Marine mammals and noise: Problems with root mean square sound pressure levels for transients

P. T. Madsen[a]
Woods Hole Oceanographic Institution, Woods Hole Road 266, Woods Hole, Massachusetts 02543

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Current mitigation levels for noise transients impinging on marine mammals are specified by rms pressures. The rms measure critically relies upon choosing the size of averaging window for the squared pressures. Derivation of this window is not standardized, which can lead to 2–12 dB differences in rms sound pressure for the same wave forms. rms pressure does not represent the energy of the noise pulse and it does not prevent exposure to high peak pressures. Safety levels for transients should therefore be given by received peak–peak sound pressure and energy flux density instead of rms sound pressure levels.

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I. INTRODUCTION

The critical role of sound reception makes cetaceans susceptible to effects of manmade noise in terms of direct physiological damage, threshold shifts, masking, and disruption of normal behavior (Richardson *et al.*, 1995). The increasing concerns about the effects of underwater manmade noise on marine mammals calls for a standardized system of how to quantify and mitigate noise exposure with relevant and reproducible measures.

The magnitude of sound pressure levels in water is normally described by sound pressure on a dB scale relative to a reference rms pressure of 1 μPa (dB re 1 μPa). The nonintuitive nature of decibels, and the different reference values and properties of air and water have led to a plethora of misconceptions concerning the magnitude and potential effects of noise levels in air and water (Chapman and Ellis, 1998). An absolute dB measure should always be provided with a reference value, but it is equally important to state how the magnitude of the sound pressure was quantified. Sound pressures in underwater noise studies and bioacoustics are variously reported in terms of peak-peak, 0-peak, peak of envelope, peak-equivalent rms and rms. For the same transient wave form, levels in decibels may vary by 10 dB or more between these different measures of pressure, making comparisons futile. Thus, quantitative measures of underwater sound, and in particular, noise transients are haunted by inconsistency and lack of adequate information to reproduce and compare measurements, and there is a need for clarity and standardization (Richardson *et al.*, 1995; NRC, 2000).

The sound pressure of a continuous signal is normally parametrized by a rms measure, while the sound pressure of a transient is normally given in terms of peak pressure measures. For a pure sine wave the ratio between peak–peak and rms is 9 dB, but for aperiodic or low duty cycle signals the difference between peak–peak and rms varies widely and can often be 15 dB or more. Peak sound pressure values of transient signals are relevant measures of high level exposures with the risk of causing physical damage in auditory systems (Coles *et al.*, 1968). However, since the mammalian ear operates as an energy detector (Plomp and Bouman, 1959; Green, 1985), it also seems relevant to implement measures that include temporal integration when assessing sensation and damaging levels of transient noise.

For marine mammals, a rms level of safe exposure has been adapted in an attempt to accommodate how the animal may sense the received noise levels (NMFS, 2003). Broad band received levels of 180 dB re 1 μPa (rms) and 190 dB re 1 μPa (rms) are currently the lower limits for concern about temporary or permanent hearing impairment in cetaceans and pinnipeds (NMFS, 2003), and these levels form the basis for estimating impact radii of active sound sources at sea (e.g., Blackwell *et al.*, 2004; Tolstoy *et al.*, 2004). This paper explores the consequences of using the rms measure for safety levels of different noise transients impinging on marine mammals.

II. MATERIALS AND METHODS

Four commonly encountered transient signals (all sampled at 48 kHz) from high level underwater sources with the same modeled peak–peak received level of 189 dB re 1 μPa (pp) were chosen for analysis: (1) an on-axis version of the p1 pulse of a sperm whale usual click, (2) a 390 ms frequency modulated pulse akin to that of a ping from a mid-frequency sonar, (3) a short transient comparable to the on-axis signature from a powerful, impulse sound source such as an air gun array or an underwater explosion, and (4) the same impulse sound after propagation in a highly reverberant environment. The root of the mean of the squared pressure (rms) of a plane wave in a time window from 0 to T is given by

$$p_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T p^2(t)\,dt},$$

$$\text{rms sound pressure level} = 10\log\left(\frac{1}{T}\int_0^T p^2(t)\,dt\right),$$

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[a] Electronic mail: pmadsen@whoi.edu

where $p(t)$ is the instantaneous pressure (Urick, 1983). The analysis window is critical for rms measures of transient signals, the longer it is the lower the rms value will be.

