The effectiveness of acoustic harassment devices in the Bay of Fundy, Canada: seal reactions and a noise exposure model

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Abstract

Acoustic harassment devices (AHDs) are used by the Atlantic salmon (*Salmo salar*) industry to deter harbour seals (*Phoca vitulina*) from aquaculture cage sites. Two preliminary behavioural studies suggest that many harbour seals in the Bay of Fundy, Canada, have habituated to the sounds of AHDs. Although the sample size was low, no response or change in behaviour of seals in the water occurred when a nearby AHD was activated. Some seals came within 45 m of an active AHD. Seals also passed close by an active AHD when moving to a haulout site. *In situ* sound pressure level measures were made around the periphery of nine aquaculture cage sites in the Deer Island area of the Bay of Fundy. Sound pressure levels at 1, 5 and 10 m depths within the aquaculture cage sites were generally ≤ 162 dB re 1 μPa. The individual pulse lengths of the AHD pulse trains were typically 2 msec. Ambient noise levels at 9–11 kHz did not vary with time of day, but were influenced by weather. The highest sound level recorded at cage sites within 10 m of the surface was 168 dB re 1μPa which is about 80 dB above the seal's detection threshold for short pulses at these frequencies. On most days, AHD sounds would be clearly audible to harbour seals at ranges of 1.1 to a theoretical maximum of 20.2 km, depending on the ambient noise levels and sound transmission characteristics in the region adjacent to the cage site. Our results suggest that harbour seals in the study area are not frightened away by the sounds of AHDs and that the sound levels throughout most of the cage sites do not reach the likely pain threshold.

Key words: acoustic deterrent, harbour seals, *Phoca vitulina*, aquaculture, underwater noise

Introduction

Harbour seal (*Phoca vitulina*) predation on cultured Atlantic salmon (*Salmo salar*) is of concern among fish farmers. It is believed that seals cause significant damage by destroying nets and fish (Morris, 1996). A number of seal deterrent methods have been developed. Of these, Acoustic Harassment Devices (AHDs) are designed to frighten seals or induce auditory discomfort upon approach. Attached to permanently deployed aquaculture cages, they often are operated continuously (Johnston & Woodley, 1998). AHDs are costly and could be associated with the displacement of harbour porpoise (*Phocoena phocoena*) and other marine mammals (Morris, 1966; Johnston & Woodley, 1998; Morton & Symonds, 2002).

Although AHDs are thought to be successful in some areas (Morris, 1996; Yurk & Trites, 2000), other studies indicate that they have only limited success, especially over extended periods of time (Anderson & Hawkins, 1978; Akamatsu *et al.*, 1996). Artificial sounds, such as those produced from AHDs, are generally less effective than those that are biologically significant (Fish & Vania, 1971; Cummings & Thompson, 1971). The continuous exposure of harbour seals in the aquaculture areas of the Bay of Fundy to AHD sounds (Johnston & Woodley, 1998) could result in the seals habituating to these sounds.

Based on the hearing characteristics of harbour seals, the masking effects of ambient noise levels, the sound transmission characteristics in the region, and the sound levels of AHDs, noise exposure models can be generated to estimate the ranges at which the AHD sounds could be influencing the behaviour of seals and other marine mammals. Richardson & Malme (1995) identified four zones: (1) the zone of audibility in which the marine mammal could hear the sound, (2) the zone of responsiveness in which the marine mammal reacts behaviourally or physiologically to the sound, (3) the zone of masking in which the sound interferes with the animal's ability to detect useful sounds or the calls of conspecifics, and (4) the zone of hearing loss, in which the sound levels are high enough to cause discomfort or damage to their hearing
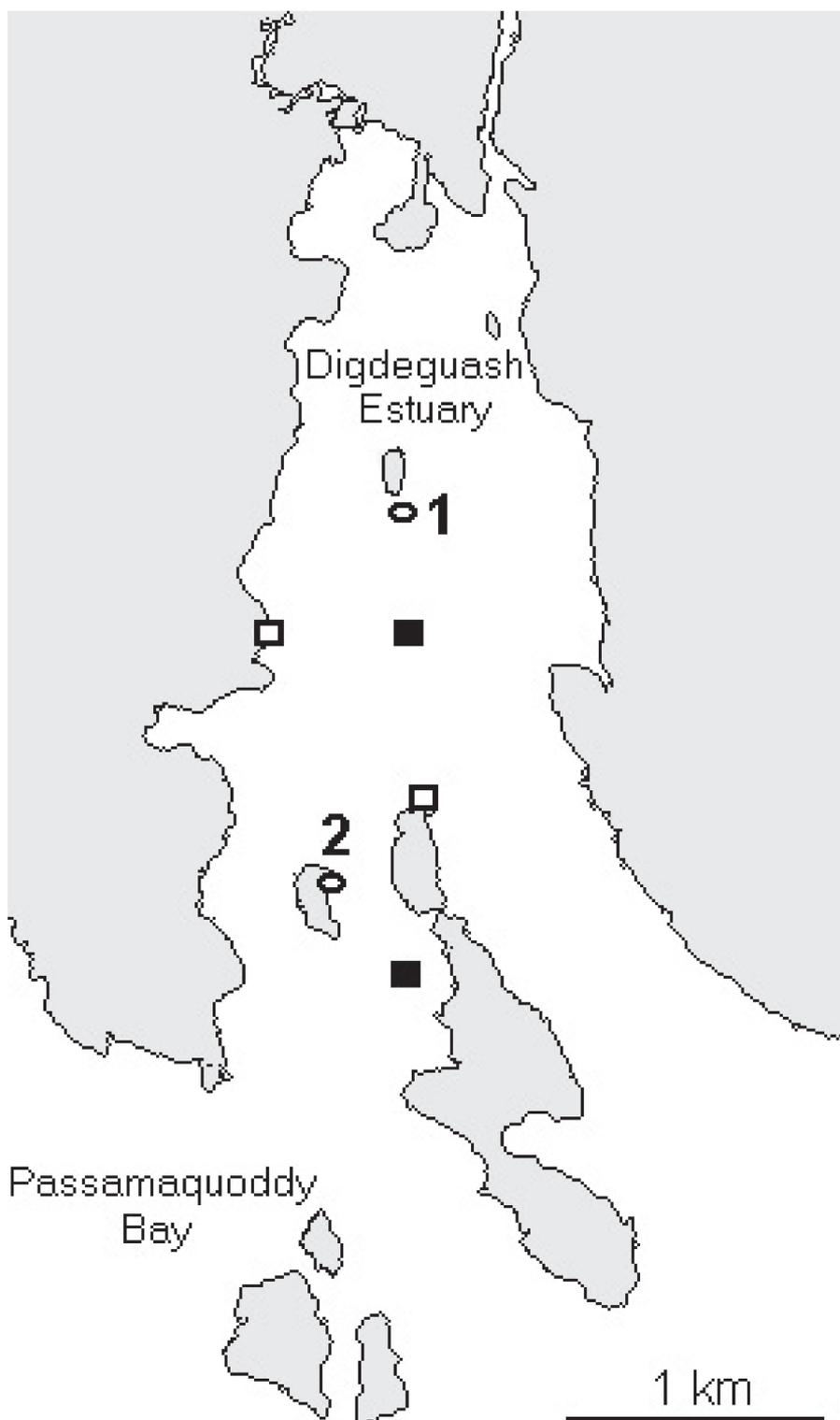
systems. The ranges of these zones will suggest the possible impact of AHD usage on harbour seals and other marine mammals.

