Behavioural effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*)

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Abstract: Humpback whale (*Megaptera novaeangliae*) entrapment in nets is a common phenomenon in Newfoundland. In 1991–1992, unusually high entrapment rates were recorded in Trinity Bay on the northeast coast of Newfoundland. The majority of cases occurred in the southern portion of the bay close to Mosquito Cove, a site associated with construction operations (including explosions and drilling) that presumably modified the underwater acoustic environment of lower Trinity Bay. This study reports the findings of the resulting assessment conducted in June 1992 on the impact of the industrial activity on humpback whales foraging in the area. Although explosions were characterized by high-energy signatures with principal energies under 1 kHz, humpback whales showed little behavioural reaction to the detonations in terms of decreased residency, overall movements, or general behaviour. However, it appears that the increased entrapment rate may have been influenced by the long-term effects of exposure to deleterious levels of sound.

Résumé : L'enchevêtrement de Rorquals à bosse (*Megaptera novaeangliae*) dans des filets de pêche est un phénomène fréquent à Terre-Neuve. En 1991–1992, un nombre particulièrement élevé de cas d'enchevêtrements ont été rapportés à Trinity Bay, sur la côte nord-est de Terre-Neuve, et la plupart ont été enregistrés dans la portion sud de la baie, au voisinage de Mosquito Cove, un site de manoeuvres de construction (explosions, forage) qui ont probablement pour effet de modifier l'environnement acoustique sous-marin dans la partie basse de la baie. Les résultats que nous présentons ici sont ceux d'une étude effectuée en juin 1992 sur les effets de l'activité industrielle sur les rorquals qui se nourrissent dans ces eaux. Les explosions étaient caractérisées par une énergie très forte (énergies principales de moins de 1 kHz), mais les rorquals ont réagi très peu aux détonations et nous n'avons pas observé de diminution des individus résidants, ni d'émigrations massives ou de modifications du comportement général. Toutefois, l'augmentation du nombre d'enchevêtrements peut avoir été influencée par les effets à long terme d'une exposition à des phénomènes acoustiques dangereux.

[Traduit par la Rédaction]

Introduction

Humpback whales (*Megaptera novaeangliae*) visit feeding grounds off the coast of Newfoundland annually between April and October. They are often seen in inshore areas from June to August as they move northward. During the same months (except since the Canadian Government's groundfish moratorium of 1993), fishing activity for capelin (*Mallotus villosus*), cod (*Gadus morhua*), and other groundfish species is intense. Because of the spatially overlapping high density distributions of both nets and local humpback populations, entrapment of humpbacks in fixed fishing gear is a common problem (Lien 1994).

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The causes of entrapment are not fully understood, although indirect evidence collected over the past decade provides several explanations. Data suggest that entrapment is partly an acoustic problem; that is, whales fail to detect the net acoustically in time to avoid it because of either cryptic, masked, or weak acoustic cues produced by the net (Lien et al. 1991*b*; Todd 1991). Todd (1991) demonstrated a negative correlation between strength of acoustic cues produced by a net and probability of entrapment. Devices designed to increase acoustic detectability of nets decrease the probability of entrapment. For example, Lien et al. (1991*b*) reported on the partial success of alarm systems designed to reduce entrapments by acoustically enhancing the net. Acoustic alarm systems of other designs (Lien et al. 1992; Todd et al. 1992) have also proved effective in reducing entrapment rates.

However, a number of other trends are seen in cases of entrapment that are not necessarily explained by an acoustic model. For example, most animals caught appear to be young males (Lien 1980). Furthermore, humpbacks appear to learn from the experience of entrapment, as previously caught animals do not subsequently become re-entrapped (Lien 1980).

Rates of entrapment in Newfoundland have been monitored since 1980 (Lien 1994). Since the numbers of entrap-

Fig. 1. Map of Newfoundland, with inset detailing Trinity Bay. The explosions occurred in Mosquito Cove, Bull Arm.
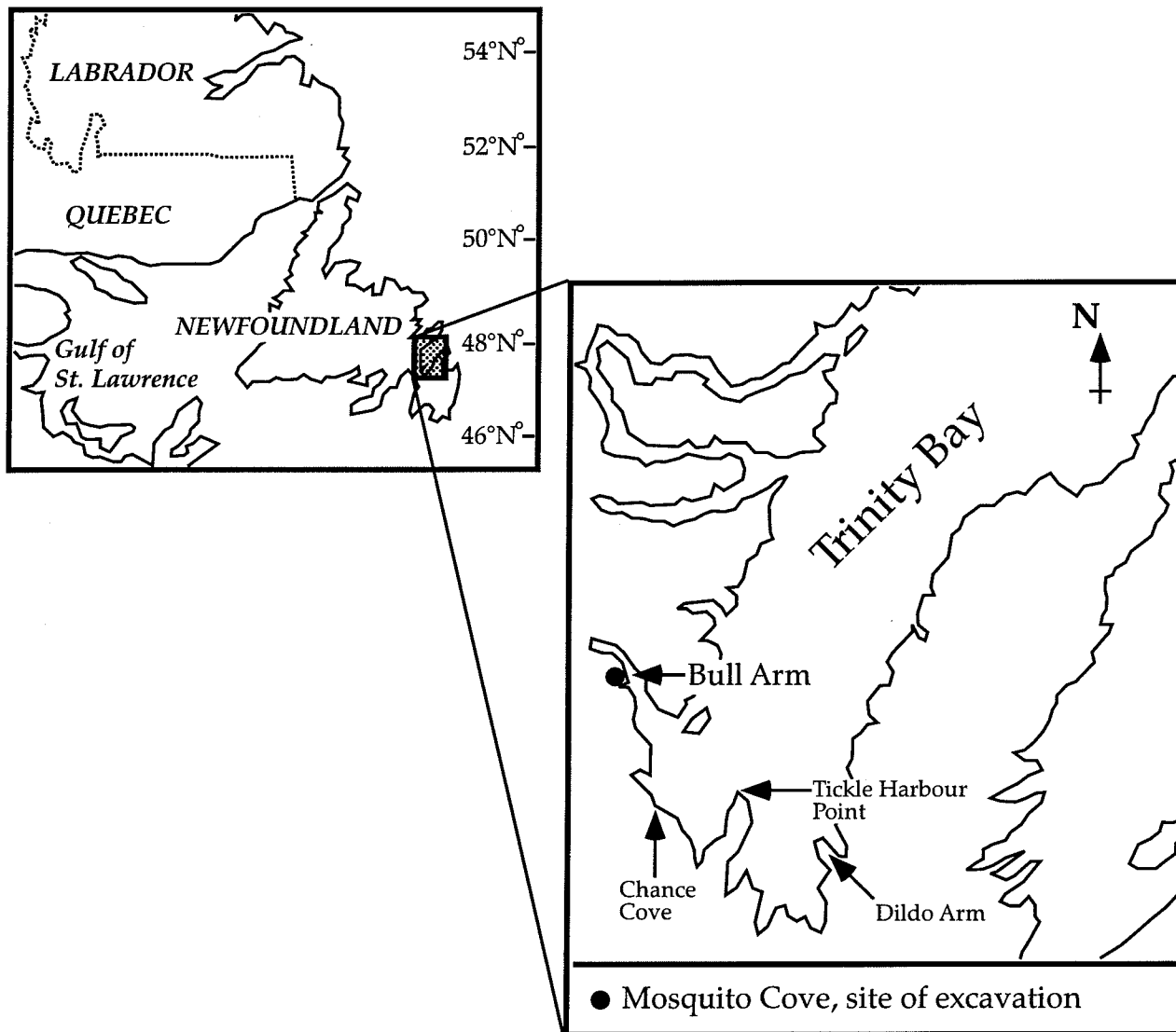
ments vary each year (Lien 1979; Lien and McLeod;[2] Lien and Aldrich;[3] Lien et al. 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990, 1991a, 1993), one method of assessing the occurrence of entrapments on a per area basis is to calculate the percent contribution of any one area to the annual total. Because of the non-normal distribution of such proportional data, comparisons between years should be performed using randomization methods such as those reviewed by Crowley (1992) and as used below.

