Some examples of marine mammal ‘discomfort thresholds’ in relation to man-made noise

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Abstract
World-wide a concern exists about the influence of man-made noise on marine life and particularly on marine mammals and fish. One of the acoustic polluters of the world’s oceans is high-power active sonar, but also pile driving and seismic activities at sea are of concern with respect to animal welfare. At TNO, acoustic criteria are being developed to protect marine animals from severe disturbance (or worse) due to man-made noise. One of the ‘stages’ in ‘dose-response relationships’ is the ‘discomfort threshold’, the received noise level at which a marine animal turns when approaching a noise source. In The Netherlands discomfort thresholds for a number of sound types have been determined for harbour porpoises, harbour seals and some North Sea fish species. This paper shows how those measurements were carried out and compares some results with proposed TNO dose-response relationships for marine mammals.

Key words: bio-acoustics, marine mammal, porpoise, seal, disturbance, discomfort threshold, man-made noise

1 Introduction
World-wide a concern exists about the influence of man-made noise on marine life and particularly on marine mammals and fish. One of the acoustic polluters of the world’s oceans is high-power active sonar, but, for instance, also pile driving and seismic activities produce high sound levels in the water. Roughly, the physical and physiological effects of man-made noise on the hearing system of animals can be divided into the following grades:

1. No influence.
2. Masking of activities, such as forage.
3. Behavioural disruption and habituation.
4. Temporary Threshold Shift (TTS) of hearing perception.
5. Permanent Threshold Shift (PTS) of hearing perception.
6. Injury (even death due to severe injury).

Each of these influences can be represented by a certain ‘sphere’ around the sound source (so-called *zones of influence* - Figure 2). The relationship between man-made noise levels and their (behavioural) effects on marine animals, called *dose-response relationship*, is species, as well as sound type dependent.

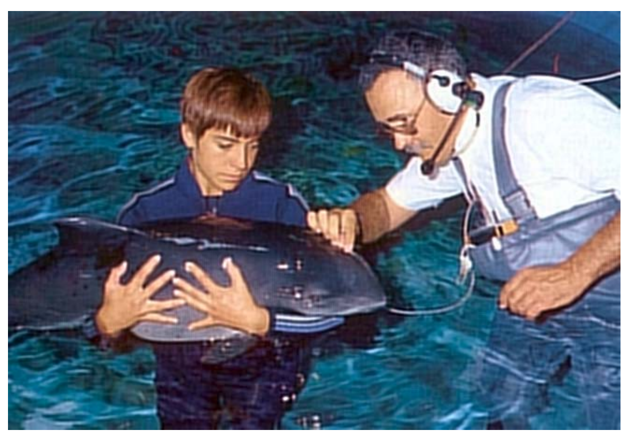

Figure 1: Acoustic research on a Harbour porpoise in the Netherlands.

For marine animals this relationship has not been investigated extensively. In the past some attempts were made by researchers to derive level criteria for the various effects, based on very diverse considerations. At TNO, man-made noise criteria with respect to marine mammals have been drafted, mainly based on extrapolation of human hearing data. The aim is to prevent marine animals for severe disturbance (or worse). Therefore marine mammals were divided into *hearing sensitivity groups*, because it is unlikely that all marine mammals are equally sensitive to man-made noise [1] [2]. One of the 'stages' in the dose-response relationship is the *discomfort threshold*, the received noise level (also called *exposure level*) at which a marine animal turns when it approaches a sound source. In The Netherlands discomfort thresholds have been determined for harbour porpoises, harbour seals and some North Sea fish species for a number of sound types.

This paper explains, in general terms, the notions of hearing sensitivity group, dose-response relationship and discomfort threshold, shows how discomfort thresholds are determined and compares some research results with our dose-response relation levels for two marine mammal species.

