

# Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions

James J. Finneran<sup>a)</sup>

Space and Naval Warfare Systems Center D351, 49620 Beluga Road, Room 204, San Diego, California 92152-6266

Carolyn E. Schlundt

Science Applications International Corporation, Maritime Services Division, 3990 Old Town Avenue, Suite 105A, San Diego, California 92110

Donald A. Carder

Space and Naval Warfare Systems Center D351, 49620 Beluga Road, Room 204, San Diego, California 92152-6266

Joseph A. Clark and Jane A. Young

Naval Surface Warfare Center, Carderock Division, Bethesda, Maryland 20084

Joel B. Gaspin

Naval Surface Warfare Center, Indian Head Division, Indian Head, Maryland 20903

Sam H. Ridgway

Space and Naval Warfare Systems Center D3503, 49620 Beluga Road, Room 204, San Diego, California 92152-6266

(Received 1 December 1999; accepted for publication 14 April 2000)

A behavioral response paradigm was used to measure masked underwater hearing thresholds in two bottlenose dolphins and one beluga whale before and after exposure to impulsive underwater sounds with waveforms resembling distant signatures of underwater explosions. An array of piezoelectric transducers was used to generate impulsive sounds with waveforms approximating those predicted from 5 or 500 kg HBX-1 charges at ranges from 1.5 to 55.6 km. At the conclusion of the study, no temporary shifts in masked-hearing thresholds (MTTSs), defined as a 6-dB or larger increase in threshold over pre-exposure levels, had been observed at the highest impulse level generated (500 kg at 1.7 km, peak pressure 70 kPa); however, disruptions of the animals' trained behaviors began to occur at exposures corresponding to 5 kg at 9.3 km and 5 kg at 1.5 km for the dolphins and 500 kg at 1.9 km for the beluga whale. These data are the first direct information regarding the effects of distant underwater explosion signatures on the hearing abilities of odontocetes.

[S0001-4966(00)04807-4]

PACS numbers: 43.80.Nd, 43.80.Lb [WA]

## INTRODUCTION

It is becoming increasingly clear that intense anthropogenic (human-generated) underwater sound may adversely affect the hearing and behavior of many marine mammals. Cetaceans, which spend their entire lives in water, may be particularly vulnerable because of their relatively high auditory sensitivity, wide frequency bandwidth, and their reliance on acoustic stimuli to navigate, forage, and communicate (Ridgway, 1997). Unfortunately, there are few direct data regarding the effects of intense sound on cetaceans, making it extremely difficult to predict safe exposure levels for these mammals.

Exposure to intense sound may produce an elevated hearing threshold, also known as a threshold shift (TS). If the threshold returns to the pre-exposure level after a period of

time, the TS is known as a temporary threshold shift (TTS); if the threshold does not return to the pre-exposure level, the TS is called a permanent threshold shift (PTS). Studies of PTS and TTS were instrumental in establishing noise-exposure limits in humans; however, there are no data on PTS and few data on TTS in cetaceans. There have been to date only two studies of TTS in cetaceans: Au *et al.* (1999) measured TTS in a single bottlenose dolphin exposed to 50 min of octave-band noise centered at 7.5 kHz; Schlundt *et al.* (2000) measured temporary shifts of masked-hearing thresholds (MTTS) in bottlenose dolphins and white whales exposed to 1-s pure tones at frequencies of 0.4, 3, 10, 20, and 75 kHz. These data included and expanded on the original pure-tone MTTS data for bottlenose dolphins described in a technical report by Ridgway *et al.* (1997).

Although pure-tone stimuli are fair representations of many military and commercial sonars, many anthropogenic

<sup>a)</sup>Electronic mail: finneran@spawar.navy.mil

TABLE I. Animal subjects used in this study.

Species	Animal identification	Gender	Weight (kg)	Length (cm)	Age (yrs)
<i>Tursiops truncatus</i>	BEN	M	250	270	35
<i>Tursiops truncatus</i>	NEM	M	250	280	33
<i>Delphinapterus leucas</i>	MUK	F	550	350	31

sources of intense sound produce impulsive signals, i.e., transient signals with rapid rise times and high peak levels. Impulsive sources include seismic air guns and underwater explosions. Peak sound-pressure levels (SPLs) of underwater explosions may exceed 250–260 dB *re*: 1  $\mu$ Pa at 1 m (1  $\mu$ Pa-m) (Richardson *et al.*, 1995). Air guns used in geophysical surveys are routinely operated at peak source levels exceeding 210 dB *re*: 1  $\mu$ Pa-m (Richardson *et al.*, 1995). TTS data obtained with pure-tone stimuli may suggest the effects of impulsive sounds; however, the relationship between hearing loss and the fundamental parameters of sound such as peak frequency, duration, rise time, peak pressure, and total energy are unknown; thus, TTS measurements with impulsive stimuli are still needed for direct predictions.

This report presents the results of a study designed to measure TTS in bottlenose dolphins (*Tursiops truncatus*) and beluga whales (*Delphinapterus leucas*) exposed to impulsive sounds with pressure waveforms resembling those produced by underwater explosions (HBX-1, charge weight 5 or 500 kg) at ranges of 1.5 to 55.6 km. A behavioral response paradigm was used to measure hearing thresholds before and after exposure to the impulsive sounds. The test site in San Diego Bay featured a relatively high and variable ambient noise background dominated by shipping as well as biological sources such as snapping shrimp and other animals housed at the facility. Bandlimited white noise (masking noise) was therefore introduced to create a floor effect and keep thresholds consistent despite fluctuations in the ambient noise level. The presence of masking noise has been shown to decrease the amount of TTS observed in humans (e.g., Parker *et al.*, 1976; Humes, 1980) and the amount of PTS in terrestrial mammals (Ades *et al.*, 1974). To indicate that the thresholds presented here were measured in the presence of masking noise, we use the term MTTs to identify these data. The effects of the masking noise on the measured thresholds are discussed as well.

## I. METHODS

### A. Experimental animals

Cetacean species potentially usable in a study of TTS are currently limited to those animals under human care at research facilities and oceanaria. This limitation excludes the study of baleen whales and allows only the study of smaller odontocetes such as dolphins and porpoises. Table I lists the experimental animals used in this study: two bottlenose dolphins and one beluga whale. A fourth subject (beluga whale, male, age 22 years) was rejected during the course of the study after being diagnosed with a systemic fungal infection. No substantial TSS (i.e., at or above 6 dB) were observed in this subject during any of the tests in which he participated.

The remaining three subjects were healthy and were not known to have any hearing deficits at the frequencies at which they were tested. Animals were housed in floating net enclosures (10×10 m to 13×25 m) located in San Diego Bay. All animals were under constant veterinary supervision in accordance with applicable federal regulations. The study followed a protocol approved by the Institutional Animal Care and Use Committee under guidelines of the Association for the Accreditation of Laboratory Animal Care.

Behavioral audiograms measured for *Delphinapterus leucas* (White *et al.*, 1978; Awbrey *et al.*, 1988; Johnson *et al.*, 1989) and *Tursiops truncatus* (Johnson, 1967) show these species to have hearing ranges and sensitivities equivalent to or better than many marine mammals (see Fay, 1988; Richardson *et al.*, 1995). *Delphinapterus* and *Tursiops* may thus be considered representative of many marine mammals that have broad auditory bandwidth and high sensitivity. These mammals also are widely distributed across the globe: *Tursiops* has an around-the-world distribution in temperate and tropical waters (Wells and Scott, 1998) and *Delphinapterus* has a wide distribution in arctic and subarctic waters (Brodie, 1989), as far south as the St. Lawrence River mouth in the Atlantic (rarely as far south as New Jersey) and Sakhalin Island in the Pacific. Their wide distribution and keen hearing give these animals the potential to be impacted by a variety of acoustic devices.

## B. Experimental apparatus

### 1. Underwater stations

Figure 1(a) illustrates the test apparatus. This 8×8-m floating net enclosure featured two underwater listening stations, designated “S1” and “S2.” The S1 station was the site for presentation of the “start” tone for the animal to begin hearing tests, as well as the impulsive stimulus. The actual hearing tests were conducted at the S2 station. Each station consisted of a polyvinyl chloride (PVC) frame with a plastic biteplate on which the subject was trained to station. The S1 and S2 biteplates were located at depths of approximately 4 and 2 m, respectively. Each station contained an underwater video camera which was used to observe each subject on the biteplate. A third video camera was located in-air with a view of the entire test enclosure.

The S1 station [Fig. 1(b)] contained a single sound projector (ITC 1042) that was used to emit a 1-s tone as the start signal for the subject to begin hearing tests. These start tones, or “S1 tones,” were at a frequency of 20 kHz and an SPL of approximately 140 dB *re*: 1  $\mu$ Pa. The S1 start tones were produced using a programmable function generator (Wavetek 178), filtered (Ithaco 4302), and amplified (BGW PS4) before being input to the S1 sound projector.

The S2 station [Fig. 1(c)] contained two sound projectors: one (ITC 1001) mounted 1.5 m below the animal’s ears and used to project hearing test tones, or “S2 tones,” and one (NRL J9) located 1.5 m in front of the animal and used to project masking noise. Masking noise was generated on a dedicated computer running custom software (Finneran *et al.*, 1999). This system allowed for the continuous generation of masking noise whose frequency spectrum was com-

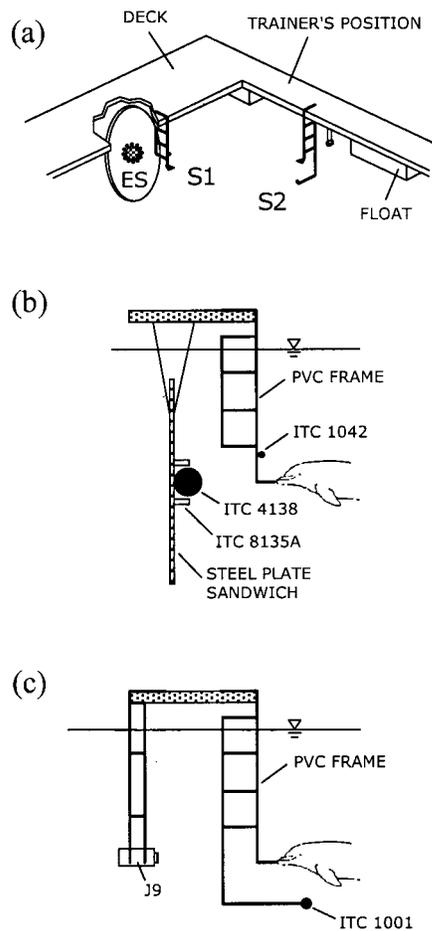


FIG. 1. (a) Schematic of the test apparatus showing the locations of the S1 and S2 underwater listening stations. The deck is shown cut-away to reveal the explosion simulator (ES). (b) Horizontal detail view showing the ES and the S1 station. (c) Horizontal detail showing the S2 station.

compensated to eliminate the effects of projector frequency-dependent transmission characteristics and acoustic standing waves. The projected masking noise had a spectral density level of 95 dB *re*:  $1 \mu\text{Pa}^2/\text{Hz}$  and frequency bandwidth of 0.8–3 kHz; the noise spectral density was flat within  $\pm 2$  dB over this range. The S2 tones were 250 ms in duration including 50-ms rise and fall times. S2 tones were generated using a digital computer and multifunction board (National Instruments PCI-MIO-16E-1), filtered (Ithaco 4302), and amplified (BGW PS4) before being input to the ITC 1001 projector.