The number of entrapments occurring in Trinity Bay (Fig. 1) relative to other areas is typically low (Table 1). However, beginning in 1991 and continuing throughout 1992, an offshore drilling support site was built at Mosquito Cove in Bull Arm, a small fjord leading into lower Trinity Bay

(47°45′N, 53°50′W) (Fig. 1). Simultaneously with the onset of industrial activity in Bull Arm, entrapments in the Trinity Bay area increased dramatically; the combined average contribution of Trinity Bay to the annual entrapment figures for 1991–1992 (mean ± SD = 19.34 ± 6.20) was significantly higher than for previous years (mean ± SD = 3.54 ± 3.02) (Monte Carlo randomization t test, 3000 iterations, $p <$ 0.0001; see Table 1). In addition, the majority of these entrapments were occurring in the lower areas of Trinity Bay, close to the opening of Bull Arm (Figs. 2, 3), even though fishing communities, and therefore the potential area of entrapment, extended north up both sides of the bay. The average distance from a Trinity Bay entrapment site to Mosquito Cove was significantly greater for the years prior to 1991 (mean distance ± SD = 62.29 ± 42.29 km) than during construction years (mean distance ± SD = 35.71 ± 21.99 km) (Monte Carlo randomization t test, 3000 iterations, $p <$ 0.0001; see Table 2). Also in 1992, two re-entrapments occurred in Trinity Bay.

Some of the construction work at Bull Arm required drilling activity and sequences of underwater explosions. Initially,

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[2] J. Lien and P. McLeod. 1980. Humpback collisions with fishing gear: arbitration and education in a whale–fisherman dispute. Unpublished report.

[3] J. Lien and D. Aldrich. 1981. Damage to inshore fishing gear in Newfoundland and Labrador by whales and sharks during 1981. Unpublished report.
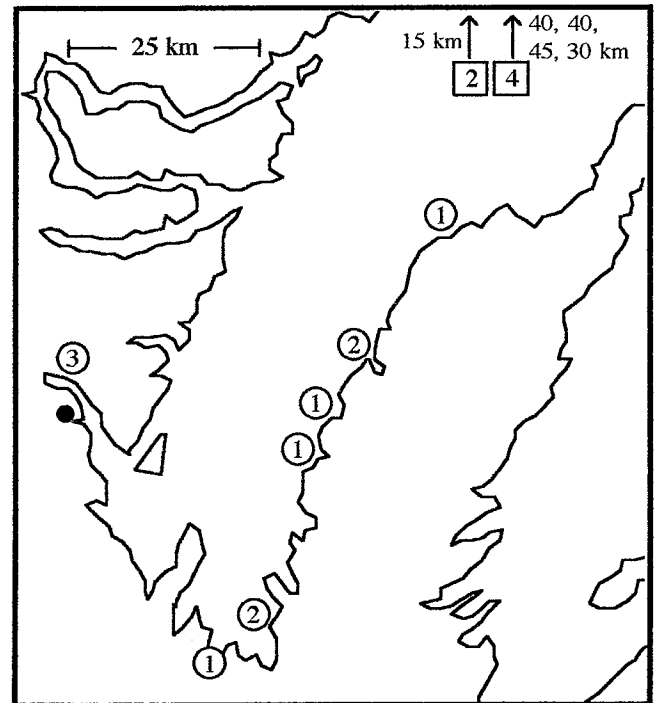
Table 1. Percent contribution of entrapments in Trinity Bay to the annual total for Newfoundland and Labrador (see Figs. 2 and 3 for data sources) for preblasting (1979–1990) and blasting (1991–1992) periods.

Year	Number of entrapments		% of total
	Total	Trinity	
1979	36	2	5.55
1980	200	14	7.00
1981	30	1	3.33
1982	33	0	0.00
1983	35	0	0.00
1984	26	2	7.69
1985	53	0	0.00
1986	33	1	3.03
1987	44	0	0.00
1988	62	2	3.22
1989	70	5	7.14
1990	73	4	5.48
1991	127	19	14.96
1992	59	14	23.73

Fig. 2. Entrapment locations in Trinity Bay for the period 1979–1990, i.e., prior to the onset of increased industrial activity. Number of entrapments and approximate location are shown in circles. Number and location of entrapments in Trinity Bay outside the range of the map are shown in squares, with approximate direction and distance from the upper edge of the map. Data for 1980 (14 entrapments) are omitted, as information was not available for precise locations (data are compiled from Lien 1979; Lien and McLeod, see footnote 2; Lien and Aldrich, see footnote 3; Lien et al. 1982, 1983, 1984, 1985, 1986, 1987, 1988, 1989, 1990). ●, site of excavation.

fishermen in the area inferred a connection between the increased number of whale collisions and the explosions. It was reasonable to expect higher noise levels in the lower Trinity Bay area as a result of industrial operations for the period 1991–1992. The above findings indicated that the increased entrapment rate coincided with the onset of industrial activity.

In fact, little is known about the effects of high-amplitude rapid-onset acoustic signals on the behaviour of marine mammals. Recent comprehensive reviews by Richardson et al. (1991, 1995) and Reeves (1992) suggest that the majority of noise-impact studies focus on continuous noise production. Importantly, explosions differ from continuous noise in that they have rapid "rise time," and produce both an acoustic and a shock-wave component (Greene and Moore 1995). Although underwater explosions represent one of the highest amplitude point-source signals in the ocean environment, few studies document reactions of baleen whales to them (Richardson 1995a). In the one species for which data are available (the gray whale, *Eschrichtius robustus*), the findings are ambiguous, ranging from no response to possible displaced migration (Richardson 1995a). It is thought that the sensitivity of mysticetes to low-frequency sound might heighten their susceptibility to underwater blasts (Richardson and Würsig 1995), but the modelling of any deleterious effects is complicated by a lack of empirical data (Richardson and Malme 1995; Ketten 1995). It is assumed that at some critical exposure level, ear damage, manifested as temporary threshold shifts in acoustic sensitivity, will occur. As exposure level increases, such shifts become permanent (Richardson and Malme 1995). The consequences of such ear damage may range from subtle, through modification of certain behaviours that require a modicum of hearing ability, to acute, where concussive effects may lead to death (Ketten 1995).

