

Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations

Brandon L. Southall, Ann E. Bowles, William T. Ellison, James J. Finneran, Roger L. Gentry, Charles R. Greene Jr., David Kastak, Darlene R. Ketten, James H. Miller, Paul E. Nachtigall, W. John Richardson, Jeanette A. Thomas, & Peter L. Tyack

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Aquatic Mammals



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Acronyms

| Acronym | Definition |
|-------------------|---|
| A-weighting | Frequency-selective weighting for aerial hearing in humans derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies |
| ABR | Auditory brainstem response |
| ADD | Acoustic deterrent device |
| AEP | Auditory evoked potentials |
| AHD | Acoustic harassment device |
| ANSI | American National Standards Institute |
| ASSR | Auditory steady-state response |
| ATOC | Acoustic Thermometry of Ocean Climate program |
| CF | Center frequency |
| C-weighting | Frequency-selective weighting for aerial hearing in humans derived from the inverse of the idealized 100-phon equal loudness hearing function across frequencies |
| EFR | Envelope following response |
| EPA | U.S. Environmental Protection Agency |
| ES | Explosion simulator |
| f_{high} | Estimated upper functional hearing limit |
| f_{low} | Estimated lower functional hearing limit |
| HESS | High Energy Seismic Survey |
| HPA | Hypothalamic-pituitary-adrenal axis |
| IMAPS | Integrated Marine Mammal Monitoring and Protection System |
| ISO | International Standards Organization |
| JNCC | U.K. Joint Nature Conservation Committee |
| L_{eqT} | Equivalent-continuous sound level over period T |
| L_{impT} | Impulse equivalent-continuous sound level over period T |
| LFA | Low Frequency Active (sonar) |
| M-weighting | Generalized frequency weightings for various groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds |
| M_{lf} | Frequency weighting for low-frequency cetaceans (mysticetes) |
| M_{mf} | Frequency weighting for mid-frequency cetaceans (most odontocetes) |
| M_{hf} | Frequency weighting for high-frequency cetaceans (odontocetes specialized for use of very high frequencies) |
| M_{pw} | Frequency weighting for pinnipeds, listening in water |
| M_{pa} | Frequency weighting for pinnipeds, listening in air |
| MMPA | U.S. Marine Mammal Protection Act |
| NIHL | Noise-induced hearing loss |
| NIPTS | Noise-induced permanent threshold shift |
| NIOSH | U.S. National Institute for Occupational Safety and Health |
| NMFS | U.S. National Marine Fisheries Service |

| Acronym | Definition |
|------------|---|
| NOAA | U.S. National Oceanic and Atmospheric Administration |
| NRC | U.S. National Research Council |
| NRL | U.S. Naval Research Laboratory |
| P_{\max} | Maximum sound pressure |
| OBN | Octave-band noise |
| PCAD | National Research Council's Population Consequences of Acoustic Disturbance Model |
| PICE | Porpoise incidental catch elimination |
| PTS | Permanent threshold shift |
| REFMS | A computer program for predicting shock-wave propagation from underwater explosions |
| RL | Received level |
| RMS | Root-mean-square |
| SEL | Sound exposure level |
| SL | Source level (received level measured or estimated 1 m from the source) |
| SLM | Sound level meter |
| SPL | Sound pressure level |
| TS | Threshold shift |
| TTS | Temporary threshold shift |
| USC | United States Code |
| VAFB | Vandenberg Air Force Base |

Overview

A group of experts in acoustic research from behavioral, physiological, and physical disciplines was convened over a several year period. The purpose of this panel was to review the expanding literature on marine mammal hearing and on physiological and behavioral responses to anthropogenic sound, and to propose exposure criteria for certain effects. The group employed all available relevant data to predict noise exposure levels above which adverse effects on various groups of marine mammals are expected. Recent advances in these fields and the pressing need for a science-based paradigm to assess the effects of sound exposure were the primary motivations for this effort. Two categories of effects were considered: (1) injury and (2) behavioral disturbance. The proposed criteria for the onset of these effects were further segregated according to the functional hearing capabilities of different marine mammal groups, and according to the different categories and metrics of typical anthropogenic sounds in the ocean. The group achieved many of its objectives but acknowledges certain limitations in the proposed criteria because of scarcity or complete absence of information about some key topics. A major component of these recommendations is a call for specific research on critical topics to reduce uncertainty and improve future exposure criteria for marine mammals. This publication marks the culmination of a long and challenging initial effort, but it also initiates a necessary, iterative process to apply and refine noise exposure criteria for different species of marine mammals.

The process of establishing policy guidelines or regulations for anthropogenic sound exposure (i.e., the application of these exposure criteria) will vary among nations, jurisdictions, and legal/policy settings. Such processes should carefully consider the limitations and caveats given with these proposed criteria in deciding whether sufficient data currently exist to establish simplistic, broad criteria based solely on exposure levels. In many cases, especially for behavioral disturbance, context-specific analyses considering previous studies on species and conditions similar to those in question might, at least for the foreseeable future, be more appropriate than general guidelines.

State of Current Knowledge

The available data on the effects of noise on marine mammals are quite variable in quantity

and quality. In many respects, data gaps severely restrict the derivation of scientifically-based noise exposure criteria and, in some cases, explicit threshold criteria for certain effects are not appropriate given the amount and type of data available. Scientific inquiry into acoustic communication among marine mammals extends back more than half a century, but most of the specific data relevant to the proposed criteria have been published within the last two decades. Owing to the mounting public, scientific, and regulatory interest in conservation issues related to acoustics, the available science is progressing rapidly (e.g., see NRC, 2003, 2005).

This paper proposes, for various marine mammal groups and sound types, levels above which there is a scientific basis for expecting that exposure would cause auditory injury to occur. Controlled measurements of hearing and of the effects of underwater and aerial sound in laboratory settings have greatly expanded the ability to assess auditory effects. While understanding of the hearing capacities among all marine mammals remains admittedly rudimentary, there is a fairly detailed understanding of some key aspects of underwater and aerial hearing in a few representative species of odontocetes, pinnipeds, and sirenians, although hearing in mysticetes remains untested. Available data, along with the compelling evidence of similar auditory processes among all mammals, enables some reasonable extrapolations across species for estimating auditory effects, including the exposure levels of probable onset of injury. Recent evidence suggests that exposure of beaked whales to underwater noise may, under certain (generally unknown) conditions, result in non-auditory injury as well (e.g., Fernández et al., 2005). At present, however, there are insufficient data to allow formulation of quantitative criteria for non-auditory injuries.

There are many more published accounts of behavioral responses to noise by marine mammals than of direct auditory or physiological effects. Nevertheless, the available data on behavioral responses do not converge on specific exposure conditions resulting in particular reactions, nor do they point to a common behavioral mechanism. Even data obtained with substantial controls, precision, and standardized metrics indicate high variance both in behavioral responses and in exposure conditions required to elicit a given response. It is clear that behavioral responses are strongly

affected by the context of exposure and by the animal's experience, motivation, and conditioning. This reality, which is generally consistent with patterns of behavior in other mammals (including humans), hampered our efforts to formulate broadly applicable behavioral response criteria for marine mammals based on exposure level alone.

Frequency-Weighting Functions

In humans, hearing processes in a large number of male and female subjects of different ages have been tested to determine a basic audiometric curve, equal-loudness curve, and the levels and exposure durations needed to induce either recoverable hearing loss (called temporary threshold shift or TTS) or permanent threshold shift (PTS). In addition, the manner in which successive exposures to noise contribute to TTS growth has been well-documented in humans (e.g., Kryter, 1994; Ward, 1997). In assessing the effects of noise on humans, either an A- or C-weighted curve is applied to correct the sound-level measurement for the frequency-dependent hearing function of humans. Early on, the panel recognized that similar, frequency-weighted hearing curves were needed for marine mammals; otherwise, extremely low- and high-frequency sound sources that are detected poorly, if at all, might be subject to unrealistic criteria.

One of the major accomplishments in this effort was the derivation of recommended frequency-weighting functions for use in assessing the effects of relatively intense sounds on hearing in some marine mammal groups. It is abundantly clear from measurements of marine mammal hearing in the laboratory, call characteristics, and auditory morphology that there are major differences in auditory capabilities across marine mammal species (e.g., Wartzok & Ketten, 1999). Most previous assessments of acoustic effects either failed to account for differences in functional hearing bandwidth among marine mammal groups or did not recognize that the "nominal" audiogram might be a relatively poor predictor of how the auditory system responds to relatively strong exposures.

The authors delineated five groups of marine mammals based on similarities in their hearing, and they developed a generalized frequency-weighting (called "M-weighting") function for each. The five groups and the associated designators are (1) mysticetes (baleen whales), designated as "low-frequency" cetaceans (M_{lf}); (2) some odontocetes (toothed whales), designated as "mid-frequency" cetaceans (M_{mf}); (3) odontocetes specialized for using high frequencies (i.e., porpoises, river dolphins, and the genera *Kogia* and *Cephalorhynchus*) (M_{hf}); (4) pinnipeds (i.e., seals, sea lions, and walruses) listening in water (M_{pw});

and (5) pinnipeds listening in air (M_{pa}). These criteria do not specifically address sirenians, the sea otter, or the polar bear, in part because of the lack of key data in these species.

The M-weighting functions were defined based on known or estimated auditory sensitivity at different frequencies rather than vocal characteristics per se. Owing to the paucity of relevant data, these auditory functions are intentionally precautionary (wide) and likely overestimate the functional bandwidth for most or all species. Their primary application is in predicting auditory damage rather than levels of detection or behavioral response. Consequently, it is more appropriate to use "flatter" functions than would be obtained by employing a simple inverse-audiogram function.

Exposure Criteria Metrics

To further complicate the derivation of noise exposure criteria, sounds can be described with various acoustic metrics, including sound pressure levels and sound exposure levels. The latter is a measure of received sound energy. Available literature provides a mixture of both measures, but many sound sources have primarily been described in pressure level units. To accommodate these two measures, and to account for all relevant acoustic features that may affect marine mammals, we developed dual criteria for noise exposures in each of the five functional hearing groups, using both sound pressure and sound exposure levels.

Exposure Criteria for Injury

Another area in which we provide substantive conclusions is in the determination of sound exposures believed to cause direct auditory injury to marine mammals. By all accounts, the inner ear is the organ system most directly sensitive to sound exposure and, thus, the most susceptible to sound-derived damage. We define the minimum exposure criterion for injury as the level at which a single exposure is estimated to cause onset of permanent hearing loss (PTS). Data on TTS in marine mammals, and on patterns of TTS growth and its relation to PTS in other mammals, were used to estimate thresholds for injury. Owing to the limited availability of relevant data on TTS and PTS, the extrapolation procedures underlying these estimations are necessarily precautionary.

To account for all of the potentially injurious aspects of exposure, dual criteria for injury were established for each functional marine mammal hearing group based on instantaneous peak pressure (unweighted) and total energy (M-weighted). Exposure criteria for injury are given for two types of sounds, pulse and nonpulse, and for single and multiple exposures. The term *pulse* is used here to describe brief, broadband, atonal, transients (ANSI,

1986; Harris, 1998, Chapter 12), which are characterized by a relatively rapid rise-time to maximum pressure followed by a decay that may include a period of diminishing and oscillating maximal and minimal pressures. Examples of pulses are sounds from explosions, gunshots, sonic booms, seismic airgun pulses, and pile driving strikes. Nonpulse (intermittent or continuous) sounds can be tonal, broadband, or both. They may be of short duration but without the essential properties of pulses (e.g., rapid rise-time). Examples of anthropogenic, oceanic sources producing such sounds include vessels, aircraft, machinery operations such as drilling or wind turbines, and many active sonar systems. As a result of propagation, sounds with the characteristics of a pulse at the source may lose pulsatile characteristics at some (variable) distance and can be characterized as a nonpulse by certain receivers.

Regardless of the anthropogenic sound, if a marine mammal's received exposures exceed the relevant (pulse or nonpulse) criterion, auditory injury (PTS) is assumed to be likely. Chapter 3, "Criteria for Injury," provides details regarding the exposure levels required to cause TTS-onset and the extrapolation of those results to estimate levels above which PTS-onset may occur. For all five functional hearing groups, we propose dual exposure criteria above which auditory injury is likely.

Exposure Criteria for Behavior

One challenge in developing behavioral criteria is to distinguish a significant behavioral response from an insignificant, momentary alteration in behavior. For example, the startle response to a brief, transient event is unlikely to persist long enough to constitute significant disturbance. Even strong behavioral responses to single pulses, other than those that may secondarily result in injury or death (e.g., stampeding), are expected to dissipate rapidly enough as to have limited long-term consequence. Consequently, upon exposure to a single pulse, the onset of significant behavioral disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e., TTS-onset). We recognize that this is not a behavioral effect *per se*, but we use this auditory effect as a *de facto* behavioral threshold until better measures are identified. Lesser exposures to a single pulse are not expected to cause significant disturbance, whereas any compromise, even temporarily, to hearing functions has the potential to affect vital rates through altered behavior.