2 Hearing sensitivity groups

Because it is practically impossible to establish dose-response relationships for all species, in the TNO noise criterion system, marine mammals have been divided into *hearing sensitivity groups*, under the assumption that there will be differences in hearing sensitivity and dynamic hearing range between the various species. It is for instance likely that there are small differences between hair (or true) seals and eared seals. This hypothesis is stated in literature [3] [4]. Also cetaceans can be divided into hearing sensitivity groups. Ketten [5]-[9] defines cetacean hearing as follows:

1. *infrasonic balaenids* - probable functional hearing ranges 15 Hz - 20 kHz, good sensitivity between 20 Hz and 2 kHz at thresholds speculated to be 80 dB re 1 μPa
2. *sonic to high frequency species* - hearing range 100 Hz - 100 kHz at minimum thresholds of 50 dB re 1 μPa, sound production with widely variable peak frequencies
3. *ultra-sonic dominant species* - hearing range 500 Hz - 200 kHz at minimum thresholds of 40 dB re 1 μPa, sound production between 16 kHz and 120 kHz.

Based on practical considerations, such as frequency range and source level of their vocalizations, the number of hearing sensitivity groups in our system has been increased to ten (Table 1). At present noise criteria are being drafted for all groups.

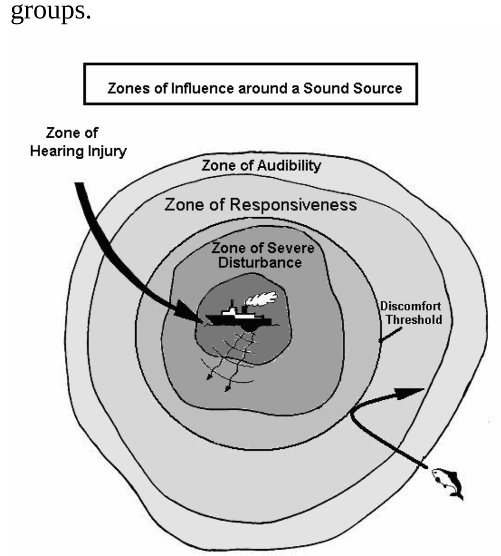

Figure 2: Around a sound source various 'Zones of Influence' can be defined in which an approaching marine animal experiences certain changes in behaviour (due to the sound). Discomfort threshold is one of them and is the boundary of the area the animal does not enter due to the 'unpleasant' sound level.

3 Dose-response relationship

The dose-response relationship for humans is discussed extensively in literature (for instance [10]-[14]). The human hearing threshold is defined as 0 dB re 20 μPa (in air). The criterion level for severe disturbance, for continuous broadband sounds, can be taken at 80 dB(A). This means that, when the sound spectrum is corrected for (filtered by) the inverse shape of the human audiogram, the total broadband level of the sound is 80 dB above hearing threshold. Hearing injury for humans occurs at approximately 130 dB(A) and higher. Some guideline human dose-response relation levels are given in Table 2.

Table 1: Hearing Sensitivity Groups, as proposed by TNO

Group	*Families*	*Max. SL in dB re 1 μPa (RMS) at 1 m distance*	*Vocalization range*
1a	Mysticeti (baleen whales)	190 dB	Dominant sounds (moans) below 250 Hz; no clicking
1b	Mysticeti (baleen whales)	190 dB	Dominant sounds below 1 kHz; click sounds
2a	Largest Odontoceti and possibly the smallest Mysticeti	high	Click sounds below 20 kHz
2b	Most (offshore) Odontoceti	above 190 dB	Usually click sounds 40 - 80 kHz, but higher frequencies are possible
2c	Ziphioidea (beaked whales)	above 200 dB	Click sounds possibly around 7 kHz and above 20 kHz
2d	(Smaller) inshore and riverine Odontoceti	165 dB	Click sounds above 80 kHz
3	Sirenia	low	Sounds below 20 kHz
4a	Phocidae (seals)	low	Variable
4b	Otarioidae (sea lions)	low	Variable
4c	Odobenidae (walrus)		Variable