From the above data, it was clear that behaviour of resident humpback whales in Trinity Bay had in some way been altered, as reflected by higher entrapment rates. Thus, it was postulated that the increased entrapment rate was linked to the onset of large-scale industrial operations in Trinity Bay.

In June 1992 we monitored the movements and behaviour of humpback whales in Bull Arm to evaluate this hypothesis. We sampled the acoustic environment during periods before and after explosions to determine the consequences of increased noise levels.

Methods

Observations were recorded over a 19-day period in June 1992. Census teams in two small boats photographed individual humpbacks as they moved in and out of Bull Arm and other areas of lower Trinity Bay. Sampling was performed daily (weather permitting) along standard zigzag transects, an effort being made to document all humpbacks observed and to minimize resightings of the same individuals within any 1 d (for further details of the sampling protocol see Mattila et al.[4]). The sampling protocol ensured equal

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4 D. Mattila, P. Clapham, J. Lien, F. Larsen, J. Sigurjonsson, N. Øien, S. Katona, J. Beard, P. Palsbøll, T. Smith, and P. Hammond. 1991. Yonah: years of the North Atlantic humpback whale. Unpublished manuscript.

Fig. 3. Entrapment locations in Trinity Bay during the years of industrial activity (1991–1992). Number of entrapments and approximate location are shown in circles. Number and location of entrapments in Trinity Bay outside the range of the map are shown in squares, with approximate direction and distance from the upper edge of the map (data are compiled from Lien et al. 1991*a*, 1993). ●, site of excavation.
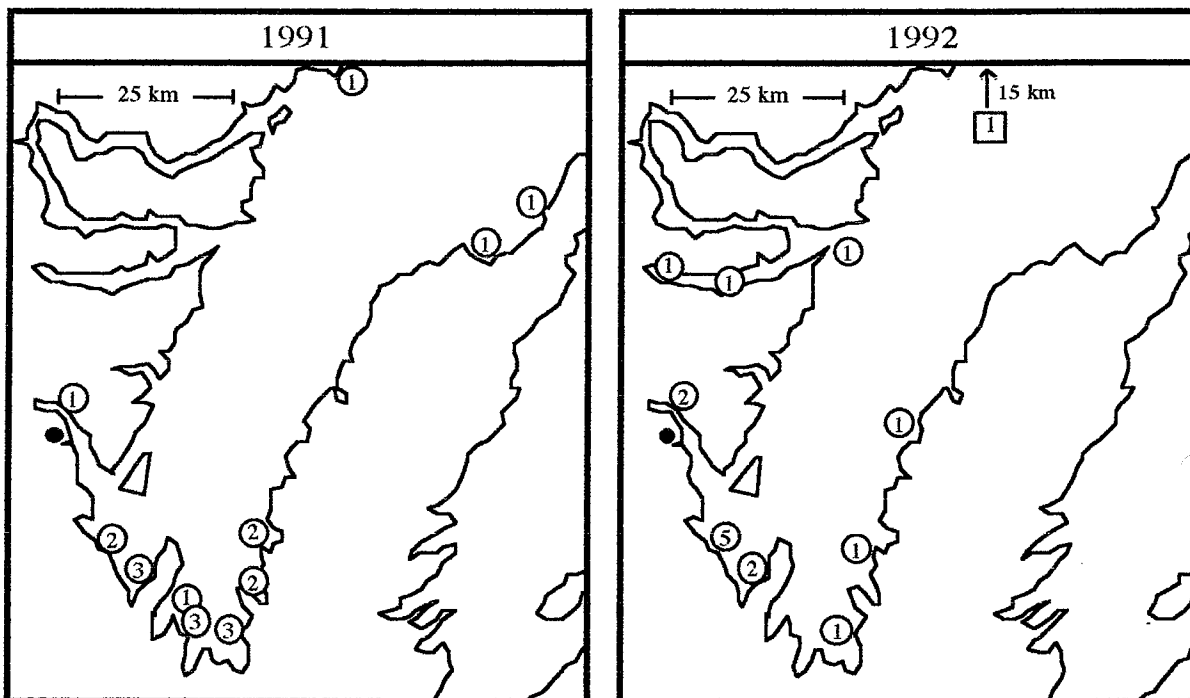

Table 2. Mean distance between the site of entrapment in Trinity Bay and Mosquito Cove, Bull Arm (for data source see Figs. 2 and 3), for preblasting (1979–1990) and blasting (1991–1992) periods.

Year	Distance (km)	SE
1979	22.4	15.7
1981	33.6	—
1984	6.7	0.0
1986	92.1	—
1988	61.8	26.0
1989	62.3	19.1
1990	84.5	23.3
1991	37.0	5.3
1992	31.9	6.1

Note: Years 1982–1983, 1985, and 1987 are omitted, as no entrapments occurred in Trinity Bay during these time periods. Data for 1980 are also excluded, as precise locations for entrapments were not available. Two re-entrapments are excluded from calculations for 1992 to ensure independence of data.

effort inside and outside of Bull Arm, despite varying weather (and visibility) conditions. A Global Positioning System (GPS) was used to locate sightings. Censuses were performed before, during, and after explosions. Wherever possible, census teams were blind to experimental conditions, i.e., explosion or no explosion. Individual whales were catalogued and matched for previous sightings using GPS locations to plot movements in the bay. These data were used to calculate residency, resighting rates, and net movement toward or away from the noise source on an individual basis.

Another team monitored noise levels during and after explosions. Acoustic events were recorded on a Sony (DAT) TCD-D10 Pro II system with a 20 Hz − 22 kHz flat response (±1 dB), using a pair of Brüel and Kjaer 8105 omnidirectional hydrophones directed through Brüel and Kjaer 2635 charge amplifiers. Recordings were taken at a distance of approximately 1 nm (1.835 km) from the blast at a depth of 10 m (the depth of the water at this range was approximately 200 m). The recording system was calibrated using a piston hydrophone (Brüel and Kjaer Type 4223) emitting a 250-Hz calibration tone of 151 dB referenced to 1 μPa at 1 m. A continuous temperature−depth probe (Vemco Inc., Armdale, Nova Scotia) was used to sample boundary conditions throughout the water column. A sounder was used to monitor prey abundance outside and inside Bull Arm.

In one instance, blast recording coincided with the presence of a group of three humpbacks near the recording platform. Since explosions were easily seen (and heard) from the recording platform, "blind" behavioural observations of animals were not possible. However, direct behavioural consequences of an underwater explosion could be observed, including respiration rates (blow interval) and surface behaviour.

Recordings were analyzed using Canary, a sound-analysis system developed for the Macintosh PC, with an upper frequency analysis limit of 11 kHz. Sound files were analyzed utilizing a sampling rate of 22.3 kHz, and a Fast Fourier Transform (FFT) of 1024 points (frame length 46 ms, filter bandwidth 88.24 Hz).

