group (FHWG), which included environmental, scientific and engineering experts, and representatives from NOAA Fisheries, California Department of Fish and Game, and the U.S. Department of Transportation (DOT), to work towards consensus on noise exposure criteria for fish. They also teamed with the DOT, and state departments of transportation in Washington and Oregon to form a pooled fund to support research needed to understand the effects of pile driving sound on fish. The first research project was funded in 2006.

The oil and gas industry also focused its efforts to address the effects of sound from offshore exploration and production (E&P) activities on marine life. In August 2005 the International Association of Oil and Gas Producers held an International Workshop on Sound in the Marine Environment in Halifax with over 50 participants from the global research community to help draft a research agenda for a proposed funded research program to address important issues and information gaps. Then, in May 2006, seven international companies formed an executive committee to run the second phase of a joint industry program (JIP) to address E&P Sound and Marine Life. Since that time corporate membership in the JIP has more than doubled. This group regularly posts requests for proposals on its website, www.soundandmarinelife.org. During its first 12 months, the JIP issued 27 research contracts for nearly $8 million dollars (JIP, 2007). This level of funding will help fill critical data gaps needed to understand and improve mitigation of acoustic impacts in the ocean environment.

Progress in understanding the effects of sound on marine animals

Research on effects of sound in the marine environment has focused primarily on understanding criteria and thresholds for physiological and behavioral effects, location and abundance of marine animals, and sound source characteristics and propagation paths. These studies include laboratory experiments on captive animals where received sound levels are carefully measured and correlated with tissue damage, changes in hearing sensitivity, and/or changes in behavior; controlled exposure experiments in the wild to determine behavioral responses where the sound incident on an animal or group of animals is measured and the transmission path between the sound source and animal receivers is defined; and numerical modeling efforts to integrate large data sets with physical understanding to form predictive models to aid in risk analyses and environmental planning. In addition, research on monitoring and mitigation of potential acoustic impacts has facilitated advances in both fixed and deployable passive acoustic monitoring systems for detection, classification and localization of marine mammals. These systems can also be used in the field to study the behavior of vocalizing and echolocating marine mammals.