It is difficult to predict underwater sound transmission in shallow areas and where items in the water (such as the aquaculture cages themselves) block sound. The manner in which AHD transducers (sound generators) are deployed and their actual sound output also will influence the sizes of the various zones of influence. There is a clear requirement to employ *in situ* sound level measurements to determine the actual sound levels of AHDs within or near the cage sites. This will be necessary to assess the potential influence of the zones of responsiveness or hearing loss, discomfort, or damage at close range. Measures at a distance from the cage sites will be necessary to assess the potential area of the zones of audibility and masking, including possible effects on unintended species (Johnston & Woodley, 1998; Morton & Symonds, 2002).

We conducted some preliminary studies on the behaviour of harbour seals in the immediate vicinity of an active AHD to determine if they would react to the sounds or pass through an ensonified area to get to a haulout site. We also measured the sound levels of nine finfish aquaculture sites, both within and beside the cages, and at ranges up to 4 km. Sound level measurements were used to produce a noise exposure model and estimate the zones of audibility and discomfort (Richardson & Malme, 1995), of AHD sounds on harbour seals in the Bay of Fundy.

Materials and Methods

The field work associated with this study was conducted between 15 December 1999 and 29 August 2000. The study area included Passamaquoddy Bay, Deer Island and Campobello Island and adjacent islands in the lower Bay of Fundy, Canada (45°N, 67°W). Previous findings indicated that the AHDs in use in this area were predominately Airmar™ devices. All observations and sound measures were made during favourable weather conditions with relatively low wind speeds and little, if any, precipitation.

Part I a: seal reactions to an operating AHD
Hauled out harbour seals were flushed into the water by approaching the haulout site with a 13–m research vessel near midday during a falling tide (when the number of hauled out seals is highest; Pauli & Terhune, 1987a). Harbour seal haulout site

numbers are highest on bright, sunny days, with low winds and minimal waves (Pauli & Terhune, 1987b). If all the seals did not enter the water upon approach, a whistle or a compressed air horn was sounded. Once in the water, the seals were given a 2 min acclimatization period during which the vessel drifted adjacent to the location where the seals entered the water. After the acclimatization period, four AHD (Airmar dB Plus II) transducers were lowered into the water and activated. The Airmar dB PLUS II has a ramp-up time of 70 s (to prevent auditory damage to marine mammals); the highest sound levels were therefore not initially generated. The source sound pressure level of the AHD used throughout the reaction studies was determined using the calibrated recording system described in Part II of this study. The seal behaviour was observed and recorded on video. Distances of seals and the haul out sites from the vessel were measured using an optical range finder (Bushnell Yardage Pro: 20–300 m). At control sites, seals also were approached, flushed into the water, and observed with silent transducers placed into the water. These trials were conducted on 6 days, with five control sites and 11 treatment sites.