For other anthropogenic sound types (multiple pulses, nonpulses), we conducted an extensive review of the available literature but were unable

to derive explicit and broadly applicable numerical threshold values for delineating behavioral disturbance. We did develop a quantitative scoring paradigm that numerically ranks, as a severity scaling, behavioral responses observed in either field or laboratory conditions. We applied this approach to the appropriate behavioral data for multiple pulses and nonpulses. Some of these data suffer from poor statistical power, limited information on received sound levels and background noise, insufficient measurements of all potentially important contextual variables, and/or insufficient controls. Some such data are analyzed here solely for illustrative purposes. Most behavioral studies suffered from at least some of these problems. Therefore, we do not intend to give uniform scientific credence to all of the cited data, and we expect future studies to give greater attention and rigor to these critical requirements.

This review and scoring process, while not a formal meta-analysis for normalizing and pooling disparate observations, corroborated certain interesting aspects of marine mammal behavioral responses to sound exposure. Foremost was that a behavioral response is determined not only by simple acoustic metrics, such as received level (RL), but also by contextual variables (e.g., laboratory vs field conditions, animal activity at the time of exposure, habituation/sensitization to the sound, etc.). Also important is the presence or absence of acoustic similarities between the anthropogenic sound and biologically relevant natural signals in the animal's environment (e.g., calls of conspecifics, predators, prey). Within certain similar conditions, there appears to be some relationship between the exposure RL and the magnitude of behavioral response. However, in many cases, such relationships clearly do not exist, at least when response data are pooled across multiple species and contexts. This argues for a context-based approach to deriving noise exposure criteria for behavioral responses. That concept, along with our review and scaling of the available observational data, provides a foundation for establishing dose-response relationships for some specific circumstances and a starting point for future analyses when additional data are available.

Conclusions and Research Recommendations

This process has resulted in several significant advances. These include a review and interpretation of the available literature on injury and behavioral data using precautionary extrapolation procedures, derivation of marine mammal frequency-weighting functions, specification of quantitative criteria for auditory injury, and derivation of a "severity scale" for behavioral responses.

The inability to identify broadly applicable, quantitative criteria for behavioral disturbance in response to multiple-pulse and nonpulse sounds is an acknowledged limitation.

Our efforts to derive marine mammal noise exposure criteria clearly illustrate the fact that, at present, research in this field remains limited in many areas. The need for extrapolation procedures and precautionary assumptions points directly to research needs in a variety of areas on a variety of species. In certain conditions, proposed criteria for an entire marine mammal group are based on the most precautionary measurement or observation for a species within that group, despite the fact that, for other species within that group, there are empirical data indicating that higher exposures are required to induce the same effect. We believe it is appropriate to use the most precautionary data in proposing group-wide criteria applicable for species where there are no direct measurements. We also feel it is appropriate on a case-by-case basis to apply the most relevant empirical data (i.e., from the species or genus of concern) in setting the exposure thresholds specified in policy guidelines.

Finally, we emphasize that exposure criteria for single individuals and relatively short-term (not chronic) exposure events, as discussed here, are insufficient to describe the cumulative and ecosystem-level effects likely to result from repeated and/or sustained human input of sound into the marine environment and from potential interactions with other stressors. Also, the injury criteria proposed here do not appear to predict what may have been indirect injury from acoustic exposure in several cases where cetaceans of several species mass-stranded following exposure to military sonar.

The extensive research recommendations given here (see Chapter 5) represent our collective view of the concerted effort that will be required over the coming decades. High priority categories of research include (1) continued expansion of knowledge on basic marine mammal hearing capabilities, including sound localization, the detection of realistic sound signals, communication masking, and auditory "scene analysis"; (2) continued expansion of knowledge on baseline marine mammal behavioral patterns; (3) well-controlled, direct measurements (using appropriate, standardized acoustic metrics) of the effects of sound exposure on marine mammal hearing, behavior, and physiology; and (4) risk-assessment studies of the cumulative and synergistic effects of noise and other exposure(s) on individuals and populations.

Understanding and managing the effects of noise on marine life without unjustifiably

constraining important human activities in the oceans will continue to be challenging for the foreseeable future. With sustained and focused research in key areas, future scientists will be equipped to make informed improvements to the initial scientific recommendations presented here. These improvements should ideally be integrated into science-based risk assessment models that consider all aspects of sound exposure and other potential stressors on individual marine mammals, populations, and marine ecosystems.

1. Introduction

Objectives

Recent interest and concern about the effects of anthropogenic noise on marine mammals has triggered considerable new research (e.g., Costa et al., 2003; Fristrup et al., 2003; Finneran et al., 2005a), summaries of available information (Richardson et al., 1995; Wartzok & Ketten, 1999), and recommendations for specific action (NRC, 1994, 2000, 2003, 2005). Systematic, objective, science-based interpretation of the available data is critically needed to inform management agencies charged with mitigating adverse effects of anthropogenic noise on protected species. In response to this need, we use here the full body of scientific data on marine mammal hearing and the effects of noise on hearing and behavior, augmented where appropriate by interpretations of terrestrial mammal (including human) data, to develop proposed exposure criteria that are as comprehensive, defensible, and precise as is currently possible. The scope of these criteria includes injurious and behavioral effects of a single noise exposure event on an individual cetacean (whales, dolphins, and porpoises) or pinniped (seals, sea lions, and walrus).

The recommended noise exposure criteria are science-based, developed without addressing the commercial, societal, or practical ramifications of implementing the conclusions reached here. We intend to mirror the process used in the development of damage risk criteria for humans (see Crocker, 1997). Policy "guidelines" developed for regulatory and societal purposes are based both on scientific evidence (as summarized in this paper for marine mammals) and on other considerations (e.g., economic, practical, social, and ethical) not dealt with here. Thus, on certain points, policy guidelines that are developed separately for the purposes of various jurisdictions, nations, or users of these criteria may differ from the science-based criteria recommended here.

All forms of anthropogenic noise received by marine mammals were considered, whether produced under water or in air, and we adopted a comparative approach, which we regard as essential to any criteria-setting process for nonhuman animals. For most of the ~128 marine mammal species and subspecies (Rice, 1998) considered here, no empirical data were available on nominal hearing characteristics or on the effects of noise on hearing or behavior. Practical, ethical, and

legal considerations limit the level of scientific information that is available for deriving criteria applicable to either humans or marine mammals. Consequently, certain assumptions and criteria proposed here were based on information from other mammalian groups, where justified. Where such data present a variety of options, we made intentionally precautionary decisions (i.e., lower proposed exposure levels) to reduce the risk of assuming no effect when one was actually present. The term "precautionary" is used here without reference to any regulatory or policy implication of this word. Scientists would more conventionally use the term "conservative" in this regard rather than the more bureaucratic "precautionary," but in certain complex instances here, the term "conservative" would be potentially ambiguous, depending on the perspective of the reader. When information was limited, extrapolations were made cautiously to minimize the risk of failing to recognize an effect when one actually occurs (Type-II statistical error) as can occur with small sample sizes or imprecise measurements.

Each generalization/extrapolation was identified, all precautionary decisions were noted, and the logic leading to each proposed criterion was specified. Thus, when new data become available, appropriate modifications can be made readily. Studies that are needed to resolve the uncertainties encountered in developing the current criteria are discussed in detail (see Chapter 5, "Research Recommendations"). Realistically, however, the generalization of information between related species will remain essential in many cases for the foreseeable future.

Our intent was to derive recommended noise exposure criteria using the best information currently available, identify weaknesses in the present approach, call for relevant research, and structure the criteria such that future improvements can be incorporated easily. Lack of data limited the proposed noise exposure criteria to individual marine mammals exposed to acute exposure events (such as the passage of one vessel or a series of active sonar transmissions). Also, the proposed criteria are limited to cetaceans and pinnipeds. We expect that noise exposure criteria for other marine mammals (manatees, dugongs, polar bears, and sea otters), as well as other marine taxa, will be developed as additional data become available and are evaluated. In fact, a separate expert panel (S3/

WG92: "Effects of Sound on Fish and Turtles") has been established under the Standards Committee (S3) of the Acoustical Society of America to consider noise exposure criteria for fish and turtles. Additionally, criteria are clearly needed for cumulative effects and for effects at species or even ecosystem levels, but data to support those types of criteria do not currently exist.

The present recommended criteria represent a major step in initiating a lengthy, systematic process to predict and identify acoustic exposure conditions (natural or anthropogenic) associated with various effects on marine mammals. This paper is deliberately structured in a somewhat formulaic and report-like manner so that the logic underlying certain assumptions and extrapolations (as well as the data needed to test and/or strengthen them) is self-evident. We expect there will be an iterative process of improving and expanding the complexity of the exposure criteria, similar to the decades-long development of human noise exposure criteria (see Crocker, 1997). Because of the matrix structure of the proposed criteria, thresholds in specific cells can be updated independently as new information becomes available.

There is an extensive history and diversity of exposure criteria for humans with various kinds of acoustic exposure. A full discussion of these criteria is beyond the scope of this paper, but examples include workplace noise standards (e.g., NIOSH, 1998), standards for the protection of military personnel (U.S. DoD, 1997), and national policy guidelines (e.g., EPA, 1974; BG PPG, 1994). Several additional examples were also considered, whether received under water or in air, in various decisions underlying the marine mammal criteria proposed here. The process of establishing human noise exposure criteria has been difficult and contentious, but establishing noise exposure criteria for marine mammals is considerably more daunting given the diversity of marine mammal species across three orders, the complexity of aerial and underwater acoustic exposures, and profound data limitations.

Historical Perspective

Concerns about potential adverse effects of anthropogenic noise on marine life began in the 1970s (e.g., Payne & Webb, 1971) and expanded in the 1980s. Experiments during the 1980s with seismic airguns indicated that bowhead whales (*Balaena mysticetus*) and gray whales (*Eschrichtius robustus*) exhibited clear, sustained avoidance of operational areas at distances where pulse root-mean-square (RMS) sound pressure levels (SPLs) were 160 to 170 dB re: 1 μ Pa (Malme et al., 1983, 1984, 1986, 1988; Richardson et al., 1986; Ljungblad

et al., 1988). In contrast, early observations of bowhead and gray whales exposed to continuous industrial sounds, such as those associated with drilling operations, suggested 120 dB re: 1 μ Pa as the approximate threshold for behavioral disturbance of these baleen whales (Malme et al., 1984; Richardson et al., 1990a, 1995 [pp. 286-287]). Significant individual variability was noted in "typical" behavioral responses, however, with some individual whales responding only when very close to sound sources and others reacting at much longer distances (and to lower received sound levels). This variability raises questions as to whether behavioral responses are most appropriately described by the exposure received level (RL) of the stimulus at the animal, the signal-to-ambient noise differential, the rate of change of the signal, or simply to the presence of the human activity as indicated by acoustic cues and/or visual stimuli.

Concern about the effects of acoustic pulses from seismic exploration and continuous sound from other industrial activities resulted in the imposition of mitigation requirements on some industrial activities in certain jurisdictions by the early- to mid-1980s. Subsequent events, such as the Heard Island Feasibility Test in 1991 (Baggeroer & Munk, 1992), the Acoustic Thermometry of Ocean Climate (ATOC) program in the late-1990s (see NRC, 1994, 2000; Au et al., 1997; Costa et al., 2003), and the U.S. Navy's low-frequency active sonar program (e.g., Croll et al., 2001) resulted in popular and governmental interest in setting criteria for safe levels of sound for marine mammal exposure (NRC, 1994, 2000, 2003; Richardson et al., 1995). This interest has expanded with the finding that tactical, mid-frequency, military sonar transmissions are sometimes correlated, in specific conditions, with mass stranding events of (predominantly) several beaked whale species, including Cuvier's (*Ziphius cavirostris*), Blainville's (*Mesoplodon densirostris*), and Gervais' (*Mesoplodon europaes*) beaked whales (see Evans & England, 2001; Fernández et al., 2005; Cox et al., 2006).