Although many questions remain to be answered, much

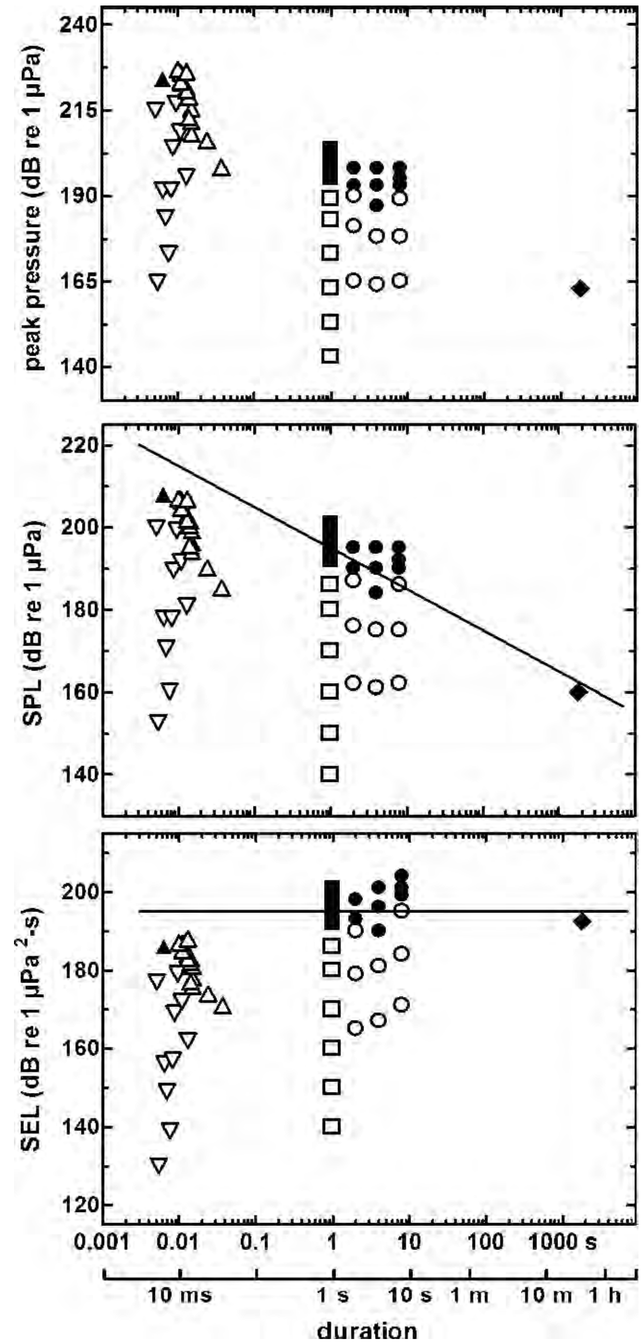

Fig. 1. Summary of bottlenose dolphin and white whale temporary threshold shift (TTS) experimental data showing relationship between level and duration of exposures that produce measurable TTS adapted from Fig. 9 of Finneran et al. (2005). Data are from Finneran et al. (2000 and 2002) (triangles–explosion simulator and watergun sources), Schlundt et al. (2000) (squares–pure tones), Nachtigall et al. (2003 and 2004) (diamonds–band-limited white noise), and Finneran et al. (2005) (circles–3 kHz pure tones). Closed symbols represent exposures where TTS was observed and open symbols indicate exposures that did not produce a measurable TTS. Solid lines represent an equal-energy condition.

progress has been made in several areas during the last two decades. Research activity is evident by the increase in number of scientific publications and special conferences, workshops and symposia over the last 10 years. The state of scientific knowledge and recommendations for future research on marine mammals and noise through 2005 are summarized in the latest reports published by the NRC (2003, 2005). These reports were researched and written by balanced study panels of scientific experts and anonymously peer-reviewed prior to publication. The proceedings of an International Conference on the Effects of Noise on Aquatic Life, held August 2007 in Nyborg, Denmark—the first to include both marine mammals and fish—will soon be published in the journal, *Bioacoustics*. So the following provides only a brief summary of past findings and an update on research activity since 2005.

Probably the most progress in any area during the last 15 years has been achieved in quantifying the effects of sound exposure on hearing in dolphins, white whales, seals, sea lions, and several species of fish. Exposure to excessive sound energy may reduce hearing sensitivity by producing an elevated hearing threshold, also known as a threshold shift. If the hearing threshold returns to the pre-exposure level after a period of time, the shift is a temporary threshold shift or TTS. If the threshold does not return to the pre-exposure level, then it becomes a permanent threshold shift (PTS).[7] Through TTS experiments, scientists at SSC San Diego, HIMB and UCSC have greatly advanced our understanding of the effects of sound on hearing in odontocetes and pinnipeds (Kastak and Schusterman, 1995; Ridgway *et al.*, 1997; Kastak and Schusterman, 1999; Kastak *et al.*, 1999; Schlundt *et al.*, 2000; Finneran *et al.*, 2000; Kastak and Schusterman, 2002; Finneran *et al.*, 2002; Nachtigall *et al.*, 2003; Finneran *et al.*, 2003; Nachtigall *et al.*, 2004; Kastak *et al.*, 2005; Finneran *et al.*, 2005; Yuen *et al.*, 2005; Kastak *et al.*, 2007). One outcome of this research indicates that TTS in dolphins and white whales depends on the duration as well as SPL, and onset of TTS correlates with sound exposure level (SEL) for several different types of sound sources.

Finneran *et al.* (2005) concluded that collectively these data indicate an SEL of 195 dB re 1 μPa^2-s as a reasonable threshold for the onset of TTS in dolphins and white whales. But in the absence of data for other species, these findings (Fig. 1) have provided a useful baseline to estimate effects of sound on hearing in other odontocetes. Current hearing research efforts are focused on understanding the effects of lengthy continuous exposures, and of intermittent exposure and recovery to multiple pulses such as those transmitted by active sonar or a seismic air gun.