Part I b: seal reactions to an AHD deployed nearby
The second test was designed to determine whether or not seals would pass through an ensonified zone (area with sound). The experiment was conducted in the narrow estuary of the Digdeguash River (Fig. 1) which provided the seals access to known haulout sites upstream (Jacobs & Terhune, 2000). The numbers of seals observed on one or two haulout sites in the estuary were recorded every 5 min from high to low tide. Observations of seals on haulout sites 1 and 2 began on 29 June and 9 August 2000, respectively. On separate days, the seals either had to pass through the area with an active AHD device suspended from the vessel, with an inactive device suspended from the vessel, or while under observation from shore without the vessel, to obtain access to the haulout site. On days when the research vessel was used, individual counts were taken by two observers, one on shore and one on the vessel. Often one observer was able to view a larger proportion of the haulout site so the higher of the two haulout site counts was used for analysis. On days with no vessel, only counts from shore were made. Three trials were conducted with an activated AHD operating from the vessel, four with an inactive device suspended from the

Figure 1. The Digdeguash Estuary in Passamaquoddy Bay, New Brunswick, showing the locations of the two harbour seal (*Phoca vitulina*) haulout sites (open circles), research vessel (closed box), and shore observation points (open box): modified from a topographical map produced by the Canadian Department of Energy, Mines and Resources, 1980.

Table 1. Location and physical parameters of the aquaculture sites in the Quoddy region of the Bay of Fundy from which data for the Acoustic Harassment Device (AHD) noise exposure model were collected.

Site	Location	Number of cages per assemblage	Total number of transducers
F	Deer Island	4, 22, 24, 22	10
K	Letite	2, 12, 4	4
FH	Campobello Island	18	4
L	Deer Island	16	1
C1	Back Bay	16	6
C2	Back Bay	5	2
FB	Campobello Island	21	4
B	Frye Island	8, 8, 8, 6, 6, 6	4
S	Campobello Island	14	2

vessel, and three from shore without the vessel or active AHD. The ranges of the number of seals hauled out between treatments were compared.

Part II: sounds of AHDs

Recordings of acoustic harassment devices were made at 9 aquaculture sites between 20 December 1999 and 2 August 2000. A Sony™ Digital Audio Tape Walkman TCD-D7 or TCD-D100 (± 1 dB from 0.02–20 kHz), and a calibrated Vemco™ VHLF hydrophone (± 4 dB, 0.03–20 kHz), were used to record the sound levels. A calibration tone of 1 kHz at 94 dB re 20 µPa (Bruel and Kjaer™ 4230) was recorded via a Realistic™ sound level meter (Cat. No. 33–2050) at the beginning of each session. The Vemco hydrophone and 94 dB tone were calibrated against a Bruel and Kjaer 8100 hydrophone with a known frequency response (comparison method; Caruthers 1977). These calibrations indicated that the tone was equivalent to a sound pressure level (SPL) of 139 dB re 1 µPa at 10 kHz from the hydrophone.

On-site recordings were made at 1 to 4 locations in equidistant intervals around the perimeter of each cage when access to these locations by boat or walkways was possible. Automatic feeding systems often inhibited access inside the cage assembly. In cases where access was not possible, recordings were made only on the perimeter of each cage. Recordings were made at 1, 5, and 10 m hydrophone depths for the duration of a complete firing cycle (the time required for all transducers to fire). Details concerning the aquaculture sites from which the data were collected are reported in Table 1. A series of distance measures between cage assemblies and between cages were made with an optical rangefinder (Bushnell™ Yardage Pro; 20–300 m). A detailed map was drawn of each site and used to determine the distance between each recording location and the nearest transducer.

Off-site recordings were made from the aquaculture sites listed in Table 1, with the exception of site S (owing to the unavailability of the research vessel). Complete firing cycles were recorded at approximately 0.05, 0.1, 0.2, 0.3, 0.5, 1, 1.5, 2, 3, and 4 km from the sites along one, two, or three linear transects contingent on the presence of physical obstacles around each site. Recordings were made at hydrophone depths of 1, 5, and 10 m at each location. Distances from each aquaculture site were determined with an optical range finder (up to 300 m) or Magellan™ Trailblazer XL Global Satellite Positioning System (0.3–4 km).

The sound levels of the AHD pulses (on-site and off-site) were measured by playing the signal through a Krohn-Hite™ model 3550 filter, with a bandwidth of 2–20 kHz to a Gould™ Model 1425 20 MHz digital storage oscilloscope. The wide bandwidth was to ensure that no part of the AHD signal would be in the roll-off zone of the filter. The peak-to-peak amplitudes of the AHD pulses were converted into dB re 1 µPa in relation to the peak-to-peak amplitude of the sinusoidal calibration tone (see Terhune, 1988). Data analysis was conducted using the loudest pulse at each location and depth. The source levels of two AHDs were measured. One transducer from each unit was lifted to a depth of 5 m and recordings were made at distances of 5 m and 10 m at 1 m, 5 m, and 10 m hydrophone depths.

One- and two-way ANOVA was used to determine if the AHD sound levels varied with respect to aquaculture site, hydrophone depth, and distance from the transducer for both the onsite and offsite recordings.

Five, 25-h ambient noise recording sessions were completed in the Deer Island area from a moored research vessel between 15 December 1999 and 13 June 2000. Recordings were made for 20 min every hour at a hydrophone depth of 5 m. From each 20 min recording, 10 spectral slices (0 to 22.05 kHz;

analyzing bandwidth 172.3 Hz) were randomly selected. Analyses were performed using Multi-speech Model 3700, version 2.01 (Kay Elemetrics Corp.) with a sampling rate of 44.1 kHz. A subset of the data was taken of the sound levels between 9 and 11 kHz, the frequencies 1 kHz above and below that of the Airmar dB PLUS II AHD. A cumulative frequency distribution of sound levels from each hour of all five days was generated to determine the sound levels of this frequency band present (or exceeded) 95, 50, and 5% of the time (quietest 5%, median and loudest 5%). A MANOVA was used to determine if there was a significant difference between hours and days.