In 1995, the U.S. National Marine Fisheries Service (NMFS) set underwater "do not exceed" criteria for exposure of marine mammals to underwater pulses from seismic airguns. These criteria were 190 dB re: 1 μ Pa for pinnipeds and most odontocete cetaceans and 180 dB re: 1 μ Pa for mysticetes and sperm whales (*Physeter macrocephalus*) (and, by inference, for pygmy and dwarf sperm whales [*Kogia* spp.]). These exposure limits were intended as precautionary estimates of exposures below which physical injury would not occur in these taxa. There was no empirical evidence as to whether exposure to higher levels of

pulsed sounds would or would not cause auditory or other injuries. Given the limited data then available, however, it could not be guaranteed that marine mammals exposed to higher levels would not be injured. Further, it was recognized that behavioral disturbance could, and in some cases likely would, occur at lower RLs.

In June 1997, the High Energy Seismic Survey (HESS) team (1999, Appendix 5) convened a panel of experts to assess noise exposure criteria for marine mammals exposed to seismic pulses. The consensus was that, given the best available data at that time, exposure to airgun pulses with RLs above 180 dB re: 1 μ Pa (averaged over the pulse duration) was “likely to have the potential to cause serious behavioral, physiological, and hearing effects.” The panel noted the potential for \pm 10 dB variability around the 180 dB re: 1 μ Pa level, depending on species, and that more information was needed.

The NMFS has continued to use a “do not exceed” exposure criterion of 180 dB re: 1 μ Pa for mysticetes and (recently) all odontocetes exposed to sequences of pulsed sounds, and a 190 dB re: 1 μ Pa criterion for pinnipeds exposed to such sounds. Higher thresholds have been used in the U.S. for single pulses such as explosions used in naval vessel-shock trials. Behavioral disturbance criteria for pulsed sounds have typically been set at an SPL value of 160 dB re: 1 μ Pa, based mainly on the earlier observations of mysticetes reacting to airgun pulses (e.g., Malme et al., 1983, 1984; Richardson et al., 1986). The relevance of the 160 dB re: 1 μ Pa disturbance criterion for odontocetes and pinnipeds exposed to pulsed sounds is not at all well-established, however. Although these criteria have been applied in various regulatory actions (principally in the U.S.) for more than a decade, they remain controversial, have not been applied consistently in the U.S., and have not been widely accepted elsewhere.

More recently, a considerable body of data has accumulated on the levels at which transient and more prolonged sounds cause the onset of temporary threshold shift (TTS) and various behavioral reactions. Some of these data are not consistent with the aforementioned *de facto* criteria used in recent years in the United States.

One main purpose of this paper is to synthesize and apply all available information to derive proposed objective noise exposure criteria for a large subset of marine mammals. The effect levels considered (injury and significant behavioral disturbance) were generally consistent with the definitions of levels A and B harassment, respectively, of the U.S. Marine Mammal Protection Act (MMPA) of 1972 (16 USC, § 1361); however, many of the behaviors considered at the lower end

of our severity scaling paradigm would almost certainly not constitute biologically significant disturbance (or consequently level B harassment under the MMPA). However, our exposure criteria were derived without regard for policy decisions of the U.S. or any nation and should therefore not be assumed to correspond with regulatory categories or definitions of effects. Since harassment definitions under the MMPA are not uniform for all human activities and are subject to change, additional interpretation of the information presented would be required to evaluate effects with regard to this (or any other) statute.

Acoustic Measures and Terminology

This section briefly considers those acoustic measures and terminology that are directly relevant to these marine mammal exposure criteria. More detailed descriptions of some of the terms given in this and other sections, including equations relevant to many of the definitions, are given in Appendix A. Basic acoustic terminology is presented in numerous other sources (e.g., Kinsler et al., 1982; ANSI, 1986, 1994; Richardson et al., 1995; Harris, 1998; NRC, 2003).

Sound is appropriately described as having two components: (1) a pressure component and (2) a particle motion component. Particle motion—the oscillatory displacement, velocity, or acceleration of the actual “particles” of the medium at a particular location—is directional and best described by a 3-dimensional vector. Marine mammal sensitivity to particle motion is poorly understood, but it appears to be functionally limited (Finneran et al., 2002a) in contrast to the sensory capabilities of most or all fish (see Popper et al., 2003). Conversely, as compared to fish, marine mammals generally have greater sensitivity to sound pressure (lower detection thresholds) and much wider functional hearing bandwidths (see Fay, 1988; Richardson et al., 1995; Popper et al., 2003). Consequently, in considering the potential effects of sound on marine mammals, particle motion is rarely discussed. Except for special circumstances (e.g., plane and spherical waves), there is no simple relationship between pressure and particle velocity. The vast majority of studies of hearing in captive marine mammals have been conducted in relatively small enclosed volumes of water, making the plane wave assumption (and *a priori* knowledge of the relationship between pressure and velocity) invalid.

It is important to distinguish between the *source level* (SL), or level measured 1 m from the source, vs the *received level* (RL), which is the level measured at the receiver (usually a marine mammal herein).

The term “intensity” is often used generally with respect to subjective acoustic parameters (i.e., loudness), but it is used here in a strict sense. Sound intensity is normally defined as the time-averaged active intensity (Kinsler et al., 1982; Fahy, 1995); this quantity corresponds to local net transport of sound energy and is related to the product of the sound pressure and the particle velocity component in-phase with the sound pressure. In the majority of laboratory studies, complex sound fields typically create complex, spatially varying relationships between pressure and velocity. In these circumstances, sound intensity cannot be estimated from pressure measurements alone (which assume that pressure and particle velocity are in-phase), and specific measurements of the sound particle velocity (or pressure gradient) are required in order to characterize intensity.

We distinguished two basic sound types: (1) *pulse* and (2) *nonpulse*. Our operational definitions of sound types are given in Chapter 2, “Structure of the Noise Exposure Criteria,” and are discussed at greater length in Appendix A. The pulse/nonpulse distinction is important because pulses generally have a different potential to cause physical effects, particularly on hearing (e.g., Ward, 1997).

Peak sound pressure (P_{\max}) is the maximum absolute value of the instantaneous sound pressure during a specified time interval and is denoted in units of Pascals (Pa). It is in no sense an averaged pressure. Peak pressure is a useful metric for either pulse or nonpulse sounds, but it is particularly important for characterizing pulses (ANSI, 1986; Harris, 1998, Chapter 12). Peak-to-peak sound pressure is the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure. The mean-squared pressure is the average of the squared pressure over some duration. Sound pressure levels are given as the decibel (dB) measures of the pressure metrics defined above. The RMS SPL is given as dB re: 1 μPa for underwater sound and dB re: 20 μPa for aerial sound. Peak sound pressure levels are denoted hereafter as dB re: 1 μPa (peak) in water and dB re: 20 μPa (peak) in air. Peak-to-peak sound pressure levels are dB re: 1 μPa (peak-to-peak) in water and dB re: 20 μPa (peak-to-peak) in air.

Duration is the length of a sound in seconds. Duration is important because it affects other sound measures, specifically mean-square and/or RMS sound pressure (Madsen, 2005). Because of background noise and reverberation, duration can be difficult to specify precisely, but a functional definition (see Appendix A) is used here.

Sound exposure level (SEL) is a measure of energy. Specifically, it is the dB level of the

time integral of the squared-instantaneous sound pressure normalized to a 1-s period. It can be an extremely useful metric for assessing cumulative exposure because it enables sounds of differing duration, sometimes involving multiple exposures, to be compared in terms of total energy. Several methods exist for summing energy over multiple exposures to generate a single exposure “equivalent” value. The relatively straightforward approach used here is described in Appendix A (eq. 5). This summation procedure essentially generates a single exposure “equivalent” value that assumes no recovery of hearing between repeated exposures. As discussed below, recovery functions for marine mammal TTS during and following multiple exposures are still unknown; however, considering nominal TTS recovery functions in terrestrial mammals when exposures occur minutes to hours apart (see Kryter, 1994; Ward, 1997), the above summation procedure would likely overestimate the effect of multiple exposures in many conditions. This summation procedure was intentionally selected as a precautionary measure in the absence of empirical information, although note the temporal conditions given in the “Sound Types” section of Chapter 2. The appropriate units are dB re: 1 $\mu\text{Pa}^2\text{-s}$ for underwater SEL and dB re: $(20 \mu\text{Pa})^2\text{-s}$ for aerial SEL.

Frequency-selective weighting is often employed to measure (as a single number) sound pressure or energy in a specific frequency band of sound, with emphasis or de-emphasis on particular frequencies as a function of the relative sensitivity of a receiver. For aerial hearing in humans, A-weighting is derived from the inverse of the idealized 40-phon equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz (Harris, 1998). This provides level measures denoted as dB(A). C-weighting is determined from the inverse of the idealized 100-phon equal loudness hearing function (which differs in several regards from the 40-phon function), standardized to 0 dB at 1 kHz (Harris, 1998). This provides level measures denoted as dB(C). In the absence of equal-loudness contours for marine mammals, special frequency-weighting functions based loosely on human C-weighting and general knowledge of functional hearing bandwidth were developed here for functional marine mammal hearing groups (see the “Marine Mammal Functional Hearing Groups” section of Chapter 2).

Other measures of noise interference with critical functions in humans, including the Articulation Index (French & Steinberg, 1947) and the more recent Speech Interference Level (see Beranek & Ver, 1992), focused on the perception of speech and effects of noise. Consequently, exposure criteria geared toward speech perception (e.g., Beranek, 1989) focus on a frequency

bandwidth narrower than the audible bandwidth. For a detailed discussion of speech intelligibility and noise impacts, see Chapter 6 in Kryter (1994). It is clear that the perception of conspecific vocal signals in marine mammals is critically important in various life history functions (discussed below; see Wartzok & Ketten, 1999) and that interference with these functions may have particularly negative consequences.

The hypothesis that vocalizations coincide with the range of hearing is based on an adaptive argument that vocal energy should be selected to lie within the range of hearing for maximum efficiency of communication. However, several lines of evidence suggest that other adaptive pressures may shape the vocal range. First, vocal anatomy may produce energy at other frequencies as a byproduct of producing sound within the hearing range. If there is no pressure to eliminate these frequencies, they can be expected to persist. An example is the ultrasonic components of hummingbird song, which lie well outside the range of bird hearing (Pytte et al., 2004). Second, to promote long-range transmission, the vocal range may be adapted to produce greater energy at the low end of the range than would be expected based on the auditory threshold function (Larom et al., 1997). Greater relative energy at low frequencies is also seen in a number of primate species as a byproduct of producing the formant structure of their calls (Fitch & Hauser, 1995). Finally, animals may produce sounds with disproportionate low-frequency information to signal greater size, potentially targeting predators rather than conspecifics (Fitch, 1999; Matrosova et al., 2007). Thus, a number of selective forces can drive the development of an emphasis on low-frequency energy in vocalizations not matched by the shape of the auditory threshold function. While vocal range can be expected to correlate with hearing range to some degree, giving a rough indication of the frequency range of hearing, it cannot be used to estimate either the shape of the auditory threshold function or to assign upper and lower frequency limits.

We lack sufficient empirical data on whether vocal frequency range sufficiently predicts all frequencies that are biologically significant, however.

Certain marine mammal responses to anthropogenic sounds, such as the sometimes strong reactions by beaked whales to mid-frequency sonar, would not be expected if only sounds within the bandwidth of vocal output were important in predicting a behavioral response. Hence, our precautionary frequency-weighting approach assumes that the full audible band is relevant. As additional data become available on both hearing capabilities (specifically, equal-loudness contours)

and behavioral responses to natural (including conspecific) and anthropogenic sounds, a more refined means of frequency-weighting than the intentionally precautionary (broad) M-weighting functions may be recommended.

Kurtosis is a statistical measure of a probability distribution often applied to describe the shape of the amplitude distribution (Hamernik & Hsueh, 1991; Lei et al., 1994; Hamernik et al., 2003). In some regards, it appears to be a highly relevant metric in that impulsive sound with high negative kurtosis, rapid onset, and high instantaneous peak-pressure may be particularly injurious to some mammals (Hamernik et al., 2003).

Sound Production and Use in Marine Mammals

As a general statement, all studied marine mammals can produce sounds in various important contexts. They use sound in social interactions as well as to forage, to orient, and to respond to predators. Interference with these functions, through the various effects of noise on hearing and/or behavior identified below, thus has the potential to interfere with vital rates identified by the NRC (2005) as particularly significant effects of exposure.

The noise exposure criteria given here are focused on current knowledge of hearing and the effects of noise on hearing and/or behavior in marine mammals. Thus, a detailed discussion and review of the expansive literature on the production and the uses of sound is beyond the scope of this paper; interested readers are referred to the many reviews of marine mammal acoustic signals (e.g., Schusterman, 1981; Watkins & Wartzok, 1985; Au, 1993; Richardson et al., 1995; Wartzok & Ketten, 1999; Clark & Ellison, 2004). Because of the extreme importance of detecting conspecific social signals in marine mammal life history functions, however, a brief and very general discussion of sound output characteristics in the major marine mammal groups is given here.