In research on auditory traumas in humans, impulse wave forms are often modeled by a Friedlander wave that describes the idealized signature of a zero-rise time impulse (Hamernik and Hsueh, 1991). The rms value of such an impulse can be computed using different temporal definitions that relates to nulls or amplitude thresholds in the wave form (For review see, Hamernik and Hsueh, 1991). However, underwater noise pulses seldom render themselves suited for the temporal measures derived for the Friedlander wave. The *D* duration, which is given by the -10 dB end points relative to the peak of the envelope of the wave form, has been applied to determine the durations of biological transients (Møhl *et al.*, 1990). The envelope is computed by taking the absolute value of the analytical signal (Hilbert transformed wave form, relating the real and imaginary parts of the analytical signal) (Randall, 1987). As a variation of this approach, Madsen *et al.* (2002) and Møhl *et al.* (2003) used -3 dB end points relative to the peak of the envelope when computing rms measures of reverberant air gun pulses and p1 pulses in sperm whale clicks.

For signals with a good signal to noise ratio (SNR), a more common approach is to determine the duration of transients by using the relative energy in a window that incorporates the entire signal wave form along with short samples of noise on either side. In this approach the duration is often given by the part of the window that makes up 90% of the total cumulative energy in the window including the sound pulse (Malme *et al.*, 1986; Blackwell *et al.*, 2004). For short duration, well-defined clicks from toothed whales a 97% energy approach has also been implemented (Au, 1993; Madsen *et al.*, 2004). To test the effects of these temporal definitions on the duration of different transients, the -3 dB, -10 dB, 90%, and 97% approaches have been applied to the four transients signal types.

Acoustic impact is not only given by peak pressure, but also by the energy flux density of the sound pulse (Ward, 1997). The energy flux density or the sound exposure level of a sound pulse propagating as a plane wave in an unbounded medium is given by the time integral of the pressure squared (Urick, 1983; McCauley *et al.*, 2003). The energy flux density in dB re 1 $\mu\text{Pa}^2\,\text{s}^{\text{i}}$ of transients can thus be approximated by 10 log to the time integral of the squared pressure over the duration of the pulse (Young, 1970), which for the same duration, *T*, is simply the rms level (in dB)$+10\log(T)$:

$$\text{Energy flux density} = 10\log\int_0^T p^2(t)\,dt$$

$$= 10\log\left(\frac{1}{T}\int_0^T p^2(t)\,dt\right) + 10\log(T),$$

where *T* is the window length in seconds. This estimation of energy flux density is in line with Finneran *et al.* (2002b) based on the assumption of individual pressure measurements of a plane wave. The intensity of a sound field is given by the product of the pressure and the particle velocity components divided by the specific acoustic impedance of the medium (Urick, 1983). But since marine mammals only seem to detect the pressure component of the sound field (Kastak and Schusterman, 1998; Hastings, 2004), the above-given formula can be used when assuming exposure to a plane wave well in the far-field of the sound source (Finneran *et al.*, 2002a). This approach has accordingly been used to compare the energy flux density of the four pulse types with identical peak–peak pressure, but with varying durations and rms levels.

