Reactions of Hector's dolphins to acoustic gillnet pingers

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ABSTRACT

During 19 days in January 1999, three acoustic gillnet pingers were tested to measure the *in situ* behavioural and acoustic reactions from 188 Hector's dolphin groups in Akaroa Harbour, New Zealand. We examined group size, behavioural response, and vocalisations of these 188 groups in the presence of three different pinger types and one control. Each pinger had different frequency characteristics, and each dolphin group approach was counted as an event (white pinger—38 events, red pinger—45 events, black pinger—56 events, and control—49 events. The average number of dolphins per event was 3.64 ± 0.29 and there was no significant difference in group size among all events. The most significant reaction difference among pinger types was in behaviour observed. Over half (62.5%) of the dolphins exhibited avoidance when exposed to the white pinger. There were no significant differences in the rate of echolocation clicks per dolphin, ($P = 0.44$) or per dolphin group ($P = 0.63$), although the dolphins vocalised longer clicks after exposure to the black pinger. There were no significant differences among the peak frequencies ($P = 0.18$) of the subset of clicks. From these data, the white pinger used in the study elicited the strongest reaction from the dolphins. This white pinger had a fundamental frequency of 10 kHz with harmonics up to 160 kHz. For bycatch management/mitigation, Hector's dolphin would probably react strongest to a higher-frequency pinger.

Keywords: Hector's dolphin, *Cephalorhynchus hectori*, pingers, dolphin sonar, bycatch mitigation, marine mammals, behaviour, New Zealand

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1. Introduction and background

Large increases in fishing during the latter half of the 20th century brought total world fisheries production from 20 million metric tons (mt) in 1950 to over 100 million mt in the 1990s (FAO 1993, 1995; Hilborn 1990; Safina 1995). Wild caught marine fish account for approximately 85% of this production (Mace 1997). These impressive increases were possible because of growth in world population, more fishing vessels, and the development of technologies that enabled more fish to be caught per unit of effort. Many of these technologies grew out of developments from WW II such as electronic navigation which enabled boats to return to good fishing locations time after time, hydraulic winches for hauling nets and traps with fewer people, sonar for finding fish schools underwater, and new types of nets and hooks that proved more efficient and durable.

A deleterious aspect of this massive global fishing industry is bycatch: the unintentional catching and killing of birds, non-target fish species, marine turtles, and marine mammals during the course of normal fishing operations (Mooney-Seus & Muraski 1999). The problem lies in the fact that ocean ecosystems are usually composed of multi-species complexes, while most fishing operations are non-discriminatory, and usually catch other animals in the course of harvesting the target species. These incidentally caught animals are the bycatch. While there is variation in bycatch rates between fisheries world wide, it is estimated that on average the total bycatch or discards is approximately 20%, that is for every five kilograms of a target species caught there is one kilogram of bycatch thrown overboard usually dead (Alverson et al. 1994).

All major stakeholders (scientists, environmentalists, and the fishing industry) are concerned about this problem. There are now efforts throughout the world to try and reduce bycatch and, in many cases, the fishing industry is leading in the development of technologies to mitigate bycatch (Mooney-Seus & Muraski 1999).

1.1 GILLNETS AND BYCATCH

Gillnet fishing is only one of many different types of fisheries that have by-catch. Gillnets are made of either multi-filament twine or monofilament nylon, woven into netting designed to lock behind the gills of fish. Gillnets come in all sizes and range from the large pelagic driftnets that can reach lengths of 50–60 km down to small coastal nets less than 30 m (Northridge 1991; Richards 1994). However, in all cases gillnets sometimes catch other animals that were not the target species of the fishery including other fish, turtles, birds, and marine mammals.

Marine mammals, especially dolphins and porpoises, are particularly susceptible to being caught in gillnets. When the flippers, dorsal fins, tails, or heads of these animals become entangled underwater in the webbing of a gillnet, the animal will soon drown. Northridge (1984, 1991) and then Perrin et al. (1994) describe the extent of this problem and estimate that many tens of thousands of marine mammals, most of them dolphins and porpoises, are caught and killed in passive (gillnets and fish traps) fishing gear world-wide.

