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Assessing hearing and sound production in cetaceans not available for behavioral audiograms: Experiences with sperm, pygmy sperm, and gray whales

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Abstract

We developed and tested field-portable systems to make recordings of physiological and acoustic measurements on three stranded cetaceans during medical treatment and rehabilitation. Two whales (a pygmy sperm, *Kogia breviceps*, and a gray whale, *Eschrichtius robustus*) were later released after long-term care. The sperm whale neonate (*Physeter macrocephalus*) died after eight days of rehabilitation efforts. We divided sounds produced by the sperm whale neonate into two categories. Clicks had peak frequencies of 500 Hz to 12 kHz (two classes, low and high) and grunts had most energy below 3 kHz. Auditory brainstem response (ABR) assessment of hearing abilities indicated that the neonate was most sensitive to sounds between 5 kHz and 20 kHz. The pygmy sperm (*Kogia breviceps*) produced echolocation pulses with peak frequencies at 125 kHz to 130 kHz. We found that it was most sensitive to sounds between 90 kHz to 150 kHz, measured by ABR and mid-brain response methods. Our preliminary measurements from the gray whale (*Eschrichtius robustus*) were equivocal and emphasize the need for improvements in portable instrumentation for assessing hearing abilities in baleen whales.

Key words: gray whale, pygmy sperm whale, sperm whale, hearing, sounds, audiogram.

Introduction

Defining the hearing sensitivity of an animal by establishing an audiogram is important for understanding its ability to detect and respond to sounds of various frequencies and amplitudes. So far, audiograms reported for cetaceans are U-shaped, which is generally typical of mammals (e.g., Fay, 1988). This U-shape audiogram begins with relatively low sensitivity (high threshold) under 1 kHz, and increases sensitivity (low threshold) with frequency to perhaps 100 kHz or more. A steep rise in threshold occurs near the highest frequencies tested (*ca.* 150 kHz; e.g., Johnson, 1967). Of some 80 species of extant cetaceans, audiograms are available for fewer than 10 species (Au, 1993; Richardson *et al.*, 1995), all for smaller odontocete cetaceans. Most are very sensitive to sounds between 10 kHz and 100 kHz (Au, 1993; Richardson *et al.* 1995). These sensitivities have generated substantial scientific and media discussion and debate about the possible effects of intense anthropogenic sound on the ears of sea mammals (e.g., Mulroy, 1991; Revelle, 1991; Green *et al.*, 1994; Richardson *et al.*, 1995; Popper *et al.*, 2000). Sounds that whales hear (i.e., supra-threshold sounds) may influence their behavior in various ways. For example, a whale might approach to investigate or swim away to avoid a sound. Whales might begin to produce sounds or become silent. Intense sonic emissions might mask echolocation, communication, or other sounds that are otherwise important to the individual and its group. Moreover, permanent auditory damage may result from single or repeated exposure to very intense sounds, especially impulsive noise.

A zone of sonic influence for the auditory system of a whale is the region around a sound source where projected sound intensity exceeds the hearing threshold. The extent of this region depends on hearing threshold and also on the efficiency of the path from the source to the whale, the level of background noise, and the frequency spectrum of the source. The efficiency of the sound path can be affected by water temperature profiles, organisms in the water, air bubbles or particulate matter in suspension (Urick, 1982). Background noise is generated by, *inter alia*, wind and wave motion, soniferous animals, pounding surf, grinding sea ice, or ships and aircraft (Green *et al.*, 1994; Richardson *et al.*, 1995). Higher frequencies tend to propagate for shorter distances than low frequencies due to a more rapid absorption in seawater (Urick, 1982).