Threshold estimates obtained with a behavioral response paradigm using animal subjects are generally time consuming; thus, the number of S2 frequencies that could be tested was limited. Hearing tests were originally performed at two S2 frequencies: 1.2 and 1.8 kHz; these frequencies were selected because they corresponded to the approximate peak frequency of the impulses (see Sec. 1B 2 and Fig. 3 below) and a frequency 1/2 octave above the peak frequency, respectively. At high levels of exposure, TTS has been shown to occur at frequencies above the exposure stimulus frequency, often at a frequencies 1/2 octave to one octave above (Yost, 1994). A third frequency (2.4 kHz) was added shortly after the start of the test sequence, to help insure that shifts occurring at frequencies one octave above the impulse spec-

tral peak would be detected. The order in which the S2 frequencies were tested was counterbalanced between sessions and days.

The acoustic pressure during each S2 tone presentation was measured using a B&K 8103 hydrophone (mounted to the S2 PVC frame) and a B&K 2635 charge amplifier, digitized using the PCI-MIO-16E-1 multifunction board, and stored on a personal computer. The pressure during the S1 start-tone presentation was also measured using a B&K 8103 hydrophone (mounted to the S1 PVC frame), amplified and filtered (B&K 2635), and digitized (PCI-MIO-16E-1). The computer was also used to record the time each S1 and S2 tone was produced.

## 2. Explosion simulator

For ‘high’ explosives like TNT and its derivatives (including HBX-1), the velocity of detonation is extremely fast and a spherically symmetric shock wave is produced along with an oscillating globular mass of gaseous materials (Weston, 1960; Urick, 1967). At close range the pressure signature of an underwater detonation of HBX-1 therefore consists of the shock wave followed by a number of bubble pulses (Urick, 1967). At longer ranges, the signature is complicated by surface and bottom reflections, attenuation, and refraction effects. Pressure signatures of underwater explosions at large distances therefore cannot simply be produced by smaller charges at close range.

In this study, impulsive sounds were generated by a piezoelectric transducer array specifically designed to replicate pressure waveforms produced by distant underwater explosions. This system, referred to here as the explosion simulator (ES), is described in Clark *et al.* (1999); only the salient features are repeated here. The ES consisted of a backplate and an array of projectors. The backplate was constructed out of two 3-m diameter, 0.6-cm-thick stainless-steel plates with a 0.6-cm viscous rubber layer sandwiched between. A 50-cm-diameter piezoelectric sphere (ITC 4138) was located on the backplate at the center. Twelve cylindrical piezoelectric projectors (ITC 8135A) were also mounted on the backplate around the sphere in a 60-cm-radius circle. The ES was suspended from the test enclosure at a depth of 4.3 m, with the backplate vertical in the water column and the projectors facing the S1 biteplate, as shown in Fig. 1(b). The ES was located at a horizontal distance of approximately 1.5 m from the subjects’ ears. For stimulus levels 1–8, the S1 biteplate was 0.6 m above the depth of the ES center. For levels 9 and 10, the S1 biteplate and the ES were at the same depth.

Calibration of the ES was a two-step process. First, a system identification was performed *in situ* (using a swept sine wave) to determine the system impulse response relating acoustic pressure to source input voltage. The system impulse response was then used to derive the input voltage waveforms for the spherical and cylindrical projectors required to generate the desired pressure waveform.

Table II shows the test matrix. Each impulse was assigned a nominal stimulus level, from 1 to 10, in order of increasing peak pressure. Simulated explosions ranged from a 5-kg charge at 55.6 km (level 1) to 500 kg at 1.7 km (level 10). Pressure signatures were based on predictions from the

TABLE II. Specifications for the ten impulse levels used in this study.

Level	Equiv. HBX-1 charge weight [kg (lb)]	Equiv. range [km (naut. mi.)]	SPL <sub>p-p</sub> (dB re: 1 μPa)	p <sub>p</sub> [kPa (psi)]	U <sub>T</sub> [dB re: 1 J/m <sup>2</sup> (1 μPa <sup>2</sup> s)]	τ (ms)
1	5 (11)	55.6 (30)	170	0.17 (0.025)	-52 (130)	5.4
2	5 (11)	37 (20)	179	0.45 (0.065)	-43 (139)	7.6
3	5 (11)	18.5 (10)	189	1.5 (0.22)	-33 (149)	6.9
4	5 (11)	9.3 (5)	196	3.8 (0.55)	-26 (156)	6.4
5	500 (1100)	27.8 (15)	196	3.9 (0.57)	-25 (157)	8.2
6	5 (11)	3.7 (2)	200	6.0 (0.87)	-20 (162)	13
7	5 (11)	1.5 (0.8)	209	16 (2.3)	-13 (169)	8.7
8	500 (1100)	3.7 (2)	213	27 (3.8)	-10 (172)	11
9	500 (1100)	1.9 (1)	220	56 (8.2)	-5 (177)	5.1
10	500 (1100)	1.7 (0.9)	221	70 (10)	-3 (179)	9.5

U.S. Navy's REFMS numerical modeling program (e.g., Britt, 1987; Britt *et al.*, 1991) for mid-depth in 24 m of water at a typical test site in the Baltic Sea (the Baltic was chosen because of test requirements of the German Navy and the University of Kiel, who furnished support for developing the ES). The data in Table II are the mean values from calibration measurements conducted prior to testing each day and include the peak-to-peak SPL (SPL<sub>p-p</sub>), peak pressure (p<sub>p</sub>), duration (τ), and total energy flux (U<sub>T</sub>). Individual pressure signatures were measured using a B&K 8105 hydrophone located at a position estimated to lie approximately between the subjects' ears. The hydrophone output was filtered from 2 Hz–200 kHz and amplified (B&K 2635), then digitized (256 kSamples/s), using an HP3561A digital signal analyzer. The digitized waveforms were transferred to a digital computer and analyzed using custom software to calculate SPL<sub>p-p</sub>, p<sub>p</sub>, τ, and U<sub>T</sub>.

The peak pressures in Table II were based on the absolute values of the measured waveforms (i.e., the maximum negative or positive peak). The duration of each impulse was defined using the first and last time values at which the absolute value of the waveform reached an amplitude of -20 dB relative to the maximum amplitude. The energy flux spectral density  $E(m)$  was calculated as outlined by Fricke *et al.* (1985) and Johnston *et al.* (1988)

$$E(m) = \frac{1}{\rho c} |P(m)|^2, \quad m = 0, 1, \dots, N-1, \quad (1)$$

where ρ is the medium density, c is the sound speed,

$$P(m) = \Delta t \sum_{n=0}^{N-1} p(n) e^{-j2\pi mn/N}, \quad m = 0, 1, \dots, N-1, \quad (2)$$

p(n) is the digitized time series (the measured pressure waveform), P(m) is the discrete Fourier transform of p(n), N is the number of samples in the time series, Δt is the sampling interval, and j = (-1)<sup>1/2</sup>. Fourier analysis of each signal was based on a 20-ms time window, regardless of the calculated duration. Note that Eq. (1) implicitly assumes plane waves or far-field conditions away from any reflective surfaces, such that the acoustic particle velocity magnitude v = p/(ρc). The medium characteristic impedance ρc is often removed from Eq. (1) so that the energy flux

spectral density may be expressed in units of μPa<sup>2</sup>s/Hz, rather than J m<sup>-2</sup> Hz<sup>-1</sup> (0 dB re: 1 J m<sup>-2</sup> Hz<sup>-1</sup> ≈ 182 dB re: 1 μPa<sup>2</sup>s/Hz, for seawater with nominal values of ρ = 1026 kg/m<sup>3</sup> and c = 1500 m/s). The total energy flux U<sub>T</sub> was calculated using

$$U_T = \Delta f \sum_{k=0}^{N-1} E(k), \quad (3)$$

where Δf = 1/(NΔt). The energy flux is sometimes expressed in μPa<sup>2</sup>s, rather than J/m<sup>-2</sup> (0 dB re: 1 J/m<sup>2</sup> ≈ 182 dB re: 1 μPa<sup>2</sup>s, for seawater with ρ = 1026 kg/m<sup>3</sup> and c = 1500 m/s).

Figure 2 shows representative pressure waveforms and energy flux spectral densities measured for each of the ten impulse levels. The fidelity of each measured ES waveform to the corresponding REFMS prediction was evaluated by comparing features such as peak pressure, 1/3-octave spectra, and major peaks in the time histories. The measured (synthesized) waveforms were in good agreement with the predicted waveforms, with the exception of the frequency range below approximately 1 kHz, where the ES was incapable of producing sufficient amplitudes to match the predictions (see Clark *et al.*, 1999).