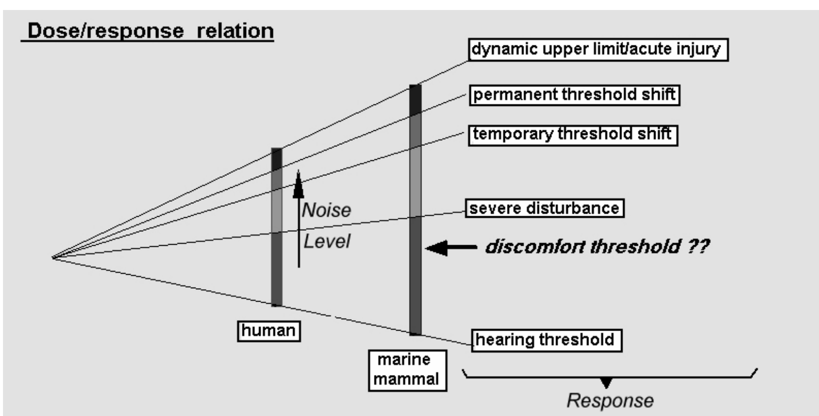

Figure 3: The (known) human dose-response relationship may be extrapolated in order to find the relationship for marine mammals. Maintaining the human ratio between the responses, the marine mammal relationship can be found when two responses are known, for instance the hearing threshold and the TTS causing level.

Table 2: Dose-response relationship for two marine mammals, valid for continuous broadband noise signals; 'weighted' levels in dB re 1 μPa (in water). For comparison also levels for humans are given (in dB(A) re 20 μPa in air)

Species	*Hearing Threshold*	*Severe Discomfort*	*TTS*	*Hearing Injury*	*Dynamic Hearing range*
Harbour seal	60 dB	140 dBw [1])	150 dBw	190 dBw	60-200 dB
Harbour porpoise	40 dB	125 dBw	137 dBw	180 dBw	40-190 dB
Human in air [3])	0 dB	80 dB(A) [1])	90-125 dB(A) [2])	130 dB(A)	0-140 dB

Notes:

[1]) *dBw and dB(A) means that the signal is 'weighted' for the inverse shape of the relevant audiogram*

[2]) *the TTS criterion level for continuous broadband noise has been taken at 90 dB(A); TTS criterion level for broadband noise bursts with a duration between 1 and 90 s and one exposure per 8 hours is stated to be 125 dB(A)*

[3]) *the reference level for sound pressure levels in air is 20 μPa*

The structure and dimensions of marine mammal hearing systems resemble those of humans; the shape of the audiograms is roughly the same, but the frequency range may differ strongly. Also other properties have a striking resemblance, critical bandwidth for instance. A hypothesis of our system is that the human dose-response relationship can be converted to that of a marine mammal, maintaining the mutual relation of the effects, but adapting the frequency range and dynamic hearing range. To estimate dose-response relation levels for marine mammals, one must know the hearing threshold and the dynamic hearing range. The relation (ratio) between the various levels may be taken equal to that of humans (Figure 3). In many cases hearing thresholds are known, but usually dynamic hearing ranges are unknown and have to be estimated or derived from known criteria levels, for instance measured TTS levels [15]-[18].

Calculated in the way mentioned above, Table 2 gives a review of some dose-response relationships for harbour porpoises and harbour seals, as derived by TNO and applied in Dutch environmental regulations. This table is only valid for continuous broadband noise signals, 'weighted' for the relevant audiogram shape (indicated by 'dBw'). For other types of sound (pulses, narrow-band noise, etc.) these levels have to be corrected. More information can be found in [1] [2].

4 Discomfort threshold

A part of the Zones of Influence (Fig. 2) around a sound source is the *discomfort threshold*. An acoustic discomfort threshold is defined as the boundary between the area that an animal generally occupies when exposed to (man-made) sound and the area that it generally does not enter during sound exposure. During sound experiments animals are often observed to swim towards their preferred areas, sometimes near the sound source, but then turn and swim away from the sound source to an area where the sound level is acceptable to them. The discomfort threshold will be somewhere between *hearing threshold* and *severe discomfort* (Fig. 3).