Results

Part I a: seal reactions to an operating AHD
The source level of the AHD used in the behavioural studies was 172 dB re 1 µPa. Throughout all trials, no observable reactions by the seals to the AHD were noted. The harbour seals exhibited individual differences in reactions to the research vessel and to the disturbances used to flush them into the water. On most occasions it was not possible to flush all the seals into the water simply by approaching them in the research vessel (usually up to 90 m). On one occasion a distance of 35 m was reached while a few seals remained on the site. Similar differences were seen when a loud whistle was blown to flush the seals into the water. When a compressed air horn was used, all seals rushed into the water immediately on all (9) occasions.

When the AHD was turned on, no fright reactions (such as rapid swimming, porpoising, or immediate haul-out; Mate & Harvey, 1986) were observed. Seals in the vicinity of the research vessel showed no apparent difference in reaction between treatments when the AHD was active and inactive, though not all seals were accounted for and observations below the water surface were not possible. During all trials, most seals were between the research vessel and the shore, about 200 m away. The closest distance between the research vessel and a seal at the surface while the AHD was turned on was 43 m.

Part I b: seal reactions to an AHD deployed nearby
The range of harbour seal counts on the identified haulout sites (Fig. 1) per treatment varied with day (Table 2). All treatments resulted in similar variability of numbers of hauled-out harbour seals. On 14 August 2000, while moored in the middle of the Digdeguash Estuary, a group of seals swimming together were observed 77 m from the active AHD (and research vessel). One seal was observed 44 m from the vessel and dove under water a minute

Table 2. Maximum and minimum harbour seal (*Phoca vitulina*) counts on two haulout sites in the Digdeguash Estuary (1 and 2: Fig. 1) when the research vessel was (Vessel) and was not (Shore) present in the estuary and when an Acoustic Harassment Device (AHD) was deployed from the vessel (Vessel/AHD).

Date	Treatment	Site(s)	Maximum	Minimum
29 June	Vessel	1	37	0
7 July	Shore	1	2	0
9 July	Shore	1	5	0
13 July	Vessel	1	13	0
14 July	Vessel/AHD	1	10	0
30 July	Vessel/AHD	1	29	0
9 August	Shore	1	0/59	0/5
12 August	Vessel	1/2	0/27	0/0
14 August	Vessel/AHD	1/2	0/31	0/0
29 August	Vessel	1/2	7/37	0/0

later. Seals also were observed 45 and 46 m from the operating AHD 17 min later.

Part II: sounds of AHDs
The Airmar AHDs produced a series of pulses (<2 kHz bandwidth) at 10 kHz for 2.5 s. Each pulse was 1.8 ms long and was repeated every 40 ms. Source levels measured along the acoustic axis of the transducer for the AHD systems on sites B and F were 179 and 178 dB re 1µPa, respectively.

A two-way ANOVA of the variation in sound level with depth at each aquaculture site indicated that the sound levels at 10 m were slightly higher than those at 1 or 5 m depth ($F=11.94$, df$=2,1379$, $P<0.001$). The differences between the means at 1 m and 10 m varied between 0.04 and 3.14 dB. There were significant differences in sound levels among sites ($F=490.21$, df$=8,1379$, $P<0.001$) with no interaction between aquaculture site and depth ($F=1.34$, df$=16,1379$, $P=0.14$).

A one-way ANOVA of the on-site data of the variation in sound levels with the distances up to 100 m to the nearest transducer (Fig. 2) indicated that there was a significant difference in the sound level of the acoustic harassment device with distance ($F=12.03$, df$=1284$, $P<0.001$). Sites L and FB had the lowest sound levels overall.

All far range recordings were made adjacent to the aquaculture sites visited for on-site recordings except S. The far range recordings for sites C1 and C2 were combined due to the close proximity of these two sites (approximately 400 m apart).