Results

Acoustic analysis

Explosions followed a characteristic sequence. Between approximately 1 and 20 min before the main blast, a series

Fig. 4. Blast schedule for Mosquito Cove. The shaded area indicates the period of study (explosion dates and charge sizes were supplied by Newfoundland Offshore Development Constructors (NODECO)).
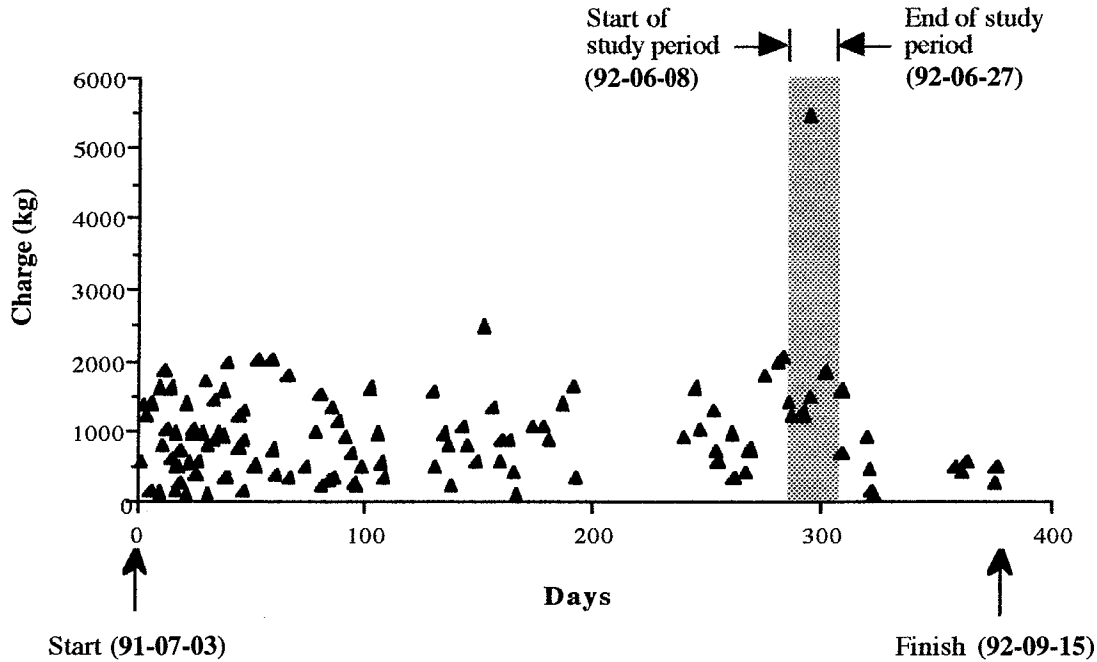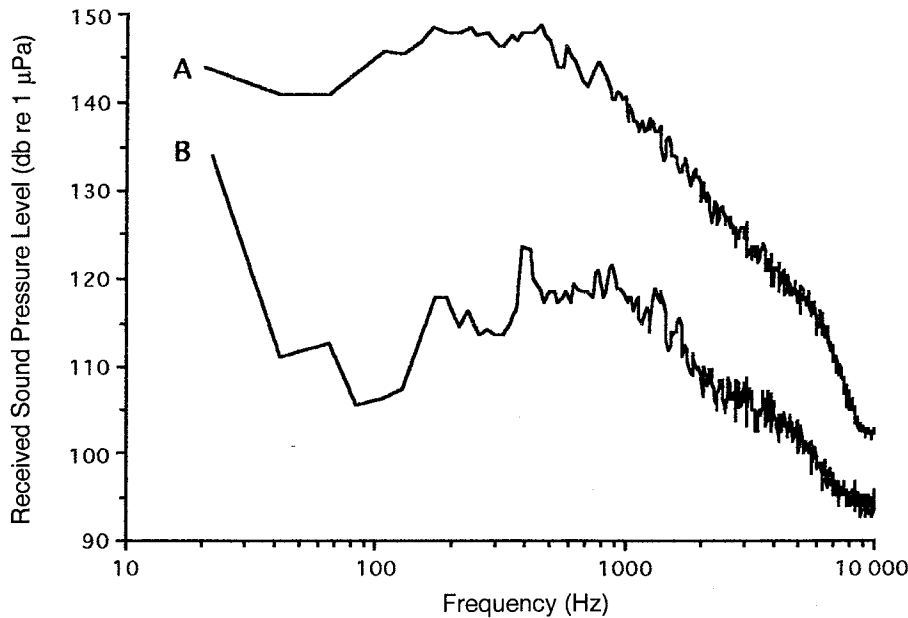

Fig. 5. Typical power spectra for the two types of explosion monitored at Bull Arm, recorded 1.83 km from source at 10 m depth, averaged across the duration of the signal, showing main-excavation explosion (A) and fish-deterrent explosion (B).

of smaller charges were detonated. These acted as fish deterrents, causing fish in the vicinity to move away from the blasting area. These fish-deterrent charges ranged from 30 to 60 g and were detonated in sequences that lasted 1−2 s.
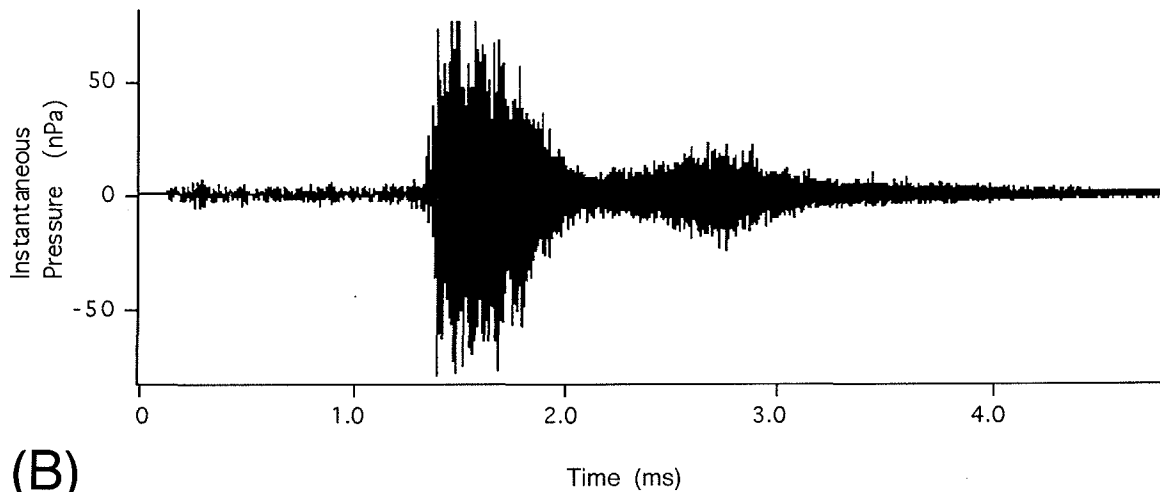
The larger, main charges (Tovex™) typically varied between 1000 and 2000 kg, with a maximum of 5500 kg. Charges were detonated in (maximum) 248-kg packages delayed in sequence by a few milliseconds, the entire charge lasting 2−3 s. Charges were laid in boreholes ranging from

3 to 10 m deep in a depth of water ranging from 0 to 15 m. The blast schedule varied from three per day to one per 7 days. Figure 4 shows the blast schedule for a 400-day period with size of charge detonated.