At large distances from any real source, the relationship between acoustic pressure and particle velocity magnitude approaches the plane wave relationship v = p/(ρc). As the distance (relative to the acoustic wavelength) from any real source decreases, a larger acoustic particle velocity is associated with a given pressure amplitude. Distant signatures from underwater explosions would be expected to obey the plane wave relationship; however, the proximity of the ES to the test subjects compelled measurement of the acoustic particle velocity to insure that it was not substantially elevated from the plane wave value. The acoustic particle velocity was therefore estimated from pressure gradient measurements (using a two-hydrophone technique) at the location of the test subjects. These data did not show any substantial increase in the particle velocity (compared to the plane wave value) at frequencies above 1 kHz, where the bulk of the energy of the impulses used in this study existed.

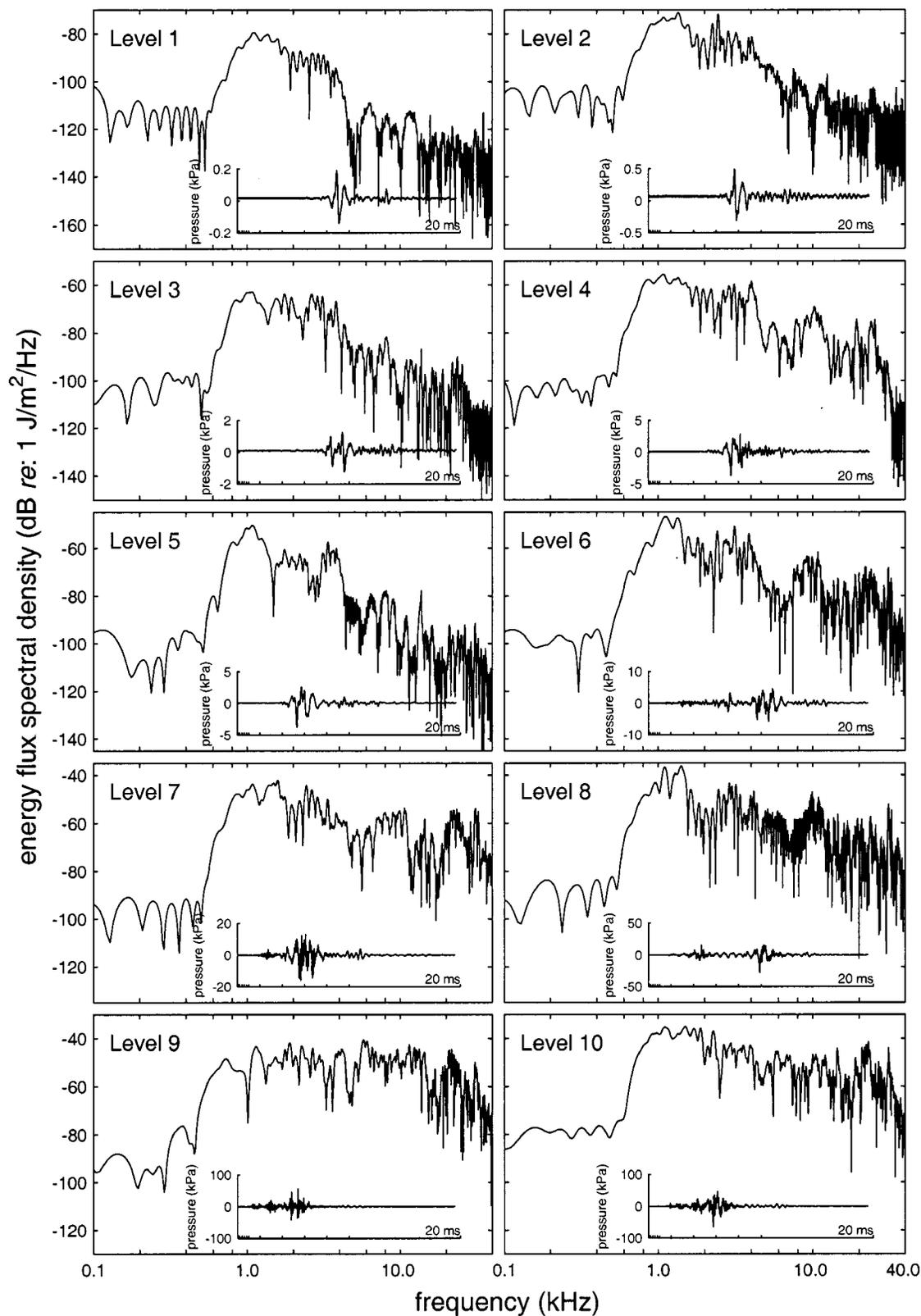


FIG. 2. Representative pressure signatures and energy flux spectral densities for the ten impulse levels. The analysis frequency bandwidth was 6.1 Hz.

### C. Procedure

The experimental procedure consisted of the following steps: (1) measure the subject's pre-exposure hearing thresholds at each S2 frequency; (2) expose the subject to an impulse generated by the ES; (3) immediately measure the sub-

ject's hearing thresholds at each S2 frequency (postexposure thresholds); (4) measure the subject's hearing thresholds at each S2 frequency approximately 1–1.5 h after exposure (first recovery thresholds); and (5) measure the subject's hearing thresholds at each S2 frequency approximately 2–3

h after exposure (second recovery thresholds). Subjects were tested at each condition shown in Table II. Testing began with each animal at level 1. The impulse level for each animal was incremented by one each test day as long as no MTTs (see Sec. IC 5) had been observed.

Each test day was divided into four sessions: (1) pre-exposure, (2) post-exposure, (3) first recovery, and (4) second recovery. During each session, hearing thresholds were measured at several frequencies. The order in which the frequencies were tested was counterbalanced between sessions and days. Each threshold measurement consisted of several “dives” and multiple S2 hearing-test tones were presented during each dive. Sessions, dives, and the hearing-test procedure are described in more detail next, within the context of a pre-exposure session. Post exposure and recovery sessions are then described.

### 1. Pre-exposure sessions

Pre-exposure sessions consisted of individual hearing threshold measurements conducted at each of the S2 frequencies. The hearing-test procedure was based on the method of free response, or MFR (Egan *et al.*, 1961). Each subject was presented with a number of S2 tones during a relatively long observation period, designated here as a “dive.” Each threshold measurement required approximately 1–4 dives. Multiple dives were required to allow the subjects to periodically surface for air. Each dive began with the trainer directing the animal (with a hand signal) to the S1 station. The subject was trained to remain on the S1 station until presented with the S1 start tone. Upon hearing the S1 start tone, the subject proceeded directly to the S2 station for hearing tests.

Once the animal was positioned at the S2 station, S2 tones were presented. The time interval between tones (the interstimulus interval, or ISI) was randomized and the subject did not know when the next tone would occur. Subjects were trained to whistle if they heard a tone and to remain quiet otherwise (see Ridgway and Carder, 1997). The amplitudes of the S2 tones were adjusted using a modified staircase procedure (e.g., Cornsweet, 1962; Rosenberger, 1970): the amplitude was decreased 4 dB following each hit (a whistle response to a tone) and increased 2 dB following each miss (no whistle response to a tone). After a variable number of tones, the trainer sounded an underwater buzzer which signaled the animal to leave the S2 station and return to the surface for a fish reward. The next dive was then begun, if necessary.

Hearing thresholds were defined as the mean SPL of the first ten hit–miss/miss–hit reversal points. The first three tones were presented at suprathreshold levels (as warm-up tones) and were not included in the threshold determination. A subject’s threshold at any given frequency could usually be estimated after presenting 15 to 30 tones.

The time period between 0.05 and 2.05 s immediately following each tone start was designated as a “hit interval.” Only whistle responses occurring within a hit interval following a tone onset were recorded as hits. Any whistle response by a subject not occurring within a hit interval was recorded as a false alarm. The ISI (defined from the start of

one tone to the start of the next tone) was randomly varied between 5–8 s; thus, the majority of time spent on the S2 station was outside any hit intervals and functioned as a “catch trial” period. Time catch trials (Ljungblad *et al.*, 1982), or no-tone periods, with durations of between 10–60 s, were also randomly introduced while the animal was on the S2 station.

It has been demonstrated that variations in a measured sensory threshold may result from changes in a subject’s response bias, rather than an actual change in sensitivity *per se* (Schusterman, 1980). False-alarm rates provide some insight into a subject’s response bias from session to session. For this study, the false-alarm rate  $r$  was defined as the number of false alarms,  $N_{FA}$ , divided by the total amount of time during which the subject was on the S2 station with no hit interval present. To obtain a dimensionless quantity,  $r$  is multiplied by the hit interval duration  $T_1$

$$rT_1 = \frac{N_{FA}}{T - N_{S2}T_1} T_1, \quad (4)$$

where  $T$  is the total amount of time the animal spent on the S2 station and  $N_{S2}$  is the number of S2 tones presented. For the MFR,  $rT_1$  values calculated using Eq. (4) are analogous to false-alarm rates obtained from a single interval experiment (Miller, 1969). This study employed a modified version of the MFR: the distribution of S2 tones did not follow a Poisson distribution because of the 5–8-s ISI (i.e., the ISI was not open-ended). The  $rT_1$  values calculated here are therefore not strictly analogous to those obtained with the MFR or to false-alarm rates obtained from a single interval experiment; however, we still computed  $rT_1$  values in order to assess a subject’s response bias from session to session. The use of  $rT_1$  was a method of normalizing the number of false alarms with respect to the number of tones presented and the total time that the subject was on the S2 station.

### 2. Postexposure sessions

Postexposure sessions were identical to pre-exposure sessions with the following exception: a single impulse was produced by the ES 30 ms after the start of the first S1 start tone cuing the animal to the S2 station. The postexposure threshold at the first S2 frequency tested was generally obtained within 2–3 min following exposure to the impulse. Thresholds at the remaining S2 frequencies were normally obtained within 5–15 min following the impulse. After all S2 frequencies had been tested, threshold measurements were repeated at the first S2 frequency tested after exposure. In some circumstances (e.g., if the first postexposure threshold at a frequency suggested a potential shift) testing was also repeated at one or more of the other S2 frequencies.

### 3. First recovery sessions

Threshold measurements were also repeated at approximately 1–1.5 h following the postexposure session; these test sessions were designated as “first recovery sessions.” During first recovery sessions, thresholds were again measured at all S2 frequencies; these sessions were conducted in a manner identical to that of pre-exposure sessions.