A two-way ANOVA of the variation in sound level with depth at each aquaculture site at distances up to 4 km indicate that there was no significant difference in sound level at 1, 5, or 10 m
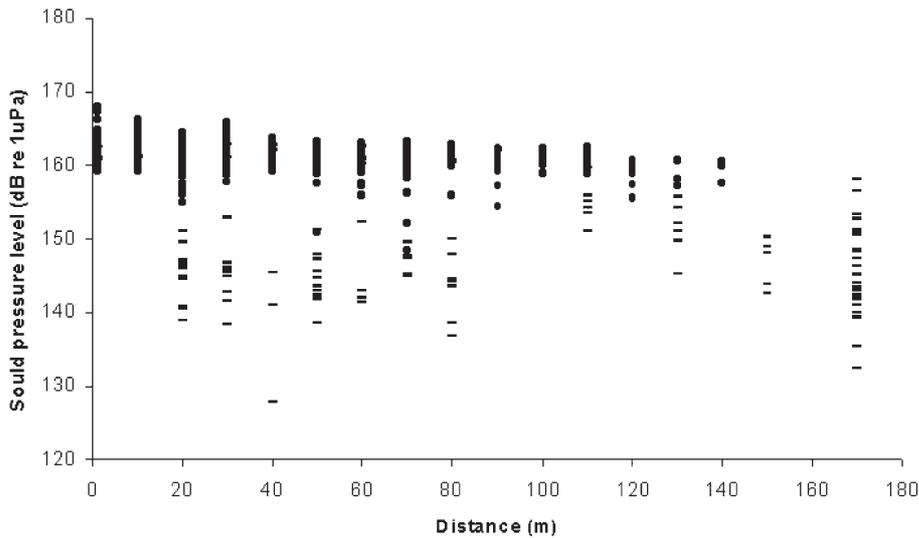
Figure 2. Close range sound pressure levels (dB re 1 μPa) of Acoustic Harassment Devices (AHDs) from nine aquaculture cage sites in the Bay of Fundy, Canada; closed circles=data from seven aquaculture sites, dashes=data from two aquaculture sites with lower sound levels.
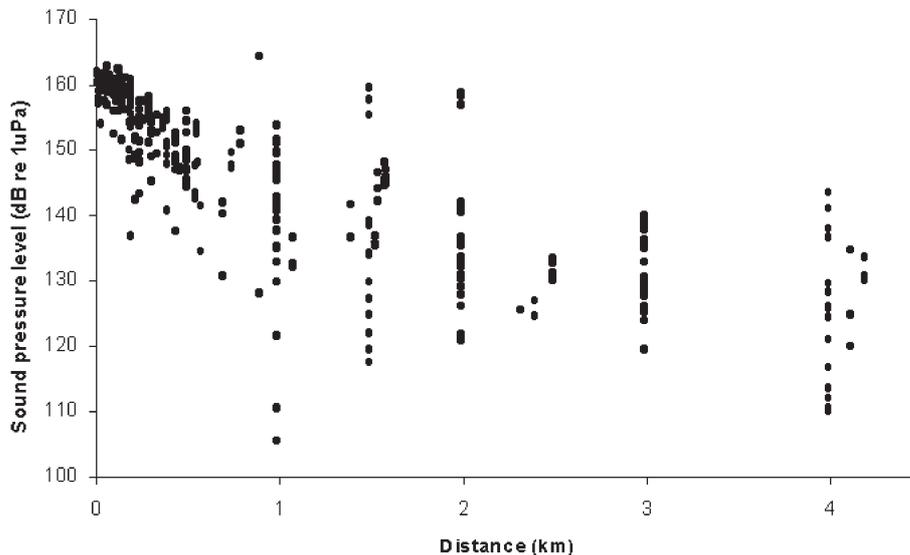
Figure 3. Far range sound pressure levels of Acoustic Harassment Devices (AHDs) recorded from seven aquaculture sites in the Bay of Fundy, Canada. Other nearby AHDs have likely compromized the distance measures (see text).

(F=0.35, df=2,311, P=0.703). There were significant differences in sound levels between sites (F=8.33, df=6,311, P<0.001) with no interaction between depth and site (F=0.11, df=12,311, P=0.99).

A one-way ANOVA of the sound levels up to 4 km from the aquaculture site (Fig. 3) indicated that there was a significant difference with distance (F=8.33, df=3,87, P<0.001). At least two (maximum eight) other aquaculture sites were located within the 4-km radius of the far range recordings of each aquaculture site measured. It was not possible to ensure that AHDs on these sites were turned off during data collection. It is likely that some of the distance measures presented in Figure 3 are incorrect due to there being another

aquaculture site with an active AHD closer than the one under study. Because of the similarity of the AHD sounds it was not possible to distinguish among different machines.

Ambient noise levels
Ambient spectrum noise levels (means ± standard deviation) from 9 to 11 kHz present or exceeded 95, 50, and 5% of the time were 45.2 ± 6.0, 61.4 ± 7.4, and 69.9 ± 13.5 dB re 1 µPa, respectively. The sample size was 119; on some days up to two recordings were not obtained due to technical difficulties. A MANOVA on the combined ambient noise levels per hour indicated that there was no significant difference among hours (Rao's R=0.67, df=96,363, P=0.99), but there was a difference among days (Rao's R=12.58, df=20, 365, P<0.01).

Noise exposure model
The noise exposure model is a compilation that incorporated the hearing threshold variability of the subject, the ambient noise levels, the critical ratio of the subject, the increase in threshold associated with short pulse durations, and the level of the signal/ noise at different ranges from the source. It is necessary to incorporate as many *in situ* influences as possible in this model to improve the accuracy, especially with respect to the levels of the interfering noises.

The hearing range of harbour seals extends to high frequencies, with an upper limit above 60 kHz (Møhl, 1968). The detection threshold, the sound level at which a signal is detected 50% of the time, of a harbour seal at 10 kHz (frequency of sound from the AHDs used in this study) is 65–70 dB re 1 µPa (Møhl, 1968; Terhune & Turnbull, 1995). We used a detection threshold of 70 dB re 1 µPa for calculations. Certain detection of a sound is likely 20 dB above the detection threshold (Terhune & Turnbull, 1995). The critical ratio, the difference between the sound level of a barely audible sound and the spectrum level of background noise (1 Hz bandwidth) at adjacent frequencies for a harbour seal was 23 dB (Turnbull & Terhune, 1990).

The detection threshold is affected by the duration of the signal. Very short signals (<40 ms at 10 kHz; Terhune, 1988) require a higher sound level to be detected by the listening organism. Consequently, the detection threshold of a harbour seal is increased by 20 dB when pulse durations are only 2 ms at 10 kHz (Terhune, 1988).