It is difficult to estimate bycatch in gillnet fisheries. Generally, the bycatch of marine mammals is under-reported until there is an independent observer program in place to identify and count the marine mammal by-catch. Understandably, the fishing industry has been hesitant to report the full extent of marine mammal bycatch voluntarily because of potential closure of the offending fishery and negative public sentiment often follows the disclosure of such information. Independent observers who accompany the fishermen during operations at sea are the best way to discover the full extent of marine mammal by-catch (Gus van Helvoort 1986).

1.2 HECTOR'S DOLPHINS

Hector's dolphin (*Cephalorhynchus hectori*) is one of the rarest marine mammals in the world (Klinowska 1991). The genus *Cephalorhynchus* is exclusive to the southern hemisphere and Hector's dolphin is endemic to New Zealand. Like Hector's dolphin, the three other genus members all occur in neritic habitats, often very close to shore. In all cases, *Cephalorhynchus* species are relatively small in size and found in regions of temperate/cool waters. One species is found only in South Africa: Heaviside's dolphin (*Cephalorhynchus heavisidii*); one is found in South America, the Falkland Islands and the Kerguelen Islands: Commerson's dolphin (*Cephalorhynchus commersonnii*); and one is found only in South America: the Chilean black dolphin (*Cephalorhynchus eutropia*) (Brownell & Donovan 1988).

Due to their near-shore distribution, all four species are potentially influenced by and vulnerable to humans' coastal activities such as fishing operations, coastal development, ship traffic, and tourist operations. The International Union for the Conservation of Nature (IUCN) classifies Hector's dolphin as Critically Endangered (CI) for the west coast of the North Island and Endangered (E) for the rest of New Zealand. The New Zealand Department of Conservation (DOC) classifies the species as 'threatened' under the provisions of the New Zealand Marine Mammals Protection Act.

To date, the largest documented threat to Hector's dolphins has been entanglement as bycatch in gillnets. This problem became apparent in the mid-1980's when, in the Canterbury Bight/Pegasus Bay area, roughly one-third of the estimated local population was reported killed in coastal gillnets between 1984–1988 (DOC 1988). At that time, the New Zealand-wide population of Hector's dolphin was estimated to be only 3000–4000 animals (Dawson & Slooten 1988).

1.3 MARINE MAMMAL SANCTUARY

The Banks Peninsula Marine Mammal Sanctuary was created in 1988 over concern that large numbers of Hector's dolphins were being caught and killed in the fishery. The combined numbers of incidentally caught Hector's dolphins from both commercial and recreational gillnets from 1984 to 1988 was between 26 and 90 per year (DOC 1988). After the sanctuary was established, there were no reported entanglements of Hector's dolphins from fishers, although dolphin carcasses continued to wash ashore on the beaches of the Canterbury region. For example, between 1988 and 1994, there were approximately 50 dead Hector's dolphins recovered by the New Zealand DOC in the Canterbury region (DOC unpublished data). While some of these deaths were confirmed as entanglement-related as shown by net marks on the carcasses, it was impossible to determine the cause of death in every case.

During the 1997/98 fishing year, an independent observer program was undertaken on commercial gillnet and trawl fishing boats in the Canterbury region (Starr & Langley 2000). From October 1997 to July 1998, 313 days of fishing were observed in the Pegasus Bay/Canterbury Bight trawl (188 days) and gillnet fishery (125 days). A total of 25 vessels were observed, 7 of which were gillnet vessels and 22 were trawl vessels. Since vessels will deploy nets more than once a day, the total number of trawls observed was 434 and the total number of gillnet sets observed was 214. One Hector's dolphin was caught in trawl gear and 6 dead dolphins were recovered by observers from gillnets. In addition, 2 dolphins were caught and then released alive from gillnets. Concern over these entanglements lead the New Zealand DOC to commission this study to assess what frequency of pinger is most likely to mitigate Hector's dolphin entanglement in nets.

It should be noted that while by-catch of marine mammals is a formidable problem in gillnet fishing, there are positive sides to this fishing technique when compared to other fishing methods. Gillnet causes little harm to the ocean floor and juvenile fish can swim through the nets. Also, if the nets are set in areas and at times when the target fish congregate and exhibit a minimum of mixing with other species, bycatch of other fish can be reduced.