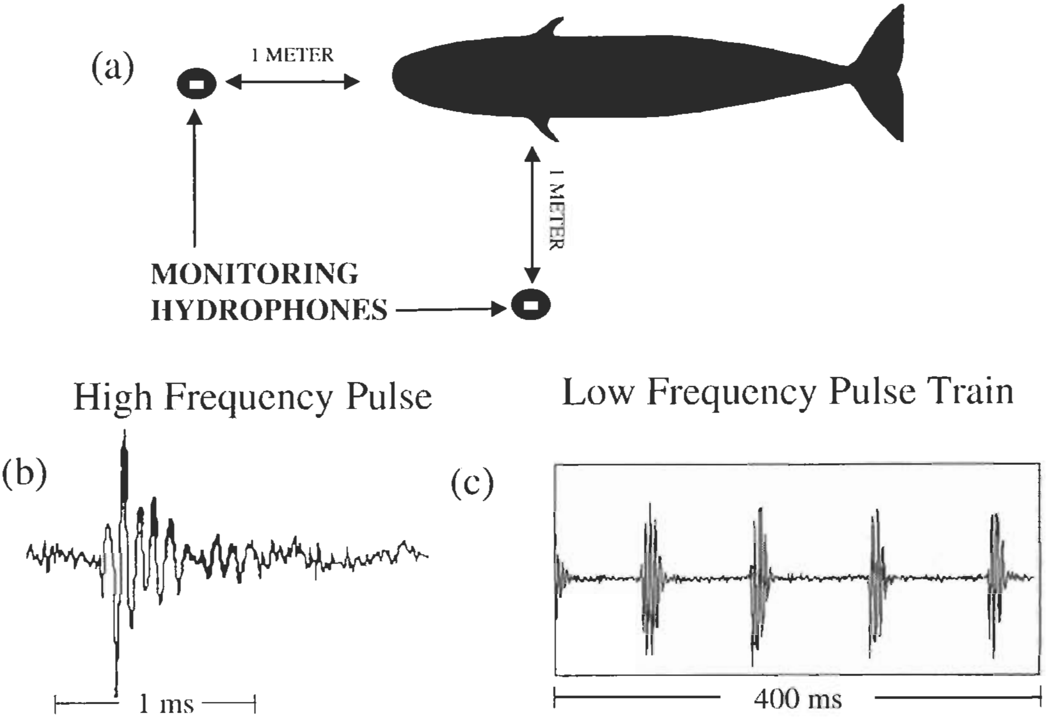

Figure 1. (a) Sperm whale sound recording schematic showing placement of the B & K 8103 hydrophones relative to the whale's head, (b) high-frequency pulse recorded 1 m in front of the whale, and (c) low-frequency pulse train recorded from the hydrophone 1 m in front of the whale.

Because low frequencies propagate for relatively great distances, they have a much greater potential for sonic influence on marine mammals that are sensitive to low frequencies. Whales sensitive to low frequencies might hear the sounds at considerable distances from the source (Payne & Webb, 1975). The production of lower frequency sounds by large whales (Green *et al.*, 1994; Richardson *et al.*, 1995) and their ear anatomy (Ketten, 1992) suggest that they might be sensitive to sounds of very low frequency. It is possible that their audiogram is shifted downward with greater sensitivity at frequencies below 1 kHz or even into infrasonics. But, as yet, there are no empirical data to determine the hearing abilities of baleen whales directly, despite public controversy and a range of opinions.

Traditionally, hearing ability of cetaceans has been assessed by long-term behavioral observations, often lasting several years and focusing on only one to several well-trained animals. Alternative physiological methods have been proposed to address these logistical constraints to allow more rapid assessment of a larger number of free-ranging individuals and species. (cf., Ridgway *et al.*, 1981; Green *et al.* 1994). Electrophysiological methods have been used to document the responses of auditory centers to sound of various characteristics (e.g., duration, rise-time, frequency-modulation, amplitude-modulation, frequency-tuning; Bullock *et al.*, 1968; Bullock & Ridgway, 1972; Bullock & Gurevich, 1979; Popov & Supin, 1990; Supin & Popov, 1995; Dolphin, 1997; Szymanski *et al.*, 1998). However, only recently have behavioral and physiological methods been used to compare results from the same individual (e.g., Szymanski *et al.*, 1999). Szymanski *et al.* (1999) found a close match between hearing abilities in killer whales (*Orcinus orca*) measured with auditory brainstem response (ABR) versus behavioral methods. Here, we describe recent efforts to document the hearing abilities of two odontocete species (*Physeter macrocephalus*, *Kogia breviceps*) and one mysticete whale (*Eschrichtius robustus*) using electrophysiological methods.

Materials and Methods

Animals studied

A male, sperm whale neonate (*Physeter macrocephalus*) stranded near Sabine Pass, Texas in early September 1989, and was taken for rehabilitation to