For humans, the effects of high noise levels are known; temporary threshold shifts (a decrease in auditory sensitivity) occur at about 90–100 dB above hearing threshold. Extrapolating these values and applying them to marine mammal systems has obvious problems, but using a value of 80 dB above threshold (Richardson & Malme, 1995) may present conservative findings with respect to the potential noise damage to harbour seals by AHDs.

To construct a noise exposure model, whether the range of detection is influenced by the threshold of the target organism or by the level of ambient noise must first be determined (Richardson & Malme, 1995). If the ambient noise plus the critical ratio of the target organism exceeds the detection threshold, the maximum range of potential detection will be limited by the ambient noise level, rather than by the absolute hearing threshold.

Our model incorporated the mean sound levels from the on-site data up to 0.15 km and calculated sound levels for ranges between 0.15 and 20 km with attenuation due to spherical spreading alone or a combination of spherical and cylindrical spreading. A theoretical equation was used because interference from other AHDs operating close by was noted when far range recordings were made. Both types of spreading were considered to describe sound transmission in both shallow and deep water. Source SPLs, from a previously unused device, of 175 dB re 1 µPa were used in the model. The source level of 175 dB re 1 µPa incorporated the sound levels of 195 dB re 1 µPa (Terhune, unpublished observations) and the 20–dB loss associated with the short pulse duration (Terhune, 1988). The 195 dB re 1 µPa source levels are higher than those actually used in the study area, but are used here because they present an estimate of potential disturbance that could be present in the near future should new AHDs be installed. The equations used to describe transmission losses are (Malme, 1995):

(a) Spherical spreading: $SPL=175–20 \, logR–AR$ (deep water transmission)
(b) Spherical and cylindrical spreading: $SPL=175–15 \, log \, R–AR$ (shallow water transmission)

where, R is the range from the source (m) and A is an absorption factor (0.0011 dB per m; Albers, 1965).

The ambient noise data between 9 and 11 kHz were then incorporated into the model using the mean noise levels present or exceeded 95%, 50%, and 5% of the time and the 23-dB critical ratio for a harbour seal listening in the presence of ambient noise was added (Turnbull & Terhune, 1990). If this value is higher than the threshold (70 dB for a harbour seal; Møhl, 1968), detection is limited by ambient noise. Audiograms generally describe the 50% detection threshold; the minimum sound level detectable 50% of the time. Twenty decibels were added to ensure certain detection (Terhune & Turnbull, 1995), giving the *in situ* certain detection threshold. Once plotted, the x-intercept with the sound levels of the AHD was determined for both

Table 3. Example calculations of sound pressure levels (dB re 1 μPa) used in the noise exposure model of a harbour seal (*Phoca vitulina*) exposed to AHD sounds at a range of 1 km under conditions of spherical spreading. The audibility is expressed as dB above the sound pressure level at which the signal would be clearly audible. The range of certain detection would be the distance at which the audibility drops to 0 (Fig. 4; Table 4).

Factor	Lowest 5% noise levels	Highest 5% noise levels
A. absolute threshold (50%)	70	70
B. ANL	45	70
C. ANL+23 dB	68	93
D. 50% detection threshold	70	93
E. add 20 dB (certain detection)	90	113
F. AHD source level at 1 m	195	195
G. minus 20 dB (short pulse)	175	175
H. AHD at 1 km (equations in text)	114	114
I. Audibility of AHD (H-E)	24	1

categories of spreading, giving a distance at which the corresponding sound levels occur. Sample calculations are shown in Table 3.

The noise exposure model of an AHD is presented in Figure 4. Based on average on-site sound levels of 162 dB re 1 μPa (Fig. 2), the perceived sound level of an AHD by a harbour seal within the first 150 m is 142 dB re 1 μPa (162–20 dB, due to short duration pulse). Distances at which AHD SPLs reached the *in situ* detection threshold of a harbour seal are presented in Table 4.

Discussion

Part I: seal reactions to an operating Acoustic Harassment Device
A difference between the response by the seals to the approaching vessel, the whistle, and the compressed air horn in this study suggested that the latter is either too loud or frightening for the seals. The approaching vessel and whistle; however, were not as effective since only part of the group responded each time. The compressed air horn is a very loud and uncommon stimulus and harbour seals did not appear to habituate to the sound during the few exposures associated with the reaction study. The lack of observable responses, by even a small proportion of the seals to the AHD sounds, suggests that those devices are not frightening.

The sound source level (not corrected for the short pulse duration effect) from the AHD used during the reaction studies was 172 dB re 1 μPa, 23 dB lower than would be expected from a new AHD (195 dB re 1 μPa) at 1 m. Sound levels produced from AHDs are not identical and can vary for a number of reasons including fouling, low batteries, and long cable lengths between the signal generator and the transducers. At 40 m, the SPL of the AHD used in the reaction studies would be 140 dB re 1μPa, about 70 dB above threshold. The close proximity of some seals to this AHD does not infer that they are not reacting to loud sounds, but rather that they do not appear to find the AHD sounds frightening.

A study by Yurk & Trites (2000) concluded that AHDs can repel seals up to 50 m. They recognized; however, that this effect might only be temporary since pinnipeds are known to habituate to sounds quickly. Changes in motivation, i.e., a depleted source of food, could cause a change in behaviour, which could cause a seal to ignore the AHDs instead of avoiding them. Mate & Harvey (1986) found that seals reacted to a deployed AHD by swimming away. They also noted that seals within 50 m of the transducers often had their heads above water (where the sounds would be quieter).