Several workshops and research studies have also addressed effects of sound exposure on hearing and tissue injury in fish. In 2004 Caltrans supported a comprehensive literature review complete with recommendations for noise exposure criteria (based on available data at that time) and research needed to understand the effects of pile driving sound on fish (Hastings and Popper, 2005). These recommendations for research have provided a framework for projects to be supported through the Transportation Pooled Fund Program. The federal courts directed the U.S. Navy to look at the effects of LFA transmissions on fish after acceptance of the final Overseas Environmental Impact Statement and final Environmental Impact Statement for SURTASS LFA (DoN, 2001). In response, the Navy funded a controlled exposure experiment (CEE) on caged fish at Seneca Lake (see Fig. 2) to prepare for a supplemental environmental impact statement. Results recently published by Popper *et al.* (2007) indicate that freshwater rainbow trout did not have any auditory or non-auditory tissue damage even though they experienced a significant amount of TTS after continuous exposures to LFA transmissions for 216 seconds. Additional data on other species are still being analyzed. The Chief of Naval Operations Environmental Readiness Division (CNO N45) sponsored a Workshop on Mid-Frequency Sonar and Marine Fishes in April 2007 to reach consensus among the scientific community and other stakeholders on research recommendations to address this issue (Read *et al.*, 2007). Presently a CEE with mid-frequency sonar, similar to that conducted for SURTASS LFA, is in progress at Seneca Lake.

Fish have suffered hearing loss and damage to auditory sensory cells when exposed to seismic air gun emissions. Previous studies indicated that lengthy exposure to low frequency continuous tones (Hastings *et al.*, 1996) with an SPL of 180 dB re 1 μPa or multiple emissions from a seismic air gun at close range (McCauley *et al.*, 2003) could destroy sensory hair cells in the inner ears of fish. But in a recent study by Popper *et al.* (2005), fish that received a cumulative sound exposure similar to that reported in the McCauley *et al.* (2003) study when exposed to multiple emissions from a small air gun array in a river delta, experienced only TTS that recovered within 18-24 hours without hair cell damage. Understanding the differences among results of these studies is a topic of current research.

Studying the behavior of marine animals in the wild is very difficult, but much progress has been achieved in understanding both natural behaviors and the effects of sound on short-term behaviors of many marine animals. Because of potential effects on commercial fisheries, the behavior of fish in response to exposure to seismic air gun emissions has been studied for many years primarily via visual observation or underwater video (Falk and Lawrence, 1973; Pearson *et al.*, 1987 and 1992; Løkkeborg and Soldal, 1993; Wardle *et al.*, 2001, Thomsen 2002; Gausland, 2003; Hassel *et al.*, 2004). Although catch rates are reported to decrease after air gun shooting and some fish have shown aversive reactions to the sound, overall the data are not easily extrapolated to other field operations. Research in this area as well as in behavioral responses of fish to other types of underwater sound is ongoing.

Richardson *et al.* (1995) provide the most comprehensive summary of short-term behavioral responses to sound by marine mammals for a number of different offshore industrial activities. Changes in behavior attributed to underwater sound vary with age, sex, activity engaged in at the time of exposure (e.g., resting, foraging, socializing), perceived motion of the sound, and the nature of the sound source. Two CEE studies with SURTASS LFA signals indicated temporary alterations in behavior of marine mammals. Migrating gray whales avoided a stationary underwater sound projector playing back SURTASS LFA sonar signals when the source was located in their migratory path off the California coast (Tyack and Clark, 1998; NRC, 2003). But the whales seemed to ignore the sound source when it was located seaward of their migratory path, even when received levels were higher, indicating that the location of the sound source, not just its level, was critical to their behavioral response. In the second study, Miller *et al.* (2000) found that some, but not all, humpback whales exposed to SURTASS LFA signals made louder and longer songs during exposure. But the song duration and loudness returned to normal levels immediately afterwards. The long term significance of these changes in behavior is unknown.