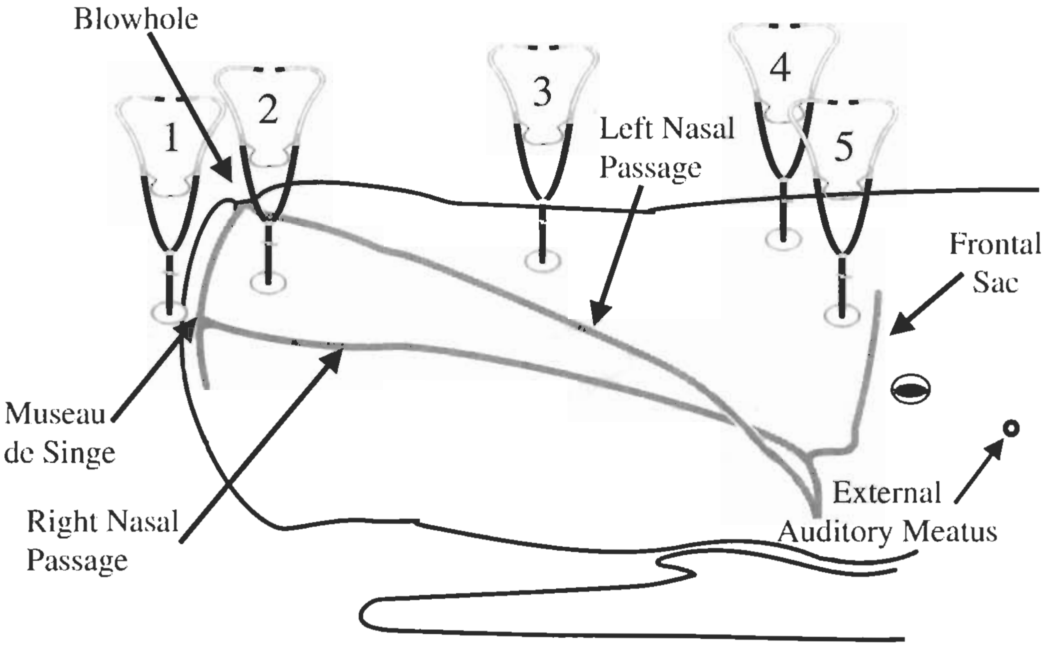

Figure 2. Location of stethoscope listening sites about the sperm whale's head. From stations 1 and 2, clicks were high in amplitude. From station 3, clicks and grunt class sounds were low in amplitude or inaudible; however, breath sounds of air flowing through the left nasal passage were high in amplitude. From stations 4 and 5, grunts were high in amplitude but click-class sounds were low in amplitude or inaudible.

Sea-Arama Marine World, Galveston, Texas where it survived for eight days. We judged the whale to have been less than two weeks old based on an unhealed umbilicus, and its length (341 cm) and mass (546 kg) relative to published data (*cf.*, Best *et al.*, 1984). This animal was smaller than the published estimates of 3.92 to 4.25 m length at birth (Best *et al.*, 1984). We made a series of electrophysiological measurements of hearing abilities of the whale during the eight-day rehabilitation period.

A female pygmy sperm whale (*Kogia breviceps*) stranded in poor condition on the shore of New Jersey in late November, 1994 and was taken to the National Aquarium in Baltimore, Maryland for rehabilitation. It had numerous surface infections, was dehydrated and its stomach full of plastic items (including a mylar balloon) which were removed during initial medical treatment. Its health subsequently improved and it was released several months later in good condition and weighed 147 kg and was 2.0 m long. We made several attempts to record sounds and measure the whale's hearing ability just prior to release.

We also made several attempts to measure the hearing abilities of a California gray whale calf (JJ) that was rehabilitated at Sea World of San Diego from January 1997 until its release in March 1998. Recording sessions were mostly during periodic physical exams when the calf was moved into a small pool with a moveable false bottom raised temporarily to restrain her by simply stranding. The duration of those sessions was determined by, and sometimes constrained by her behavior, her medical care, and by other considerations.

Monitoring and recording whale sounds

Recordings of the sounds produced by the sperm whale were made with a broadband Racal recorder and two matched broadband hydrophones (Brüel & Kjær 8103) placed 1 m ahead of the blowhole and 1 m lateral to the eye (Fig. 1a). The two calibrated hydrophones were connected to preamplifiers (Brüel & Kjær 2635). The amplified hydrophone output was recorded on a broadband Racal recorder for later analysis. During periods when the whale was making sound, we listened with a stethoscope (Littmann Cardiology II) at various locations on the head (Fig. 2).

