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Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises

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ABSTRACT

The impact of underwater noise on marine life calls for identification of exposure criteria to inform mitigation. Here we review recent experimental evidence with focus on the high-frequency cetaceans and discuss scientifically-based initial exposure criteria. A range of new TTS experiments suggest that harbour and finless porpoises are more sensitive to sound than expected from extrapolations based on results from bottlenose dolphins. Furthermore, the results from TTS experiments and field studies of behavioural reactions to noise, suggest that response thresholds and TTS critically depend on stimulus frequency. Sound exposure levels for pure tones that induce TTS are reasonably consistent at about 100 dB above the hearing threshold for pure tones and sound pressure thresholds for avoidance reactions are in the range of 40–50 dB above the hearing threshold. We propose that frequency weighting with a filter function approximating the inversed audiogram might be appropriate when assessing impact.

1. Introduction

Hearing is the primary sense for much marine life for detecting signals from prey, predators, conspecifics, competitors and the environment. Noise introduced into the environment by human activities thus has the potential to interfere with auditory detection and thereby affect the animals directly as well as indirectly via prey and predators (e.g. Richardson et al., 1995; National Research Council, 2003, 2005; Nowacek et al., 2007; Weilgart, 2007). The magnitude of this problem has been realised slowly over the last four decades and as a consequence underwater noise has gradually moved up on the political agenda (see Simmonds et al., 2014). In an influential review of the field, Richardson et al. (1995) focused primarily on the descriptive; a collection of all available information on relevant noise sources and studies of their impact on marine mammals. A decade later Southall et al. (2007) made an updated review of the literature and offered the first published scientific guidance regarding noise exposure criteria.

Although scientifically based, this paper is heavily influenced by, and targeted to, policy in the United States because the suggested criteria are based on the legal definitions of injury and behavioural harassment under the U.S. Marine Mammal Protection Act (MMPA). As a consequence of this, the scientific recommendations provided by Southall et al. (2007) may not be appropriate for direct application in other countries, or even under other domestic legislations in the United States, such as the Endangered Species Act. Several non-U.S. legal frameworks, such as the European Habitats Directive (European Commission, 1992) and the Marine Strategy Framework Directive (European Commission, 2008) focus more on sustaining populations, the habitats that support them and the ecosystems of which they are a part, rather than accounting for takes of individual animals as is the case in the MMPA.

Nevertheless, the criteria suggested by Southall et al. (2007) filled a large global policy vacuum. As a consequence of the pressing need for actual exposure criteria, the suggestions of Southall et al. (2007) have quickly acquired status as the *de facto* standard in many political processes around the world, despite the limitations, caveats and lack of information and imperfect understanding carefully emphasised by Southall et al. (2007). Further there has been surprisingly little constructive debate over the contents of the initial recommendations of this paper and no substantive alternatives or augmentations have yet been offered (but see Ellison et al., 2011). As a result, the recently proposed criteria for acoustic injury by the U.S. National Oceanic and Atmospheric Administration (NOAA, 2013) builds directly on methodology and exposure criteria presented by Southall et al. (2007), updated in light of new experimental data obtained after 2007 and considering additional discussions on weighting functions (Finneran and Jenkins, 2012).

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Southall et al. (2007) should be credited for suggesting actual exposure criteria, as such a move inevitably attracts criticism from those believing them to be too high, those asserting that they are too low, and those merely seeking to improve the science upon which they are based. One of the clearly stated shortcomings of Southall et al. (2007) is that exposure criteria are provided for all cetaceans, divided into three groups, low-frequency (LF), mid-frequency (MF) and high-frequency (HF) cetaceans even though they are all based on experiments on a few species of MF-cetaceans. The MF criteria were then extrapolated to the LF-cetaceans (large whales) and HF-cetaceans (narrow-band high-frequency odontocetes, including porpoises).

Since the review by Southall et al. (2007) a substantial number of studies on other species, particularly the harbour porpoise (*Phocoena phocoena*), have become available. In the light of these new results and in attempt to further the process of identifying meaningful approaches to mitigate noise effects on marine mammals we here undertake a critical, but constructive review of the guidance and recommendations presented by Southall et al. (2007). We then proceed to apply the consequences of that review in a discussion of exposure criteria for the harbour porpoise, a high frequency species where much recent data has been collated. While we use porpoises as a model species, we believe that the scope of the proposed impact assessment has a wider relevance beyond the consideration of any specific legislative standards or species.