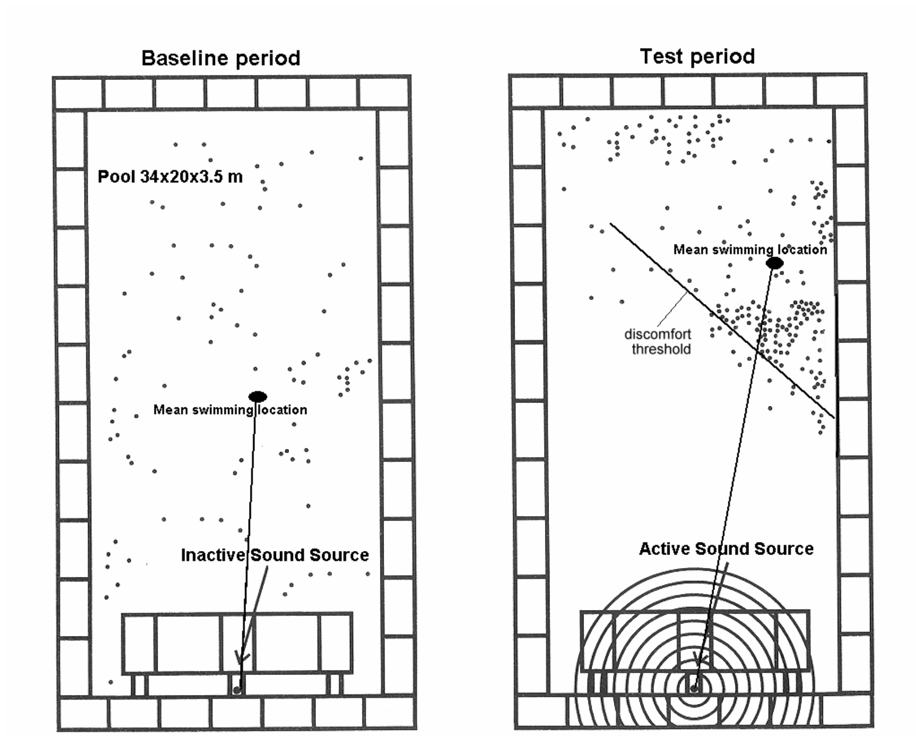

Figure 4: Principle of a discomfort threshold measurement. Black dots are the surfacing locations of harbour porpoises in a 34 x 30 x 3.5 m pool. During the baseline period the surfacings are randomly spread over the pool; in the test period the porpoises surface at larger distances from the underwater sound source in an area where the sound level is acceptable to them. The difference in mean surface distance indicates the deterrent effect of the sound. The discomfort threshold is the sound level in the boundary between the occupied and non-occupied area, indicated here as a line.

5 Discomfort threshold measurement method

Discomfort thresholds may be determined as follows (harbour porpoise study [19]): animals are observed during daily sessions when they swim in an enclosed area, a floating pen for instance. Each session consists of a 15-minute baseline period, when no sound is emitted, immediately followed by a 15-minute test period with sound emission. The difference in distance between the sound source and the (mean) surfacing areas of the animals during these periods is used as an indicator of the deterrent effect of the sound (Figure 4). The number of respirations (mean respiration interval time) during the sessions is used as an indicator of the level of agitation.

The emitted sound level is such that the animals are displaced only a limited distance, but not so much that they are driven to the borders of the pool. This means that the animals are able to choose a swimming area in which the sound is acceptable to them.

Cameras, mounted on high poles, are used to film the entire water surface of the pool and are used to determine the effects of the emitted sounds. From the recordings scanning samples (scores) are taken every 10 s. The locations where the animals during the baseline and test periods surface are marked. This is done by drawing a grid over the TV monitor screen which corresponds to a pool grid of 2 x 2 m. To facilitate mapping of the locations, ropes with markers are strung across the pool. It appeared that on days when the water was clear, the animals were never seen swimming far away from their surfacing locations. Hence, it is assumed that respiration locations are a good indication of the general swimming area of the propoises. The total number of surfacings in each grid section during all 15-minute sessions is determined. From this, the following response variables are derived: the number of respirations (or surfacings) and the distances between the sound source and the surfacings during baseline and test periods.