The difference between the results of this study and those of Mate & Harvey (1986) and Yurk & Trites (2000) suggest that the seals have habituated to the sounds of the Airmar dB PLUS II, in the Deer Island region where there are a high number of these devices operating often throughout the year (Johnston & Woodley, 1998). It is also probable that the SPLs of the AHDs in the other studies were higher and the amplitude of the sound could have had an effect. This emphasizes the need for obtaining *in situ* SPLs. It is also possible, though unlikely, that a proportion of seals in the study area were hearing impaired.

Part II: sounds of AHDs
Only the signal levels of the loudest pulses were used in this analysis. We assumed that the loudest pulses would be those responsible for eliciting a response, if any. Thus, the results present a liberal
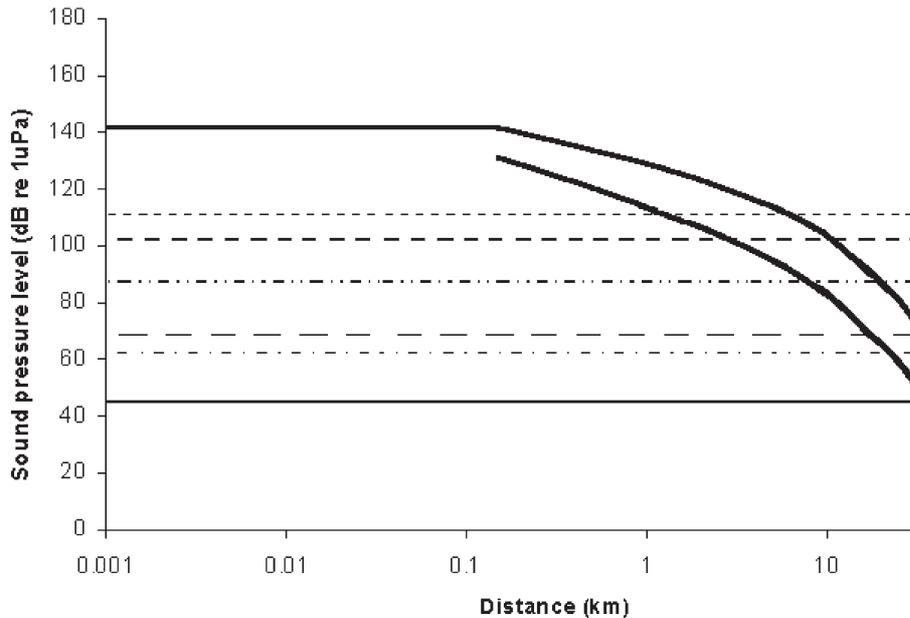
Figure 4. Noise exposure model of an Acoustic Harassment Device (AHD) using recorded sound levels (dB re 1 μPa) from nine aquaculture sites for on-site sound levels (<150 m from the nearest transducer) and the sound pressure level (SPL) transmission equation SPL=175–15 Log (Distance) − (0.0011 × Distance) for off-site (>150 m from the nearest cage) sound level attenuation due to cylindrical and spherical spreading (upper curve) and SPL=175–20 Log (Distance) − (0.0011 × Distance) for off-site sound level attenuation due to spherical spreading (lower curve) in relation to harbour seal hearing thresholds. Note: —— Ambient noise levels (ANL, spectrum level) exceeded 95% of the time (=quietest 5%), – · – · – ANL 50%, - - - - - ANL 5% (=loudest 5%), – · · – · · – SPL of AHDs clearly detectable during quietest 5% of the time, – – – – SPL of AHDs clearly detectable 50% of the time, and —— SPL of AHDs clearly detectable during loudest 5% of the time (see text for details).

Table 4. Calculated zones of audibility for harbour seals (*Phoca vitulina*) for an Acoustic Harassment Device (AHD) with a source sound pressure level of 195 dB re 1 μPa at 1 m using different spreading losses and ambient noise levels in the Bay of Fundy, Canada.

Spread loss	Ambient noise level (% of time)	*In situ* threshold (dB re 1 μPa)	Range (km)
Spherical	Loudest 5%	113	1.1
	Median (50%)	104	2.5
	Low (5%)	90	8.0
Spherical and Cylindrical mix	Loudest 5%	113	5.5
	Median (50%)	104	9.7
	Low (5%)	90	20.2

estimate of noise impact on seals; many of the pulses that the seals hear will be quieter. Audiometric data have only been obtained from a few seals and cannot be used to quantify the hearing abilities of the total population of harbour seals.

Obtaining source sound levels from the AHDs from all sites is recommended. To do this, it is necessary to obtain accurate distance measures from the source at close range (5 and 10 m) and the hydrophone must be located along the acoustic axis

of the transducer. Often it was not possible to make recordings near the cages without interference from the nets. Source levels were only calculated from two systems where recordings could be made along an unobstructed acoustic axis.

Aquaculture sites using AHDs with low SPLs or few transducers are poorly protected (Table 1; Fig. 2). The AHD SPLs did not vary much up to 110 m from the transducers (Fig. 2). Reflections of sounds off the surface and bottom and a probable directional transmission of the sound close to the transducers are likely responsible. The sound levels within 1 m of the transducer cable (where the hydrophone was above the transducer) were not higher than levels measured 20–40 m away (Fig. 2). This suggests that the sound travels from the source in a horizontal cone-like direction, creating a 'shadow' zone (area with a lower SPL) immediately above and below the transducer. This would account for the similar sound levels being found directly above the transducer and at a distance. Recordings made at a distance from the source were influenced by transmission loss and the presence of cages and fish. The presence of the nets themselves, creating shadow zones on the opposite side, would also influence the sound levels of recordings made above the bottom of the net. This and other on-site characteristics relating to shallow water transmission resulted in relatively uniform sound levels for distances up to 180 m (Fig. 2). Where the transducer is below the cage netting, the loudest sound levels encountered would be no higher than 179 dB re 1 µPa at 1 m. The SPLs underneath the cage sites may be slightly higher than those within 10 m of the surface.