1.4 ACOUSTIC DEVICES AND MARINE MAMMAL CONFLICTS IN FISHERIES

Marine mammals have excellent hearing and use sound in various ways in the ocean to navigate and communicate (Thomas et al. 1992). It is, therefore, not surprising that efforts to introduce sound into the ocean to solve marine mammal bycatch problems dates back to the 1980s.

Sound generators were used in an effort to keep pinnipeds away from aquaculture operations in the Pacific Northwest and the North Atlantic (Johnston & Woodly 1998; Mate 1993; Mate & Harvey 1987;Wickens 1995; Wickens et al. 1992). These 'Acoustic Harassment Devices' (AHDs) emit pulsed frequency sweeps in the 11–17 kHz range at source levels of ~187–195 dB. Initially there was a substantial deterrent effectiveness, but it declined slowly over time. It was reported that some individuals became habituated and were actually attracted to the sound, and the term 'dinner-bell' effect was introduced to describe this phenomenon (Mate 1993). Small explosive charges (seal bombs), other pyrotechnics, and gunshots have also been used to deter pinnipeds from aquaculture operations with varying degrees of success (Morris 1996; Rueggeberg & Booth 1989).

Wooldridge & Belton (1980) reported on electronically produced 'roar' sounds to deter polar bears (*Ursus maritimus,* Gervais 1855) in the 100–600 Hz range, which showed some deterrent effect on the animals. Davis et al. (1987) reported that sea otters were not deterred by an airborne warble sound near 1 kHz or by air horns at 0.5–20 kHz underwater.

Lien et al. (1992; Lien 1994) experimented and showed some success with low frequency sounds to keep humpback whales out of cod traps in coastal Newfoundland (Canada) fisheries. Up to six alarms with peak frequencies around 5 kHz were installed in each net 2 m below the surface. The sample consisted of 2,223 days of fishing without alarms and 2,392 days with alarms. There were a total of 129 collisions between whales and traps that did not have alarms and 37 collisions with nets that did have alarms.

Our understanding of odontocetes sound production and use of sound has been facilitated by dolphins, which are relatively easy to keep in captivity and study when compared to large whales. Dolphins use sound for communication and for echolocation (Au 1993). There have also been studies and observations of odontocetes related to sound, echolocation, and net entanglement (Jefferson & Curry 1994; Reeves et al. 1996). Reports included watching the behavioural effects on wild animals to banging pipes underwater (Akamatsu et al. 1993; Kasuya 1985), studying the echolocation and reaction of captive animals to the presence of nets (Akamatsu et al. 1994; Hatakeyama & Soeda 1990; Kastelein et al. 1995), and actual trials of acoustic pingers in gillnet fisheries (Gearin et al. 1996; Kraus et al. 1997). Both Gearin et al. (1996) in the eastern North Pacific, and Kraus et al. (1997) in the western North Atlantic, showed significant decreases in the rates of harbour porpoise (*Phoceana phoceana*) observed caught in gillnets. There are also now numerous uses of pingers throughout the world, but few controlled experiments like those described above. In those field trials some nets were left as controls with no pingers, while a comparable number were equipped with pingers. The observed catch rates of these two experimental conditions were then used as a basis to show the effectiveness of pingers. Finally, The International Whaling Commission's small cetacean committee held a special meeting in the April 1999 to further address the topic of acoustic alarms on fishing nets (IWC 2000).

What is lacking in all the above studies are simultaneous observations of odontocete behaviours and sounds in the presence of acoustic pingers. This may be the best way to understand the interactions between pingers and dolphins, and answer one of the major outstanding questions of whether pingers are alerting or deterring the animals from the nets (Kraus 1999). If the alarms were deterring, then animals will be scared away from the sound and nets; if dolphins were alerted, then they would pay attention to the sound and detect the nets either with sonar or sight. Combining observations of behavioural and acoustic responses of dolphins to pingers may be the best way to test this hypothesis.