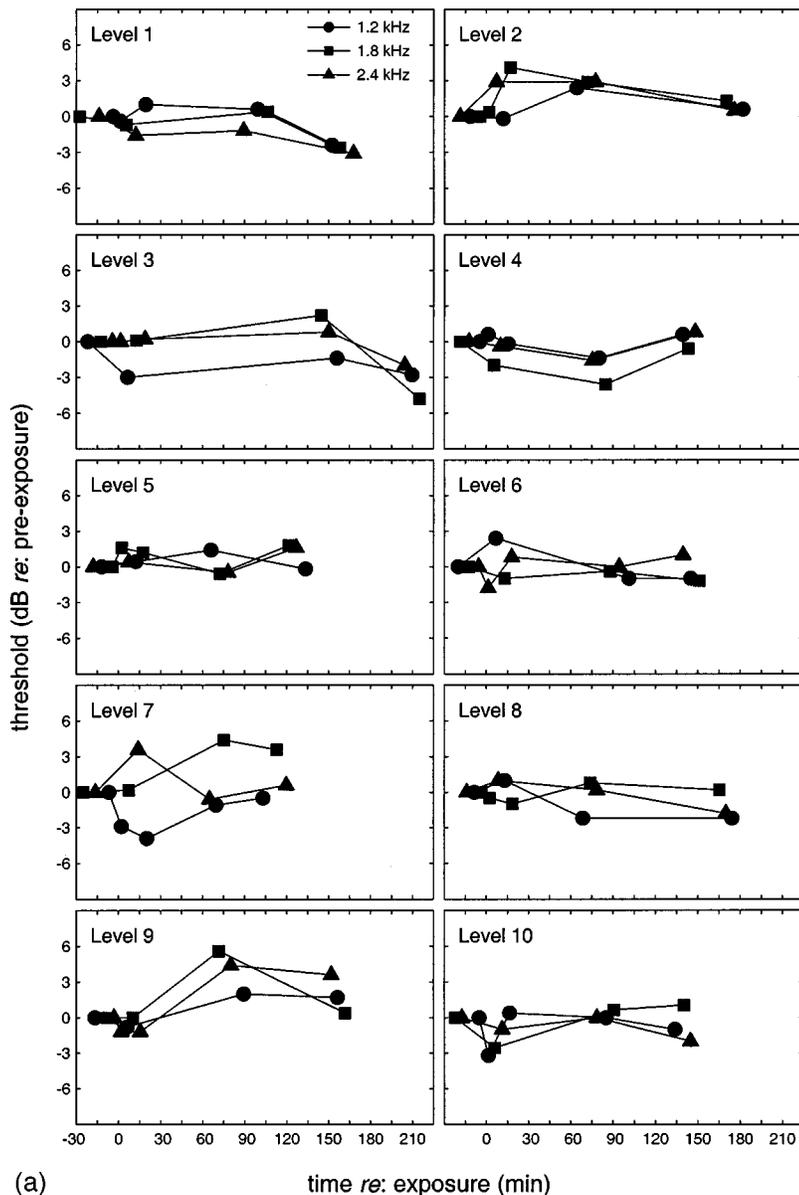


FIG. 3. Pre-exposure, postexposure, and recovery thresholds for subjects (a) BEN, (b) NEM, (c) MUK as functions of the time relative to exposure, for each of the ten impulse levels.

#### 4. Second recovery sessions

The “second recovery session” consisted of threshold measurements conducted at approximately 2–3 h following the postexposure session. The second recovery sessions were conducted identically to pre-exposure sessions and thresholds were again measured at all S2 frequencies.

#### 5. MTTs criterion

Postexposure and recovery hearing thresholds were compared to pre-exposure thresholds to determine if a subject experienced MTTs, defined as a 6-dB or larger increase in threshold over the pre-exposure threshold at that frequency. This 6-dB criterion was based on a substantial amount of threshold data for these animals obtained at several frequencies over a period of several years (e.g., Ridgway and Carder, 1997; Ridgway *et al.*, 1997; Schlundt *et al.*, 2000) and was considered to be the minimum shift that was clearly larger than any day-to-day or session-to-session variations in the subjects’ masked-hearing thresholds. Studies of TTS in terrestrial mammals have shown that TTSs

larger than 40 dB may be fully recovered without a PTS or the loss of sensory hair cells (e.g., Ahroon *et al.*, 1996); therefore, the 6-dB criterion was also considered well below levels capable of causing a PTS.

## II. RESULTS

Table III presents the means and standard deviations for the pre-exposure thresholds measured for each subject, at each S2 frequency, for the ten impulse levels. These data confirm that there were no significant differences between

TABLE III. Mean values for the pre-exposure masked hearing thresholds (dB re: 1  $\mu$ Pa) and standard deviations (s.d.) measured for the three test subjects.  $n=10$  for all categories, except: NEM at 2.4 kHz ( $n=7$ ) and MUK at 2.4 kHz ( $n=8$ ).

Subject	1.2 kHz	1.8 kHz	2.4 kHz
BEN	123 (s.d. 1.6)	120 (s.d. 1.6)	119 (s.d.1.2)
NEM	122 (s.d. 1.6)	116 (s.d. 2.2)	117 (s.d.1.8)
MUK	121 (s.d. 2.6)	119 (s.d. 2.7)	123 (s.d.0.73)

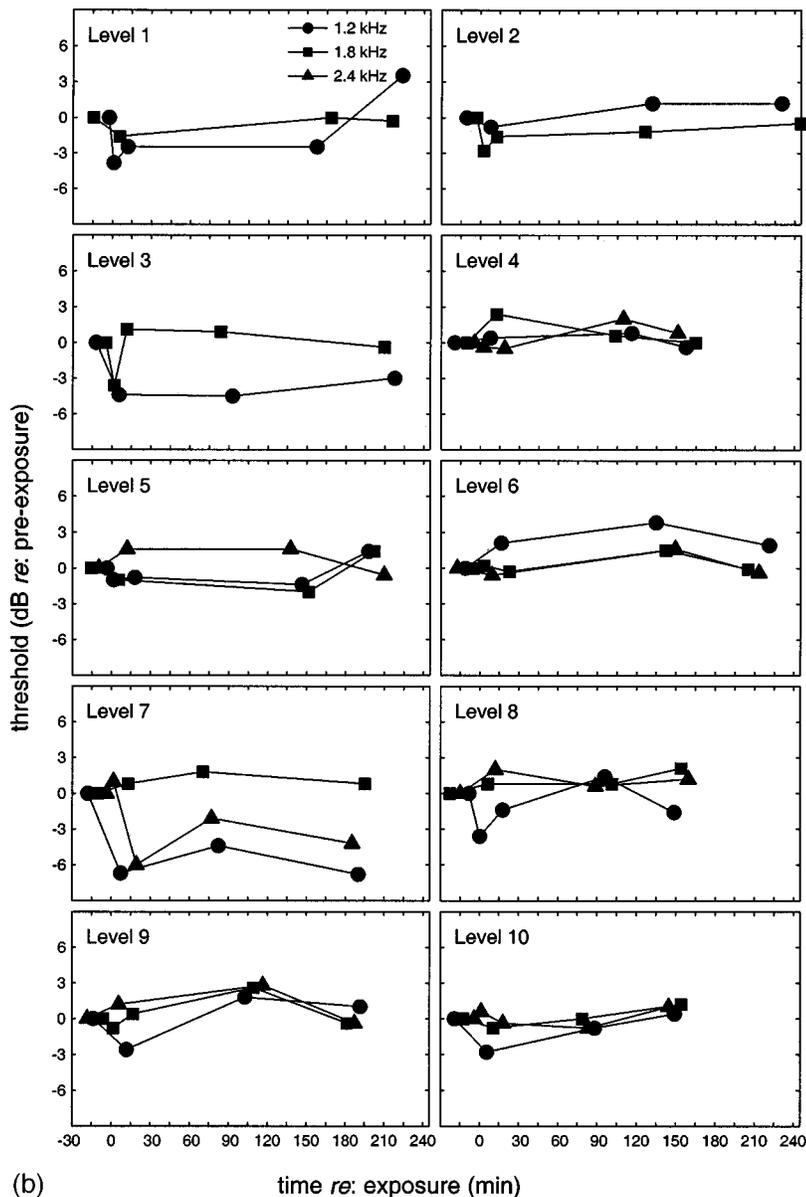


FIG. 3. (Continued.)

pre-exposure thresholds measured during the 4-month period of this study and that there were no PTSs produced from any cumulative effects of the exposures.

Figure 3 shows the pre-exposure, postexposure, and recovery thresholds measured for subjects (a) BEN, (b) NEM, and (c) MUK for each of the ten impulse levels. The abscissa is time relative to the time of the impulse; the time for each threshold measurement was defined as the mean time between the first and last S2 tone presentations at that frequency. The ordinate is the measured threshold, expressed in dB relative to the pre-exposure threshold for that frequency measured that day. The circles, squares, and triangles represent the thresholds measured at 1.2, 1.8, and 2.4 kHz, respectively. Thresholds at negative times (i.e., before the impulse) correspond to pre-exposure thresholds and have normalized amplitudes of 0 dB. The cluster of thresholds just after time zero are postexposure thresholds. The first and second recovery thresholds are visible as two separate data clusters at approximately 60–90 min and 120–240 min, respectively, after the impulse. Technical difficulties prevented recovery

thresholds from being measured for MUK at level 1.