III. RESULTS AND DISCUSSION

The p1 wave form of an on-axis sperm whale usual click is shown in Fig. 1(a), with its envelope in Fig. 1(b) and the cumulative energy flux density in Fig. 1(c). Figures 2(a)–2(c) is for a 390 ms sonar pulse and Fig. 3(a) depicts a custom generated single cycle 189 dB (pp) transient representative of the signature of an impulse sound source such as an air gun or a chemical explosive. Figure 3(b) displays the wave form of the same impulse with similar peak–peak received level as in Fig. 3(a), but in this case the pulse has propagated in a highly reverberant environment.

Figures 1(b) and 1(c) illustrate that the duration of the sperm whale p1 pulse can vary between 47 and 125 μs depending on how the duration is derived. The duration derived from -3 dB re peak of the envelope covers less than a full cycle of the wave form, so it is not surprising that this duration measure renders the highest rms level of 183 dB re 1 μPa (rms). All the three other duration measures are approximately twice as long and render essentially identical rms received levels 2–3 dB lower. However, the energy flux density of the pulse is within 1 dB around 141 dB re 1 μPa^2 s for the four duration measures. Consequently, for short, well-defined transients such as odontocete clicks with good SNR, the rms measure is quite robust and not very sensitive to the criterion used to establish the integration window, except that the -3 dB measure seems to lead to a rms sound pressure level that is significantly higher (2–3 dB) than the three others (Table I).

When comparing the different duration measures for a very different manmade transient like the sonar ping in Fig. 2(a), it is seen that the -3 dB approach again yields a rms level that is 2 dB higher than the three others, which relates to the higher average squared pressure in the -3 dB window than in a larger window where the sound pressures fluctuates more due to interference of multipaths [Fig. 2(b)]. As is the case for the sperm whale click, the -3 dB duration covers such a small part of the actual wave form that its use cannot be justified [Fig. 2(a)]. This argument is strengthened by the fact that the energy flux when using the -3 dB measure is 25 times smaller (14 dB) than when using the three other duration measures including a much larger fraction of the pulse (Table I).

Although the sonar pulse of Fig. 2(a), has the same peak–peak received level as the sperm whale click, its rms sound pressure level is between 177 and 179 dB depending on the duration used (the variance is caused by interference of multipaths). Thus, the sperm whale p1 pulse exceeds the safety limit of 180 dB re 1 μPa (rms), but the sonar ping with the same peak–peak pressure level does not. The