Another reason to conduct such trials is to test whether different species react differently to various frequencies. It is known that different dolphin and porpoise species produce different frequency sounds (Au 1993). It is possible that different species react differently to various pinger frequencies (Kraus 1999). Consequently, in may be necessary to test different pingers on different dolphins to determine the most effective mitigation frequency for each species.

Stone et al. (1997) plotted the distribution of Hector's dolphins relative to the position of an active and a control pinger in Akaroa Harbour in 1997. The pinger used in this experiment was a white pre-production model pinger manufactured by the Dukane® Corporation. This pinger has peak frequency at approximately 10 kHz, but strong harmonics up to 160 kHz and was the model used in the Kraus et al. (1997) study with Harbour porpoise. Results from Stone et al. (1997) showed that animals moved farther away from the active pinger than they did from the control (passive) pinger. At the time of this study, there was only one pinger type available, while now there are two other models.

The success of pingers in other fishery trials (Kraus et al. 1997; Gearin et al. 1996), the data from Stone et al. (1997), and the reports of dolphin mortalities in the Canterbury gillnet fishery in 1998 (Starr & Langley 2000) lead to a request from DOC for a study to record the sounds and behaviours of Hector's dolphins in the presence of different pingers. The aim was to guide the New Zealand government and fishing industry in the selection of pingers for use in the coastal gillnet fishery in Canterbury.

While the previous study demonstrated that Hector's dolphins responded to one type of pinger, there was the need to determine if there might be differences in the reaction of the dolphins to different pingers based on their frequency. This information can guide managers and fishers in the selection of the best type of frequency and pinger for their area and species.

2. Equipment

The hardware set-up at the University of New Hampshire's Ocean Engineering Laboratory used for recording and quantifying acoustic outputs in this experiment is shown in Fig. 1. The acoustic measurement system used for both pinger signal evaluation in the laboratory, and for acoustic recordings in the field was made up of the following components. An ITC 8095 hydrophone was used to receive the acoustic signals. The hydrophone pre-amplifier was energised using an Ithac P-12 power supply. The signals were next filtered using an ITHACO 4113 bandpass filter. Amplification was achieved with an ITHACO 451 amplifier. All the ITHACO components were housed in a common frame. The signal was subsequently connected to a National Instruments DCMCIA DAQ 5102 card for A/D conversion. The digitised signal was then displayed on the laptop monitor and stored using National Instruments Virtual Bench Software version 2.1.1.

When the acoustic measurement system was used for pinger characterisation the filter was set to band pass signals between 2 kHz and 200 kHz. The amplifier

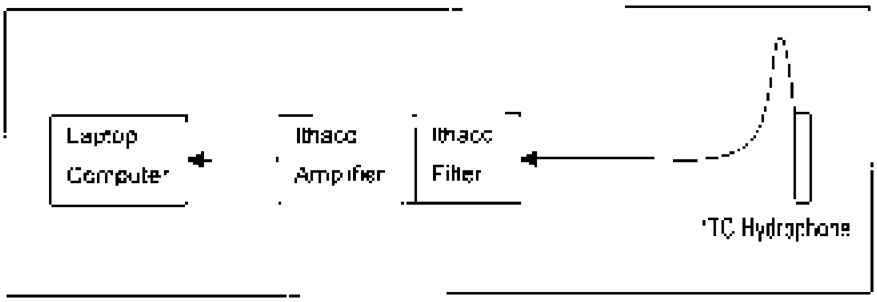

Figure 1. Schematic diagram to show instrument configuration used in laboratory sound analysis.

gain was set at 30dB. The recorded signals were corrected for the hydrophone sensitivity and amplifier gain prior to further analysis. The FFT (fast Fourier transform) of the ping was taken over 24 2048-point sections of the ping and averaged. It was then converted to power spectral density units. (Representative spectral plots for each type of pinger are included as Figs 16, 17, and 18.)

To quantify the acoustic outputs, each pinger (Fig.2) was tested at the University of New Hampshire's Ocean Engineering Laboratory as described above. The sound levels in decibels (dB) for all pingers were comparable, but there were differences in frequency characteristics that are described below.