For the ten impulse levels, there were no substantial MTTs (i.e., 6-dB or larger increases) in any of the subjects tested. The majority of the postexposure and recovery thresholds (264/280, 94.3%) was within 4 dB of the pre-exposure values. There were some (9/280, 3.2%) small (4–5.6 dB), yet statistically significant, threshold increases [e.g., the dolphin BEN at level 9 (5.6 dB at 1.8 kHz,  $t=8.73$ ,  $p<0.01$ ; 4.4 dB at 2.4 kHz,  $t=4.64$ ,  $p<0.01$ ) and the whale MUK at level 10 (4.0 dB at 2.4 kHz,  $t=5.61$ ,  $p<0.01$ )], which may suggest that the impulses were approaching levels sufficient to induce an MTTs according to our 6-dB criterion. For the dolphin BEN, these small threshold increases all occurred during the first recovery sessions; five out of six of the (4–5.6-dB) threshold shifts observed in the whale MUK occurred during the second recovery sessions. It is difficult to state whether these small shifts seen during recovery sessions (approximately 180 min postexposure) were caused by exposure to the impulses or were behavioral artifacts caused by subject

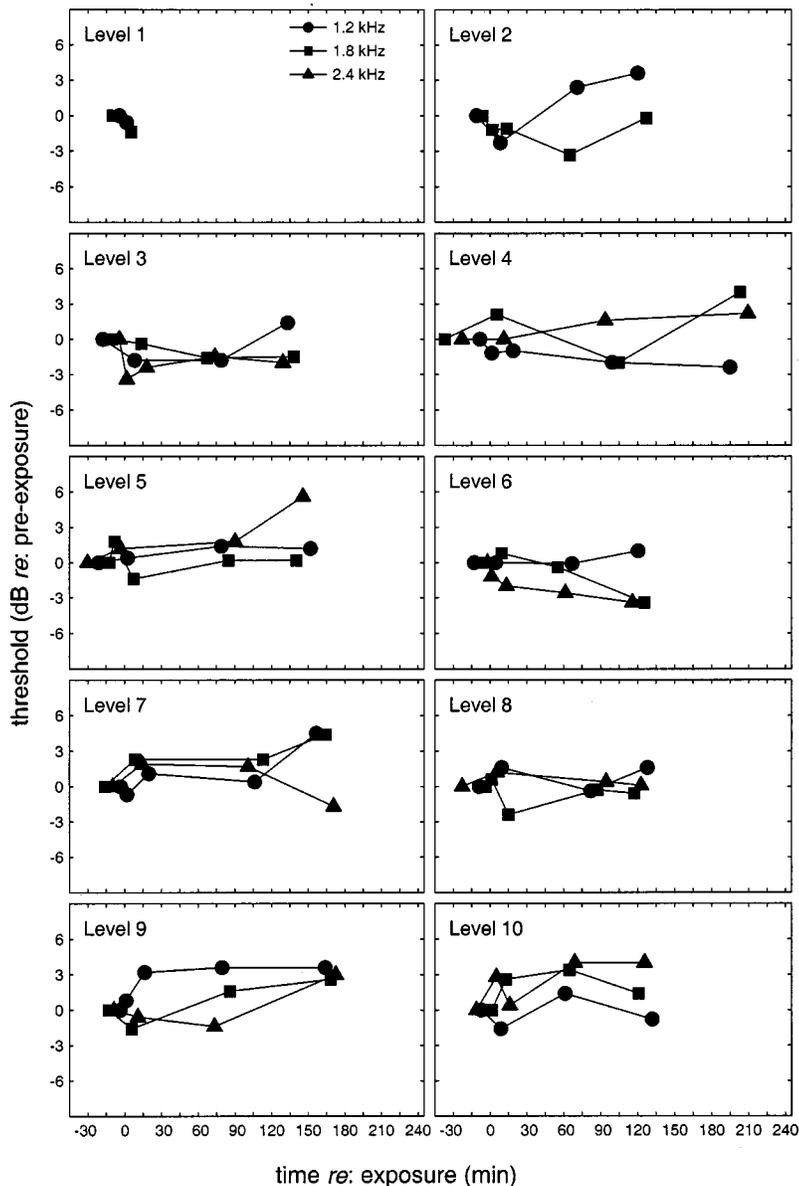


FIG. 3. (Continued.)

fatigue, or declining food motivation coincident with testing later in the day.

In some cases (7/280, 2.5%), thresholds decreased following exposure [e.g., BEN at level 7 (-3.9 at 1.2 kHz)]. It has been suggested that hypersensitivity such as this may occur at levels approaching those sufficient to induce a TTS (Silbiger, 1965; Hodge and McCommons, 1966; Schlundt *et al.*, 2000). If negative TTSs are real and occur at levels preceding actual TTS, they may provide some predictive effect.

Figure 4 presents the  $rT_1$  values for subjects (a) BEN, (b) NEM, and (c) MUK for each frequency at each of the ten levels. These data are presented in a manner analogous to Fig. 3 (i.e., each symbol in Fig. 4 corresponds to a hearing threshold in Fig. 3) and may be used to determine if any changes in the subjects' response bias occurred. For example, the dolphin NEM at level 7, 1.2 kHz had significantly lower postexposure, first recovery, and second recovery thresholds (-6.7, -4.4, -6.8 dB, respectively); however, these were accompanied by an  $rT_1$  increase from 0.023 (pre-

exposure) to 0.096, 0.059, and 0.052 for postexposure, first recovery, and second recovery thresholds, respectively.

Figure 5 presents histograms of the  $rT_1$  values (pooled regardless of frequency or impulse level) for (a) BEN, (b) NEM, and (c) MUK. Using Fig. 5, the subjects' response criteria were categorized according to  $rT_1$ :  $rT_1 \leq 0.01$  was considered conservative,  $0.01 < rT_1 \leq 0.05$  was considered moderate, and  $rT_1 > 0.05$  was considered liberal. The beluga whale MUK was generally conservative and rarely committed false alarms; the dolphins were more liberal, but still in the range of conservative to moderate. A multiple regression analysis with dummy coding (Pedhazur, 1982) was used to compare postexposure and recovery  $rT_1$  values to those obtained during pre-exposure sessions. The results of the regression were significant for the dolphins NEM ( $F_{3,115} = 4.14$ ,  $p < 0.01$ ) and BEN ( $F_{3,126} = 2.94$ ,  $p < 0.05$ ). For NEM, there was a statistically significant increase in postexposure  $rT_1$  values compared to pre-exposure values ( $t = 2.50$ ,  $p < 0.05$ ). The mean values for  $rT_1$  were 0.020 and 0.037 for pre- and postexposure sessions, respectively. A

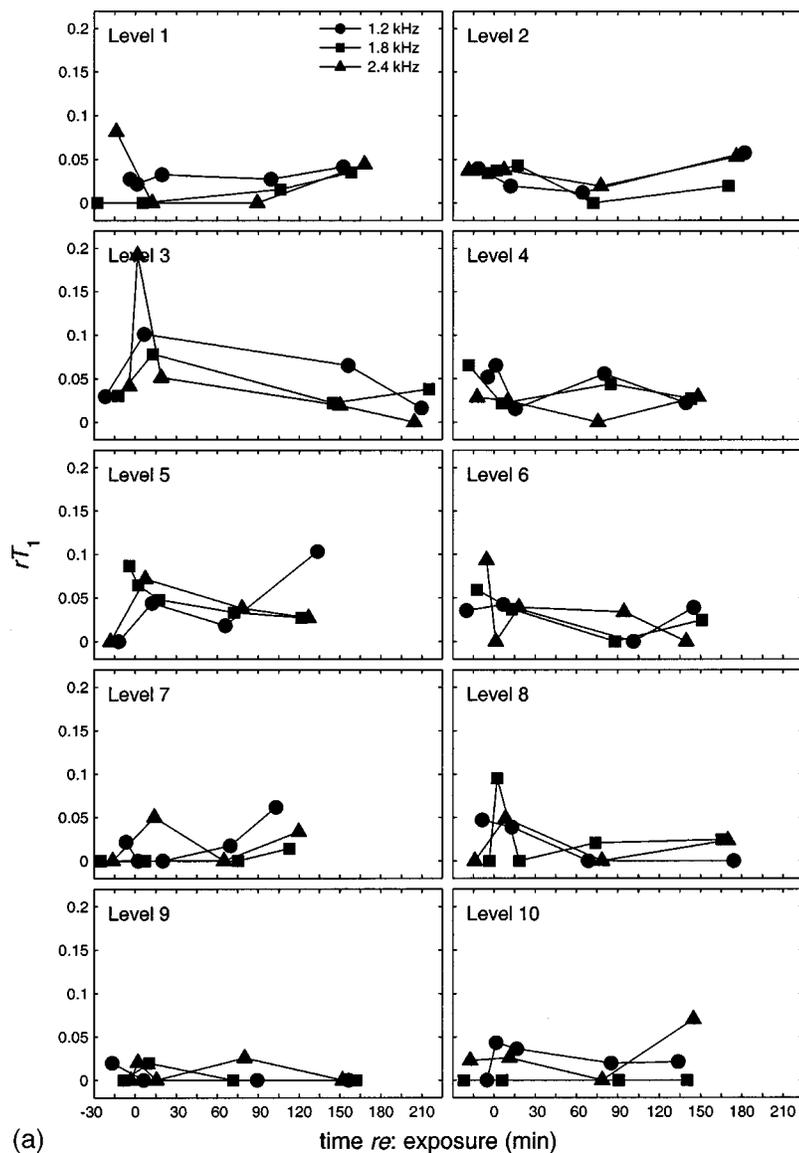


FIG. 4. Values of  $rT_1$  measured during pre-exposure, postexposure, and recovery sessions for subjects (a) BEN, (b) NEM, (c) MUK, plotted as functions of the time relative to exposure, for each of the ten impulse levels.

similar increase in false-alarm rates was also observed in pinnipeds by Kastak *et al.* (1999). For the subject BEN, the mean values for  $rT_1$  were 0.027 and 0.016 for the pre-exposure and the first recovery sessions, respectively; however, this difference was not significant. No significant differences in  $rT_1$  were found for the beluga whale MUK between pre-exposure and the postexposure and recovery sessions.

As in previous studies of TTS in marine mammals (Ridgway *et al.*, 1997; Kastak *et al.*, 1999; Schlundt *et al.*, 2000), the animals began to exhibit alterations in their trained behaviors as the intensity of the fatiguing stimulus increased. These behaviors included remaining on the S1 station after being presented with an impulse until a second S1 tone was presented (i.e., not recognizing the S1 tone as the start signal), swimming around the enclosure before proceeding to the S2 station, refusing to return to the S1 station on subsequent dives (in which case the subject was cued directly to the S2 station for hearing tests), and vocalizing after exposure to the impulse. Behavioral alterations began at levels 4 (5 kg at 9.3 km) and 7 (5 kg at 1.5 km) for the dolphins

NEM and BEN, respectively, and at level 9 (500 kg at 1.9 km) for the whale MUK. Behavioral alterations continued for each animal at the higher test levels as well; however, the impulses were presented in increasing intensity from level 1 to level 10; thus, this pattern could have been an order effect. As noted by Schlundt *et al.* (2000), the beluga whale MUK appeared to be more tolerant of intense sounds than were either of the dolphins.