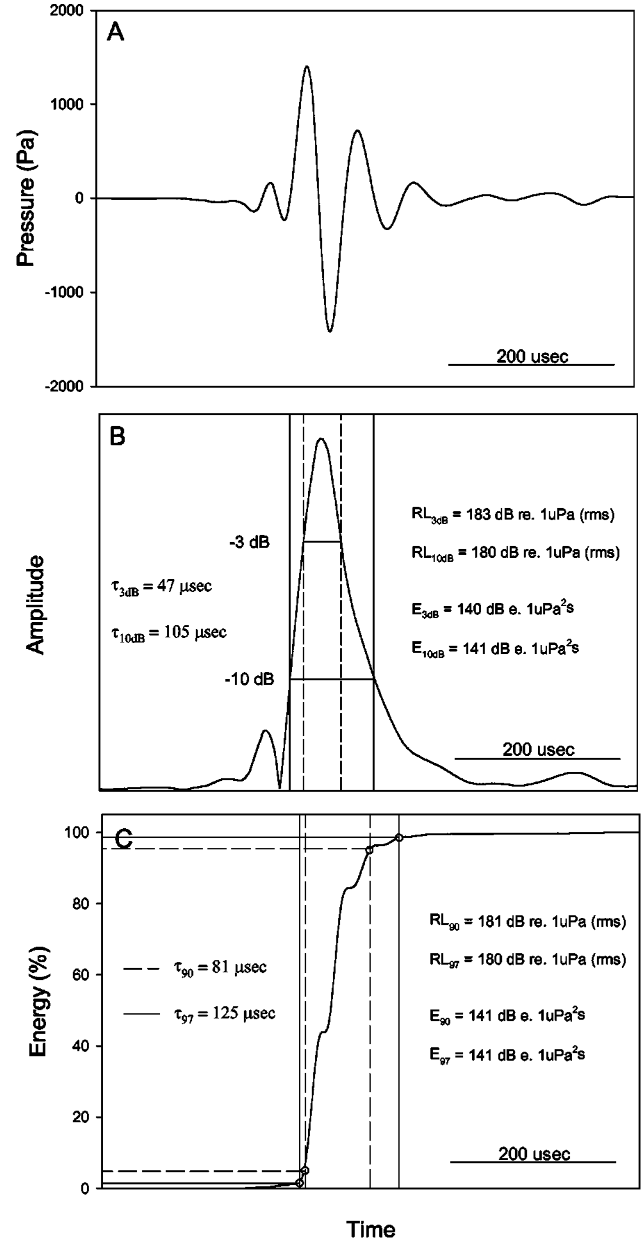

FIG. 1. (A) Wave form of p1 pulse of sperm whale click with a received sound pressure level of 189 dB re 1 μPa (pp). (B) Envelope of the wave form shown in (a). −3 and −10 dB levels for the durations of $t_{-3\ \mathrm{dB}}$ and t_{-10} dB are shown by dotted and solid gray lines. The resulting rms [dB re 1 μPa (rms)] and energy flux density (dB re 1 $\mu\mathrm{Pa}^2$ s) levels are provided for each of the duration measures. (C) The relative cumulative energy of the wave form in Fig. 1(a). The duration measures t_{90} and t_{97} is given by the windows containing 90% and 97% of the total relative energy in a window including the sound pulse.