Figure 2. Photograph of the pingers used in this experiment. The red DUKANE® and black PICE® are both commercially available pingers, and the white DUKANE® is an experimental model developed by the company as a prototype in 1994.

2.1 BLACK PICE® PINGER

This pinger has a signal that possesses random bandwidth, pulse length, and time between pulses. The pinger has a bandwidth between 50 and 80 kHz, the frequency peaks change with each ping. The pulse length is nominally 300 milliseconds. The time between pulses varies from 4 to 30 seconds.

2.2 RED AND WHITE DUKANE® PINGERS

The red and white pingers have a signal with a duty cycle of approximately 7-10%. The pulse length is nominally 400 msec with a time between pulses nominally four seconds. The red pinger has its fundamental frequency at approximately 10.2 kHz. The white pinger has its fundamental frequency at approximately 9.6 kHz. The red pinger has 10 frequency components above 110 dB re 1 mPa/Hz$^{1/2}$. The white pinger has 6 components above that level. The red pinger has 3 frequency components below 100 dB re 1 mPa/Hz$^{1/2}$. The white pinger has 4 components below that level. From this information, it would appear that the red pinger has a stronger signal. The red pinger has its highest peak at its fundamental frequency. The white pinger has its highest peak at one of its harmonics. When looking at only the peaks (Fig. 3), the red pinger has a more irregular shape than the white pinger. The white pinger seems to have a pattern to the peaks through the harmonic range. It must be stressed that only one type of each pinger was used in the Hector's dolphin experiments. The type of pinger used may not be indicative of all pingers of that type.

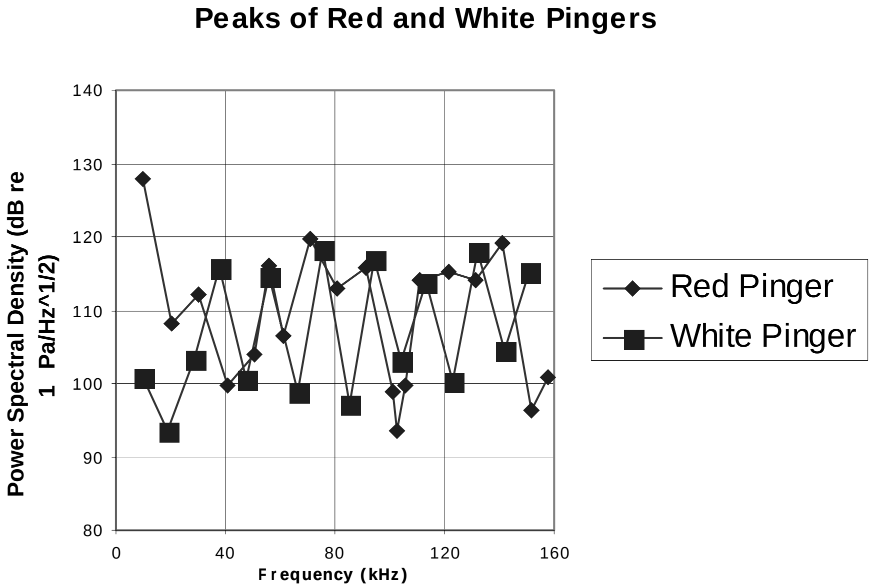

Figure 3. Representative spectral frequency for red and white Dukane® pingers.

3. Methods

Acoustic data were collected from Hector's dolphins during January 1999 in the Banks Peninsula region of New Zealand. The dolphins were sighted from a 6 m boat. Surveys of Akaroa Harbour for dolphins were conducted on all days when the wind speeds were less than 25 km/hr. Observers would begin searching for dolphins from the north end of Akaroa Harbour, near the town of Duvauchelle and progressively move south out to Akaroa Heads. Surveys would generally begin between 6.00 a.m. and 7.30 a.m. and usually concluded by 1.00 p.m. or 2.00 p.m., or when the wind speeds became too high, or if it rained.

The same survey pattern was used on each day. As the boat moved south through the harbour any observed dolphin groups would be approached. If the group remained within 10–20 m of the vessel the group would be counted as *an event*, and the experiment would begin. An event is defined as an encounter with one or more dolphins.