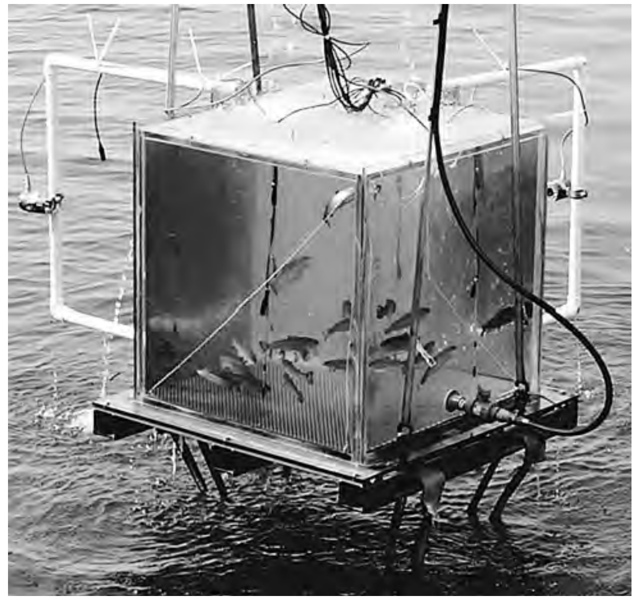

Fig. 2. Rainbow trout in test tank being removed from Seneca Lake after exposure to the U.S. Navy's Surveillance Towed Array Sensor System, Low Frequency Active (SURTASS LFA) transmissions. Photo from Popper et al. (2007).

In the mid-1990's advances in satellite tag technology enabled several large scale natural behavioral studies of marine mammals (Mate *et al.*, 1998 and 1999; Lagerquist *et al.,* 2000). Satellite-monitored tags transmit a radio signal that allows tracking day-to-day movements of animals that migrate over tens of thousands of miles in the ocean each year. The tags are safely implanted in the skin-blubber layer of marine mammals (Fig. 3), and similar externally mounted tags have been used on turtles, fish, and even seabirds. This information has established previously unknown migratory corridors, feeding grounds, and movement patterns of several populations of whales. Perhaps the most ambitious and successful project is Tagging of Pacific Predators (TOPP), which began in 2000 and is part of the Census of Marine Life (www.coml.org), a 10-year worldwide effort to assess diversity and abundance of life in the oceans. TOPP is managed by a team of scientists from Stanford University's Hopkins Marine Lab, NOAA Southwest Fisheries Science Center, and UCSC (see www.topp.org for more information). The use of these tags has dramatically improved understanding of the range and habitat use of large whales, sharks, tuna, turtles, and many other marine species. These data are critical for planning and mitigating potential adverse impacts of sound-producing activities in the ocean.

During the last decade many passive acoustic monitoring (PAM) tools have been developed that are useful for large scale natural behavioral studies. These include low cost, hand-deployable listening arrays and 'leave-behind' retrievable devices that are now widely used by scientists to assess the underwater acoustic environment and study animal

Fig. 3. Satellite tag on a sperm whale.

movement and behavior. An example of the latter is the Autonomous Acoustic Recording Packages (ARPs) developed at the Scripps Institution of Oceanography (Wiggins, 2003). These packages are mounted on the sea floor and provide continuous monitoring of whale migrations and regional populations for a year or more. ARPs have been deployed to record baleen whale sounds in the Bering Sea, Beaufort Sea, Gulf of Alaska, off the coast of southern California, near the West Antarctic Peninsula, and near Hawaii. NOAA Fisheries uses these types of passive acoustic recording instruments in their marine mammal censuses.