6 Harbour porpoise and harbour seal discomfort thresholds

Two discomfort threshold experiments have been carried out by Seamarco and TNO, one with two harbour porpoises and one with nine harbour seals in a floating pen. At present some North Sea fish species are tested. Test sounds were four different communication sounds (like the sounds of a computer modem). The sounds had a noisy character with varying tonals and had a bandwidth of two 1/3-octave bands (the 10 and 12.5 kHz bands). The results were that the test sounds displaced the animals from their usual swimming area(s) to areas that are assumed to have acceptable sound levels for each animal, but the animals did not move further away from the sound source than necessary. In general their respiration rate was only slightly higher in test periods, compared to baseline periods. Statistical Analyses Of Variance (ANOVA) on distances from the sound source confirmed that the animals swam further from the source during test periods than during baseline periods. The ANOVA on the number of surfacings revealed a significant, but small effect of period (more surfacings during test than during baseline). So, the animals were affected by the sounds, and responded by swimming away from the source, surfacing (and respiring) slightly more frequently than during the baseline period. The next step was to measure the sound distribution in the pool, especially in the area to which the animals were displaced during sound emissions. The (mean) sound level in the boundary between the generally occupied area and the generally non-occupied area during test periods was taken as the discomfort threshold level (Fig. 4).

Detailed results of these Dutch discomfort threshold measurements have been published in [19] [20]. It appeared that, due to the underwater communication sounds used, the harbour porpoises were displaced between 5 and 13 m depending on the type of sound, as well as they surfaced slightly more frequently. For the harbour seals the mean displacement was around 5 m, but their mean respiration rate was not affected. For harbour porpoises, the discomfort levels were between 97 and 111 dB re 1 μPa (Root Mean Square) depended on the type of sound; those for the harbour seals were very stable, being 107-108 dB re 1 μPa (RMS), so sound type independent.

Another (short) test was carried out with both species: an Airmar acoustic alarm used to reduce accidental porpoise bycatch in fisheries, producing 11 kHz pulses (pulse duration 0.3 s, interval 4.3 s) with harmonics to above 100 kHz and a broadband source level of 133 dB re 1 μPa (RMS), was held in the pool for a short while. The effect was that both species panicked: the porpoises started swimming in circles at a very high speed and the seals swam as far away as possible and some animals came out of the water (a behaviour they never exhibit during daylight in that facility). The exposure levels during this test must have been considerably less than 133 dB re 1 μPa (RMS), but nevertheless, the effects were surprisingly dramatic.

Table 3: Discomfort threshold; levels in dB re 1 μPa (RMS) in water

Type of sound	*Discomfort threshold Porpoises*	*Discomfort threshold Seals*
Chirp	97 dB	108 dB
Direct sequence spread spectrum	103 dB	107 dB
Frequency sweep	97 dB	107 dB
Modulated freq. Shift keying	111 dB	107 dB

Note: for more information, see [19] for harbour porpoises and [20] for harbour seals.