For each event the following data were recorded:

- Location (GPS latitude and longitude)
- Boats in the vicinity (recorded as a code, Table 1)
- Sea state, water temperature, water depth, water visibility
- Dolphin group size
- Dolphin behaviour (recorded as a code, Table 1)
- Number of dolphin approaches observed toward the hydrophone and pinger.

  Because dolphin echolocation is highly directional (Au 1980, 1993), it was important to count the number of times observed dolphins swam directly at and faced the hydrophone with their heads. This was logged as the number of approaches.

TABLE 1. RECORDING CODES USED FOR DOLPHIN BEHAVIOUR AND FOR BOATS.

CODE	DOLPHIN BEHAVIOUR AND DESCRIPTION
(0)	Surface Swimming: swimming at surface with no dives, jumps, or splashes.
(1)	Porpoising: jumping slightly out of the water on each surfacing, usually associated with rapid movement.
(2)	Logging: lying motionless at the surface for five seconds or longer.
(3)	Breaching/jumping: jumping completely out of the water into the air.
(4)	Milling: slow swimming in circles or in relatively the same place.
(5)	Bow riding: porpoising or surface swimming in the bow wave of the boat.
(6)	Social Behaviour: touching other animals with snout, or flippers.
(9)	Avoidance: animals abruptly leaving or diving usually with vigorous tail kicks.
(10)	Investigate pinger: swimming directly up to pinger to within 0.5 m, snout first.
CODE	**BOAT TYPE**
(1)	Commercial dolphin swimming boat
(2)	Recreational boat (fishing, kayak, etc.)
(3)	Commercial fishing boat
(3)	Water skiing boat
(4)	Research boat

Sea state was estimated using the Beaufort scale (1–12). Water temperature was measured in degrees centigrade, and water depth and water visibility were measured in meters with a secchi disk. On three occasions a total depth temperature profile was taken using multiple casts of a Nansen bottle.

Each day four different acoustic conditions, using one of the three pingers (see Fig. 2) or a control, were used in the experiment. A new condition would be used for each group of dolphins encountered. The conditions were:

- Hydrophone with no pinger attached
- Hydrophone with a black PICE® pinger attached
- Hydrophone with a white DUKANE® pinger attached
- Hydrophone with a red DUKANE® pinger attached

Each day a sequence of acoustic conditions was selected randomly. There were 24 different combinations (e.g. red, control, white, black is one combination, control, black, red, white, is another, and so on). There were 24 different combinations that were cycled through during the study and a random start was used to determine which combination to begin with on the first day.

The research boat would be moved to a new dolphin group for each event (pinger trial) or after all four pinger conditions had been trailed. If we stayed with the same group for more than one pinger trial (the use of just one pinger sound), we would alter the cycle above by conducting a control (no sound) between the active pinger trials. Groups of Hector's dolphins in Akaroa harbour are often mixing and changing constantly. For example there might be a larger group of 25–40 animals within a square kilometre region. This larger group was typically broken up into 6–10 smaller groups that were dynamic in their composition, animals moving between groups and groups combining and breaking up. Due to this mixing and changing, our sample on any given day was well mixed, but a control would still be run between active pingers if there was a chance that the same dolphins were in the area. This ensured that the dolphins were not repeatedly exposed to different 'active pinger types in succession.

For each event, the hydrophone was lowered to a depth of 2.7 m over the starboard side as the dolphins approached the boat. The frequency range emitted by the dolphins is 82 kHz to 135 kHz (Dawson 1988; Thorpe & Dawson 1991). The band pass filter was selected to eliminate sources of sound outside of this range.

3.1 CLICK RATES

Acoustic data were collected on the number of dolphin clicks in a three-minute time interval. Because the click length of a Hector's dolphin is 80 to 800 microseconds (Thorpe & Dawson 1991), the time base was set to allow clicks within this range to be seen. Clicks were counted manually as they appeared on the screen during each three-minute interval.