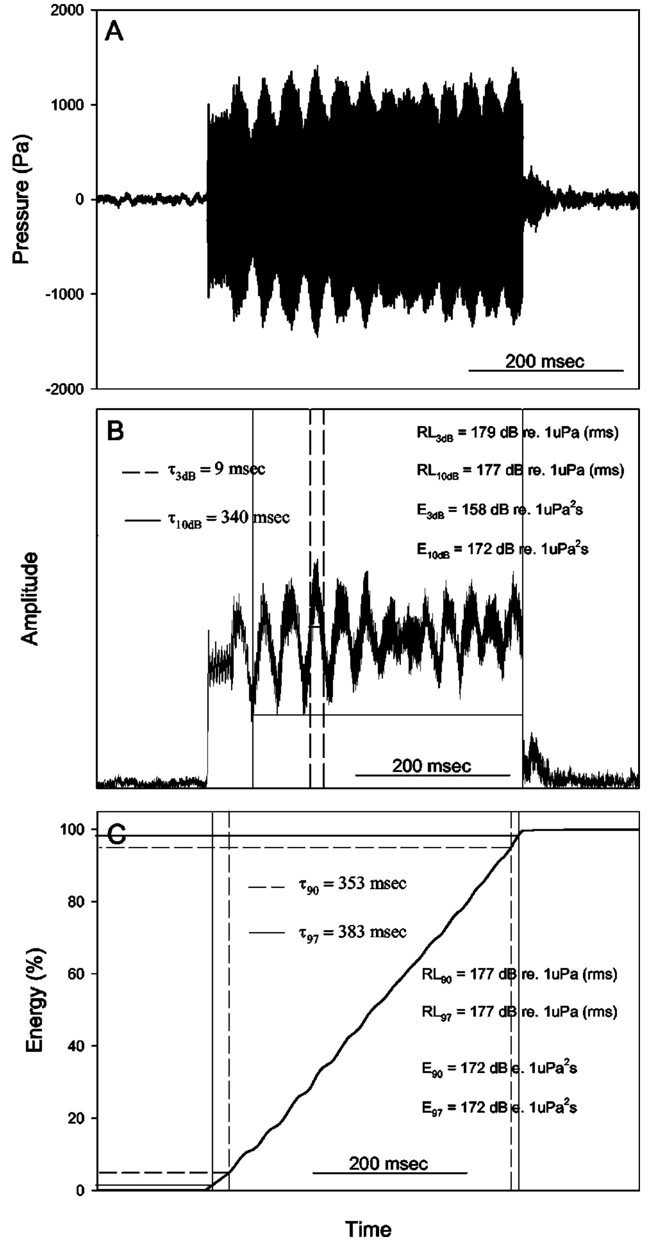

FIG. 2. (A) Wave form of $p1$ pulse of a mid-frequency sonar pulse with a received sound pressure level of 189 dB re 1 μPa (pp). (B) Envelope of the wave form shown in Fig. 2(a). −3 and −10 dB levels for the durations of $t_{-3\ \mathrm{dB}}$ and t_{-10} dB are shown by dotted and solid gray lines. The resulting rms (dB re 1 μPa (rms) and energy flux density (dB re 1 $\mu\mathrm{Pa}^2$ s) levels are provided for each of the duration measures. (C) The relative cumulative energy of the wave form in Fig. 1(a). The duration measures t_{90} and t_{97} are given by the windows containing 90% and 97% of the total relative energy a window including the sound pulse.

multipath-induced pressure fluctuations of the sonar ping lead to a lower average squared pressure than the effectively single cycled sperm whale pulse. However, when looking at the energy flux density of the sonar ping, using duration measures that essentially cover the pulse, the sonar ping is seen to carry 1000 times (30 dB) more energy than the sperm whale click for the same peak–peak received sound pressure. Thus, if the peak–peak pressure received levels of the two transients were considered, they would have an equal impact on the exposed animal. If the rms measures are used, no matter how the averaging duration is determined, the sperm whale click will exceed the 180 dB re 1 μPa (rms) limit, while the sonar ping will not, despite the fact that it is carrying more energy than the sperm whale click by three orders of magnitude (Table I). It is therefore not reasonable to compare the acoustic impact of a mid-frequency sonar pulse with that of a sperm whale click (Møhl, 2002).

The impulse sound in Fig. 3(a) has almost the same duration as the sperm whale click and about the same rms sound pressure levels of around 182 dB. Accordingly, this impulse with a similar peak–peak received sound pressure level as the three other transients of 189 dB re 1 μPa (pp),