If AHDs are to be used, the transducers should be located on the perimeter of the cages to prevent the creation of shadow zones by the cages themselves. Such zones would enable a seal to approach the cages while remaining in an area of lower sound levels. Shadow zones within the assembly would be of less concern if the perimeter is well protected. Sites with only a few transducers will have areas within the cage assembly where the sound levels are very low.

Noise exposure model
Previous research on AHDs and possible effects on target and non-target species have not considered *in situ* sound levels or *in situ* hearing thresholds. This study found that using AHD source levels of 195 dB re 1 µPa for attenuation calculations may not be warranted since *in situ* sound level measures were lower than anticipated. The pain threshold, or the intensity at which a signal causes physical discomfort, is difficult to determine for non-human auditory systems. Often, the mechanism of an

avoidance response is misinterpreted. It is not always possible to distinguish between a reaction to a painful stimulus or to a frightening stimulus.

Our study found that the average on-site signal levels did not exceed 162 dB re 1 µPa. This level would be 92 dB above the detection threshold of a harbour seal if the pulses were longer than 40 ms (Terhune, 1988). Since short duration pulses associated with the Airmar signal increases the detection threshold of a harbour seal by 20 dB, perceived on-site sound levels are only 72 dB above the harbour seal detection threshold. Such sound levels would not likely cause any auditory damage. However, the received on-site sound levels should be louder along the acoustic axis of a new AHD at depths beneath the cages. It is possible that, under these conditions, received sound levels could reach 180 dB re 1 µPa close to the transducer.

Using only the 50% detection threshold of a harbour seal in the noise exposure model is unwarranted because ambient noise, the critical ratio, certain detection and the properties of the signal (short pulse length) influence the detection threshold *in situ*. The mean range at which the AHD sound level reaches the *in situ* detection threshold of a harbour seal with ambient noise levels present or exceeded 95% of the time (that is, during the quietest 5% of the time) is about 8 km, 50% is 2.5 km, and the loudest 5% is 1.1 km (Table 4). These values will vary considerably on a day-to-day basis; however, because of the variability of the noise levels. The standard deviation of the levels of the loudest 5% of the ambient noise levels per hour was 13.5 dB. Where sound levels decrease by 6 dB with each doubling of the distance from the source, a 13 dB variation in noise would result in the detection ranges varying by 1/4 to 4 times that calculated using the mean. Unfortunatley, the density of the AHDs in our study area precluded obtaining measures of SPLs at long ranges. Thus, the detectability of AHDs at the distances presented in Table 4 are not proven.

The calculated ranges of the zone of audibility with attenuation due to shallow water effects (both spherical and cylindrical spreading) were 5.5–20.2 km, depending on the noise levels present (Table 4). The zone of audibility will be greatly reduced when noise levels are much higher i.e., during a rainstorm. However, the calculated zone of audibility will not give an indication of effectiveness of AHDs as a deterrent technique.

The sound levels that apply to the zones of severe disturbance and hearing damage, loss, and injury were never reached in this study. This suggests that the AHDs in use in the Bay of Fundy during the study period would not operate by causing pain to approaching seals.

Recommendations

When trying to determine the effectiveness of a deterrent system, *in situ* data must be collected. In this study, the source sound levels of the AHDs were lower than expected.

The harbour seals in the Deer Island region appear to have habituated to the sounds from the AHDs. It is recommended that the current methods of use (i.e., continuous operation with few transducers on each site) be discontinued. At the very least, the AHDs should be turned off when seal attacks are unlikely (during the late spring, summer and early fall; Jacobs & Terhune, 2000) and during the day when workers are on site.

The AHDs used in the study area were neither painfully loud nor frightening to harbour seals. It is possible to create a system that produces a louder sound level and longer pulses. This would increase the power necessary to operate the device and therefore incur a higher cost of operation and possibly the risk of affecting non-target species (Johnston & Woodley, 1998). A very loud device that is activated by the presence of a seal (i.e., by disturbances to the predator nets around the cages) could therefore be more effective. This feature has been investigated by some manufacturers, but the triggering system has encountered problems (Iwama *et al.,* 1998).

Sound transmission along the acoustic axis of the transducer will be spherical until the bottom or water surface cause reflections. As a result, there will always be a significant decrease in the sound level close to the source (6 dB from 1 to 2 m, another 6 dB from 2 to 4 m etc.). Sound sources that are very loud at 1 m will be 60 dB lower at 100 m, perhaps more if nets are blocking the sound pathway. The inability to produce loud sound fields in a cost effective manner and the potential for habituation by seals suggest that AHDs may have limited usefulness. In general, the use of acoustic deterrents in animal damage control have not been shown to be effective in the long term (Bomford & O'Brien, 1990). We recommend that other methods of seal protection, including more effective physical barriers, such as taut anti-predator nets, be explored. It is also recommended that any new methods of deterrence be investigated for their effectiveness over longer periods of time prior to use for industrial purposes.

Acknowledgments

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