### III. DISCUSSION

This study used a modified version of the MFR where the ISI was randomized between 5–8 s and was not open-ended. The minimum ISI was limited by the time required to digitize and write to disk the acoustic pressure measured during each hit interval (the S2 tone as well as the subject's whistle response, if present). The maximum ISI was restricted to 8 s to insure that thresholds could be collected quickly. The modified MFR used in this study allowed behavioral thresholds to be measured very quickly (see Fig. 3) following exposure to the impulse; the first threshold esti-

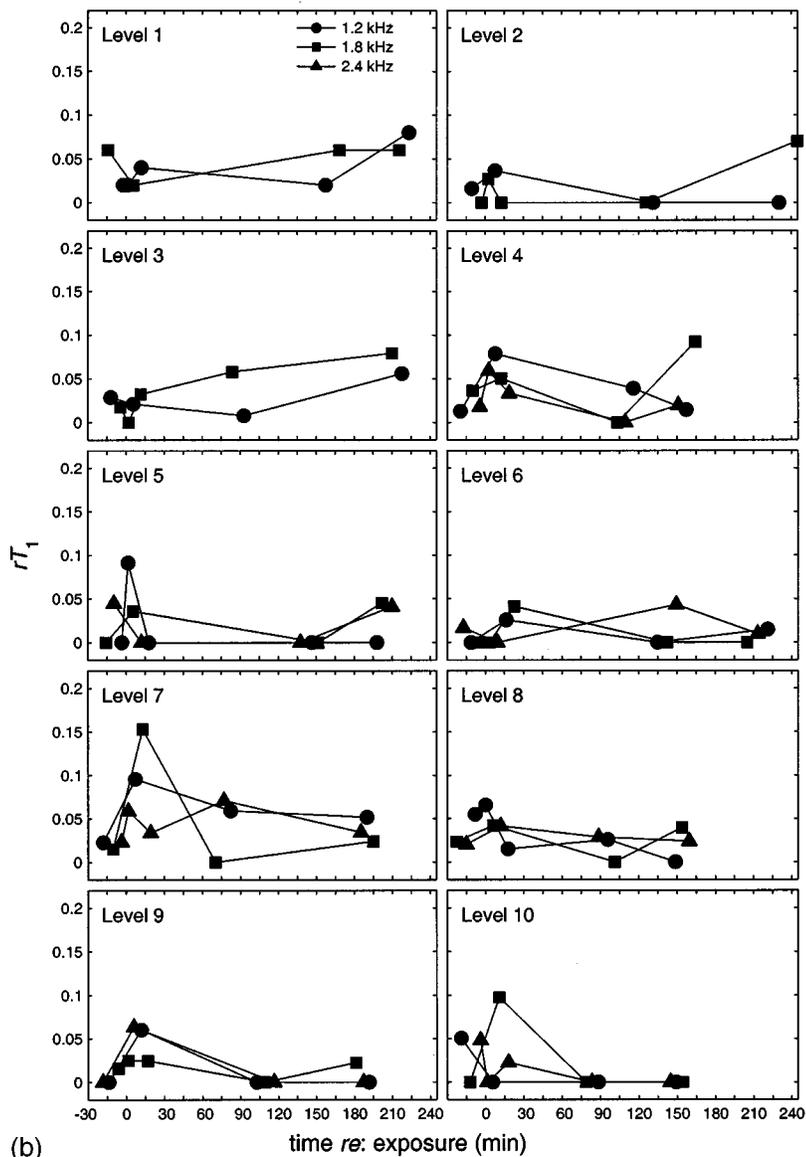


FIG. 4. (Continued.)

(b)

mate, based on ten reversals, was normally obtained within 2–3 min. A high level of computer control also allowed the precise times of the S1 start signals and S2 tones to be recorded.

Although no 6-dB or larger MTTs were actually observed, the results of this study are still valuable because they are the first direct measurements of the effects of distant signatures of underwater explosions on the hearing abilities of odontocetes. There are some indications that the maximum impulse levels obtained may have been approaching those sufficient to induce MTTs. These include apparent hypersensitivity in some cases as well as some smaller (4–5.6 dB), yet statistically significant increases in threshold measured in recovery sessions.

#### A. Impulsive stimuli

The time waveforms and 1/3-octave energy spectra of the synthesized impulses were in close agreement with those predicted using the REFMS numerical modeling program, with the exception of the frequency range below 1 kHz, where the ES could not produce sufficient pressure to match

the predicted waveforms. It is important to note the differences between these waveforms (and distant signatures of underwater explosions in general) compared to near-blast pressure signatures which are dominated by a single shock wave with a very large peak pressure and very fast rise time. Most studies of the auditory effects of impulsive sounds in terrestrial mammals have dealt with subjects exposed to aerial gunfire or similar sounds at relatively close range. These sources *do* produce pressure signatures consisting of a single high-peak pressure with a rapid rise time, followed by smaller oscillations, similar to the Friedlander wave with a finite rise time (Hamernik and Hsueh, 1991). The differences between these aerial waveforms and those found at even modest ranges from an underwater source must be considered when extrapolating data from impulsive tests on terrestrial mammals to predict the effects of underwater impulsive sounds on marine mammals, unless the mammals are very close to the source, in which case a TTS would be of minor importance compared to near-blast trauma.

As stated previously, the ES could not produce sufficient

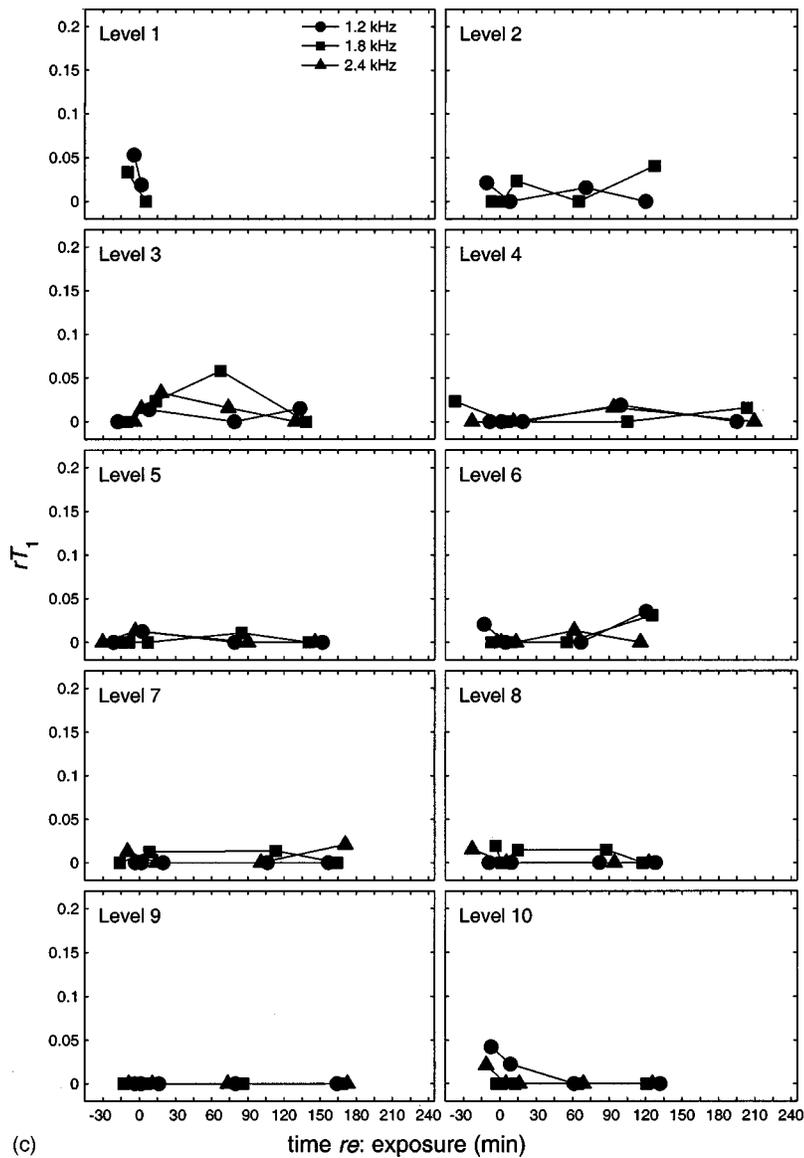


FIG. 4. (Continued.)

(c)

pressures at frequencies below 1 kHz to match the REFMS predictions. The effects of the pressure signature low-frequency energy deficit is uncertain. Distant signatures from actual explosions would be expected to contain more energy at frequencies below 1 kHz and as a result more total energy as well. *Tursiops* and *Delphinapterus* have relatively poor hearing sensitivity at frequencies below 1 kHz; however, it is not certain if the effects of low-frequency sound are reduced as a result. Some PTS studies in terrestrial mammals suggest that the effects of lower-frequency sounds are mitigated by properties of the outer and middle ear and that the higher frequencies cause the bulk of the damage (e.g., Price, 1974); however, these data are based on exposure to stimuli that create large amounts of PTS and it is not clear whether the odontocete middle ear or other adaptations are suited to perform a similar function underwater. It is clear that caution should be exercised in the interpretation of the results of the current study; those extrapolating these data to other impulsive waveforms must keep in mind that the results presented here are valid only for comparable waveforms and may have been influenced by the relative lack of low-frequency energy.