The large whales (mysticete cetaceans, as described below) generally produce low-frequency sounds in the tens of Hz to the several kHz band, with a few signals extending above 10 kHz. These sounds appear to serve predominantly social functions, including reproduction and maintaining contact, but they may also play some role in spatial orientation.

The dolphins and porpoises (odontocete cetaceans, also described below) produce sounds across some of the widest frequency bands that have been observed in animals. Their social sounds are generally in the range audible to humans, from a few hundreds of Hz to several tens of kHz, but specialized clicks used in biosonar (echolocation)

systems for prey detection and navigation extend well above 100 kHz.

Pinnipeds (seals, sea lions, and walrus) also produce a diversity of sounds, though generally over a lower and more restricted bandwidth (generally from 100 Hz to several tens of kHz). Their sounds are used primarily in critical social and reproductive interactions. Pinnipeds spend time both at sea and on land, however, and thus produce sounds in both water and air.

Because sound production in marine mammals is integral to so many important behaviors, interference with these communicative functions is considered to be particularly adverse (see severity scaling described in Chapter 4, "Criteria for Behavioral Disturbance"). As discussed in Chapter 5, considerable additional research is needed to identify conditions in which anthropogenic noise exposure interferes with acoustic communication as well as ways in which marine mammals cope with masking noise to overcome interference in detecting real-world signals in complex, 3-dimensional marine environments.

Responses to Sound

Animals exposed to either natural or anthropogenic sound may experience physical and psychological effects, ranging in magnitude from none to severe. This brief discussion considers the range of potential impacts, which depend on spatial relationships between a sound source and the animal receiver; sensitivity of the receiver; received exposure level, duration, and duty cycle; and many other factors (see also Richardson et al., 1995).

The same acoustic source may have radically different effects depending on operational and environmental variables, and on the physiological, sensory, and psychological characteristics of exposed animals. It is important to note that these animal variables may differ (greatly in some cases) among individuals of a species and even within individuals depending on various factors (e.g., sex, age, previous history of exposure, season, and animal activity). Responses elicited can depend both on the context (feeding, mating, migrating, etc.) in which an individual is ensounded and on a host of experiential variables (see Wartzok et al., 2004). Consequently, certain effects may be poorly described with simple measures such as SPL alone, and may only be predictable when additional variables are considered. We considered all known factors in developing the noise exposure criteria proposed here, but data limitations precluded the derivation of explicit exposure criteria for all of the effects discussed below.

Audibility

When a sound can be perceived amidst background noise, it is considered to be audible. Audibility can differ from detectability in that a receiving system may detect a signal at some level even when it is incapable of meaningful perception. Audibility is determined by the characteristics of received sound, characteristics of the receiving system, and background noise conditions (either external or internal). Audition (hearing) is a well-developed and primary sensory modality for most, if not all, marine vertebrates (Schusterman, 1981; Tyack, 1998; Fay & Popper, 2000). It involves coding, processing, integrating, and responding to sound in a variety of ways, some not outwardly evident (Yost, 2000). Like other animals, marine mammals have multiple sound-reception pathways and rely on signal processing at multiple levels integrated within the cochlea and nervous system to optimize perception.

Marine mammal hearing capabilities are quantified in live subjects using behavioral audiometry and/or electrophysiological techniques (e.g., Schusterman, 1981; Au, 1993; Kastak & Schusterman, 1998; Wartzok & Ketten, 1999; Nachtigall et al., 2000, 2007; Finneran & Houser, 2006; André & Nachtigall, 2007; Supin & Popov, 2007). For species not studied with *in vivo* audiometry, some auditory characteristics can be estimated based on sound production frequencies; on observations of sound characteristics that either do or do not elicit behavioral responses in untrained animals (e.g., Richardson et al., 1995; Erbe, 2002); or on auditory morphology, including biomechanical properties of the basilar membrane and other characteristics (Wartzok & Ketten, 1999).

Behavioral audiograms are obtained from captive, trained animals using standard psychometric testing procedures. With appropriate controls and sufficient training, behavioral data are presently considered to most accurately represent hearing capabilities of a test subject. Behavioral audiometric studies are time-consuming, however, and the results depend on the training and attention of subjects as well as the background noise conditions in captive settings. Because marine mammals are large and difficult to maintain, behavioral audiograms representing an entire species are typically based on a few individuals (often one animal). Additionally, subjects are generally obtained opportunistically (e.g., individuals rehabilitated after stranding) rather than by random sampling of individuals from wild populations. This may provide a somewhat biased representation of "normal" hearing for the species if rehabilitated animals have compromised hearing capabilities (see André et al., 2007). Individual differences in hearing sensitivity among subjects,

and methodological differences among investigators, can lead to improper conclusions when nominal species audiograms are based on data from a single animal (e.g., compare Hall & Johnson, 1972, with Szymanski et al., 1999). Hearing sensitivity has been measured using behavioral methods in fewer than 20 of the ~128 cetacean and pinniped species (based on the taxonomy of Rice, 1998).

Electrophysiological audiometry involves measuring small electrical voltages (auditory evoked potentials [AEPs]) produced by neural activity when the auditory system is stimulated by sound. With this technique, neural responses are typically averaged while many relatively short duration signals are presented. This technique is comparatively fast and less sensitive to factors such as subject experience and reproductive, behavioral, or motivational states that affect behavioral audiometry. Whereas behavioral audiograms can only be made with trained, captive animals, AEP measures of sound detection can also be made with untrained individuals that are stranded, temporarily restrained, or in rehabilitation (see Cook et al., 2006; André et al., 2007; Delory et al., 2007; Taylor et al., 2007).

AEP and behavioral techniques measure different features of the auditory system and may generate somewhat different measured results. Relevant comparisons of AEP and behavioral audiograms are limited and are the subject of ongoing scientific investigation. Besides the need to obtain both types of data on the same individuals, there are complications due to differences in the types of test stimuli used by different researchers, problems in estimating the true RL at the relevant sensory organ(s), and the difficulty of determining absolute signal amplitudes that barely elicit neural responses. Even so, Yuen et al. (2005), Finneran et al. (2007b), and Schlundt et al. (2007) demonstrated that, with carefully calibrated and repeated measurements, the two procedures can produce comparable detection thresholds in at least a few cetacean species.

An auditory threshold, estimated by either behavioral or electrophysiological responses, is the level of the quietest sound audible in a specified percent of trials. An auditory threshold is not an invariant critical value above which a sound is always heard and below which it is never heard. Instead, it is a sound level at which there is an explicit signal detection probability (often 50%; determined *a priori*). This probability depends on a number of intrinsic factors (Green & Swets, 1974; Egan, 1975; McMillan & Creelman, 1991). In all species tested thus far, the hearing response in relation to frequency is a generally U-shaped curve with a frequency range of best sensitivity

(lowest hearing thresholds) and frequencies both below and above this range where sensitivity is relatively poor (higher threshold values). Species differ in absolute sensitivity and functional frequency bandwidth (see Fay, 1988; Richardson et al., 1995), such that identical sounds may be perceived radically differently by individuals of different species. Individual differences within species have also been demonstrated in some terrestrial species (see Fay, 1988) and, to a lesser extent, in marine mammals as well (see Houser & Finneran, 2006b, for the most definitive example of this). Sounds whose levels barely exceed background noise levels may be detectable but may or may not elicit changes in individual behavior. Ideally, “absolute” or unmasked hearing thresholds should be measured in low background noise conditions such as anechoic testing enclosures. While this is standard practice in human audiometry, very few of the marine mammal hearing data obtained to date have been measured in such conditions. Limited recent data obtained with pinnipeds tested in a hemi-anechoic testing chamber in air (described in Kastak et al., 2005) suggest that masking from environmental noise in testing enclosures may have significantly affected measurements of “absolute” hearing; thresholds in a harbor seal (*Phoca vitulina*) were in fact ≥ 30 dB lower in very low background noise conditions (Holt et al., 2001).

While the above concepts and studies are essential in understanding general hearing capabilities (e.g., functional bandwidth, range of best hearing sensitivity) of marine mammals, animals in the “real world” rarely listen for simple acoustic signals from point sources and do not live in a noise-controlled environment. Rather, they are presented with spatially complex and time-varying streams of acoustic information in often noisy environments. Measurements using simple sound stimuli have indicated that marine mammals are generally quite adept at localizing acoustic sources in laboratory conditions (Møhl, 1964; Gentry, 1967; Terhune, 1974; Moore & Au, 1975; Renaud & Popper, 1975; Holt et al., 2004, 2005). Many of the behavioral observations discussed in Chapter 4 (and in Appendices B & C) indicated relatively precise orientation behaviors to sound sources (or sound localization) in the field as well. Limited laboratory data are also available regarding how marine mammals detect relatively simple stimuli over background masking noise (discussed below). A more complex perceptual matter related to localization and detection over masking noise is the manner in which vertebrates process complex information to perceive the acoustic (or auditory) scene—that is, gain useful information from

the suite of sounds around them in the real world (e.g., Fay & Popper, 2000).

Bregman (1990) considered how the human auditory system constructs a perceptual acoustic image of the surrounding environment and events occurring in that environment. He posits that, as in visual perception, hearing systems are organized in such a manner that related acoustic events (such as the frequency structure of a harmonic signal or a repeated signal from the same source in a 3-dimensional space) are grouped perceptually in a meaningful way. According to the process of *auditory scene analysis*, the auditory system sorts-out related elements of a complex natural acoustic environment into those arising from different sound sources. Furthermore, previous experience can have powerful effects on the processing and interpretation of sounds. This too is similar to psychological processes underlying visual perception in which the range to an object may be inferred from knowledge of an object's general size and physical appearance.

Presuming such capabilities occur in marine vertebrates, which is logical given the importance of sound to marine mammals, it seems likely that they could perceive range and the general nature (e.g., movement) of sound sources. *Acoustic stream segregation*, the identification of relatively simple stimuli from different, overlapping patterns, has been demonstrated in several bird and bat species (MacDougall-Shackleton et al., 1998; Moss & Surlykke, 2001). Neither acoustic stream segregation nor auditory scene analysis has yet been investigated in marine mammals (but see Madsen et al., 2005a). Each of these processes, along with more data on sound localization, may be relevant in the continued development of appropriate marine mammal noise exposure criteria (see the "Marine Mammal Functional Hearing Groups" section of Chapter 5, for research recommendations).

Auditory Masking

Noise may partially or entirely reduce the audibility of signals, a process known as *auditory masking*. The extent of interference depends on the spectral, temporal, and spatial relationships between signals and masking noise, in addition to other factors. Human auditory systems perform frequency-based assessment (similar to Fourier analysis) on incoming signals such that, for most exposure levels, significant masking of tonal signals is almost exclusively by noise in a narrow band (called the critical band) of similar frequencies (Wegel & Lane, 1924; Fletcher, 1940; Greenwood, 1961). With increasing masker level, however, there is an asymmetrical spread in the masking effect such that detection of frequencies

above those of the masking stimulus is more significantly impeded (see Buus, 1997; Yost, 2000).

Because of common biomechanical cochlear properties across taxa (Echteler et al., 1994), masking is expected to follow similar principles in other mammals (including marine mammals). The structure and function of the outer and middle ear differ profoundly between terrestrial and marine mammals (Wartzok & Ketten, 1999); however, the characteristics of auditory masking are strikingly similar among nonspecialized mammals in general (Fay, 1988; Echteler et al., 1994), including marine mammals tested in air and in water (Turnbull & Terhune, 1990; Southall et al., 2000, 2003). Similarities in morphology and mammalian cochlear functional dynamics (as revealed by masking studies) suggest that auditory data from terrestrial mammals may be reliably used in some situations where marine mammal data are lacking. Data on auditory masking in marine mammals are not presented in detail here because they are not directly used in formulating the recommended noise exposure criteria (but see Southall et al., 2000, 2003, for reviews).

Auditory Threshold Shift

Animals exposed to sufficiently intense sound exhibit an increased hearing threshold (i.e., poorer sensitivity) for some period of time following exposure; this is called a *noise-induced threshold shift* (TS). Factors that influence the amount of TS include the amplitude, duration, frequency content, temporal pattern, and energy distribution of noise exposure. The magnitude of TS normally decreases over time following cessation of the noise exposure. The amount of TS just after exposure is called the initial TS.