Since 2003, three biennial International Workshops on the Detection and Classification of Marine Mammals Using Passive Acoustics (Halifax 2003, Monaco 2005, and Boston 2007) have produced three special issues of peer-reviewed scientific journals that represent the state-of-the-art in signal processing for automatic detection, classification and localization of multiple marine species. These signal processing techniques have been applied to small deployable hydrophone arrays as well as to development of the Marine Mammal Monitoring on Navy Ranges (M3R) program. This program was funded by ONR to develop data acquisition and signal processing systems to detect, classify and localize different groups of whales on a range in real time by recording sounds through the range's existing array of bottom-mounted hydrophones. Classification is limited to families of whales (e.g., beaked whales, sperm whales, pilot whales, etc.) that echolocate while foraging. With support of CNO N45, this system is now being ported to multiple ranges to be used for monitoring marine mammal activity; however, these systems can also be used to study the natural behavior of animals and their responses to sound exposure.

Perhaps the two most important recent technological developments for studying the effects of sound on marine animals in the wild are acoustic data logger tags that can be used to examine their behavior in response to received sound (Burgess *et al.*, 1998; Johnson and Tyack, 2003), and field portable instrumentation to assess hearing sensitivity of untrained non-captive animals by measuring auditory evoked potentials (Casper *et al.*, 2003; Nachtigall *et al.*, 2005; Finneran and Houser, 2006; Houser *et al.*, 2007).

Acoustic data logger tags are relatively inexpensive, easily programmed, miniature sensor packages that are attached by suction cups to the body surface and can be carried by even small marine mammals and sea turtles. The tags record sounds as received by the animal simultaneously with records of swimming and diving movements as well as social sounds or sonar use by the animals themselves. They can even be configured to record heart rate and respiration if needed. These tags have been used to study the underwater behavior and calls of blue whales off the California coast and beaked whales in the Bahamas, Canary Islands, and Mediterranean Sea (Johnson *et al*., 2004; Madsen *et al.*, 2005). Madsen *et al.* (2006) used acoustic data logger tags to quantify the sound received by foraging sperm whales from seismic air gun emissions in a CEE in the Gulf of Mexico. They found that simple spherical spreading models could not be used to predict sound levels received by the animals, and that the received sound contained significant energy all the way up to 3 kHz when whales were near the surface.

Less than 10 years ago, knowledge of hearing in fish and marine mammals was generated through behavioral studies using captive animals trained to participate in hearing test procedures. This behavioral approach was expensive, time-consuming, and limited to only a very small number of captive individuals and species. An alternative to obtaining behavioral measures of hearing sensitivity is an electrophysiological technique based on the measurement of small voltages produced by the brain in response to sound. These volt-

Fig. 4. Clockwise from top left: Auditory evoked potential (AEP) measurements using surface electrodes on a stranded rough toothed dolphin (Cook, Manire and Mann, U. South Florida); needle electrodes and headphones for sound stimulus on elephant seal pup in air (Houser and Reichmuth, UCSC); needle electrodes on reef fish (Hastings, ARL Penn State); and surface electrodes on white whale in air with sound stimulus presented with jaw phone (Finneran and Houser, SSC San Diego).

ages are called auditory evoked potentials (AEPs). They are measured via electrodes on the surface of the animal's head or small needle electrodes inserted just beneath the skin (Fig. 4). This method has been applied to study hearing of human infants and land animals. Adaptation of this methodology to fish and marine mammals occurred almost simultaneously. But marine mammal scientists quickly developed field portable systems (Fig. 5) because of the need to obtain data on multiple species of non-captive animals. New hearing data for a number of species is now being collected. The state-of-the-art for AEP measurements in marine mammals is summarized in a special issue of *Aquatic Animals* published in 2007 (Vol. 33, No. 1).

Beaked whales and sonar

Understanding why beaked whales are unusually sensitive to mid-frequency sonar is necessary to manage and mitigate its potentially adverse effects (Cox *et al.*, 2006). The collective knowledge about beaked whales presented and discussed at the Marine Mammal Commission's April 2004 Beaked Whale Technical Workshop, was published in a special issue of the *Journal of Cetacean Research and Management* in 2006 (Vol. 7, No. 3). After the workshop, much more became known about the deep diving foraging behavior of these animals because of successful field studies using acoustic data logger tags (Johnson *et al.*, 2004, Madsen *et al.*, 2005). In addition AEP measurements have been made on one stranded juvenile beaked whale (Cook *et al.*, 2006)—a very small amount of data, but better than nothing at all.