## B. Masking-noise effects

Studies of TTS in humans (Parker *et al.*, 1976; Humes, 1980) have shown that the presence of masking noise results in elevated hearing thresholds (effectively simulating a pre-exposure loss in hearing sensitivity) and decreases the amount of TTS observed. Ades *et al.* (1974) also observed smaller amounts of PTS in chinchillas when thresholds were measured in the presence of masking noise compared to those PTSs observed when thresholds were measured in quiet. There are currently no conclusive data for the relationship between masking noise and TTS in odontocetes. We employed masking noise out of necessity because the test site (San Diego Bay) had a relatively high (and variable) ambient noise level. The masking noise employed was at the lowest level (above ambient) at which we could maintain uniform frequency content between 0.8 and 3 kHz. Subjects' pre-exposure hearing thresholds (Table III) were approximately 20 dB above published absolute thresholds for *Tursiops* and *Delphinapterus*; thus, we must acknowledge the possibility that larger TSs may have been observed without the

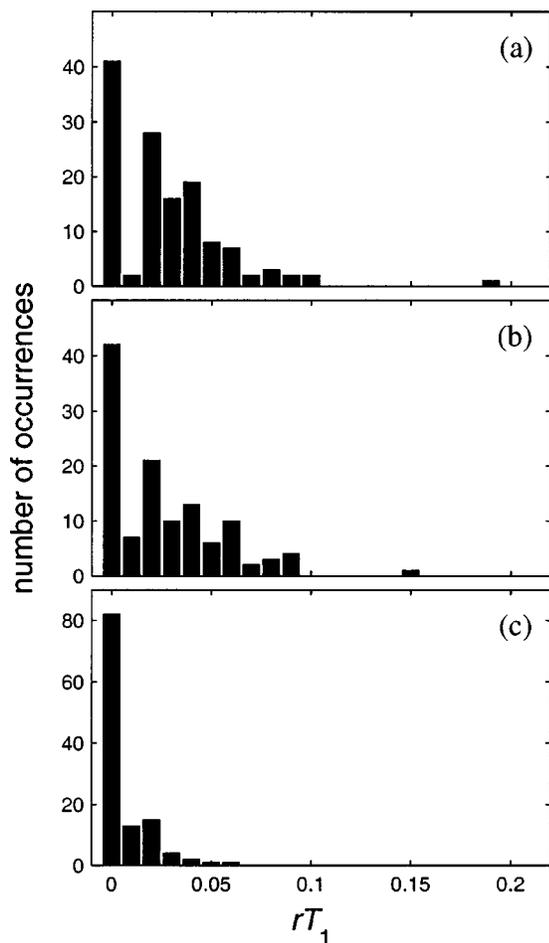


FIG. 5. Histograms of the pooled  $rT_1$  values for subjects (a) BEN, (b) NEM, and (c) MUK.

masking noise. Humes (1990) presented data for humans showing that exposure to broadband masking noise sufficient to raise pre-exposure thresholds 20 dB resulted in TTSs that were approximately 5 dB lower than those obtained without masking noise.

### C. Damage risk criteria

The long-term goal of projects such as the current study is the identification of underwater sound parameters that affect hearing loss in marine mammals and the establishment of effective damage risk criteria (DRC) for these animals. At relatively low pressure and sufficiently long exposure duration, the total acoustic energy determines the amount and type of TS; DRC for impulsive sounds are often modified to take into account the peak pressure and/or rise time because impulses may have a very high peak pressure and yet low energy if the duration is very short (Glorig, 1988). One of the chief difficulties lies in establishing where along a continuum of exposure regimes, from relatively long exposure to steady-state signals to brief exposure to a single shock wave, a particular exposure condition (i.e., pressure waveform and duration) exists.

Figure 6 compares the data from the present study to the marine mammal TTS studies of Schlundt *et al.* (2000), Au *et al.* (1999), and Kastak *et al.* (1999). Schlundt

*et al.* (2000) measured MTTs (6-dB or larger shifts) in dolphins and beluga whales exposed to 1-s pure tones at frequencies between 3 and 75 kHz (no MTTs was observed at 0.4 kHz at the highest level obtained). Au *et al.* (1999) observed 12–18-dB TTSs in a bottlenose dolphin exposed to 50 min of octave-band noise centered at 7.5 kHz. Kastak *et al.* (1999) measured mean TTSs of 4.6–4.9 dB in pinnipeds exposed to bandlimited noise with center frequencies between 100 and 2000 Hz and a bandwidth of one octave. Figure 6(a) plots the peak SPL versus the fatiguing stimulus duration from each study. The rectangles represent TTS-inducing stimulus levels from Schlundt *et al.* (2000) (3–20 kHz only), Au *et al.* (1999), and Kastak *et al.* (1999). Peak SPL values from Kastak *et al.* (1999) and Au *et al.* (1999) were approximated as the octave band (rms) level +3 dB. The open circles represent the data from the current study. Figure 6(a) also includes lines with slopes of 3-dB (solid line) and 5-dB (dashed line) per doubling of time fit to the mean values of the fatiguing stimuli used by Schlundt *et al.* (2000) and Au *et al.* (1999). The 3-dB per doubling of time slope, also called a 3-dB exchange rate (NIOSH, 1998), is equivalent to an equal energy criterion for relating SPL and permissible exposure duration (for continuous-type sounds). The 5-dB exchange rate was originally proposed to account for interruptions in the noise exposure that frequently occur during the workday (NIOSH, 1998). NIOSH previously endorsed the 5-dB exchange rate but has recently proposed the more conservative 3-dB exchange rate; however, at this time OSHA still uses the 5-dB exchange rate (OSHA, 1995; NIOSH, 1998). These exchange rates were developed for relatively long exposures and/or multiple impulses; however, NIOSH (as well as the ISO) currently recommends calculating exposure levels by integrating both impulsive and continuous-type noise over the duration of the measurement and applying the equal-energy criterion (NIOSH, 1998).

To a first approximation, exposure characteristics (i.e., peak SPL and duration) within the upper right of Fig. 6(a) are likely to produce a TS in pinnipeds and odontocetes, while those in the lower left are not likely to produce a TS. Figure 6(a) suggests that the impulses used in this study, because they model distant explosion signatures and include the effects of multipath propagation and refraction, are fairly close in their effects to the continuous signals used in the other two studies; that is, these signatures do not appear to have short-enough rise times and/or high-enough peak pressures to produce TTSs at energy levels below those of the longer duration, steady-state sounds used by Schlundt *et al.* (2000), Au *et al.* (1999), and Kastak *et al.* (1999). Figure 6(a) also suggests that for odontocetes exposed to these particular stimuli, the 3-dB exchange rate may be a more appropriate predictor than the 5-dB exchange rate.

Figure 6(b) shows the total energy flux for the fatiguing stimuli in each study plotted versus the stimulus duration. Again, the rectangles represent stimulus levels from Schlundt *et al.* (2000) (3–20 kHz only), Au *et al.* (1999), and Kastak *et al.* (1999); the open symbols represent the data from the current study. Total energy fluxes for the stimuli used by Schlundt *et al.* (2000) and Kastak *et al.* (1999) were estimated using

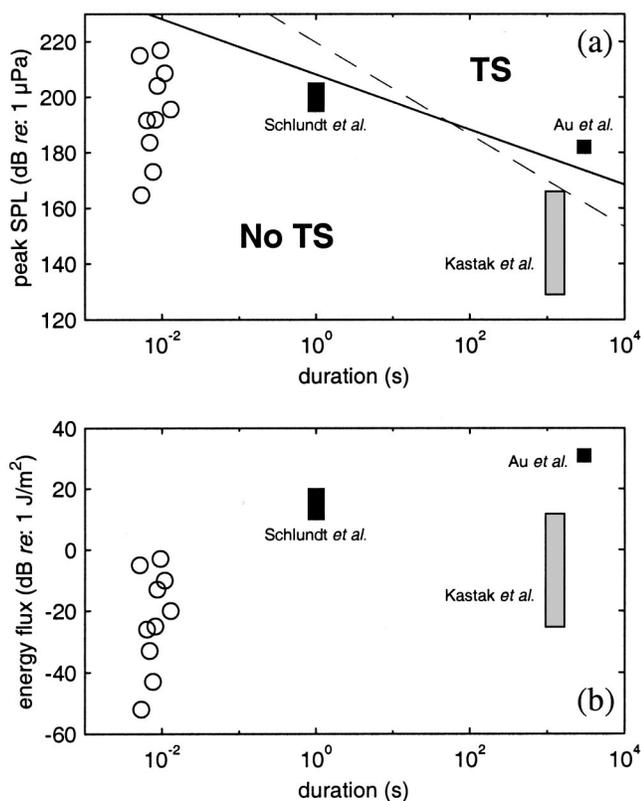


FIG. 6. Existing underwater TTS data for marine mammals plotted as (a) peak SPL versus fatiguing stimulus duration and (b) total energy flux versus duration. Open circles: present study; dashed line: 5-dB exchange rate; solid line: 3-dB exchange rate.

$$U_T = \text{SPL}_{\text{rms}} + 10 \log_{10} \tau - 182, \quad (5)$$

where  $U_T$  has units of  $\text{dB re: } 1 \text{ J/m}^2$ ,  $\text{SPL}_{\text{rms}}$  is the (octave band) rms SPL ( $\text{dB re: } 1 \text{ } \mu\text{Pa}$ ), and  $\tau$  is the exposure duration (s). The factor of 182 dB was used to convert from  $\text{dB re: } 1 \text{ } \mu\text{Pa}^2\text{s}$  to  $\text{dB re: } 1 \text{ J/m}^2$ , assuming seawater with nominal values of  $\rho = 1026 \text{ kg/m}^3$  and  $c = 1500 \text{ m/s}$ .

Figure 6 is presented here as an attempt to demonstrate how, given enough data, similar graphic aids could potentially be constructed to aid those establishing safe exposure guidelines for anthropogenic sources of underwater sound. Plots such as Fig. 6 may also be used to guide future studies of marine mammal TTS in the choice of fatiguing stimuli. Additional data using different combinations of peak SPL, energy flux, duration, and number of exposures may enable crude relationships to be established as a foundation for the establishment of a DRC for marine mammals.

A final note is in order regarding the difficulty experienced in this study (also see Ridgway *et al.*, 1997; Schlundt *et al.*, 2000) in generating sufficiently intense sounds to actually cause a reliable TTS in the dolphins and beluga whale(s) studied. Although the presence of masking noise may have reduced the TTSs observed in these studies, the extremely high pressures required imply a large dynamic range and high resilience for the odontocete auditory system. These factors make TTS studies employing impulsive waveforms resembling distant explosion signatures very challenging—it is difficult to generate sufficient source lev-

els to produce a threshold shift in odontocetes using very short duration sounds without resorting to actual impulsive sources located fairly close to the test subject.