Recordings of sounds produced by the pygmy sperm whale were made with a TDT (Tucker-Davis Technology) module that converted the analog signal to a digital signal with a sampling rate of 500 kHz. The digital signals were transferred to a computer through a fiber-optic interface and then

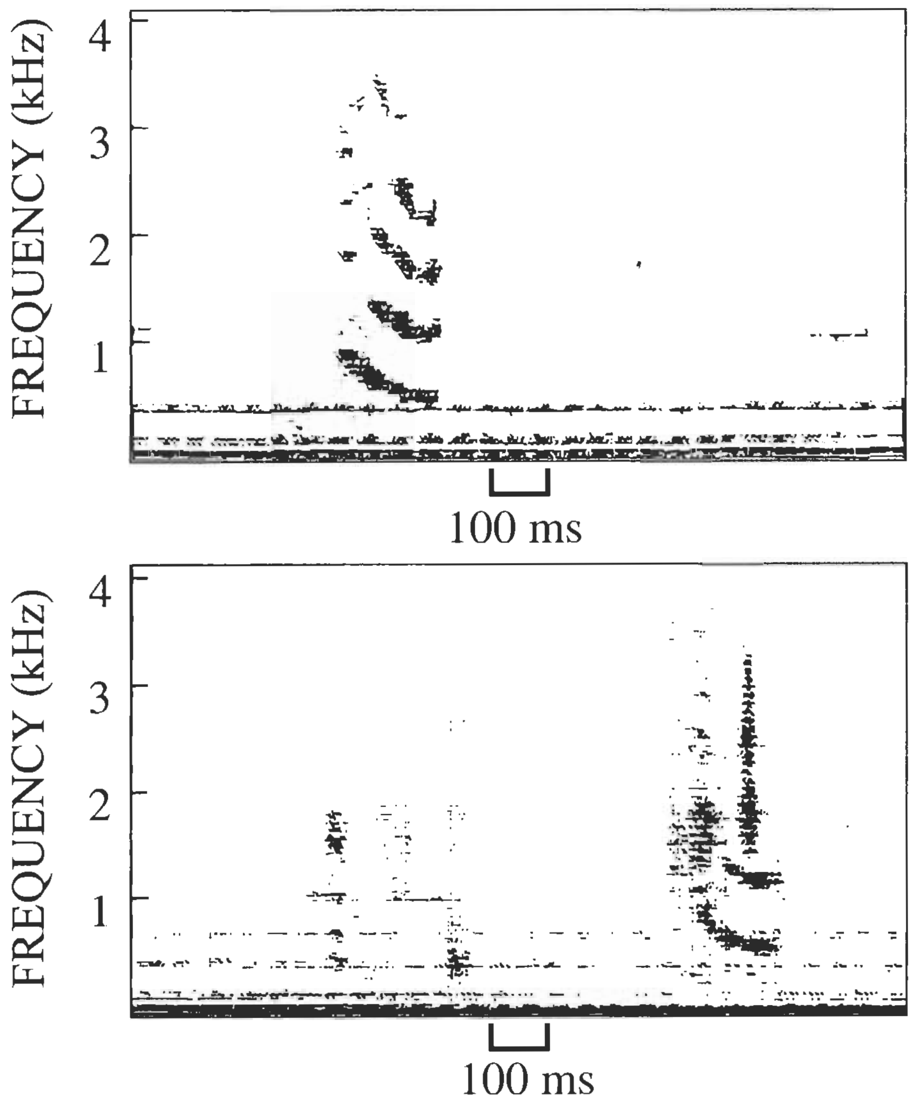

Figure 3. Spectrograms showing two types of grunts recorded from a sperm whale calf.

saved on computer disk, along with files containing system settings and all other information pertinent to the recording session.

We did not make recordings of sounds produced by JJ until long-term monitoring of her behavior by colleagues (see Wisdom *et al.*, 2001) was nearly completed to avoid disrupting those studies.

Measurement of hearing abilities

We developed a small, portable system to present sound stimuli (20 Hz to 200 kHz) and acquire and analyze sound and microvolt-level electrophysiological responses in marine animals. The characteristics of the sound stimuli could be modified to generate sounds that varied by frequency, amplitude, duration, rise- and fall-times, inter-stimulus interval, and phase. Analysis of sounds included synchronous averaging with artifact rejection. Cumulative averages were displayed on an oscilloscope and could be stored on disk or tape or printed. The weather resistant system included hardware based on a 486-computer with software for presenting shaped tones and pulses. It included suction cup electrodes, high gain (X 500K) amplifiers, analog-to-digital and digital-to-analog converters, fiber optic inter-module connection, a