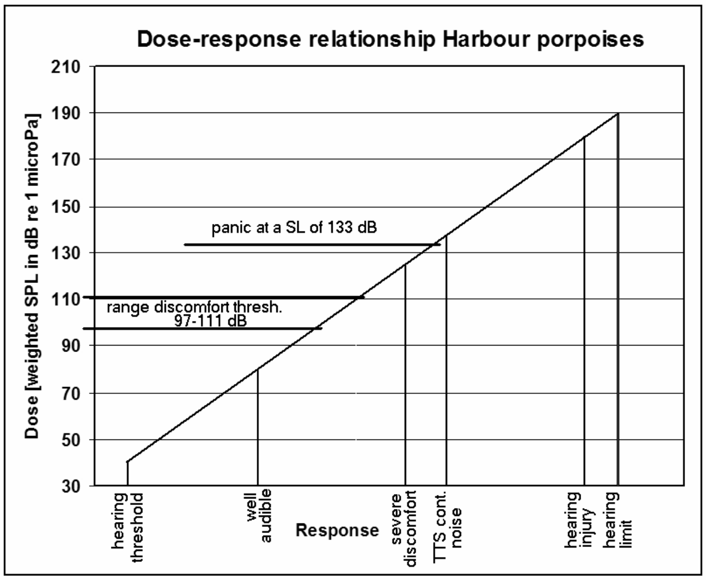

Figure 5a: The dose-response relationship for harbour porpoises (Group 2d), as proposed by TNO, and the measured discomfort threshold. The discomfort threshold is halfway between 'well audible' and 'severe discomfort'.

An acoustic alarm with a broadband source level of 133 dB (RMS) re 1 μPa at 1m - and consequently a somewhat lower exposure level – corresponding to 'severe discomfort', caused panic in the harbour porpoises.

7 Conclusions

The measured discomfort threshold of harbour porpoises and harbour seals did not differ very much and was in the range of 97-111 dB re 1 μPa (RMS). Because the used stimulus sound fell into the most sensitive part of the porpoise and seal audiograms, weighting of these levels does not change the level and the measured levels can be taken as the discomfort threshold levels.

In Figure 5 the discomfort thresholds are shown in relation to the dose-response relation levels, as proposed by TNO. The harbour porpoise discomfort threshold (Fig. 5a) is halfway between 'well audible' and 'severe discomfort', which seems to be plausible. Therefore the proposed relationship seems to be applicable. The seal discomfort threshold level (Fig. 5b) appeared to be not very much above the 'well audible' level. Therefore the proposed dose-response relationship might be somewhat optimistic. Further study will show whether it will be necessary to correct the seal relationship levels somewhat.

Our studies make clear why harbour porpoises never approach ships with mechanical propulsion, radiating unweighted broadband levels of 180-200 dB re 1 μPa (RMS).

The main message of this paper, however, is that the discomfort threshold levels of both species are low. Man-made noise criteria in certain countries tolerate maximum exposure levels of 160 dB re 1 μPa (RMS) and higher. According to the

TNO criteria these levels even approach hearing injury and therefore should be reduced considerably when applied for small marine mammals. Levels of 160 dB re 1 μPa (RMS) and higher might only be applicable for large odontocetes and baleen whales, however.

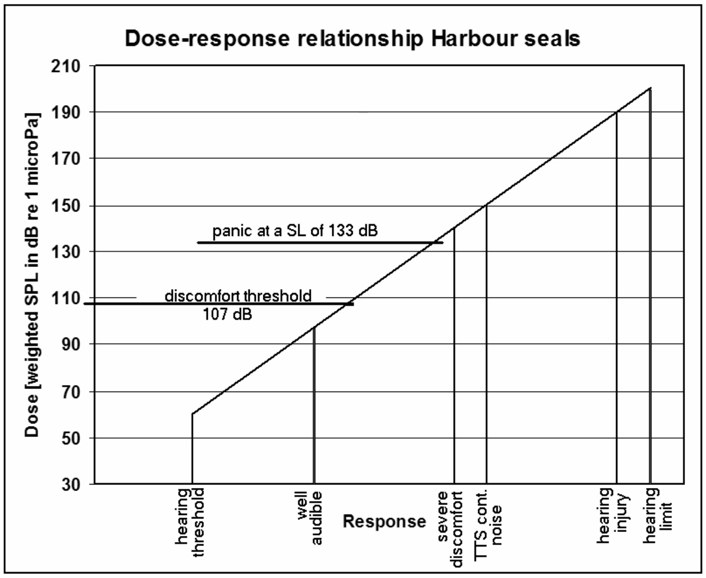

Figure 5b: The dose-response relationship for harbour seals (Group 4a), as proposed by TNO, and the measured discomfort threshold. The discomfort threshold is not far above 'well audible'.

An acoustic alarm with a broadband source level of 133 dB (RMS) re 1 μPa at 1 m – and consequently a lower exposure level – caused panic in the harbour seals.

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