If TS eventually returns to zero (i.e., the threshold returns to the pre-exposure value), it is called TTS. The following physiological mechanisms are thought to play some role in inducing TTS, also referred to as auditory fatigue: effects on sensory hair cells in the inner ear that reduce their sensitivity, modification of the chemical environment within sensory cells, residual middle-ear muscular activity, displacement of certain inner ear membranes, increased blood flow, and post-stimulatory reduction in both efferent and sensory neural output (Kryter, 1994; Ward, 1997). Where these effects result in TTS rather than a permanent change in hearing sensitivity, they are within the nominal bounds of physiological variability and tolerance and do not represent physical injury (Ward, 1997). Recovery of nominal hearing function may occur quickly, and the amount of TTS measured depends on the time elapsed since the cessation of noise exposure; subscripts are used to indicate the time in minutes after exposure. For

example, TTS₂ means TTS measured 2 min after exposure cessation.

If TS does not return to zero after a relatively long interval (on the order of weeks), the residual TS is called a noise-induced permanent threshold shift (PTS). The distinction between PTS and TTS depends on whether there is a complete recovery of TS following noise exposure. PTS is considered to be auditory injury. Some of the apparent causes of PTS in mammals are severe extensions of effects underlying TTS (e.g., irreparable damage to the sensory hair cells). Others involve different mechanisms, such as exceeding the elastic limits of certain tissues and membranes in the middle and inner ears and resultant changes in the chemical composition of inner ear fluids (Ward, 1997; Yost, 2000). The relationship between TTS and PTS depends on a highly complex suite of variables concerning the study subject and the exposure. This relationship remains poorly understood, even for humans and small terrestrial mammals in which this topic has been investigated intensively (see Kryter, 1994; Yost, 2000).

In addition to the potential for discrete, intense sounds to result in TTS or PTS, chronic sound exposure, common in industrialized societies, can result in noise-induced PTS in humans as they age (see Kryter, 1994). Reduced hearing sensitivity as a simple function of development and aging (*presbycusis*) has been demonstrated in both children (Roche et al., 1978) and adults (e.g., Brant & Fozard, 1990). In the long-term, noise-induced hearing loss and *presbycusis* appear to result in a progressive PTS that is a complex, nonlinear process and particularly affects high-frequency hearing. Limited research in cetaceans and pinnipeds has revealed patterns of *presbycusis* that are similar to those observed in humans (Ridgway & Carder, 1997; Brill et al., 2001; Schusterman et al., 2002; Houser & Finneran, 2006b; Reichmuth et al., 2007), further underscoring certain general similarities in auditory processes across mammals.

PTS and TTS data from humans and non-human terrestrial mammals were used to develop safe exposure guidelines for human work environments (e.g., NIOSH, 1998). For marine mammals, recent data are available regarding sounds that cause modest TTS (generally < 20 dB decrease in sensitivity) in a few species of odontocetes and pinnipeds. No data exist on exposures that would cause PTS in these taxa, however (see Chapter 2 for detailed discussions). Consequently, the only current option for estimating exposure conditions that would cause PTS-onset in marine mammals is to use the available marine mammal TTS data combined with data from terrestrial mammals on TTS growth rates with increasing acoustic

exposure (see the “Criteria for Injury: TTS and PTS” section of Chapter 3).

Behavioral Reactions to Sound

Behavioral responses to sound are highly variable and context-specific (see Wartzok et al., 2004, for a discussion). Some sounds that are audible to animals may elicit no overt behavioral response. This is most common when the sound does not greatly exceed the minimum detectable level and is not increasing or fluctuating (Richardson et al., 1995). Inability to detect an overt response does not necessarily mean that there is no subtle behavioral (or other) effect, however.

When observable reactions do occur, they may include orientation or attraction to a sound source; increased alertness; modification of characteristics of their own sounds; cessation of feeding or social interaction; alteration of movement/diving behavior; temporary or permanent habitat abandonment; and, in severe cases, panic, flight, stampede, or stranding, sometimes resulting in injury or death (e.g., Richardson et al., 1995; Evans & England, 2001; Gordon et al., 2004; Scheifele et al., 2005; Cox et al., 2006; Nowacek et al., 2007). Minor or temporary behavioral effects are often simply evidence that an animal has heard a sound and may not indicate lasting consequence for exposed individuals. For the purposes of setting criteria, the effects of greatest concern are those that may negatively impact reproduction or survival. Ultimately, it is the biological relevance of the reaction in terms of vital parameters that must be determined. In proposing noise exposure criteria, one must clearly and explicitly differentiate trivial effects from those with the potential to affect vital rates. However, it has proven to be exceedingly challenging to distinguish among and rank the various effects and to establish a generally accepted definition of biologically meaningful behavioral disturbance (see NRC, 2005).

Except for naïve individuals, behavioral responses depend critically on the principles of *habituation* and *sensitization*. An animal's exposure history with a particular sound affects whether it is subsequently less likely (*habituation*) or more likely (*sensitization*) to respond to a stimulus such as sound exposure. The processes of habituation and sensitization do not necessarily require an association with a particular adverse or benign outcome. Rather, individuals may be innately predisposed to respond to certain stimuli in certain ways. These responses may interact with the processes of habituation and sensitization for subsequent exposure. Where associative learning occurs, individuals link a particular exposure with a known outcome (positive, negative, or neutral) and use that information in guiding

future decisions on whether and how to respond to similar stimuli. The relationship between these two categories of learning (non-associative and associative) can be highly complex, particularly for experienced individuals (see Deecke et al., 2002).

Many contextual variables may be powerful contributors to an animal's perception of and reaction to the acoustic scene. These include the perception of source proximity (nearness), relative movement (encroachment or retreat), and general novelty or familiarity, all of which may affect the type and magnitude of the resulting behavioral response(s). In terms of proximity, the presence of high-frequency components in a sound and the lack of reverberation, both of which are indicative of proximity, may be more relevant acoustic cues of spatial relationship than simply exposure level alone (see P. Miller, 2002). If a source is perceived to be approaching, the response is often stronger. In addition, the activity of the individual and its fidelity to a current location often affect the response.

Thus, in addition to source characteristics, other factors that may be critical in determining behavioral effects include past experience, situational variables, receiver auditory systems, and the extent to which the sound resembles familiar benign or noxious stimuli (e.g., Irvine et al., 1981; NRC, 2005). Animals that fail to exhibit general avoidance when exposed to a certain sound source may still detect the sound but are either habituated to exposure or may display less dramatic behavioral responses (e.g., altering vocal behavior, modifying orientation/movement patterns).

The magnitude of a given behavioral response may not be a direct function of exposure levels or even of the animal's experiential history. If the sound triggers an anti-predator response in the subject (e.g., Irvine et al., 1981; Finley et al., 1990), the response magnitude may reflect the individual's underlying physiological condition, the relative costs in fitness of failing to respond, the availability of alternative refuges, and other factors specific to predator defense (Gill & Sutherland, 2000; Frid & Dill, 2002; Beale & Monaghan, 2004).

For all these reasons, behavioral responses to anthropogenic sounds are highly variable. Meaningful interpretation of behavioral response data (and biologically relevant conservation decisions) must consider not only the relative magnitude and apparent severity of behavioral reactions to human disturbance but also the relevant acoustic, contextual, and ecological variables. In many cases, specific acoustic features of the sound and contextual variables (e.g., proximity, subject experience and motivation, duration, or

recurrence of exposure) may be of considerably greater relevance to the behavioral response than simple acoustic variables such as exposure RL. For example, if an anthropogenic sound is perceived as indicating the presence of a predator, it is likely to trigger a strong defensive reaction at relatively low RLs. On the other hand, sounds that resemble conspecific signals may be ignored or induce approach or avoidance, depending upon the context. Further, typically neutral sounds may cause increasing annoyance reactions (such as avoidance) as a function of exposure level. This makes it difficult or impossible to justify basing broad, objective determinations of impact thresholds on RL alone. This is the primary reason why this paper does not propose explicit behavioral disturbance criteria levels for certain sound types. Rather, we collated available data relating acoustic exposure to the severity of observed behavioral response in a form that allows a variety of relationships to be estimated (Chapter 4). When research allows the separation of annoyance from cases where an animal interprets sounds as signals from predators, prey, or conspecifics, it may become possible to classify signals and predict responses more precisely.

Non-Auditory Effects

The auditory system appears to include the organs most susceptible to noise exposure, at least in humans (e.g., Ward, 1997). The limited data on captive marine mammals exposed to various kinds of noise support a similar conclusion, suggesting that TTS-onset occurs at levels which may be below those required for direct non-auditory physiological trauma (but see discussion of deep-diving species below). Noise exposure does have the potential to induce a range of direct or indirect physiological effects on non-auditory structures. These may interact with or cause certain behavioral or auditory effects, or they may occur entirely in the absence of those effects.

Noise exposure may affect the vestibular and neurosensory systems. For instance, in humans, dizziness and vertigo can result from exposure to high levels of noise, a condition known as *nystagmus* (see Oosterveld et al., 1982; Ward, 1997; Halmagyi et al., 2005). Little is known about vestibular functions in marine mammals. There are significant differences in vestibular structures in some marine mammal species compared to most land mammals (Wartzok & Ketten, 1998; Ketten, 2000). In cetaceans in particular, the vestibular components are sufficiently reduced and have such low neural representation that the principal function may be essentially to provide limited gravitational and linear acceleration cues. Pinnipeds by contrast have a well-developed,

more conventional vestibular apparatus that likely provides multiple sensory cues similar to those of most land mammals. Both pinnipeds and cetaceans retain the direct coupling through the vestibule of the vestibular and auditory systems; therefore, it is possible, albeit not known, that marine mammals may be subject to noise-induced effects on vestibular function as has been shown in land mammals and humans. Responses to underwater sound exposures in human divers and other immersed land mammals suggest that vestibular effects are produced from intense underwater sound at some lower frequencies (Steevens et al., 1997). Theoretical effects on the human vestibular system as well as other organs (e.g., lungs) from underwater sound exposures also have been explored through models (Cudahy & Ellison, 2002); however, there are no comparable measurements or models for marine mammals at this point from which to estimate such effects. Data are clearly needed for all major marine mammal taxa to more fully assess potential impacts on non-auditory systems.

Relatively low-level physiological responses include changes in cardiac rate (*bradycardia* or *tachycardia*) and respiratory patterns, which may lead to changes in metabolism. Stress reactions in humans and other vertebrates include various physiological changes to pulmonary, cardiac, metabolic, neuro-endocrine, immune, and reproductive functions (e.g., Hales, 1973; Lee, 1992; Vrijkotte et al., 2000). Studies of noise-induced stress in marine mammals are very limited, but endocrine secretions of glucocorticoids and altered cardiovascular function have been documented in odontocetes exposed to high-level sound (Romano et al., 2004; cf. Thomas et al., 1990c). Noise exposure also often leads to changes in surfacing-respiration-dive cycles of cetaceans (e.g., Richardson & Malme, 1993), which may have various physiological effects. Assuming that effects in marine and terrestrial mammals are similar, intermediate physiological responses to stressors (including noise) may accompany avoidance or aggressive behaviors and include single auditory startle responses, the initiation and sustenance of the catecholamine response, and physiological preparation for fight or flight. The most severe physiological responses would include multiple or repeated auditory startle responses, triggering of the hypothalamic-pituitary-adrenal (HPA) axis and associated elevated blood glucocorticoid level, substantially altered metabolism or energy reserves, lowered immune response, diminished reproductive effort, and potential tissue trauma (e.g., Sapolsky et al., 2000). [The issue of stress responses to noise exposure has been discussed recently by Wright et al. (in press).]

Sound at certain frequencies can cause an air-filled space to vibrate at its resonant frequency (acoustic resonance), which may increase the likelihood of mechanical trauma in the adjacent or surrounding tissue. The resonant frequencies of most marine mammal lungs are below the operating frequencies of many anthropogenic sound sources (Finneran, 2003). Further, biological tissues are heavily damped, estimated tissue displacement at resonant frequencies is predicted to be exceedingly small, and lung tissue damage is generally uncommon in acoustic-related marine mammal stranding events. For these reasons, specialists do not regard lung resonance as a likely significant non-auditory effect for marine mammals exposed to anthropogenic noise sources that operate above 100 Hz (U.S. Department of Commerce, 2002). This conclusion might not apply to lower-frequency sources that operate at a particular frequency for a significant duration.

The non-auditory effect now being most actively discussed in marine mammalogy is nitrogen gas bubble growth, resulting in effects similar to decompression sickness in humans. Jepson et al. (2003) and Fernández et al. (2004, 2005) hypothesized that lesions (gas and fat emboli) observed in individual beaked whales found stranded after military sonar exercises were somehow caused by *in vivo* nitrogen bubble formation. Osteonecrosis in sperm whales has further been suggested as a chronic result of nitrogen bubble formation (Moore & Early, 2004).