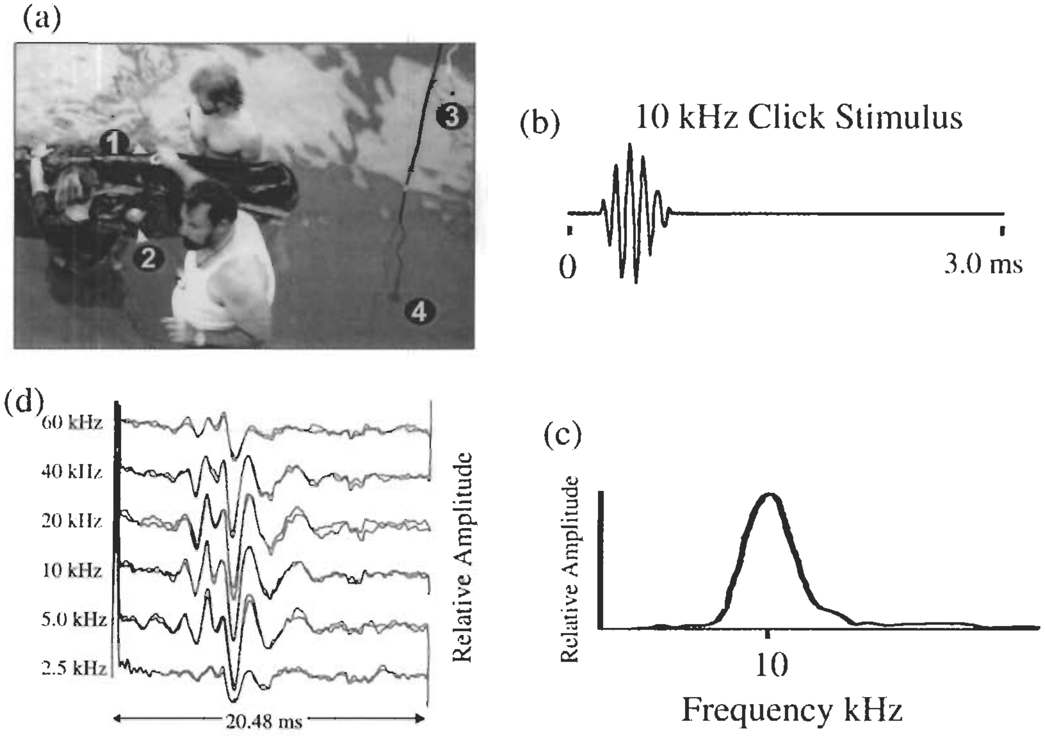

Figure 4. (a) Attendants hold the whale in position for ABR recording: (1) position of vertex suction cup electrode, (2) position of mastoid suction cup electrode, (3) cable for recording hydrophone, and (4) projector for acoustic stimuli; (b) sample waveform of 10 kHz click stimulus; (c) frequency spectrum of the click stimulus; and (d) ABRs recorded with stimuli peaking at frequencies of 2.5 to 60 kHz. Each plot shows two waveforms resulting from acoustic stimulation at the same frequency and amplitude.

computer with LCD screen that could be seen in bright sunlight, an internal 1.2-gigabyte hard disk, power amplifier, transducers, and power source. The system could be transported easily to remote sites in several small cases.

The ABR was recorded with flat silver/silver-chloride electrodes (1 cm diam) housed in a silicone rubber suction cup. These were placed on the surface of the head near the vertex of the skull. A second suction cup electrode was placed near the external auditory meatus (EAM) over the mastoid process.

Results

Sperm whale neonate

Sound production—We arbitrarily selected a sample of sounds that appeared representative of those made by the whale. They fell into two broad categories. One category consisted of clicks (Watkins *et al.*, 1988) and were of two different types: (a) high-frequency, low-amplitude clicks (Fig. 1b) with peak frequencies at 5 kHz to 12 kHz, amplitude under 140 dB re 1 µPa, and 1 to 2 ms duration); (b) low-frequency, high-amplitude (148 to 165 dB re 1 µPa) clicks with peak frequencies at 500 Hz to 3 kHz (Fig. 1c), and durations of 7 to 20 ms. Grunts (Fig. 3) were mostly low frequency sounds below 3 kHz that listeners have described as 'croaks,' 'growls,' 'grunts,' and 'lion-purr growls.' Clicks appeared to be produced near the blowhole (distal sac and museau), based on our direction observations with a stethoscope and listening in air at mid-head, the timing of the sound at the two hydrophones and palpation of the head while the whale was producing sounds. Grunts appeared to originate about 60 to 70 cm behind the blowhole (probably from the frontal sac).

