A MODEL FOR MARINE MAMMAL ACOUSTIC SAFETY CRITERIA

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Introduction Marine mammals and endangered species have been recognized by the public in general and by federal legislation in particular as valuable resources to be protected. Many species are known to employ sound in communication and echolocation for reproduction, navigation, and foraging. At present there is a critical lack of knowledge on which to base decisions concerning the effect of human-generated sound on marine species. Most studies found in the literature have focused on monitoring behavior of marine mammals in the wild in response to a particular sound source. Unfortunately, data resulting from these studies do not provide a direct correlation between received source levels and their effect on audition and thus may be difficult to use when predicting effects *a priori*. The work reported here is part of a continuing effort to provide safety criteria for the impact of human-generated underwater sound on marine mammals based on temporary threshold shift measurements as recommended by the National Research Council (1994).

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). As part of the US Navy Marine Mammal Program at the Space and Naval Warfare Systems Center, San Diego (SSC-SD), TTS measurements with trained marine mammals are used to quantify the impact of sounds and provide scientific data regarding safe levels to which marine mammals can be exposed without risk of hearing damage.

Methods A behavioral response paradigm is used to measure underwater hearing thresholds in trained marine mammals before and immediately after exposure to intense underwater sounds. The amount of TTS is determined by comparing the pre– and post–exposure hearing thresholds. Post–exposure thresholds are normally obtained within four minutes of the sound exposure. Test conditions have focused on single, continuous exposures to short–duration tones and impulsive sounds.

Subjects are trained using operant conditioning techniques (positive reinforcement) to produce audible sounds (whistles) in response to hearing test tones. The acoustic response (rather than movement) allows a relatively short time period between trials and quick threshold estimates, as well as assessment of response latency. Hearing thresholds are determined using a staircase procedure. Each trial, which may or may not contain a hearing test tone, has four possible outcomes: (1) HIT – response to a test tone; (2) MISS – no response to a test tone; (3) Correct Rejection (CR) – no response to a no–tone or "catch" trial; and (4) False Alarm (FA) – response to a catch trial. As

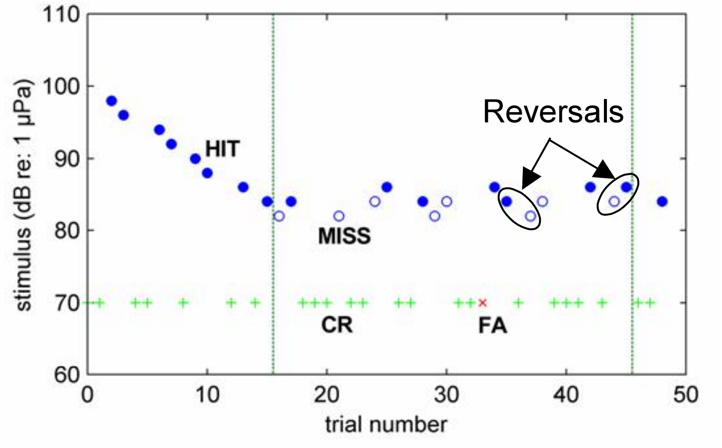

Figure 1

illustrated in Figure 1 (right), the hearing test tone level is increased after each MISS and decreased after each HIT. Each hit–miss or miss–hit is a "reversal." The hearing threshold is estimated as the average sound pressure over 10 reversals.

Results The first four TTS studies were conducted at SSC-SD during 1995–1996. In these tests, five bottlenose dolphins and two white whales were exposed to 1–s pure tones at frequencies of 20, 75, and 3 kHz (dolphins) or 3 kHz (white whales). The bottlenose dolphin data resulting from these tests were presented in a technical report (Ridgway *et al*., 1997). In 1997–1998 a series of five additional experiments were conducted with the following goals: (1) test dolphins and white whales using 1–s tones at 10 kHz, (2) test white whales with 1–s tones at 20 kHz, (3) repeat the dolphin and white whale testing with 1–s tones at 20 kHz using different masking noise levels, (4) repeat the dolphin and whale testing with 1–s tones at 3 kHz using different masking noise levels, (5) test dolphins and white whales using 1–s tones at 0.4 kHz. In addition to these experiments, the raw data from Ridgway *et al*. (1997) were re–evaluated using a more traditional method of calculating hearing thresholds. The results of these experiments, as well as the (re–evaluated) data from Ridgway *et al*. (1997), are found in Schlundt *et al*. (2000).