As dolphins swam towards the pinger and hydrophone, clicks would appear on the computer screen. As dolphins approached, pointing directly at the pinger and hydrophone, it was estimated that the clicks could be seen on the screen when a dolphin came within approximately 10–15 m of the hydrophone. Hatakeyama et al. (1988) found that a Beluga whale's 50% threshold detection range from a salmon gillnet was about 5.5 m. Since we had no way of measuring the sound source strength, we do not know if the dolphin began clicking at that range, or if the hydrophone began receiving the signal at that range. It is also very difficult to determine the directionality of a dolphin clicks in the wild except by observation of the orientation of the dolphin's head.

3.2 CLICK FREQUENCY AND DURATION

A series of full resolution dolphin clicks was recorded and analysed including clicks made by dolphins approaching under the different pinger conditions. In addition to these we recorded the clicks of a female Hector's dolphin in the water with the body of a dead calf (Stone & Yoshinaga 2000). The mother was nosing and pushing the dead calf around and we were able to record her clicks. All clicks were analysed for peak frequency (kHz) and for duration (seconds). With the exception of the clicks recorded with the female and dead calf, the clicks were recorded from a group of dolphins, so it is not possible to know if the clicks came from one or more animals.

Dolphin clicks were recorded with a lower threshold. The settings on the software were left the same, except the trigger was lowered to negative 50 millivolts and the software was set to run in single waveform mode. When a click appeared on screen, the software was used to store the clicks in a data file, so the clicks could be analysed at a later time. Using this system it was possible to store up to 500 data points per click.

The ambient noise in the harbour was recorded by a similar set-up. The hydrophone was placed in the water from the DOC 6 m Stabi-craft to receive the noise in the area. The signal received by the hydrophone was low pass filtered at 200 kHz, to avoid any effects of aliasing. The signal was then sent through the amplifier, where it was given 10 decibels of gain. The filtered, amplified signal was then acquired by the DAQ Card, and displayed on the computer monitor with the Virtual Bench software. The sampling rate was set at 200 kHz, and the signal was recorded in one-second intervals. No trigger was used. Data were taken at four depths (1 m, 3 m, 5 m, 10 m) for three locations in the harbour. Each measurement was repeated three times.

All data were summarised in the Excel® spreadsheet format and statistical values were then computed using Statistical Analysis Software (SAS®). Differences in dolphin behaviour and click frequencies were tested using ANOVA.

4. Results

We conducted survey work on 19 days in total. On the remaining days in January the wind was too high for acoustic boat surveys. Of the 19 days that the boat went out, recordings of dolphin clicks and sounds were made on 12 days. On the other 5 days, either the wind increased before recordings could be made or no dolphin groups were found. We recorded data for 188 events over these 12 days.

4.1 SEA TEMPERATURE DATA

Sea temperature profiles of Akaroa Harbour were obtained on two days in the study area (Figs 4 and 5). The profiles indicate that there are no strong thermoclines in the harbour, which could have had an effect of isolating some of the pinger sounds from the dolphins.

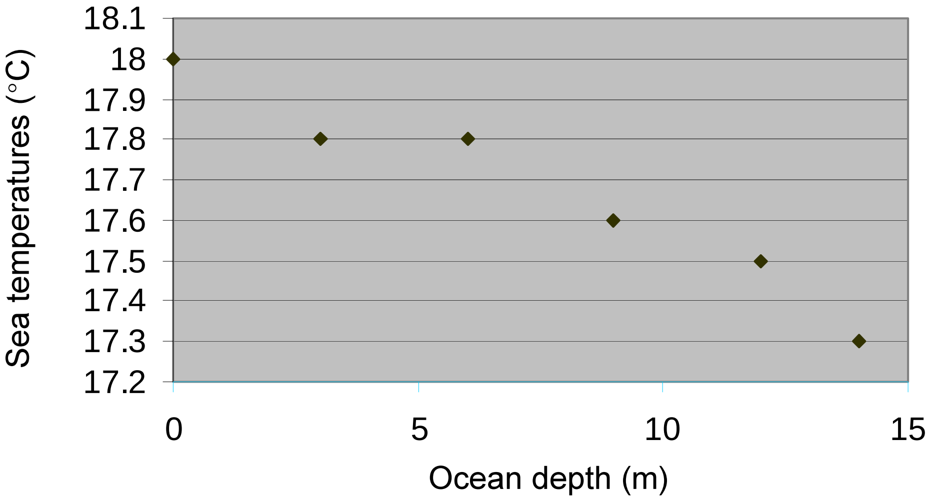

Figure 4. Sea temperature profile in Akaroa Harbour, 18 January 1999.