Hearing sensitivity—We recorded ABRs from suction cup sensors on the surface of the head (Fig. 4a) in response to pulses (Figs. 4b & 4c) presented (20 and 40 pps) under water near the right external auditory meatus and lower jaw. Their greatest amplitudes were at 5 kHz, 10 kHz and 20 kHz

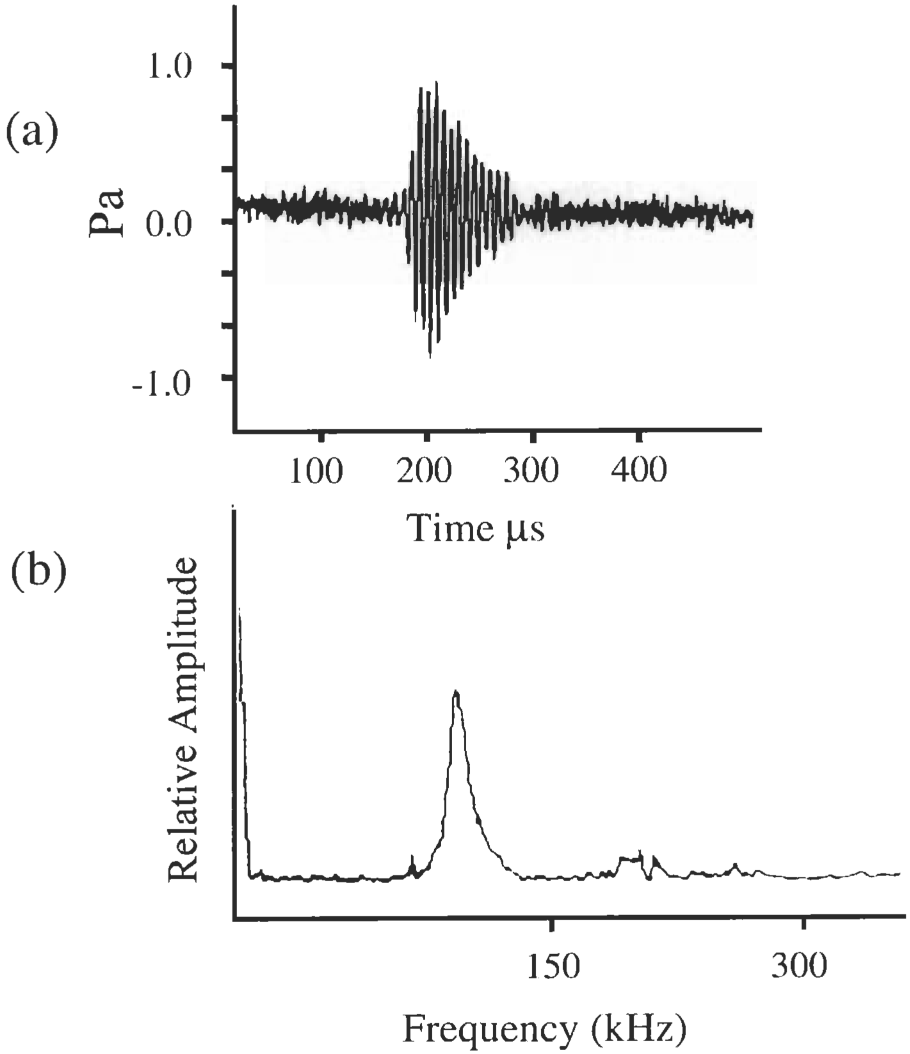

Figure 5. (a) Time series of a pulse from a young pygmy sperm whale, and (b) spectrum of the pulse shown in (a).

(Fig. 4d). Responses to 60 kHz were clearly present, but much weaker (Carder & Ridgway, 1990). Latencies from stimulus onset to response onset (Fig. 4d) were relatively long compared to dolphins, white whales (Fig. 7), and the pygmy sperm whale (Fig. 6). This long latency may be partly due to the animal's young age, but also perhaps to the much larger brain with a longer auditory pathway.

Pygmy sperm whale

Sound production—The whale approached our broadband hydrophones as soon as they were placed in the water and started emitting very high-frequency pulses. The peak energy of the pulses was around 130 kHz (Fig. 5b). We detected these trains of pulses only when the whale was oriented toward the hydrophone. They occurred most often when the hydrophones were rapidly moved about in the water or when the animal was pursuing live fish that were placed in the pool. Responses to playback of the whale's own pulses were equivocal.