Figure 5 shows characteristic power spectra for both types of explosion, recorded at a distance of 1 nm from source, calibrated and referenced to 1 μPa, averaged across the duration of the signal. Representative waveforms are given in Fig. 6. Note that both main-blast and fish-deterrent wave-

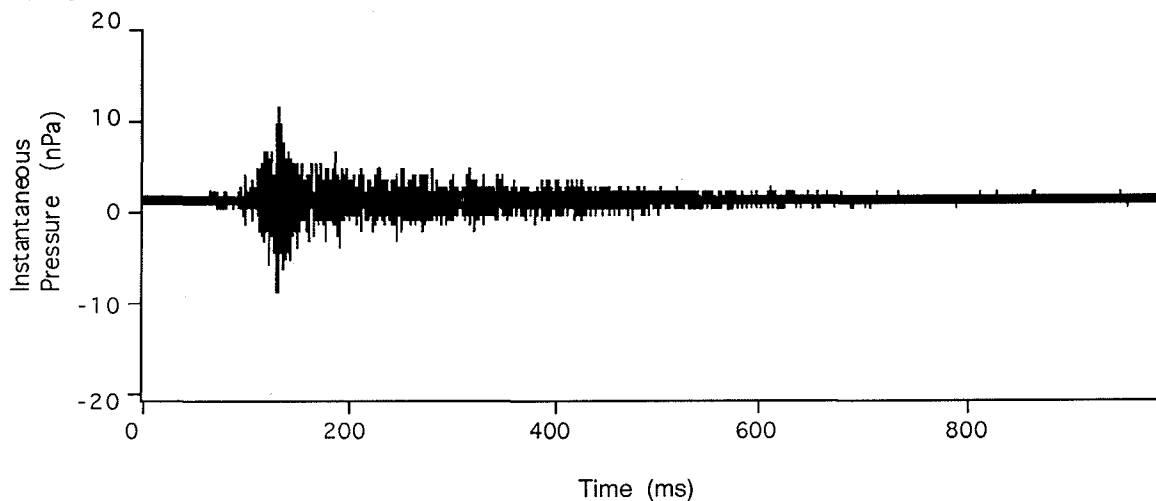**Fig. 6.** Typical waveforms (uncalibrated) for main excavation blasts (A) and fish-deterrent blasts (B).

Table 3. Characteristics of explosions in Bull Arm, recorded 1.83 km from source.

|	Charge mass (kg)	Date	Time	Peak amplitude (dB re 1 μPa)	Frequency of peak amplitude (Hz)
Deterrent	<1	92-06-25	17:17:44	123	390
Deterrent	<1	92-06-25	17:18:10	129	414
Deterrent	<1	92-06-25	17:18:37	126	390
Explosion	1450	92-06-16	12:59:10	148	283
Explosion	1510	92-06-25	17:20:58	. 149	456
Explosion	5000	92-06-25	19:04:15	153	240

Note: Fish-deterrent spectra were in fact bimodal, the first peak occurring at frequencies below the sensitivity range of the measuring apparatus; only the second, measurable peak is given here.

forms are characterized by rapid rise times (see Ketten 1995). Table 3 shows individual blast characteristics, including duration and peak amplitude. Peak source levels varied according to the size of charge, but typically reached 140 – 150 dB re 1 μPa near 400 Hz. The maximum peak source level recorded from a partially submerged charge was approximately 153 dB re 1 μPa (see Table 3). This particular blast was the largest detonated at Mosquito Cove in the 2 years of blasting.

Results from the temperature–depth probe indicated a stratified water column with two strong temperature gradients occurring at 15–40 and 40–75 m (as previously shown

Fig. 7. Temperature−depth profile of Bull Arm.
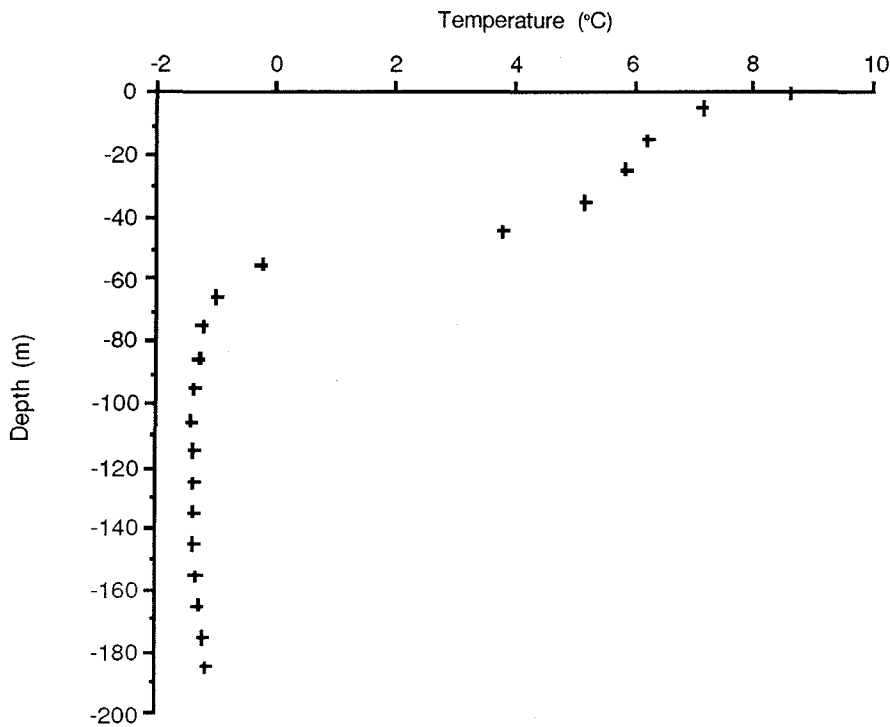
in Narayanan et al. 1991). Although no salinity or pressure readings were taken, the temperature−depth curve for this area (Fig. 7) implies a non-uniform velocity field (as per algorithms reviewed in Tolstoy and Clay 1987). Sounder observations showed an abundance of potential prey species throughout and outside of the study area, either invertebrate (euphausiids) or vertebrate (capelin, herring).

Resighting observations

Photographs for identifying individual whales were taken on 9 days during the 19-day period of study. On 5 of these days behavioural observations were also made. Blasts occurred on 8 days during the study period.

Seventy-one individuals were identified in southern Trinity Bay. Most (n = 40) were seen on more than 1 day; only 2 animals were photographed on 6 different days, and none were seen on 7 days or more. Individuals were identified over intervals ranging from 0 days (sighted only once) to 19 days. The mean sighting interval was 4.7 days for all animals, and 7.7 days for animals sighted more than once.

The distribution of humpback whales was tightly clumped. Figure 8 illustrates the distances of whale sightings from the blast site. The majority of sightings (57%) occurred between 3 and 9 km from the blast site. Whales were less abundant but present throughout the rest of southern Trinity Bay. The distribution of humpback whales did not change appreciably during the study; movement toward or away from the blast site between days was determined according to the difference between maximum recorded distances for each animal from two consecutive sightings. Of the 53 cases in which animals were identified on more than 1 day, 28 (53%) were closer to the blast site on the second sighting and 25 (47%) were farther away. Restricting this analysis to the Bull Arm area (that is, within a 10-km radius of the blast site) demonstrated

the same effect: of the 44 cases sighted, 20 (45%) were closer to the blast on the second sighting and 24 (55%) were farther away.