At the 2004 Workshop, participants discussed several potential mechanisms for the stranding behavior and subsequent deaths of beaked whales. The consensus was that the most plausible mechanism was an acoustically induced change in their normal deep diving foraging behavior, which caused them to surface too quickly and develop significant gas bubbles that damaged multiple organs or interfered with normal physiological function, similar to a human diver getting the "bends" or decompression sickness (Jepson *et al.*, 2003). Thus workshop participants recommended that CEE's to determine beaked whale behavioral responses to mid-frequency sounds should be a top research priority (Cox *et al.*, 2006).

Subsequently an international research team was formed and plans were made for a multi-year Behavioral Response Study (BRS) of beaked and pilot whales (pilot whales were involved in the 2005 North Carolina mass stranding). Last year marked the first field season of the BRS, which took place in the Bahamas' Tongue of the Ocean and utilized the M3R passive acoustic monitoring system in place at the Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) on Andros Island. During this landmark study acoustic data logger tags will be attached to whales to record their sound exposure and track their response to mid-frequency active sonar and other playback sounds. It is a huge undertaking with funding provided by CNO N45, CNO Submarine Warfare Division, ONR, the oil and gas E&P Sound and Marine Life JIP, the DoD/DOE Strategic Environmental Research and Development Program (SERDP), and NOAA Fisheries Office of Science and

Fig. 5. Field portable system developed at Space and Naval Warfare Systems Center (SSC) San Diego consisting of bioamp (in Pelican case, bottom photo, shown with system running onboard a ship), ruggedized computer with data acquisition hardware, and Evoked Response Study Tool (EVREST) software developed by J. J. Finneran for generating sound stimulus signal, recording and storing auditory evoked potentials (AEPs), and analyzing data.

Technology. The results of this study will be forthcoming over the next few years and hopefully will help solve the mystery of how these animals react to mid-frequency sonar.

The second research priority recommended by the 2004 Workshop participants was for studies of the anatomy, physiology and pathology of beaked whales. Another fundamental aspect of the interaction of beaked whales with mid-frequency sound is the potential consequences of the size of their body and anatomical features with respect to the wavelength of mid-frequency sonar transmissions. MacLeod and D'Amico (2006) compared body lengths of Cuvier's beaked whales from the mass strandings in Greece 1996 and Canaries 2002 with those of all types of Cuvier's beaked whale strandings from around the world, and found that the beaked whales which stranded coincident with sonar transmissions had body lengths less than 5.5 meters. Underwater the wavelength of sound at 3 kHz, the dominant frequency of tactical sonar transmissions, is approximately 0.5 m. Thus the characteristic dimensions of their overall size and prominent anatomical features are between about 0.1 and 10 times the wavelength of incident sound (0.05 – 5 meters). In this regime sound is partially reflected, scattered, and diffracted and these secondary waves constructively and destructively interfere with the incident sound and each other to produce regions of high and low sound intensity levels throughout the whale's body. Therefore because of their anatomy, a simple model will not accurately predict the interaction between mid-frequency sonar and Cuvier's beaked whale. To address this issue, the National Oceanographic Partnership Program funded a 3-year project last year to develop a sophisticated computational model of a "virtual beaked whale" that will accurately model this complex acoustic interaction. Results of this effort will also be forthcoming within the next 2-3 years.

Progress on recommendations for noise exposure criteria

In the absence of data, scientists and government regulators have always been precautionary in recommending noise exposure criteria for marine animals. The observations of bowhead and gray whales exposed to drilling and dredging sounds in the early 1980's indicated that a received broadband SPL of 120 dB re 1 μPa was the threshold for behavioral disturbance of baleen whales; however, strict worldwide adherence to this criterion would have effectively shut down all scientific research in the ocean—even the research needed to learn more about the effects of sound on other marine species.