The results from these eight experiments using 1–s pure tones may be summarized as follows: The levels of fatiguing stimuli necessary to induce 6 dB or larger TTSs were generally between 192 and 201 dB *re*: 1 µPa (192–201 dB *re*: 1 $\mu Pa^2 \cdot s$ total energy flux). The exceptions occurred at 75 kHz, where one dolphin exhibited an TTS after exposure at 182 dB *re*: 1 µPa and the other dolphin did not show any shift after exposure to maximum levels of 193 dB *re*: 1 µPa, and at 0.4 kHz, where no subjects exhibited shifts at levels up to 193 dB *re*: 1 µPa. The shifts occurred most often at frequencies above the fatiguing stimulus. At the conclusion of the study all thresholds were at baseline values. No conclusions could be made regarding the potential effects of masking noise on the amount of TTS observed.

In 1998–1999 a study was conducted to measure TTS in bottlenose dolphins and white whales exposed to single underwater impulses (*i.e*., transient sounds with relatively high peak pressures and broad spectral content). This study used an "explosion simulator" (ES) developed by the Navy Surface Warfare Center Carderock. The ES consisted of an array of piezoelectric sound projectors with accompanying hardware and software designed to generate impulsive sounds with pressure waveforms resembling those produced by distant underwater explosions. No substantial (i.e., 6 dB or larger) threshold shifts were observed in any of the subjects (two bottlenose dolphins and one white whale) at the highest received level produced by the ES: approximately 70 kPa (10 psi) peak pressure (221 dB *re*: 1 µPa peak–to–peak pressure and 179 dB *re*: 1 $\mu Pa^2 \cdot s$ total energy flux). Finneran *et al*. (2000) provide a detailed account of these experiments.

In 2000–2001, impulsive testing was conducted using a seismic watergun as the sound source. The watergun was used because it was capable of producing impulses with higher peak pressures and total energy fluxes than the pressure waveforms produced using the ES. The watergun was selected over other seismic sources (e.g., airguns) because watergun impulses contain more energy at higher frequencies where odontocete hearing thresholds are relatively low. The experimental approach was similar to that of Schlundt *et al*. (2000) and Finneran *et al*. (2000): a behavioral response paradigm was used to measure hearing thresholds before and after exposure to single underwater impulses. Experimental subjects consisted of one white whale and one bottlenose dolphin. TTSs of 7 and 6 dB were observed in the white whale at 0.4 and 30 kHz, respectively, 2 min after exposure to single impulses with peak pressure of 160 kPa (23 psi), peak-to-peak pressure of 226 dB *re*: 1 µPa, and total energy flux of 186 dB *re*: 1 $\mu Pa^2 \cdot s$. Thresholds returned to within ±2 dB of the pre-exposure value within 4 minutes of exposure. No TTS was observed in the dolphin at the highest exposure conditions: 207 kPa

peak pressure, 228 dB *re*: 1 μPa peak-to-peak pressure, 188 dB *re*: 1 $\mu Pa^2 \cdot s$ total energy flux. Finneran *et al.* (2002) give a detailed discussion of the experimental methods and results. Figure 2 compares the pure–tone TTS data from Schlundt *et al.* (2000), the ES study results from Finneran *et al.* (2000), and the results from the watergun project from Finneran *et al.* (2002). Also shown are the TTS data from Nachtigall *et al.* (in review–2003), who measured TTS in a bottlenose dolphin exposed to 50 minutes of octave-band noise centered at 7.5 kHz.

Figure 2 (a) displays the peak sound pressure level (SPL) versus the fatiguing stimulus duration from each study. The rectangles represent TTS-inducing stimulus levels from Schlundt *et al.* (2000) and Nachtigall *et al.* (in review, 2003). The open circles indicate exposure conditions from Finneran *et al.* (2000) (no TTS was observed). The open triangles indicate exposure conditions from the watergun tests where no TTS was observed; the closed triangles indicate the exposure condition where TTSs were observed. Peak SPL values from Nachtigall *et al.* (in review, 2003) were approximated as the octave band (rms) level +3 dB. Figure 2 (b) also includes a line with a slope of 3-dB per doubling of time fit to the mean values of the fatiguing stimuli. The 3-dB per doubling of time slope, or 3-dB exchange rate, is equivalent to an equal energy criterion for relating the SPL and permissible exposure duration (for continuous-type sounds). For the species and stimuli that have been studied, the 3-dB exchange rate provides a reasonable fit to the experimental data. Figure 2 (c) shows that all TTS stimuli considered in these studies have approximately the same acoustic energy flux.