Resighting patterns for the bay were highly variable. Overall, the resighting rate was high, with animals photographed on a mean of 2.0 days. Animals closest to the blast showed the highest resighting rates. To determine this, the mean sighting distance (MSD), defined as the average maximum distance an animal was sighted from the blast site on a daily basis, was calculated for each animal. The number of sightings (days) was then calculated for animals with a MSD in three zones: less than 10 km, between 10 and 20 km, and beyond 20 km (see Fig. 9). The mean resighting rate for each zone was significantly affected by distance to the blast site (F = 10.696, df = 2, 58, p < 0.0001); specifically, animals in the zone closest to the blast site (average resighting 3.2 days, n = 25) were sighted more often than animals in either of the other two zones combined (average resighting 1.75 days, n = 36) (p < 0.0001, Scheffé's test). Nearly half of the humpbacks identified farther than 10 km from the blast site were sighted only once.

Resighting rates did not appear to vary with blasting. To investigate this, we examined two intervals of 3 days: 92-06-09 to 92-06-12 and 92-06-12 to 92-06-15. In the first period, two blasts occurred. No blasts occurred in the second period. To compare the extent of resighting, we used a resighting factor, R, defined as

$$R = \frac{2r}{n_1 + n_2}$$

where n_1 and n_2 are the number of individuals identified on the beginning and last days of the specified interval, respectively, and r is the number of individuals identified on both

Fig. 8. Distribution of sightings as a function of distance from the blast site, Mosquito Cove. Only the closest location to the blast for each animal each day is plotted, but the same whale may be represented on several days. The distances are calculated as straight lines and do not compensate for intervening shoreline. However, the only substantial geographical feature between the blast site and any whale concentration is Tickle Harbour Point, which creates a land barrier between the blast site and Dildo Arm (see Fig. 1).
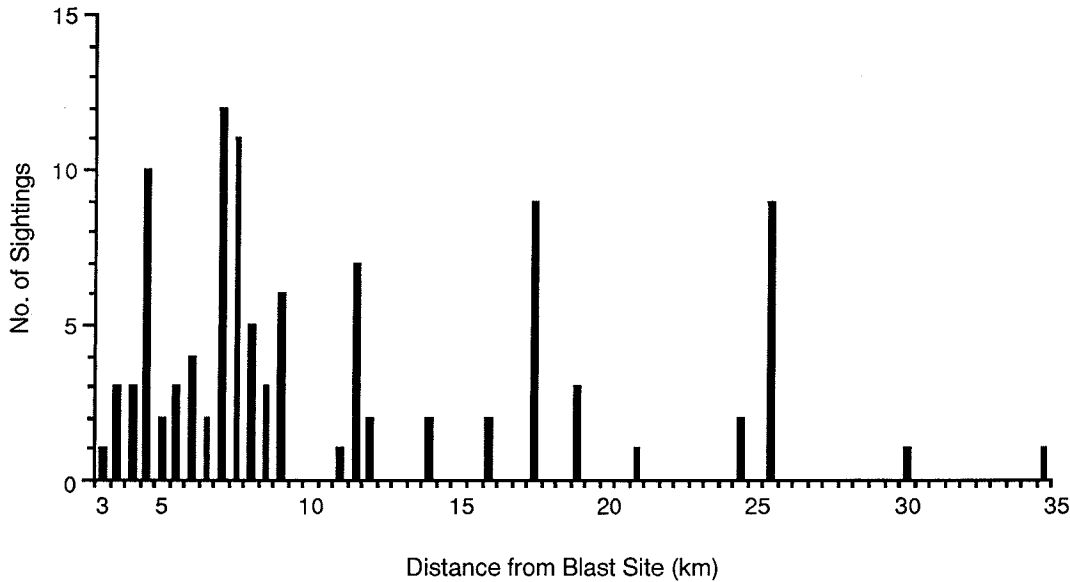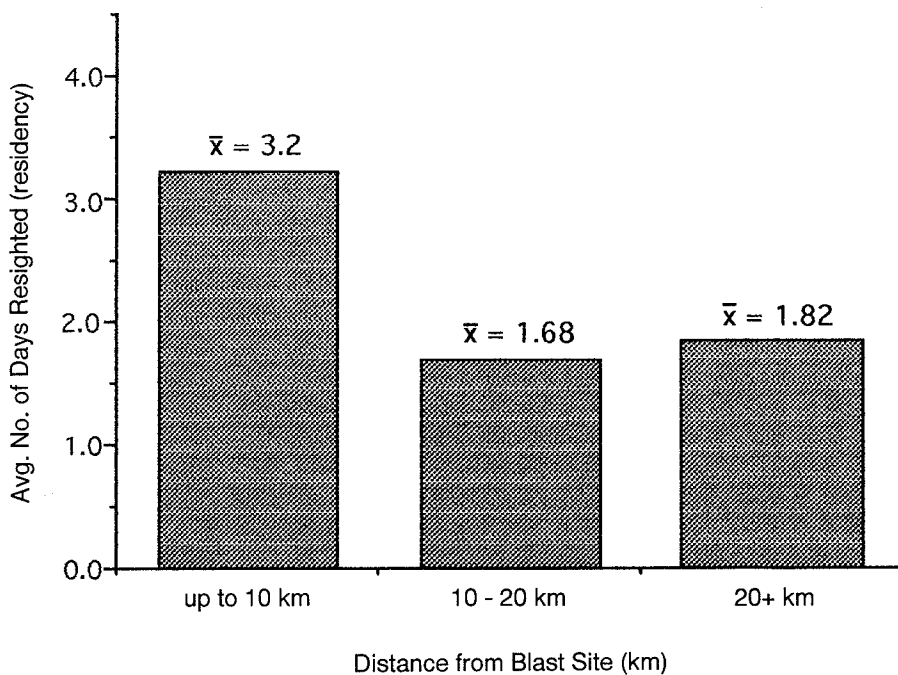

Fig. 9. Mean numbers of days on which individuals were resighted at increasing distances from the blast site.


days. R varies from 0 (where no individuals are being resighted) to 1 (where all animals are identified on both days). For the above time periods, the resighting factor was slightly higher during the period when blasting occurred ($R = 0.5789$) than during the period when no blasting occurred ($R = 0.5098$).