To date, the gas bubble hypothesis remains untested, and the acoustic causative mechanism for formation of emboli, if any, is unknown. Theoretically, bubble precursors in supersaturated, homogenized tissue may incrementally enlarge during the successive passage of compression and rarefaction portions of acoustic waves that exceed static pressure (rectified diffusion; Crum & Mao, 1996). Alternatively, a single acoustic exposure could activate bubble precursors, allowing them to grow by gradual expansion into bubbles in nitrogen-supersaturated tissue (static diffusion; see Potter, 2004). The diving patterns of some marine mammals increase gas-tissue saturation and potentially could increase the susceptibility of noise-exposed animals to bubble growth via either mechanism (Ridgway & Howard, 1979; Houser et al., 2001b). Nitrogen supersaturation levels for deep-diving species of interest, including beaked whales, are based on theoretical models, however (Houser et al., 2001b). No unequivocal support for either pathway presently exists.

The evidence for bubble formation as a causal mechanism between certain types of acoustic exposure and stranding events remains equivocal. At a minimum, scientific disagreement and/or

complete lack of information exists regarding the following important points: (1) received acoustic exposure conditions for animals involved in stranding events; (2) pathological interpretation of observed lesions in stranded marine mammals (Fernández et al., 2004; Piantadosi & Thalmann, 2004); (3) acoustic exposure conditions required to induce such physiological trauma directly; (4) whether noise exposure may cause behavioral reactions (e.g., atypical diving behavior) that secondarily induce bubble formation and tissue damage (Jepson et al., 2003; Fernández et al., 2005; Zimmer & Tyack, 2007); and (5) the extent that *post mortem* artifacts introduced by decomposition before sampling, handling, freezing, or necropsy procedures affect interpretation of observed lesions. Tests of the gas bubble hypothesis may yield data pertinent to future marine mammal noise exposure criteria, but too little is currently known to establish explicit exposure criteria for this proposed mechanism.



Courtesy: A. Friedlander

2. Structure of the Noise Exposure Criteria

When *de facto* noise exposure guidelines are used by management agencies, they generally are based on a small number of categories of marine mammals and sound types. Though it would be convenient to have a single exposure criterion for all species and sound sources, such a simplified approach is not supported by available science. However, some categorization of species and sources is warranted based on current information. The many anthropogenic sound sources used in marine environments can be categorized based on certain acoustic and operational features. Similarly, there is great diversity in hearing and in the biological effects of noise among marine mammals, but current knowledge supports some functional and/or phylogenetic groupings.

It is also neither possible nor desirable to derive distinct exposure criteria for every species and sound source. Important generalizations across taxa would be missed even if resources and time were adequate to study each species and exposure condition. Further, it is impractical to apply numerous, species-specific criteria when predicting and/or attempting to mitigate effects.

A standard scientific approach in such situations is to categorize animals based on functional characteristics and sound sources based on physical similarities, and to summarize the information in a matrix format. We subdivide cetaceans and pinnipeds into five functional hearing categories based on the frequencies they hear. Other methods of categorization are, of course, possible. For instance, Verboom (2002) relied heavily on direct measurements of noise impacts on hearing to quantify the effects of noise exposure on marine mammals. Some of his proposed criteria are comparable with those presented here. The present effort makes broader use of laboratory and field behavioral and audiometric data, additional recent data, and extrapolations from terrestrial mammals not used by Verboom. We divide sound sources into three types according to acoustic characteristics defined at the source. Note that at a distance, a sound may have significantly different features; categorizing sounds based on source characteristics is a precautionary and pragmatic approach (as is described in the next section). The justifications for and assumptions underlying our categorization of functional hearing groups and sound types are described here. The number of subdivisions in future noise exposure criteria will likely increase as more supporting data are acquired.

The format of the recommended marine mammal noise exposure criteria is thus a matrix of 15 “cells” that systematically considers three sound types (see next section) and five functional marine mammal hearing groups (see the “Marine Mammal Functional Hearing Groups” section of this chapter). Within each of those 15 cells, we consider two general acoustic metrics (see the “Exposure Criteria Metrics” section) and two levels of exposure effect (“Levels of Noise Effect: Injury and Behavioral Disturbance” section of this chapter). Sixty possible criteria result (i.e., 3 sound types \times 5 marine mammal groups \times 2 metrics \times 2 impact levels), although fewer than 60 are reported due to data limitations. Whereas sound types are defined by source features, criteria values represent levels received by individual marine mammals.

Sound Types

Three sound types are used: (1) a single pulse, (2) multiple pulses, and (3) nonpulses. The separation between pulses and nonpulses is supported by data on auditory fatigue and acoustic trauma in terrestrial mammals (e.g., Dunn et al., 1991; Hamernik et al., 1993) and is generally consistent with the sound types distinguished for damage risk criteria in humans (e.g., U.S. DoD, 1997; NIOSH, 1998).

Pulses and nonpulses are distinguished by numerous definitions and mathematical distinctions (e.g., Burdic, 1984). The empirical distinction used here is based on a measurement procedure using several temporal weightings. Various exponential time-weighting functions applied in measuring pulse and nonpulse sounds may yield different measured received levels (RLs) (see Harris, 1998). Most sound level meters (SLM) provide options for applying either a “slow” or “fast” time constant (1,000 or 125 ms, respectively) for measuring nonpulses or an impulse time constant (35 ms) appropriate for measuring pulses. For a sound pulse, the slow or fast SLM settings result in lower sound pressure level (SPL) measurements than those obtained using the impulse setting. Each of these time constants is selected based on properties of the human auditory system. These may be at least generally relevant for other mammalian auditory systems, although further empirical data on temporal resolution in marine mammals are needed (see Chapter 5, “Research Recommendations”).

Harris (1998) proposed a measurement-based distinction of pulses and nonpulses that is adopted here in defining sound types. Specifically, a ≥ 3 -dB difference in measurements between continuous and impulse SLM settings indicates that a sound is a pulse; a < 3 -dB difference indicates that a sound is a nonpulse. We note the interim nature of this distinction for underwater signals and the need for an explicit distinction and measurement standard such as exists for aerial signals (ANSI, 1986).

Harris's (1998) definitions assumed use of A-weighting as do most human-oriented definitions of acoustical measurements; however, different frequency-weighting functions should be used for various animal taxa (as discussed below). Leaving that question aside temporarily, it is instructive to compare the impulse equivalent-continuous sound level (L_{leqT}) for a sound that increases in level with the corresponding equivalent-continuous level (L_{eqT}). Here, L_{leqT} has an impulse integration time of 35 ms and L_{eqT} , defined as sound exposure divided by T, is expressed as a level. As an example, suppose that a source is examined over a 2-s period ($T = 2$ s). The highest L_{ALeq2s} ("A" here denotes A-weighting) during this period is 75.2 dB, and the highest L_{ALeq2s} is 65.1 dB. The difference of 10.1 dB is greater than the 3-dB criterion given by Harris (1998); therefore, the sound is considered to be a pulse.

The distinction between pulses and nonpulses is not always clear in practice. For instance, certain signals (e.g., acoustic deterrent and harassment devices) have characteristics of both pulses and nonpulses. Also, certain sound sources (e.g., seismic airguns and pile driving) may produce pulses at the source but, through various propagation effects, may meet the nonpulse definition at greater distances (e.g., Greene & Richardson, 1988). This means that a given sound source might be subject to different exposure criteria, depending on the distance to the receiver and intervening propagation variables. While this is certainly realistic for many real-world exposures, measurements at the animal are often not practical. Changes in sound characteristics with distance generally result in exposures becoming less physiologically damaging with increasing distance because sharp transient peaks become less prominent. Therefore, these criteria use a precautionary approach and classify sound types based on acoustic characteristics at the source. Additional empirical measurements are needed to advance our understanding of sound type classification as a function of source, range, and environmental variables. We emphasize that the use of source parameters to classify sound types does not negate our decision to recommend exposure criterion levels relative to RLs at the animal.

Treating pulses and nonpulses as discrete sound types is justified by data on mammals in general and several cetacean species in particular (Dunn et al., 1991; Hamernik et al., 1993; also see the "Effects of Noise on Hearing in Marine Mammals TTS Data" section in Chapter 3). Mammalian hearing is most readily damaged by transient sounds with rapid rise-time, high peak pressures, and sustained duration relative to rise-time (for humans: Thiery & Meyer-Bisch, 1988; for chinchillas [*Chinchilla lanigera*], Dunn et al., 1991). Consistent with these results, those odontocetes tested thus far have been shown to experience TTS-onset at lower respective exposure levels if the sound is a pulse rather than a nonpulse (Finneran et al., 2002b, 2005a).

Mammals are also apparently at greater risk from rapidly repeated transients and those with high impulse amplitude *kurtosis* (Erdreich, 1986). Hamernik et al. (1993, 2003) argued that the distinction between exposures with relatively high and low "peakedness" is to some extent an oversimplification. Highly variable threshold shifts can result from exposures of variable peakedness but comparable overall levels, depending on a host of factors. Hamernik et al. (1993, 2003) also noted that peak pressure levels sufficient to exceed mechanical limits of the cochlea, and thus more likely to induce acoustic trauma, tend to be more typical of pulses than nonpulses.

The present criteria also categorize sound types based on repetition. For mammals, single and multiple noise exposures at various levels and durations generally differ in their potential to induce auditory fatigue or trauma. This results principally from the temporal interaction between exposure and recovery periods (e.g., Kryter, 1994) and differences in received total acoustic energy. Further, multiple exposures may increase the likelihood of behavioral responses because of increased probability of detection and the (generally) greater biological significance of continued exposure as opposed to a single, transient event (although see discussion of habituation in the "Responses to Sound" section of Chapter 1).

Single exposures are considered here as discrete acoustic events in which received sound levels exceed ambient noise in at least some portion of the frequency band of functional marine mammal hearing once in a 24-h period; multi-path receptions of a single exposure are not considered multiple exposures. Multiple exposures are considered to be acoustic events causing RLs to exceed ambient noise within the functional bandwidth more than once, with an intervening quiet period not exceeding 24 h. If the exposure event is interrupted, even briefly (other than as a result of the animal's own action—e.g., breaching), it is considered a multiple exposure.

Exposures should be categorized as either pulsed or nonpulsed sounds as described above. Single and multiple exposures to either pulse or nonpulse sounds (or both) are possible. Examples of single pulses and single nonpulses are sounds from a single firing of an airgun or a single vessel passage, respectively.

Multiple pulse or multiple nonpulse sounds are more difficult to delineate, given the diversity and complexity of sound sources. A series exclusively consisting of two or more nonpulses would clearly be a multiple nonpulse exposure (e.g., multiple vessel passages). A multiple pulse exposure would similarly be described as a series exclusively containing pulses (e.g., repeated pile strikes) or a combination of pulses and nonpulses (e.g., the combined vessel noise and airgun transmissions of a seismic vessel). One justification for treating combined pulses and nonpulses as pulses is that the proposed exposure criteria for injury are more precautionary (lower) in the case of pulses than for nonpulses. Specific consideration should be given, on a case-by-case basis, as to whether such a distinction would necessarily be the more precautionary. For instance, if a compound exposure included relatively high-level nonpulses as well as relatively low-level pulses, the more appropriate and protective distinction might be to classify it as a nonpulse exposure.

The proposed exposure criteria for injury from single and multiple exposures to both sound types are numerically identical (Chapter 3). This is another precautionary decision, arising from the fact that no marine mammal data were available regarding the effects of inter-exposure interval on recovery from auditory effects (e.g., TTS). A summation procedure is applied to quantify the fatiguing effects of multiple exposures with an equivalent SEL value (Chapter 1; also Appendix A, eq. 5). The SEL metric takes account of the pressure waveform and duration of either single or multiple sound events; it represents cumulative received energy. This approach effectively

negates the need for numerically different injury criteria for single and multiple exposures at the expense of neglecting assumed, but as-yet poorly understood recovery phenomena during intervals between exposures. This is a precautionary approach, pending availability of data on acoustic recovery by marine mammals during intervals between exposures.

When considering behavioral responses, single and multiple nonpulse exposures are considered as a single category. Insufficient information exists to assess the use of SEL as a relevant metric in the context of marine mammal behavioral disturbance for anything other than a single pulse exposure. Future noise exposure criteria for behavioral disturbance may distinguish SPL and SEL exposure criteria for additional conditions, but for most sound types (the exception being single pulses), the available data are best assessed in relation to SPL (discussed in detail in Chapter 4). Consequently, the structure of the exposure criteria matrix includes a categorical distinction between single and multiple pulses given that numerical SEL thresholds are recommended for a single pulse, but not for multiple pulses. No such distinction is made for nonpulses where the available data do not (at least currently) support differential behavioral criteria for single vs multiple exposures.