In 1995, based on observations of whales exposed to seismic air gun pulses and ATOC signals, NOAA Fisheries set a sound pressure limit of 180 dB re 1 μPa that could not be exceeded for mysticetes and sperm whales, and 190 dB re 1 μPa for most odontocetes and pinnipeds. However in the late 1990's, the 180 dB limit began to be applied to all species and all sounds (including SURTASS LFA) after an expert panel convened by the High Energy Seismic Survey (HESS) team decided that the best available data in 1997 indicated that received sound pressure levels exceeding 180 ±10 dB, averaged over the pulse duration, could potentially have adverse effects with the ±10 dB variability depending on species (HESS 1999). Given the new hearing data for dolphins and white whales since that time, the 195 dB re 1 μPa^2-s SEL level for onset of TTS has recently been applied to many odontocete species.

A panel of scientific experts that was originally convened and supported by NOAA Fisheries, has met for several years and just recently completed the most comprehensive set of recommendations for marine mammal noise exposure criteria. The results of their efforts were published in a special issue of the journal, *Aquatic Mammals* (Southall *et al.*, 2007). These recommendations, which account for different types of sounds and different effects for multiple species, are yet to be vetted in the scientific and environmental communities.

Recommendations for noise exposure criteria for fish have followed a similar path, but with more emphasis on hearing and direct injury instead of behavior. Because of the relatively small size of most fish with respect to underwater acoustic wavelengths, their whole body will oscillate back and forth when exposed to most anthropogenic sound sources, making non-auditory tissue damage more likely than in marine mammals. Because smaller fish have less inertial resistance to motion, they are more at risk. The first recommendation for a noise exposure limit for fish was made in 1990 for a U.S. Navy intermediate scale submarine test facility being built on Lake Pend Oreille in Bayview, Idaho (Hastings, 1990). Very little data were available at that time so the recommendation for "no harm" was 150 dB re 1 μPa based on earlier data showing that goldfish had TTS after being exposed to pure tones near this level for 4 hours (Popper and Clarke, 1976). After the PIDP in 2000, Caltrans actively supported an assessment of all available data to establish recommendations for noise exposure criteria applicable to pulsed sound from impact pile driving. The latest recommendations (Carlson *et al.*, 2007) for direct injury exposure criteria are an SEL ranging from 183 to 213 dB re 1 μPa^2-s, depending on mass of the fish. These end points are based on data from a blast experimental study on juvenile fish (Govoni *et al.,* 2003) and the SURTASS LFA CEE on larger fish (Popper *et al.*, 2007), respectively. In addition dual criteria consisting of a peak SPL and cumulative SEL were recommended for TTS based on the results of the riverine air gun study by Popper *et al.* (2005). These data indicate that salmonids will experience a TTS of 20-25 dB after a cumulative SEL of only 185 dB re 1 μPa^2-s.

As reported in the January issue of *Acoustics Today*, in October 2007 the Accredited Standards Committee S3, Bioacoustics, approved the formation of a new subcommittee, S3/SC 1 Animal Bioacoustics (Delaney and Blaeser, 2008). Three previously existing working groups (WG) were moved into this Subcommittee, including S3/SC 1/WG 2 Effects of Sound on Fish and Turtles. This WG has been meeting since September 2004 to formulate standards for noise exposure criteria for fish and turtles. A similar working group for marine mammals would greatly facilitate establishment of standards for noise exposure criteria for these animals.

Where do we go from here?

Because beaked whales are the only group of marine mammals known to have died from exposure to anthropogenic sound, determining the causal mechanisms of those stranding events remains a top research priority in the near future. But another very critical issue is the lack of hearing data for mysticetes. There are no behavioral or electrophysiological hearing data for any species of these large baleen whales. Effects of sound on their hearing and subsequent behavior are estimated from numerical models of their middle and inner ears (Ketten, 1997 and 2000). There are no captive mysticetes, but at least one attempt has been made to measure AEP signals in the wild on a minke whale, the smallest species of this group. Other mysticete species may be too large to obtain a reliable AEP signal with commercially available electrodes. Efforts in this area need the same level of attention and planning as the BRS on beaked and pilot whales.