Behavioural observations

Direct observation of whales during blast sequences indicated no unusual behaviours associated with the blasts. In one instance, the acoustics team was able to record a blast (see Table 3, 92-06-16) while in the vicinity of a group of three humpbacks. Because of the close proximity (10 m) of the recording platform to the group, it can be assumed that recorded blast levels were similar to those received by the group. Approximately 5 s before the initiation of the blast sequence the group dived and did not return to the surface until the blast sequence had ended. During the blast sequence no abrupt surface reactions (such as sudden dives, abnormal surface behaviour, or course changes) were noted, nor were

Fig. 10. Blow intervals for three humpback whales during a blast. Time is referenced to the detonation of a 1450-kg charge on 92-06-16 (see Table 3). Fish-deterrent blasts preceding the main blast occurred more than 20 min before $t = 0$.
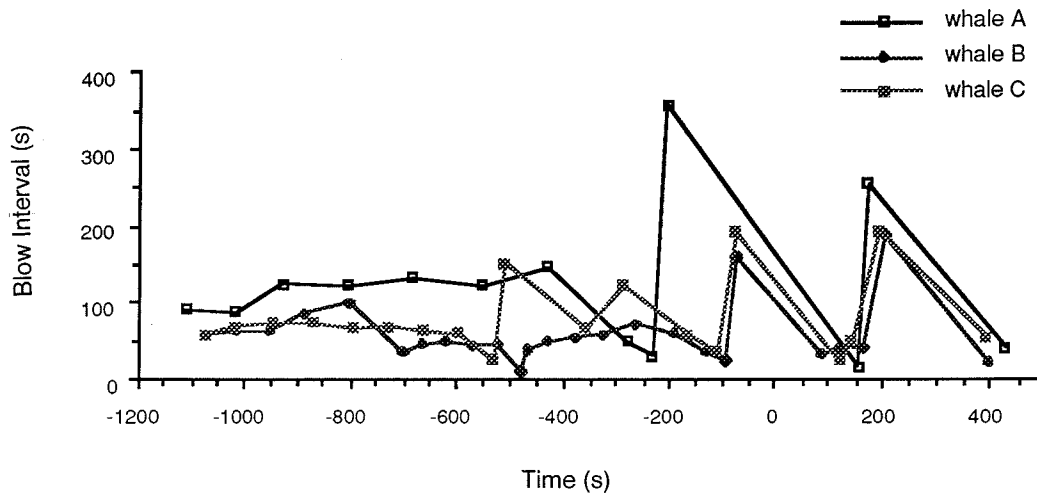
any vocalizations recorded. Following the blast, the group remained at the surface in the same location as prior to the blast until approached within 10 m by the research boat (for a record of blow sequences see Fig. 10).

Discussion

Industrial activity in ocean waters has led to concerns over noise pollution and the potential susceptibility of marine life, including marine mammals, to excess acoustic noise levels (for example, see Richardson et al. 1991, 1995; Green et al. 1994). Studies designed to identify deleterious noise levels tend to use behavioural variables as a measure of impact on the subject species (for example, see Baker et al. 1983; Ljungblad 1983; Tyack et al. 1983; Bauer et al. 1993; Frankel and Herman 1993; Richardson and Greene 1993; Richardson and Malme 1995; Tyack 1993). For convenience, these variables are typically restricted to visually observable behaviours.

This study demonstrates a paradox in behaviour-based studies. Industrial activity at Mosquito Cove, Bull Arm, during 1991−1992 produced a series of intense acoustic stimuli with most sound energy below 1000 Hz. Simultaneously, a dramatic increase in the rate of humpback whale entrapment was seen, with an apparent clumping of entrapment locations in southern Trinity Bay. The standard error for "entrapment distance" was smaller during blast years, suggesting that entrapments were occurring in the same areas and were less dispersed across Trinity Bay (see Table 2). Furthermore, entrapments in 1991−1992 occurred closer to Mosquito Cove, suggesting that the increased sound levels or energy may be a factor in the observed changes in the distribution of entrapments. Yet the behavioural assessment of humpbacks in situ, based on analysis of distribution, resighting rate, residency, and general behaviour, suggests that the animals were not reacting to the intense acoustic stimuli from the detonations.

Most humpback whale sightings occurred within a 10-km radius of Mosquito Cove. Geographically, this restricts the densest sightings to Bull Arm. Research platforms operating in Bull Arm during 1991−1992 reported a high abundance of potential prey items, mostly planktonic euphausiids. On

several occasions groups of humpbacks were observed feeding, and opportunistic fecal collections from these individuals confirmed a planktonic diet (unpublished data). It is possible that Bull Arm acted as a zone of high productivity, attracting foraging whales to the area. Thus, the clumped distribution of whales likely reflects the distribution of available food. However, transects outside the study area indicated that prey densities were high throughout lower Trinity Bay. This indicates that the animals were not constrained to stay in the area of blasting by lack of food in other locations.

Analysis of movements of animals in and out of Bull Arm suggests little overall individual location change during residency. Since blasting occurred at intervals ranging from 1 to 6 days during the study (mean blast interval 2.9 days), most animals were present in the region for at least one blast. Yet a comparison of resighting rates during and after explosions suggests that the number of animals moving toward or away from the blast area during any interval did not correlate with blasting activity in the intervening period. Furthermore, residency was high compared with that in other bays not exposed to the industrial noise. For example, Witless Bay (Newfoundland), an area of equivalent size and productivity, had an average residency of 1.13 days during the same time period (unpublished data).

Residency, measured as the mean number of days on which the whale was resighted, was longest closest to the blast site, that is, within Bull Arm. It would therefore be useful to assess the sound environment for that area. This study reports a theoretical maximum exposure of 153 dB re 1 μPa at an approximate distance of 1.8 km from source. Because of unknown propagation loss factors, exposure levels at other distances within and outside Bull Arm could not be precisely extrapolated. Exposure levels should decrease with increasing distance from the blast site. Transmission loss, as calculated from standard algorithms (Urick 1983), assumes a nonsloping smooth sea floor and sea surface, known source and receiver depth, and a uniform velocity field. Clearly, the majority of these conditions do not hold in this instance, but by using a spherical ($20 \log R$) spreading model (as given by Urick 1983) a source-level estimate of 209 dB re 1 μPa at 1 m was calculated, with a minimum level of 135 dB re 1 μPa at 10 km. Clearly, these levels exceed the so-called "120 dB

criterion'' suggested by the U.S. National Marine Fisheries Service (NMFS) as a guideline for the maximum sound level marine mammals could be exposed without sustaining harassment. However, there is much speculation as to the usefulness of this threshold level (for example, see Green et al. 1994).

No physical barrier prevented whales from approaching the noise source inside of our recording platform to a distance of approximately 100 m from the blast site (the location of a security-net boom). Strict surface monitoring by the construction company prior to explosions suggests that close proximity to a blast was highly unlikely; however, for some animals in the immediate vicinity of Mosquito Cove, exposure could exceed measured noise levels. Although never observed, such animals would likely account for only a small percentage of the whales resident in lower Trinity Bay in 1992. The above calculations are based on the highest noise levels recorded, which were caused by the largest charge mass. Because charge size was highly variable (mean mass 960 kg; range 30−5500 kg), presumably exposure levels would also vary. Finally, it should be noted that the blasts were short, suggesting that exposures to high-energy acoustic stimuli were brief. Again, this calls into question any comparison with the 120-dB harassment criterion used by NMFS, as it has been demonstrated that signals of short duration are less likely to induce a behavioural response than continuous signals of the same energy (Green et al. 1994).

Of critical importance in reviewing the impact of noise on marine mammals is a knowledge of the hearing abilities of the species involved (Richardson 1995b). Recent reviews have noted that little is known about the hearing range or sensitivity of mysticetes, although it is often assumed that mysticetes' hearing is acute at low frequencies (Fobes and Smock 1981; Herman and Tavolga 1980; Watkins and Wartzok 1985; Green et al. 1994; Richardson 1995b). Unlike odontocete studies, research on mysticetes' hearing is generally indirect and anecdotal in nature. No audiogram exists for the humpback whale. A number of playback and behavioural observation studies have inferred sensitivity to certain acoustic stimuli. Todd et al. (1992) demonstrated behavioural reactions to an acoustic alarm emitting a 1-s pulse with a frequency of 4 kHz peak at a level of 135 dB re 1 μPa at 1 m; however, the signal was sufficiently broadband that the authors were unable to specify which component of the signal the humpbacks may have used as a cue. Similar alarm designs at both lower and higher peak frequencies are also detectable by humpbacks (Lien 1980). Other studies, such as Tyack (1983), have noted reactions to playback of conspecific calls.