Thus, the current state of scientific knowledge regarding mammalian hearing and various noise impacts supports three distinct sound types as relevant for marine mammal noise exposure criteria: (1) single pulse, (2) multiple pulses, and (3) nonpulses. Examples of sound sources belonging in each of these categories (based on characteristics of the sound emitted at the source) are given in Table 1. A simplistic measurement procedure using source characteristics (the 3-dB distinction based on Harris, 1998, described above) is used here to distinguish a pulse from a nonpulse, while the simple definitions above distinguish single and multiple exposures.

Table 1. Sound types, acoustic characteristics, and selected examples of anthropogenic sound sources; note sound types are based on characteristics measured at the source. In certain conditions, sounds classified as pulses at the source may lack these characteristics for distant receivers.

| Sound type | Acoustic characteristics (at source) | Examples |
|-----------------|--|--|
| Single pulse | Single acoustic event; > 3-dB difference between received level using impulse vs equivalent continuous time constant | Single explosion; sonic boom; single airgun, watergun, pile strike, or sparker pulse; single ping of certain sonars, depth sounders, and pingers |
| Multiple pulses | Multiple discrete acoustic events within 24 h; > 3-dB difference between received level using impulse vs equivalent continuous time constant | Serial explosions; sequential airgun, watergun, pile strikes, or sparker pulses; certain active sonar (IMAPS); some depth sounder signals |
| Nonpulses | Single or multiple discrete acoustic events within 24 h; < 3-dB difference between received level using impulse vs equivalent continuous time constant | Vessel/aircraft passes; drilling; many construction or other industrial operations; certain sonar systems (LFA, tactical mid-frequency); acoustic harassment/deterrent devices; acoustic tomography sources (ATOC); some depth sounder signals |

Marine Mammal Functional Hearing Groups

Species of cetaceans and pinnipeds were assigned to one of five functional hearing groups based on behavioral psychophysics, evoked potential audiometry, auditory morphology, and (for pinnipeds) the medium in which they listen. Cetaceans and pinnipeds are broadly separable based on phylogenetic and functional differences (Reynolds & Rommel, 1999). Cetaceans were further subdivided according to differences in their measured or estimated hearing characteristics and not necessarily according to their phylogeny (as in Wartzok & Ketten, 1999). Pinnipeds are considered a single group, but as amphibious mammals, their hearing differs in air and in water (Kastak & Schusterman, 1998); separate criteria were required for each medium. The taxa in each functional hearing group (based on Rice, 1998) are given in Table 2.

Marine Mammal Hearing

All marine mammals evolved from terrestrial, air-adapted ancestors (Domning et al., 1982; Barnes et al., 1985) and, at least in part, retain the nominal mammalian tripartite peripheral auditory system

(i.e., external auditory meatus, air-filled middle ear, and spiral-shaped cochlea). Most of the mechanisms of mammalian hearing are also conserved such as the basic lever structure of the ossicles and the tonotopic organization of the hair cells along the inner ear's basilar membrane.

However, marine mammal auditory systems differ in having some adaptations that seem to be related to pressure, hydrodynamics, and sound reception in water (see Wartzok & Ketten, 1999). For instance, the pinna has been reduced or eliminated in most species, owing to hydrodynamic adaptations. Tissue modifications may enable the reduction or elimination of gas spaces in the middle ear of some marine mammals. Consequently, bone conduction, rather than the conventional ossicular chain, may be an additional (or primary) sound transmission path to the cochlea (e.g., Repenning, 1972; Au, 1993). There are important differences in these adaptations within and between marine mammal taxa.

Knowledge of marine mammal hearing varies widely among groups, but for most species it is quite limited compared to knowledge of terrestrial mammal hearing. Because of the sheer size, limited and disproportionate availability in captive

Table 2. Functional marine mammal hearing groups, auditory bandwidth (estimated lower to upper frequency hearing cut-off), genera represented in each group, and group-specific (M) frequency-weightings

| Functional hearing group | Estimated auditory bandwidth | Genera represented (Number species/subspecies) | Frequency-weighting network |
|--------------------------|------------------------------|--|---|
| Low-frequency cetaceans | 7 Hz to 22 kHz | <i>Balaena</i> , <i>Caperea</i> , <i>Eschrichtius</i> , <i>Megaptera</i> , <i>Balaenoptera</i> (13 species/subspecies) | M _{lf} (lf: low-frequency cetacean) |
| Mid-frequency cetaceans | 150 Hz to 160 kHz | <i>Steno</i> , <i>Sousa</i> , <i>Sotalia</i> , <i>Tursiops</i> , <i>Stenella</i> , <i>Delphinus</i> , <i>Lagenodelphis</i> , <i>Lagenorhynchus</i> , <i>Lissodelphis</i> , <i>Grampus</i> , <i>Peponocephala</i> , <i>Feresa</i> , <i>Pseudorca</i> , <i>Orcinus</i> , <i>Globicephala</i> , <i>Orcaella</i> , <i>Physeter</i> , <i>Delphinapterus</i> , <i>Monodon</i> , <i>Ziphius</i> , <i>Berardius</i> , <i>Tasmacetus</i> , <i>Hyperoodon</i> , <i>Mesoplodon</i> (57 species/subspecies) | M _{mf} (mf: mid-frequency cetaceans) |
| High-frequency cetaceans | 200 Hz to 180 kHz | <i>Phocoena</i> , <i>Neophocaena</i> , <i>Phocoenoides</i> , <i>Platanista</i> , <i>Inia</i> , <i>Kogia</i> , <i>Lipotes</i> , <i>Pontoporia</i> , <i>Cephalorhynchus</i> (20 species/subspecies) | M _{hf} (hf: high-frequency cetaceans) |
| Pinnipeds in water | 75 Hz to 75 kHz | <i>Arctocephalus</i> , <i>Callorhinus</i> , <i>Zalophus</i> , <i>Eumetopias</i> , <i>Neophoca</i> , <i>Phocarcos</i> , <i>Otaria</i> , <i>Erignathus</i> , <i>Phoca</i> , <i>Pusa</i> , <i>Halichoerus</i> , <i>Histriophoca</i> , <i>Pagophilus</i> , <i>Cystophora</i> , <i>Monachus</i> , <i>Mirounga</i> , <i>Leptonychotes</i> , <i>Ommatophoca</i> , <i>Lobodon</i> , <i>Hydrurga</i> , and <i>Odobenus</i> (41 species/subspecies) | M _{pw} (pw: pinnipeds in water) |
| Pinnipeds in air | 75 Hz to 30 kHz | Same species as pinnipeds in water (41 species/subspecies) | M _{pa} (pa: pinnipeds in air) |

settings, and, for many species and jurisdictions, the protected status of marine mammals, there are limitations in obtaining hearing data for many species. Behavioral or electrophysiological audiograms exist for fewer than 20 marine mammal species (of ~128 species and subspecies; Rice, 1998). By combining these data with comparative anatomy, modeling, and response measured in ear tissues from species that are difficult to study, however, it is possible to describe the frequency sensitivity and critical adaptations for underwater hearing in each of the five functional hearing groups of marine mammals considered here.

Low-frequency cetaceans consist of 13 species and subspecies of mysticete (baleen) whales in five genera (based on Rice, 1998; see Table 2). No direct measurements of hearing exist for these animals, and theories regarding their sensory capabilities are consequently speculative (for a detailed assessment by species using the limited available information, see Erbe, 2002). They are too large to maintain in the laboratory for psychophysical testing. The limited evoked potential measurements on animals of this size have not yet yielded hearing thresholds (Ridgway & Carder, 2001), but technological advances may soon enable evoked potential audiometry on relatively small and/or young mysticetes. In these species, hearing sensitivity has been estimated from behavioral responses (or lack thereof) to sounds at various frequencies, vocalization frequencies they use most, body size, ambient noise levels at the frequencies they use most, and cochlear morphometry (Richardson et al., 1995; Wartzok & Ketten, 1999; Houser et al., 2001a; Erbe, 2002; Clark & Ellison, 2004). Until better information is available regarding the relationship between auditory sensitivity and marine environmental noise, the sensitivity of mysticetes cannot be easily inferred from the acoustic environment.

The combined information strongly suggests that mysticetes are likely most sensitive to sound from perhaps tens of Hz to ~10 kHz. However, recent data indicated that humpback whales (*Megaptera novaeangliae*) produce some signals with harmonics extending above 24 kHz (Au et al., 2006). These harmonics have considerably lower levels than occur at lower frequencies, and their presence does not necessarily indicate they are audible to the whales. Nonetheless, some high-frequency energy is present. [Additionally, some recent anatomical modeling work by Ketten et al. (2007) suggested that some mysticetes may have functional hearing capabilities at frequencies as high as 30 kHz.] While we do not include these recent results at this time, we note their presence and the possibility that the upper frequency limit of the M-weighting function

for mysticetes may need to be revisited based on emerging knowledge. At present, we estimate the lower and upper frequencies for functional hearing in mysticetes, collectively, to be 7 Hz and 22 kHz (Ketten et al., 2007).

Mid- and high-frequency cetaceans are all odontocetes (toothed whales). Unlike the mysticetes, all odontocete cetaceans appear to have highly advanced echolocation (biosonar) systems that use intermediate to very high frequencies (tens of kHz to 100+ kHz: see Au, 1993; Richardson et al., 1995; Wartzok & Ketten, 1999). They also produce social sounds in a lower-frequency band, including generally low to intermediate frequencies (1 kHz to tens of kHz). Consequently, their functional hearing would be expected to cover a wider absolute frequency range than is assumed for mysticetes or has been demonstrated for pinnipeds (discussed below). This has been experimentally confirmed in the odontocete species whose hearing has been measured (discussed below); however, their best hearing sensitivity typically occurs at or near the frequency where echolocation signals are strongest. Based on the differential characteristics of echolocation signals in two groups of odontocetes (see Au, 1993) and on the hearing data described below, odontocetes were divided into mid- and high-frequency functional groups (as seen generally in Wartzok & Ketten, 1999).

Mid-frequency cetaceans include 32 species and subspecies of “dolphins,” six species of larger toothed whales, and 19 species of beaked and bottlenose whales (see Table 2). “Functional” hearing in this group was estimated to occur over a wide range of low to very high frequencies. Based on the combined available data, mid-frequency species are estimated to have lower and upper frequency “limits” of nominal hearing at approximately 150 Hz and 160 kHz, respectively. As for the other hearing groups, there is variability within and among species, intense signals below and above the stated bounds may be weakly detectable, and there is a progressive rather than instantaneous reduction in hearing sensitivity near these limits. Mid-frequency cetaceans generally do not appear well-adapted to detect or to discriminate signals outside this frequency band, however. The scarcity (and variability) of empirical data precludes a finer subdivision of this relatively diverse and large group of marine mammals, though it is acknowledged that some mid-frequency species likely have a narrower functional hearing band than the range given above.

Behavioral hearing data are available for the following mid-frequency cetacean species: bottlenose dolphin (*Tursiops truncatus*: Johnson, 1967; Ljungblad et al., 1982; Finneran et al., 2005a), beluga (*Delphinapterus leucas*: White

et al., 1978; Awbrey et al., 1988; Johnson, 1992; Ridgway et al., 2001; Finneran et al., 2005b), killer whale (*Orcinus orca*: Hall & Johnson, 1972; Szymanski et al., 1999), false killer whale (*Pseudorca crassidens*: Thomas et al., 1988, 1990a; Au et al., 1997), Risso's dolphin (*Grampus griseus*: Nachtigall et al., 1995; Au et al., 1997); and Pacific white-sided dolphin (*Lagenorhynchus obliquidens*: Tremel et al., 1998).

Audiograms derived using auditory evoked potential (AEP) methodology (Supin et al., 2001) have been obtained for a number of cetacean species. Specific AEP techniques, which involve measuring electrophysiological responses to sound, include those measuring transient evoked responses, such as the auditory brainstem response (ABR) or mid-latency response, and those measuring steady-state evoked responses such as the envelope following response (EFR) or auditory steady-state response (ASSR). Mid-frequency cetacean species tested include the bottlenose dolphin (Bullock et al., 1968; Seeley et al., 1976; Popov & Supin, 1990; Houser & Finneran, 2006b; Finneran et al., 2007a; Hernandez et al., 2007; Popov et al., 2007), killer whale (Szymanski et al., 1999), beluga (Popov & Supin, 1990; Klishin et al., 2000), common dolphin (*Delphinus delphis*: Popov & Klishin, 1998), Risso's dolphin (Dolphin, 2000; Nachtigall et al., 2005, 2007), tucuxi dolphin (*Sotalia fluviatilis*: Popov & Supin, 1990), striped dolphin (*Stenella coeruleoalba*: Kastelein et al., 2003), Pacific white-sided dolphin (Au et al., 2007), false killer whale (Supin et al., 2003), and Gervais' beaked whale (Cook et al., 2006). Additionally, Yuen et al. (2005) conducted a comparative study of behavioral and AEP thresholds for the false killer whale, and Finneran & Houser (2006), Houser & Finneran (2006a), and Finneran et al. (2007b) have compared behavioral and AEP thresholds in multiple bottlenose dolphins.