#### IV. CONCLUSIONS

A behavioral response paradigm was used to measure masked underwater hearing thresholds in two bottlenose dolphins and one beluga whale before and after exposure to impulsive underwater sounds with waveforms resembling distant signatures of underwater explosions. An array of piezoelectric transducers was used to generate impulsive sounds with waveforms approximating those predicted from HBX-1 charges of weight 5 or 500 kg at ranges from 1.5 to 55.6 km. At the conclusion of the study, no MTTs, defined as a 6-dB or larger increase in threshold over pre-exposure levels, had been observed; however, alterations in the animals' trained behavior began to occur at levels 4 (5 kg at 9.3 km) and 7 (5 kg at 1.5 km) for the dolphins and at level 9 (500 kg at 1.9 km) for the beluga whale. These data are the first information on the effects of distant underwater explosion signatures on the hearing abilities of odontocetes.

#### ACKNOWLEDGMENTS

The explosion simulator was developed and maintained by Joseph Clark, Jane Young, and Joel Gaspin. Tricia Kamolnick, Jennifer Carr, Randy Dear, Scott Peluso, Josh Rosenberg, Mark Todd, and Michelle Reddy provided animal training and/or other technical assistance. Software for computer control of stimuli and recording of animal responses was developed by Wesley Elsberry. Software for computer recognition of the animal whistle responses was developed by Diane Blackwood. We thank Robert Gisiner, Frank Stone, Tim McBride, and Paul Towner, as well as Uwe Vogel, Ursula Siebert, Klaus Lucke, and their German colleagues for encouragement. We also thank John Sigurdson for helpful comments. Funding was provided by the Office of Naval Research. James Finneran was supported by a National Research Council Research Associateship.

- Au, W. W. L., Nachtigall, P. E., and Pawloski, J. L. (1999). "Temporary threshold shift in hearing induced by an octave band of continuous noise in the bottlenose dolphin." *J. Acoust. Soc. Am.* **106**, 2251(A).
- Ades, H. W., Trahiotis, C., Kokko-Cunningham, A., and Averbuch, A. (1974). "Comparison of hearing thresholds and morphological changes in the chinchilla after exposure to 4 kHz tones." *Acta Oto-Laryngol.* **78**, 192–206.
- Ahroon, W. A., Hamernik, R. P., and Lei, S.-F. (1996). "The effects of reverberant blast waves on the auditory system." *J. Acoust. Soc. Am.* **100**, 2247–2257.
- Awbrey, F. T., Thomas, J. A., and Kastelein, R. A. (1988). "Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*." *J. Acoust. Soc. Am.* **84**, 2273–2275.
- Britt, J. R. (1987). "Shock wave reflection and refraction in multi-layered ocean/ocean bottoms with shear wave effects. A user's manual for the REFMS code." NSWC TR 87-312, Naval Surface Warfare Center, November 1987.
- Britt, J. R., Eubanks, R. J., and Lumsden, M. G. (1991). *Underwater Shock Wave Reflection and Refraction in Deep and Shallow Water: Volume I—A User's Manual for the REFMS Code (Version 4.0)* (Science Applications International Corporation, St. Joseph, LA).

- Brodie, P. F. (1989). "The white whale *Delphinapterus leucas* (Pallas, 1776)," in *Handbook of Marine Mammals: River Dolphins and the Larger Toothed Whales*, edited by S. H. Ridgway and R. Harrison (Academic, London), Vol. 4, pp. 119–144.
- Clark, J. A., Young, J. A., and Gaspin, J. B. (1999). "Validation of a system for synthesizing distant signatures of underwater explosions for sea mammal hearing studies," Proceedings of the Joint EAA/ASA meeting, Berlin, Germany, 14–19 March 1999.
- Cornsweet, T. N. (1962). "The staircase method in psychophysics," *Am. J. Psychol.* **75**, 485–491.
- Egan, J. P., Greenberg, G. Z., and Schulman, A. I. (1961). "Operating characteristics, signal detectability, and the method of free response," *J. Acoust. Soc. Am.* **33**, 993–1007.
- Fay, R. R. (1988). *Hearing in Vertebrates: A Psychophysics Databook* (Hill-Fay, Winnetka, IL).
- Finneran, J. J., Carder, D. A., Ridgway, S. H., and Schlundt, C. E. (1999). "Technique for the generation and frequency compensation of bandlimited white noise and its application in studies of masked hearing thresholds," *J. Acoust. Soc. Am.* **106**, 2130(A).
- Fricke, J. R., Davis, J. M., and Reed, D. H. (1985). "A standard quantitative calibration procedure for marine seismic sources," *Geophysics* **50**, 1525–1532.
- Glorig, A. (1988). "Damage-risk criteria for hearing," in *Noise and Vibration Control*, edited by L. L. Beranek (INCE, Washington, DC), pp. 537–553.
- Hamernik, R. P., and Hsueh, K. D. (1991). "Impulse noise: Some definitions, physical acoustics and other considerations," *J. Acoust. Soc. Am.* **90**, 189–196.
- Hodge, D. C., and McCommons, R. B. (1966). "Reliability of TTS from impulse-noise exposure," *J. Acoust. Soc. Am.* **40**, 839–846.
- Humes, L. E. (1980). "Temporary threshold shift for masked pure tones," *Audiology* **19**, 335–345.
- Johnson, C. S. (1967). "Sound detection thresholds in marine mammals," in *Marine Bio-Acoustics*, edited by W. N. Tavolga (Pergamon, New York), Vol. 2, pp. 247–260.
- Johnson, C. S., McManus, M. W., and Skaar, D. (1989). "Masked tonal hearing thresholds in the beluga whale," *J. Acoust. Soc. Am.* **85**, 2651–2654.
- Johnston, R. C., Reed, D. H., and Desler, J. F. (1988). "Special report of the SEG technical standards committee, SEG standards for specifying marine seismic energy sources," *Geophysics* **53**, 566–575.
- Kastak, D., Schusterman, R. J., Southall, B. L., and Reichmuth, C. J. (1999). "Underwater temporary threshold shift induced by octave-band noise in three species of pinniped," *J. Acoust. Soc. Am.* **106**, 1142–1148.
- Ljungblad, D. K., Scoggins, P. D., and Gilmartin, W. G. (1982). "Auditory thresholds of a captive Eastern Pacific bottle-nosed dolphin, *Tursiops* spp.," *J. Acoust. Soc. Am.* **72**, 1726–1729.
- Miller, H. (1969). "The FROC curve: a representation of the observer's performance for the method of free response," *J. Acoust. Soc. Am.* **46**, 1473–1476.
- NIOSH (1998). *Criteria for a Recommended Standard: Occupational Noise Exposure, Revised Criteria 1998*, DHHS (NIOSH) Publication No. 98–126 (NIOSH, Cincinnati, OH).
- OSHA (1996). "Occupational Noise Exposure," in OSHA Safety and Health Standards 29 CFR 1910.95, Fed. Regist. 61, 9227, 7 March 1996.
- Parker, D. E., Tubbs, R. L., Johnston, P. A., and Johnston, L. S. (1976). "Influence of auditory fatigue on masked pure-tone thresholds," *J. Acoust. Soc. Am.* **60**, 881–885.
- Pedhazur, E. J. (1982). *Multiple Regression in Behavioral Research*, 2nd ed. (Harcourt Brace Jovanovich, Fort Worth, TX), pp. 271–333.
- Price, G. R. (1974). "Upper limit to stapes displacement: Implications for hearing loss," *J. Acoust. Soc. Am.* **56**, 195–197.
- Richardson, W. J., Greene, Jr., C. R., Malme, C. I., and Thomson, D. H. (1995). *Marine Mammals and Noise* (Academic, San Diego).
- Ridgway, S. H., and Carder, D. A. (1997). "Hearing deficits measured in some *Tursiops truncatus*, and discovery of a deaf/mute dolphin," *J. Acoust. Soc. Am.* **101**, 590–594.
- Ridgway, S. H., Carder, D. A., Smith, R. R., Kamolnick, T., Schlundt, C. E., and Elsberry, W. R. (1997). "Behavioral responses and temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, to 1-second tones of 141–201 dB re 1  $\mu$ Pa," Technical Report 1751, Naval Command, Control, and Ocean Surveillance Center, RDT&E Division, San Diego.
- Ridgway, S. H. (1997). "Who are the whales?" *Bioacoustics* **8**, 3–20.
- Rosenberger, P. B. (1970). "Response-adjusting stimulus intensity," in *Animal Psychophysics: The Design and Conduct of Sensory Experiments*, edited by W. C. Stebbins (Appleton-Century-Crofts, New York), pp. 161–184.
- Schlundt, C. E., Finneran, J. J., Carder, D. A., and Ridgway, S. H. (2000). "Temporary shift in masked hearing thresholds (MTTS) of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones," *J. Acoust. Soc. Am.* **107**, 3496–3508.
- Schusterman, R. J. (1980). "Behavioral methodology in echolocation by marine mammals," in *Animal Sonar Systems*, edited by R. G. Busnel and J. F. Fish (Plenum, New York), pp. 11–41.
- Silbiger, H. R. (1965). "Temporary threshold shifts due to single clicks," *J. Acoust. Soc. Am.* **38**, 937–938.
- Urick, R. J. (1967). *Principles of Underwater Sound for Engineers* (McGraw-Hill, New York).
- Wells, R. S., and Scott, M. D. (1998). "Bottlenose dolphin *Tursiops truncatus*" (Montagu, 1821) in *Handbook of Marine Mammals: The Second Book of Dolphins and the Porpoises*, edited by S. H. Ridgway and R. J. Harrison (Academic, London), Vol. 6, pp. 137–182.
- Weston, D. E. (1960). "Underwater explosions as acoustic sources," *Proc. Phys. Soc. London* **LXXXVI**, 233–249.
- White, Jr., M. J., Norris, J., Ljungblad, D., Baron, K., and di Sciara, G. (1978). "Auditory thresholds of two beluga whales (*Delphinapterus leucas*)," Hubbs/Sea World Research Institute Tech. Rep. 78–108.
- Yost, W. A. (1994). *Fundamentals of Hearing*, 3rd ed. (Academic, San Diego).