Explosions monitored in this study fall well within the range of humpback hearing, as implied by the studies cited above, but the sensitivity to this frequency range cannot be specified. Richardson et al. (1991, 1995) review a number of studies documenting ''disturbance reactions'' of humpbacks to a variety of man-made sources, including seismic exploration devices. They conclude that humpbacks and other mysticetes ''seem quite tolerant of low- and moderate-level noise pulses ... as high as 150 dB re 1 μPa'' (Richardson et al. 1991), although they based this on limited behavioural measures and also note that there has been little documentation of their reaction to explosions. In contrast to research on gray whales, Malme et al. (1985) found no evidence of

avoidance behaviour by feeding humpbacks when exposed to airguns producing stimuli of similar amplitudes to those found in this study. The lack of reaction to the intense stimuli created by detonations in this study is also perplexing. Here we suggest several explanations.

First, since explosions were ongoing before our study began, it is possible that local whales had habituated to the sounds. Richardson et al. (1991, 1995) remark that habituation to certain stimuli, particularly boat traffic, is an observable phenomenon in humpbacks (also see Watkins 1986). However, in this study, the frequency of explosions (mean interval 2.984 days) closely matches mean residency for animals sighted in Bull Arm (3.2 days), suggesting that, on average, animals were not exposed to more than one explosion.

A second possibility is that animals remained in Bull Arm because of greater food availability there, despite the occasional high acoustic energy level. Thus, no net movements out of the bay were observed because the benefits of remaining in the bay to feed outweighed the potential hazards of acoustic exposure. If, however, serious discomfort was associated with the blasting, food was readily available in other locations throughout lower Trinity Bay. There is little doubt that whales were feeding throughout the study period. Whether they were feeding or not, no visible behavioural reactions were observed during blast sequences.

Third, our observations were of whales at the surface. We know nothing of whale movements underwater during detonation sequences. In the one case when the acoustics team was able to directly observe behaviour, the whale group dived before the beginning of a detonation sequence and surfaced following the blast in exactly the same area, suggesting no net horizontal movement by the group relative to the noise source. Because the whales surfaced in almost exactly the same location, most of the movement that occurred in this case was in the vertical plane. It is possible that by remaining at the surface during blast sequences, whales might minimize exposure to stimuli, since (i) because of the so-called ''pressure-release effect'' (cited in Reeves 1992), one might expect reduced intensity levels at the surface, and (ii) because part of the humpback's head is exposed to air at the surface, sound propagation to the ear might be reduced. Unusually long surfacing patterns would presumably lead to a higher resighting rate closer to the stimulus source. While this trend was observed, residency times (as a function of distance from source) would also explain the higher resighting rates.

Finally, exposure to such intense levels of sound (even from only one explosion) may have affected the hearing thresholds of humpbacks in the bay, thus decreasing their sensitivity to acoustic stimuli. As humpbacks are thought to use net-produced acoustic cues to avoid net collisions (Lien 1980; Lien et al. 1992), a threshold shift or damaged hearing may explain the increased entrapment rate in 1991−1992. An examination of the blast schedule for the periods in 1991 and 1992 in which entrapments occurred demonstrated that the probability of an entrapment in Trinity Bay occurring within 2 days or less of an explosion was 0.38, which was significantly greater than the calculated rate of 0.077 for entrapments occurring outside of a 2-day lag (z test of independent probabilities, $p < 0.0001$).

Two entrapped animals released by the Entrapment Assistance Program in 1992 at Sunnyside and at Chance Cove (see

Fig. 1) were individually recognized as previously entrapped. Each showed obvious fresh scarring patterns indicative of entrapment a few days earlier (Lien et al. 1993). Lien (1994) notes that, at least for the previous 15 years, animals once caught in fishing gear do not become re-entrapped. Thus, these humpbacks were the first re-entrapped animals ever observed in Newfoundland by our research team.

Tagged animal and other data indicate that entrapped animals, once freed, quickly vacate the area (personal observation; Lien 1980). However, both animals were re-entrapped within 10−20 km of their original entrapment locations, suggesting that neither exhibited the avoidance behaviours usually seen following release.

Both sites of re-entrapment were within 15 km of Mosquito Cove. An explosion recorded prior to the first entrapment of the second animal (see Table 3; 92-06-16) would indicate an exposure level of approximately 110 dB re 1 μPa (using a 15 log R spreading model for intermediate distances; Urick 1983), assuming the animal was in the vicinity of Chance Cove at the time of the explosion. If this particular acoustic event led to the entrapment of the animal, the arbitrary 120 dB re 1 μPa maintained by NMFS as a threshold harassment criterion is clearly inappropriate.

Increased entrapment rates and the apparent clumping of entrapment sites in lower Trinity Bay during 1991−1992 might also be explained by masking of net-produced cues by industrial noise. However, because they were of brief duration, it is highly unlikely that explosions could effectively mask continuous net cues. Alternatively, other industrial activities, such as drilling or dredging operations, affecting the ambient-noise curve were not measured in this study. Other studies have reviewed the potential impact of such noise sources (for example, see Malme et al. 1985), but do not assess their ability to affect orientation by masking target cues.

Little is known about the deleterious effects of exposure to noise in marine mammals (see Ketten 1995). Apart from the possible physical damage from shock waves, intense noise might lead to depressed auditory thresholds and decreased sensitivity, as in humans (Richardson et al. 1991; Ketten 1995). Dissections of the peripheral auditory systems of two whales found dead in nets in Chance Cove (see Fig. 1), conducted as part of our monitoring of the impact of explosions on humpbacks in Trinity Bay, demonstrated that both whales had damaged ear structures (Ketten et al. 1993; Ketten 1995), likely as a result of shock waves. It should not be inferred from this finding that all entrapped humpbacks had damaged hearing, as this is the first dissection of the hearing apparatus from any net-entrapped humpback, regardless of acoustic environment. It should also not be inferred that it was only the shock-wave component of the explosion that had a significant impact upon the whales; if they had survived the consequences of an explosion shock wave, they may have sustained equally serious auditory damage, perhaps affecting some vital aspect of their behaviour that requires undamaged hearing (Ketten 1995).

In summary, it is worthwhile to reevaluate the validity of visually detectable behaviours as measures of the effects of noise. In this study we have documented that exposure to intense sound did not observably alter residency or movement of humpbacks, but appeared to affect their orientation ability. This may have occurred because of sensitivity-

threshold shifts or damaged hearing. This suggests that caution is needed in interpreting the lack of visible reactions to sounds as an indication that whales are not affected, or harmed, by an intense acoustic stimulus. To determine the impact of noise on marine mammals, both behavioural (long and short term) and anatomical evidence should be examined.

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