The high-frequency cetaceans include eight species and subspecies of true porpoises, six species and subspecies of river dolphins plus the franciscana, *Kogia*, and four species of cephalorhynchids (see Table 2). "Functional" hearing in this group was estimated to occur between 200 Hz and 180 kHz. Behavioral audiograms are available for the following high-frequency cetacean species: harbor porpoise (*Phocoena phocoena*: Andersen, 1970; Kastelein et al., 2002a), Chinese river dolphin (*Lipotes vexillifer*: Wang et al., 1992), and Amazon river dolphin (*Inia geoffrensis*: Jacobs & Hall, 1972). Audiograms using AEP methodology have been obtained for three species: harbor porpoise (Popov et al., 1986, 2006; Beedholm & Miller, 2007; Lucke et al., 2007b); finless porpoise (*Neophocaena phocaenoides*: Popov

et al., 2006); and Amazon river dolphin (Popov & Supin, 1990).

The pinnipeds include 16 species and subspecies of sea lions and fur seals (otariids), 23 species and subspecies of true seals (phocids), and two subspecies of walrus (odobenids). Pinnipeds produce a wide range of social signals, most occurring at relatively low frequencies. They lack the highly-specialized active biosonar systems of odontocete cetaceans, possibly as a result of their amphibious lifestyle (see Schusterman et al., 2000). Because of this aspect of their life history, pinnipeds communicate acoustically in air and water, have significantly different hearing capabilities in the two media, and may be subject to both aerial and underwater noise exposure (Schusterman, 1981; Kastak & Schusterman, 1998, 1999). These differences necessitate separate noise exposure criteria for pinnipeds in each medium.

For pinnipeds in water, behavioral measures of hearing are available for the northern fur seal (*Callorhinus ursinus*: Moore & Schusterman, 1987; Babushina et al., 1991), California sea lion (*Zalophus californianus*: Schusterman et al., 1972; Moore & Schusterman, 1987; Kastak & Schusterman, 1998, 2002; Southall et al., 2004), northern elephant seal (*Mirounga angustirostris*: Kastak & Schusterman, 1998, 1999; Southall et al., 2004), Hawaiian monk seal (*Monachus schauinslandi*: Thomas et al., 1990b), harp seal (*Pagophilus groenlandicus*: Terhune & Ronald, 1972), ringed seal (*Phoca hispida*: Terhune & Ronald, 1975), harbor seal (Møhl, 1967, 1968; Terhune & Turnbull, 1995; Kastak & Schusterman, 1995, 1998; Southall et al., 2004), and walrus (*Odobenus rosmarus*: Kastelein et al., 2002b). Ridgway & Joyce (1975) measured the gray seal's (*Halichoerus grypus*) underwater hearing using evoked potential audiometry.

For pinnipeds in air, behavioral measures of hearing are available for the northern fur seal (Moore & Schusterman, 1987; Babushina et al., 1991), California sea lion (Schusterman, 1974; Kastak & Schusterman, 1998; Kastak et al., 2004b), northern elephant seal (Kastak & Schusterman, 1998, 1999; Kastak et al., 2004b), harp seal (Terhune & Ronald, 1971), and harbor seal (Møhl, 1968; Kastak & Schusterman, 1998; Kastak et al., 2004b). Aerial hearing in pinnipeds has also been measured using evoked potential audiometry in the gray seal (Ridgway & Joyce, 1975), California sea lion (Bullock et al., 1971; Ridgway & Joyce, 1975; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007), harbor seal (Thorson et al., 1998; Wolski et al., 2003; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007), and northern elephant seal (Houser et al., 2007; Mulsow & Reichmuth, 2007; Reichmuth et al., 2007).

The combined results of these studies indicate that pinnipeds are sensitive to a broader range of sound frequencies in water than in air. The data further suggest differences in the functional hearing range among otariids, phocids, and odobenids, especially under water (Kastak & Schusterman, 1998; Kastelein et al., 2002b). For these proposed noise exposure criteria, however, pinnipeds are considered a single functional hearing group because the data are too limited, both in terms of absolute hearing data and TTS measurements (see “The Effects of Noise on Hearing in Marine Mammals: TTS Data” section in Chapter 3), to support finer subdivisions. We estimate that pinnipeds have “functional” underwater hearing between 75 Hz and 75 kHz and “functional” aerial hearing between 75 Hz and 30 kHz. These ranges are essentially based on data for phocid seals, which have the broadest auditory bandwidths of the pinnipeds. This approach results in a precautionary functional bandwidth for estimating frequency-weighting functions (below) and noise impacts on pinnipeds.

In summary, based on current knowledge of functional hearing in marine mammals, five distinct, functional hearing categories were defined: (1) low-frequency cetaceans (i.e., mysticetes), (2) mid-frequency cetaceans (i.e., most odontocetes), (3) high-frequency cetaceans (i.e., porpoises, river dolphins, pygmy sperm whale, and *Cephalorhynchus*), (4) pinnipeds in water, and (5) pinnipeds in air. The genera in each group, and the estimated lower and upper frequency hearing “limits,” are shown in Table 2. Because the five functional hearing groups of marine mammals differ in hearing bandwidth, each may be affected differently by identical noise exposures. Therefore, frequency-weighting functions are required to develop marine mammal noise exposure criteria.

Frequency-Weighting Functions

As a general statement, animals do not hear equally well at all frequencies within their functional hearing range. Frequency weighting is a method of quantitatively compensating for the differential frequency response of sensory systems. Generalized frequency-weighting functions were derived for each functional hearing group of marine mammals using principles from human frequency-weighting paradigms, with adjustments for the different hearing bandwidths of the various marine mammal groups.

For humans, substantial improvement in dose-response models is obtained by filtering noise through equal-loudness functions, particularly the 40-phon, equal-loudness function (“A-weighting”) and the 100-phon function (“C-weighting”).

These frequency-weighting functions take into account both the frequency bandwidth of human hearing and loudness perception. For use as frequency filters, the functions are inverted; normalized to 0 dB in the frequency range of best hearing (specifically at 1,000 Hz for humans); and idealized for implementation in hearing aids, sound level meters, and other measurement devices.

At minimum, metrics used for animals should eliminate inaudible frequencies both below and above the range of functional hearing. The “absolute” auditory threshold function (audiogram) has been suggested as a frequency-weighting function for marine species exposed to underwater sound (e.g., Malme et al., 1989; Thorson et al., 1998; Heathershaw et al. 2001; Nedwell et al., 2007) as well as for terrestrial animals (Delaney et al., 1999; Bjork et al., 2000). However, the auditory threshold function does not characterize the flattening of equal-loudness perception with the increasing stimulus level that has been demonstrated in humans (Fletcher & Munson, 1933). Acoustic injury would only be expected to occur at levels far above the detection threshold—that is, levels for which the flattening effect would be expected. Consequently, it is unclear how useful or appropriate the auditory threshold function is in deriving frequency-weighting filters in marine mammals for which psychophysical equal-loudness measurements are generally unavailable (although see preliminary measurements by Ridgway & Carder, 2000). Further, the limited TTS data for cetaceans exposed to tones at different frequencies (discussed below) suggest that an audiogram-based frequency-weighting function would produce too much filtering at lower frequencies (i.e., the weighting function for hearing effects should be flatter than the inverted audiogram procedure would indicate).

Therefore, a precautionary procedure was used to derive frequency-specific, marine mammal weighting functions. Each was based on an algorithm that requires only the estimated (as ~80 dB above best hearing sensitivity) lower and upper frequencies of functional hearing as given in the above description of each marine mammal group and in Table 2. The resulting functions were designed to reasonably represent the bandwidth where acoustic exposures can have auditory effects and were designed to be most accurate for describing the adverse effects of high-amplitude noise where loudness functions are expected to flatten significantly. The weighting functions (designated “M” for marine mammal) are analogous to the C-weighting function for humans, which is commonly used in measuring high-amplitude sounds. In the general absence of empirical data, however, the upper and lower frequency roll-offs of the

M-weighting functions are symmetrical, whereas C-weighting admits more energy at the lower than at the upper frequency limits (ANSI, 2001).

The M-weighting functions assume a logarithmic reduction in auditory sensitivity outside of the range of best hearing sensitivity, with the function being 6 dB down from peak sensitivity at the lower and upper frequency “limits.” Auditory detection thresholds at these “limits” (see above discussion of lower and upper frequency “cut-offs”) can be ≥ 80 dB higher (less sensitive) than those at the frequencies of best hearing sensitivity. Consequently, these frequency filters are much “flatter” than audiograms and probably quite precautionary even considering the expected flattening of equal-loudness contours at high exposure levels. The M-weighting functions are also precautionary in that regions of best hearing sensitivity for most species are likely considerably narrower than the M-weighting functions (designed for the overall marine mammal group) would suggest. The general expression for M-weighting ($M[f]$), using the estimated lower and upper “functional” hearing limits (f_{low} and f_{high}) for each of the five functional marine mammal hearing groups, is given in Appendix A (eq. 7 & 8). These frequency-weighting functions are identified in Table 2, and each is depicted graphically in Figure 1.

The M-weighting functions de-emphasize frequencies that are near the lower and upper frequency ends of the estimated hearing range as indicated by negative relative values (Figure 1). This de-emphasis is appropriate because, to have a given auditory effect, sound at these frequencies must have higher absolute amplitude than sound in the region of best hearing sensitivity. As a corollary, sound at a given level will have less effect if it is near or (especially) beyond the lower or upper bounds of the functional hearing range than if it is well within that frequency range. It is important to note the incremental nature of the frequency-weighting functions, which approximate the gradual reduction in auditory effect at frequencies outside the range of greatest sensitivity.

Use of such M-frequency-weighting functions is superior to flat weighting across all frequencies because it accounts for known or estimated differences in the frequency response characteristics for each functional hearing group. At least in the context of injury criteria, it is superior to frequency-weighting via the inverse-audiogram method as it takes into account the expected “flattening” of equal-loudness curves at the high exposure levels where TTS and PTS are expected. It is also superior to a “boxcar-type” step function because it more closely approximates the gradual roll-off of sensitivity below and above the range of optimum sensitivity. Furthermore, each of the recommended “shallow”

frequency-weighting functions includes, within its relatively flat portion, the full audible range for each species for which auditory data are available. In other words, none of the species included within each functional hearing group has been shown or is expected to have any portion of its best hearing sensitivity outside the flat portion of the relevant frequency-weighting function. Thus, the functions are quite precautionary, which is appropriate given that data are limited or lacking for most species.

Exposure Criteria Metrics

Many acoustic metrics (e.g., RMS or peak SPL, SEL, kurtosis) could be considered in relation to noise impacts on animals. It is impossible to predict unequivocally which one is best associated with the likelihood of injury or significant behavioral disturbance across all taxa because of species differences and the fact that real-world sound exposures contain many widely differing temporal patterns and pressure signatures. To account for such differences and to allow for current scientific understanding of tissue injury from noise exposure, the proposed injury criteria incorporate a dual-criteria approach based on both peak pressure and energy. For an exposed individual, whichever criterion is exceeded first (i.e., the more precautionary of the two measures) is used as the operative injury criterion. Similarly, a dual-criterion approach (peak sound pressure and energy) is also proposed for behavioral disturbance from a single pulse.

The pressure criteria for injury are defined as those peak SPLs above which tissue injury is predicted to occur, irrespective of exposure duration. Any single exposure at or above this peak pressure is considered to cause tissue injury, regardless of the SPL or SEL of the entire exposure. For each marine mammal group, the recommended pressure-based injury criteria are the same for all sound types and are based on the criterion for a single pulse. This is a precautionary procedure; pressure criteria based on TTS data for nonpulses would yield much higher estimates of the exposure necessary for PTS-onset. By proposing, for all cases, pressure criteria appropriate to a single pulse, we protect against the possibility that, for some sound sources, one or more intense pulses may occasionally be embedded in nonpulse sounds.

For exposures lacking intense peak pressure components, available data indicate that measurements integrating instantaneous pressure squared over the duration of sound exposure are well correlated with the probability of TTS-onset and tissue injury. Consequently, for exposures other than those containing intense peak pressure transients, SEL is the (or at least one of the) appropriate