Hearing sensitivity—We observed ABR responses within 10 ms of the stimulus (Fig. 6, first three prominent positive waves) and mid-brain responses 10 to 20 ms after the stimulus. The mid-brain response was especially prominent peaking at a latency of about 12 ms (Fig. 6). All responses in the 90 kHz to 150 kHz were robust; however, lower

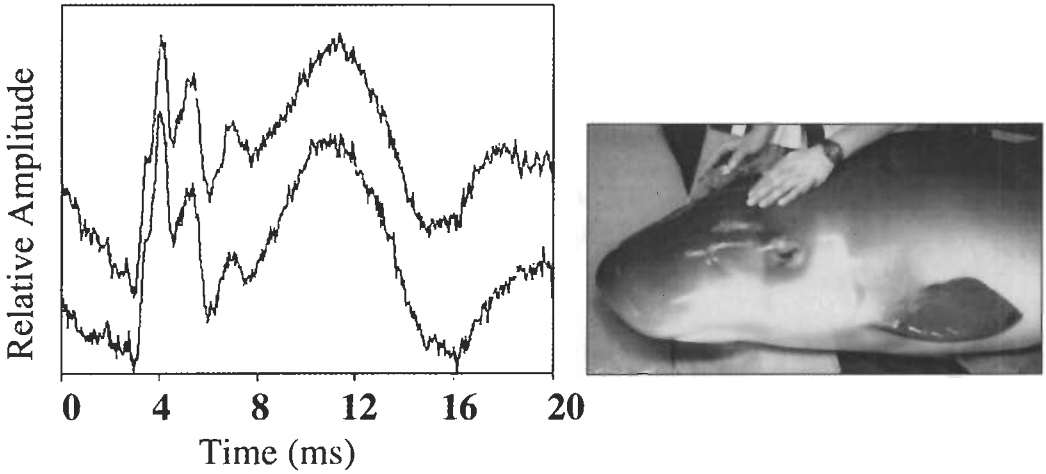

Figure 6. Plot to the left shows repeated ABR and mid-brain responses from a young pygmy sperm whale is evoked by high-frequency pulses from a suction-cup hydrophone positioned at the base of the lower jaw. The animal is shown to the right.

frequency stimuli produced responses that were weak and often equivocal (Carder & Ridgway, 1990).

Gray whale calf (JJ) hearing sensitivity

We recorded several potential ABR profiles (Fig. 7) in response to clicks and tone pips, but we were not able to replicate any of them at the same frequency. If the few patterns that we did record are valid measures, rather than artifacts of the recording system, then these data indicate that hearing may be better at 3 kHz, 6 kHz, and 9 kHz than at lower frequencies.

Discussion

The sperm whale neonate that we studied produced two types of clicks (Figs. 1b, 1c). Similar clicks have been described before (*cf.*, Watkins *et al.*, 1988), even for small calves slightly larger than the one we studied. It produced additional sounds that we describe as 'grunts' (Fig. 3). The recording of these additional sounds could have been possible because we spent several hours in the water with the whale when he was soniferous. Because this young whale already had a large head with parts of the respiratory apparatus widely spaced, we could observe a separation in the area of sound production. All click sounds were made just below the blowhole, apparently at the museau (listening areas 1 and 2 in Fig. 2.). The other sounds that were described by listeners as 'croaks,' 'growls,' 'grunts,' and 'lion-purr growls,' came from the area of the frontal sac (listening areas 4 and 5 in Fig. 2). The ABR profiles that we recorded from this whale (Fig. 4d) are the first reported from a sperm whale and from any neonate cetacean. The waveforms are similar to those evoked in other odontocetes (e.g., Ridgway *et al.*, 1981; Popov & Supin, 1990), and in mammals generally, to pulses ranging in peak frequency from 2.5 kHz to 60kHz.

Although little is known about sound production by pygmy sperm whales they nonetheless reportedly produce sounds (e.g., Caldwell *et al.*, 1966; Thomas *et al.*, 1990). The first reported data on sound production by a pygmy sperm whale were made with a contact microphone while the animal was out of the water. Spectrograms of these pulses showed only low-frequency energy, evidently owing to limitations of the methods and equipment used (Caldwell *et al.*, 1966). Thomas *et al.* (1990) recorded a 'new sound' from a stranded pygmy sperm whale in Hawaii. The recording was made the day after the stranding. The spectrogram was of a short duration (0.42 s) ascending (1.36 kHz to 1.48 kHz) sweep or 'cry.' We never detected this type of sound from the pygmy sperm whale that we studied. In contrast, the pulses that we recorded were at high frequencies, between 125 kHz and 130 kHz (Fig. 5). Consequently, it is not surprising that they were not heard by human attendants during our studies or recorded by previous investigators. However, there is some anecdotal evidence of prior detection (T. Cranford, pers. comm.) of similar pulses from a pygmy sperm whale stranded earlier in California (see also Cranford *et al.*, 1996).