2. Exposure criteria for injury

Southall et al. (2007) developed the first general exposure criteria regarding injury for marine mammals. In that process, a number of principal and necessarily simplifying assumptions were made. Of these, three are considered key assumptions by us: (1) the auditory system, being adapted for detection of very low sound levels, will be first organ system to suffer injury from sound exposure; (2) that risk of impact scales with loudness-weighted sound exposure level (signal energy); and (3) that the onset permanent threshold shift (PTS) is the basis for defining safe exposure limits. While the following discussion is specifically targeted the criteria proposed by Southall et al. (2007) it is noteworthy that NOAA's (2013) proposed acoustic injury criteria conform to these assumptions.

2.1. The auditory system as the most sensitive to injury

Marine mammals in general have acute underwater hearing, and for that reason, the auditory system is considered to be the first to suffer from injuries when exposed to increasingly powerful noise (Southall et al., 2007). Sound exposure, however, may also induce other, potentially injurious effects that are more subtle or hard to measure, and hence be overlooked, particularly in marine animals. One such parameter is physiological discomfort, which is very hard to quantify unless it is extensive enough to materialize in the forms of increased levels of stress hormones or reduced fitness over long periods of time. Several studies on human divers indicate that sound exposures can cause long term physiological effects with consequences for fitness that may not be reliably detected through elevated levels of stress hormones or reduced auditory capabilities in the form of temporary threshold shift (TTS).

Steevens et al. (1999) report two cases of what appears to be noise-induced neurological disturbances in two navy divers. The first diver was exposed to 160 dB re. 1 μPa (rms) for 15 min (190 dB SEL) at 240 Hz, causing no measurable TTS. However, at the end of the exposure he reported light-headedness, somnolescence, blurred vision and a vibratory feeling in his extremities, and he was unaware that the sound source had been turned off. Half an hour after the exposure and after being decompressed from 3 atmospheres, the diver again reported to experience nausea and only responded to strong verbal stimuli. These symptoms abated within 30 min and none of physiological variables measured during or after the exposure could explain his response. Three weeks later he again suffered from an episode of light-headedness, memory loss and nausea and, despite an intense neurological examination, no cause could be established. After 9 months he subjectively assigned continued impairments in the forms of insomnia and memory loss to the sound exposure. Sixteen months after the exposure he was undergoing anti-seizure and anti-depressant therapy.

In the second case study of Steevens et al. (1999), a diver was exposed to 181 dB re. 1 μPa (rms) for 15 min (210 dB SEL) at 1000 Hz. This exposure caused along with a moderate TTS of 19 dB, a feeling of light-headedness, inability to concentrate, agitation, blurred vision and head vibrations. The following day the diver reported an increased sensitivity to noise. Two weeks after the exposure, he still experienced heightened sensitivity to noise, increased irritability and concentration problems. A year later he reported that he still felt that he had not recovered fully having concentration problems and mood swings. Similar conditions were also reported over the short-term by Montague and Strickland (1961), although in this case the 23 subject divers also all displayed at least 6–7 dB TTS five minutes after the exposures of unspecified durations to a 1500 Hz pure tone at maximum tolerable levels (50% felt this had been reached by 200 dB re. 1 μPa, rms)

While correlation does not equate causality, these studies nevertheless suggest that exposures with SELs around or even below those shown to cause TTS may, at least under some circumstances, lead to long term neurological disturbances. The consistent effects on the visual system suggest that the mechanism behind these neurological disturbances relate to strong stimulation of the vestibular system that has a strong oculomotor feedback (Parker et al., 1978). There are to our knowledge no dedicated studies of this in marine mammals, but during intense sound exposures some navy dolphins have displayed behaviours, such as biting the experimental setup or refusing to return to the bit plate that may perhaps be indicative of some level of annoyance or physiological discomfort arising from the exposures (Schlundt et al., 2000; Finneran et al., 2002). For example, the simple act of reorienting their heads for exposures may represent an effort to reduce their own exposures due to their highly directional hearing (Au and Moore, 1984). Also Gray and Waerebeek (2011) reported apparent akinesis and possible death of a dolphin incidentally exposed to sounds from a seismic air gun at close range. It is presently unknown if such responses are short term and merely reflect annoyance on the part of the animal or if they in fact are tell-tale signs of neurological disturbances and discomfort similar to that indicated for some human divers at similar or lower sound levels.

The methodology currently in use during intense sound exposure experiments in marine mammals is, in our opinion, unable to uncover such effects. It is therefore possible that marine mammals may, in at least some cases of exposure to high intensity, low frequency sound, suffer from noise-induced neurological disorders that go undetected, but which are potentially more problematic than TTS. This possibility shed in our view doubt on the idea that PTS is an appropriate general threshold for concern about physiological effects and should accordingly motivate specific investigations on this issue for marine mammals.

2.2. Scaling of impact with loudness-weighted energy

It is impossible to develop individual exposure criteria for every possible sound source and thus there is a fundamental need for a common metric, which can be used to assess several types of sounds including those for which no experimental data are