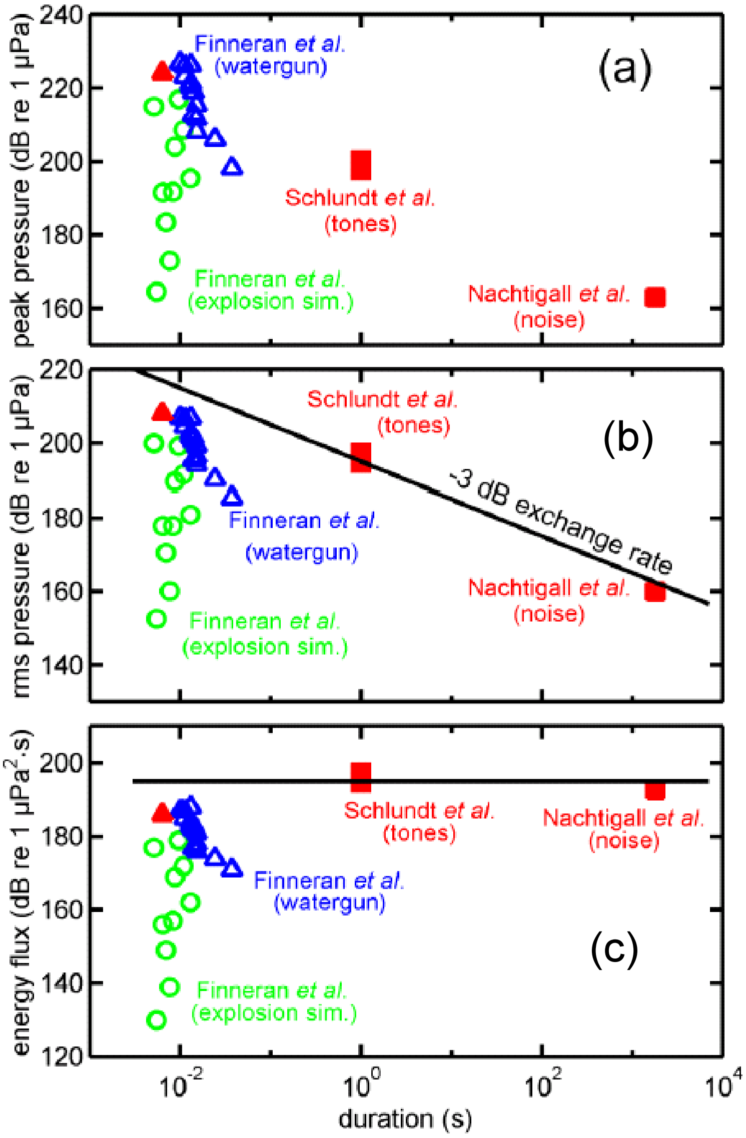

Figure 2

Discussion TTS is an objective measure that can be tested safely in marine mammals following the methodology developed at SSC-SD. The scientific literature is clear on the critical point that TTS of less than 20 to 40 dB of shift, tested within 15 minutes of exposure can be experienced without injury. To say that an animal has TTS equates to saying that those behaviors that usually link the animal to its acoustic world in a normal way are now disrupted for the period of TTS. There is a direct relationship between the amount of TTS and the ability to hear. There is also a one–to–one correspondence between the ability to hear and the ability

to perform, at the limit of sensitivity, all behaviors that depend on hearing such as echolocation and communication.

The TTS data that have been collected to date have been used extensively by Navy environmental analysts. More data are needed to prevent the temptation to over–extend the data in extrapolating effects; however, in many important cases, there are now scientific data for decisions concerning acoustic impacts on marine mammals and for use in preparation of environmental plans. Data resulting from this TTS project have been employed in recent naval exercises with no observed marine mammal impact.

Keywords marine mammals, temporary threshold shift, underwater noise

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