Although the ABR waveforms that we obtained are rather incomplete (*cf.*, Szymanski *et al.*, 1999), we do think that we documented some relevant auditory data from sperm and pygmy sperm

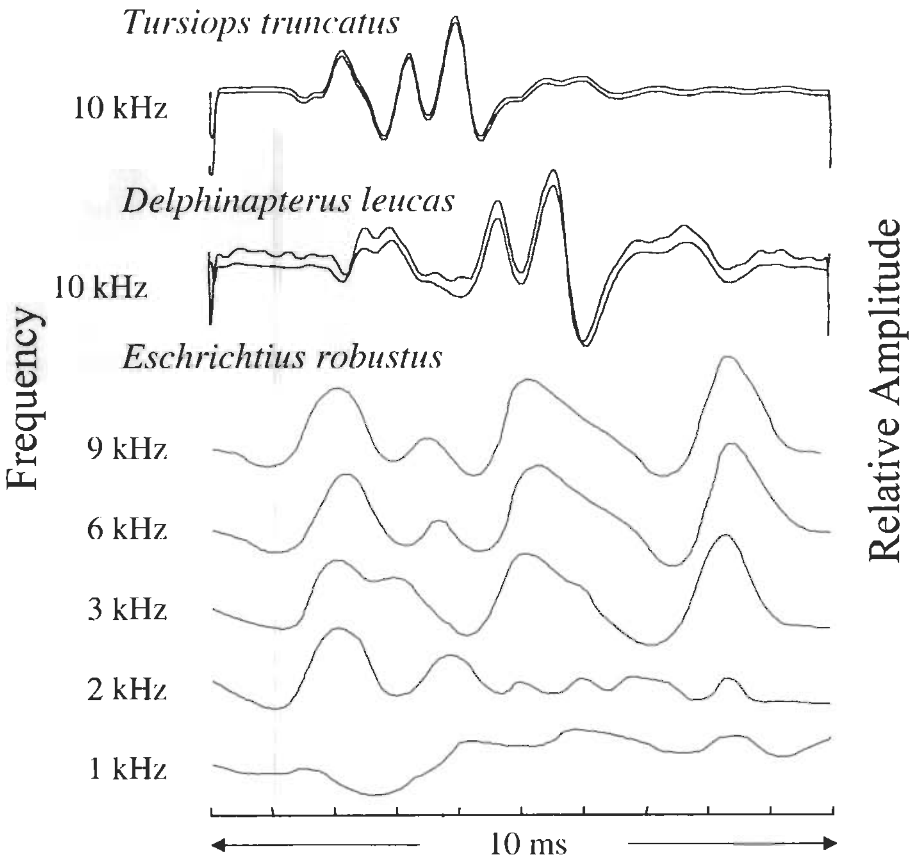

Figure 7. Standard 10 kHz ABR response from bottlenose dolphin (*Tursiops*) and white whale (*Delphinapterus*) compared to suspected ABR waveforms recorded from the gray whale (*Eschrichtius*) calf (JJ).

whales. Moreover, we demonstrated the utility of portable equipment for studying sound production and auditory sensitivity in cetaceans. Our data indicated that the sperm whale calf was most sensitive to sounds between 5 kHz and 20 kHz and that the pygmy sperm whale calf was most sensitive to sounds between 90 kHz and 150 kHz. Although we evoked some responses from the gray whale calf to various sound stimuli, our ABR recordings were equivocal, mostly because we could not replicate the few ABR waveforms we did record. If those that we did record (*cf.*, ABRs of bottlenose dolphins and white whales in Fig. 7) are valid, then we believe the calf was most sensitive at frequencies of 3 kHz, 6 kHz, and 9 kHz. But, this apparently contrasts with behavioral data for free-ranging gray whales in breeding lagoons which suggested that they were most sensitive to tones between 800 Hz and 1500 Hz (Dahlheim & Ljungblad, 1990).

Although complete audiograms were not recorded for any of the three individuals studied here, the few data obtained enhance our knowledge of sound production and auditory sensitivity of these animals. Moreover, the studies provided feedback and direction for improving portable recording instruments (Seely *et al.*, 1976) and highlighted the need for researchers to be prepared for, and be provided opportunities to apply these techniques whenever possible and particularly in unique circumstances (i.e., strandings or rehabilitation).

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