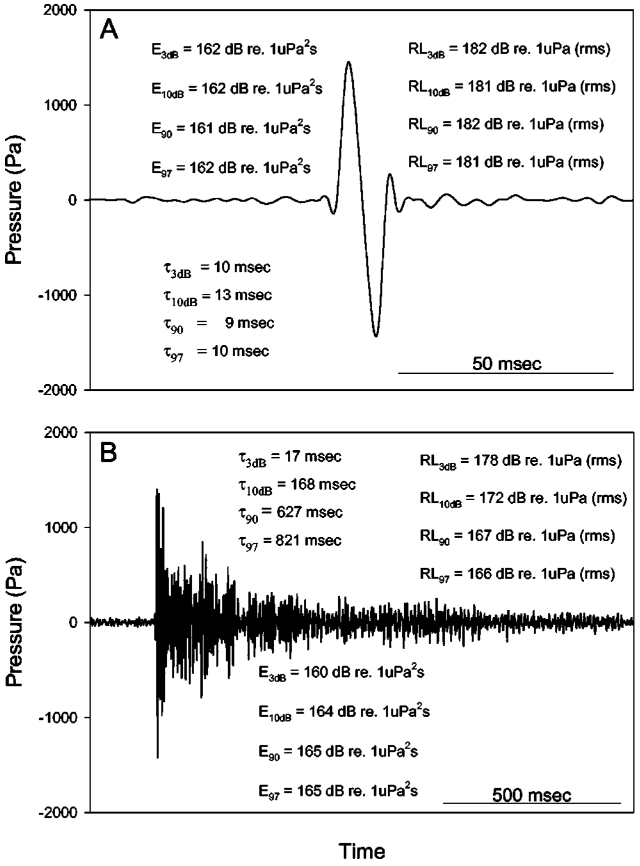

FIG. 3. (A) Transient mimicking the far-field version of a sound pulse produced by an impulse sound source in an acoustic free field. Duration, rms, and energy measures are calculated by the same means as in Figs. 1 and 2. (B) Slowly decaying transient mimicking the situation where the impulse of (a) has been propagating in a highly reverberant environment. Duration, rms, and energy measures are calculated by the same means as in Figs. 1, 2, and 3(a).

exceeds the 180 dB re 1 μPa (rms) limit. However, its energy flux density is 100 times larger than for the sperm whale click of identical peak–peak and rms received levels [Fig. 3(a)]. Thus, if energy flux density is not taken into account, the impulse would be regarded as having the same acoustical impact on an animal as the sperm whale pulse, and a larger impact than the sonar ping having 10 times (10 dB) higher energy flux density (Table I).

The wave form of Fig. 3(a) mimics the situation of a pressure wave propagating from an impulsive sound source in deep water, approaching the situation for an acoustic free-field. When such impulse sounds propagate in a highly reverberant environment such as shallow water, the energy becomes spread in time due to the variety of path lengths and group velocities supported (Greene and Richardson, 1988) as depicted in Fig. 3(b). In this case the −3 dB criterion window clearly does not cover the full extent of the pulse and neither does the −10 dB window. The choice of integration window of this slowly decaying pulse greatly affects the rms measures. However, even the highest rms measure of 178 dB re 1 μPa (rms) for this pulse, achieved with a window derived by the −3 dB criterion, is lower than the 180 dB re 1 μPa (rms) limit. Hence, multipath propagation plays an important role in determining whether the rms level received at the animal is considered too high or not, even if the energy is invariant. When using the rms measure for a transient noise pulse like the one displayed in Fig. 3(b), it is evident that the method of deriving the window may result in rms sound pressure levels that vary by as much as 12 dB (Table I). If the 90% energy measure is used for the displayed pulse, giving a window length of 627 ms, a pulse with a received peak–peak level of 202 dB re 1 μPa (pp) would still not exceed the limit of 180 dB re 1 μPa (rms). Consequently, long, fixed averaging times for calculation of rms sound pressures can yield very short safety radii around a noise source. Unless there is a specified protocol for determining the duration, it is possible to manipulate the rms level by varying the averaging window: the longer the averaging time, the lower the rms level. Measures for mitigation of sound exposure should not leave room for such analytical freedom.

The energy flux density measures the energy flow per unit area received by the animal. With the signal of Fig. 3(b), the animal is actually exposed to twice as much sound energy (3 dB) as compared to exposure to the pulse of Fig. 3(a). If the peak–peak sound pressure level is considered to indicate exposure, the pulses of Figs. 3(a) and 3(b) would be considered to have the same impact. If the rms measure was used, the pulse in Fig. 3(a) would exceed the 180 dB re 1 μPa (rms) limit, whereas the pulse of Fig. 3(b) would not even though the animal is exposed to two times the acoustic energy by the pulse in Fig. 3(b). It is also apparent that for the energy measure, durations that cover as much of the pulse as possible given the signal to noise ratio provide the highest number, which is the opposite of the rms measure.

Energy flux density is therefore a better measure for safe exposure levels than rms measures as the energy unit takes into account the overall acoustic energy impinging on the animal per unit area (McCauley *et al.*, 2003). Ears of terrestrial mammals generally integrate sound intensity over a time window of some 200 ms (Plomp and Bouman, 1959; Green, 1985), and the same appears to be the case for cetaceans at low frequencies (Johnson, 1968). It seems therefore reasonable to use 200 ms as the maximum integration time from a detector or sensation point of view (Madsen *et al.*, 2002).