Finally, in order to begin to understand "biologically significant" effects on behavior as defined within the framework outlined in the latest NRC report (NRC, 2005), multi-disciplinary basic research is needed to understand the primary and synergistic effects of sound on marine ecosystems, including crustaceans, corals, sponges, sea grasses, and all other living things in the sea. Designing experiments to learn about potential changes in the marine ecosystem, including animal habitats, over long periods of time is a very difficult task. But changes in the behavior and habitats of marine animals over the long term could significantly affect their populations as well as the overall health and stability of the marine environment.**AT**

Looking towards the future

Many scientists and others concerned about global warming were deeply troubled when the HITF and ATOC projects came under such heavy fire by a number of environmental groups in the early 1990's. Here was a solution for one environmental problem—long term monitoring of global climate change—that created another very polarized environmental concern because there were little data available to address it. This dilemma is surfacing again with the development of offshore wind farms in many parts of the world in efforts to meet requirements of the Kyoto agreement to significantly reduce CO_2 emissions by 2030. Wind farms really do produce an underwater hum, albeit at a much lower level than the ATOC source, but it can be detected by many fish and marine mammals and potentially mask interspecies communications necessary for reproduction as well as other sounds important to their well being (Wahlberg and Westerberg, 2005, Henriksen *et al.*, 2007). This time though the world is very much aware of the potentially harmful effects of anthropogenic noise in the ocean and many marine scientists are already on top of the problem.

Endnotes

1 The primary environmental laws are the Marine Mammal Protection Act (MMPA) and Endangered Species Act (ESA). In addition the National Environmental Policy Act (NEPA) requires that federal actions affecting the environment be assessed to inform regulators and other decision-makers about potential consequences and alternatives to minimize impacts.

2 Most military sonar use is passive as vessels prefer to remain silent and undetected. When sonar is active, it transmits a sound pulse or "ping" that travels through the water and reflects off objects in its path. The reflected sounds, or echoes, return to a passive receiver and are electronically transformed into images on a display screen, very similar to use of medical ultrasound to form images of internal organs and monitor fetal development. Passive sonar uses only the receivers to "listen" to sounds emitted by vessels or other objects and marine mammals.

3 'Ceteceans' include whales, dolphins and porpoises, while 'pinnipeds' include seals, sea lions, and walrus. Under the Order Cetecea, there are two suborders: (1) odontocetes or toothed whales that include dolphins, porpoises, white whales, killer whales, pilot whales, beaked whales, bottlenose whales, melon-headed whales and sperm whales; and (2) mysticetes or baleen whales that include bowhead whales, right whales, gray whales, minke whales, sei whales, Bryde's whale, blue whales, fin whales and humpbacks.

4 NOAA National Marine Fisheries Service (NOAA Fisheries) is the responsible regulatory agency for issues concerning marine animals. If justified and properly documented, NOAA Fisheries Office of Protected Resources issues permits authorizing incidental takes of marine mammals for sound-producing activities in the ocean.

5 Strandings of marine mammals are normal events that occur all the time around the world. Mass strandings involve more than two animals stranding in the same place and time.

6 At this time the UK and Norway were preparing to deploy low frequency active sonar, but with a frequency bandwidth that extended into the low kHz range.

7 Many people have experienced TTS after attending a loud music concert. Currently TTS/PTS is a major concern for soldiers and marines firing high-power weapons in Iraq and Afghanistan as well as for children and teen-agers at home using ear buds to listen to music on personal music players and movies on DVD players.

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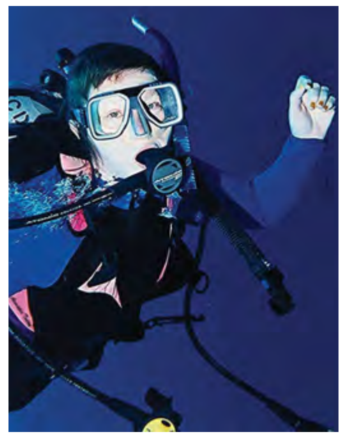

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