TABLE I. Pulse numbers refers to the pulses displayed in Figs. 1 to 3(b). RL_{pp} is the received peak–peak sound pressure in dB re 1 μPa (pp). t provides the different duration measures in ms. rms provides the root-mean-square sound pressure in dB re 1 μPa (rms) for each of the duration measures. E gives the energy flux density in dB re 1 μPa^2 s for each the duration measures.

Pulse	RL_{pp}	$t_{3\ \mathrm{dB}}$	$t_{10\ \mathrm{dB}}$	t_{90}	t_{97}	$\mathrm{rms}_{3\ \mathrm{dB}}$	$\mathrm{rms}_{10\ \mathrm{dB}}$	rms_{90}	rms_{97}	$E_{3\ \mathrm{dB}}$	$E_{10\ \mathrm{dB}}$	E_{90}	E_{97}
1	189	0.047	0.105	0.081	0.125	183	180	181	180	140	141	141	141
2	189	9	340	353	383	179	177	177	177	158	172	172	172
3A	189	10	13	9	10	182	181	182	181	162	162	161	162
3B	189	17	168	627	821	178	172	167	166	160	164	165	165

This will lead to a 3 and 0.5 dB reduction for the pulses of Figs. 2 and 3(b), respectively. However, in terms of hearing impairment due to a single, high level impulse, it has been established that the safety threshold for humans scales as $10\log(T)$, where T is the exposure duration, even if T is much longer than 200 ms (Ward, 1997). Since this issue remains to be clarified for marine mammals, it may seem reasonable to apply a conservative approach and provide energy flux density integrated both over the entire pulse duration and with a 200 ms integration time if the actual duration is longer than that. Such measures should additionally be accompanied by a figure of the wave form, and information about the recording bandwidth and the duration used for integrating the pressure squared [as stipulated by the ANSI standard for noise exposure (ANSI, 1994)].

Impulses can have very high peak sound pressure levels, but carry very little energy (Price and Wansack, 1989). Since physical damage and impairment of the auditory system is caused both by high peak pressure and energy flux (Ahroon *et al.*, 1996; Finneran *et al.*, 2002a, b; Ward, 1997), safety limits for sound exposure should include both a maximum received energy flux level along with a maximum received peak–peak pressure level. Such a protocol addresses concerns for physical damage due to short high pressure pulses as well as the effects of longer, high-energy transients with lower peak pressures.

It is concluded that rms safety measures are unsuited as a stand-alone mitigative measure for transient noise effects on marine mammals irrespective of what the absolute level is [currently 180 dB re 1 μPa (rms) for cetaceans]. In line with Finneran *et al.* (2002a, b), it is recommended that levels set to mitigate sound exposure of marine mamals include a maximum peak–peak received sound pressure level in concert with a maximum received energy flux level (McCauley *et al.*, 2003). It is suggested that the energy flux is calculated by using the 90% energy approach for derivation of the duration (Malme *et al.*, 1986; Blackwell *et al.*, 2004), since the 97% criterion requires high signal to noise ratios, and the -3 and -10 envelope criteria underestimate the durations of slowly decaying transients. It is beyond the scope of this paper to discuss the absolute levels for mitigation of received peak–peak pressure and energy flux density, but there is an urgent need for a careful assessment of such in light of anatomical, physiological, and behavioral data for different marine mammal species.

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[i] For a plane wave in an unbounded medium, the energy flux density in dB re 1 μPa^2 s can be converted to J/m^2 by dividing the summed squared pressure on a linear scale by the specific impedance Z (sound speed$\times$density) of the medium. For example, 182 dB re 1 $\mu\mathrm{Pa}^2\,\mathrm{s}=(1257\ \mathrm{Pa}_{\mathrm{rms}})^2\ \mathrm{s}/(1500\ \mathrm{m/s}\times 1040\ \mathrm{kg/m}^3)=0$ dB re 1 J/m^2=1 J/m^2.

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