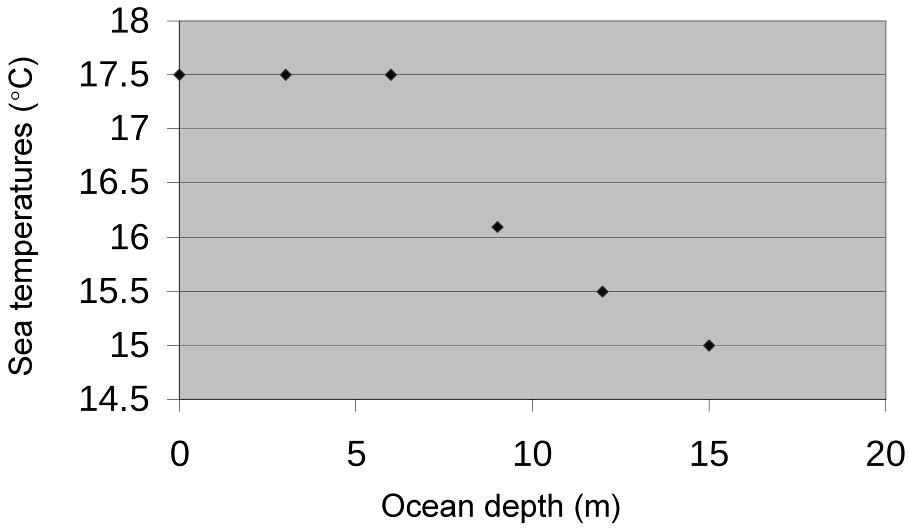

Figure 5. Sea temperature profile in Akaroa Harbour, 24 January 1999.

4.2 AMBIENT SOUND RECORDINGS

The ambient sound recordings were in the 0–5 kHz range, which indicates that the dominant ambient sound is wind.

4.3 DOLPHIN REACTIONS TO PINGERS

The distribution of the 188 events (dolphin groups) among the pingers is similar: white pinger (38 events), red pinger (45 events), black pinger (56 events), and the control (49 events).

The average number of dolphins per group was 3.64 ± 0.29 (Table 2). There were no significant differences in group size among the pinger conditions ($F = 1.35$, $P = 0.26$).

TABLE 2. NUMBER OF OBSERVED DOLPHIN GROUPS, AND GROUP SIZES FOR EACH PINGER CONDITION.

PINGER TYPE	NO. OF GROUPS	AVERAGE GROUP SIZE
White	38	3.41 ± 0.29
Red	45	3.71 ± 0.31
Black	56	3.34 ± 0.22
Control	49	4.06 ± 0.33

4.4 BEHAVIOURAL OBSERVATIONS

Of seven different behaviours recorded during pinger trials, six were observed more than twice. These six behaviours include surface swimming, porpoising, logging, jumping/ breaching, milling, and avoidance. The other observed behaviours were so infrequent that they are not included in the analysis, but included two observations of touching/sexual behaviour, once during a white pinger trial and once during a control trial. There was one observation of a dolphin approaching and exploring the pinger at close range (less than 0.5 m). This occurred during a red pinger trial. The most significant observation was the change in avoidance behaviour when among pinger conditions (Table 3, Fig. 6). Over half the observed dolphin groups (62.5%) exhibited avoidance when the white pinger was in the water. This behaviour was seen on 21 of the 32 white events.

TABLE 3. NUMBER OF EVENTS WHERE A BEHAVIOUR WAS OBSERVED FOR THE FOUR DIFFERENT PINGER CONDITIONS.

PINGER TYPE	SURFACE SWIM	JUMP/ BREACH	MILLING/ SLOW SWIM	AVOID
White	9	0	3	21
Red	23	2	4	6
Black	23	1	12	3
Control	26	1	9	1

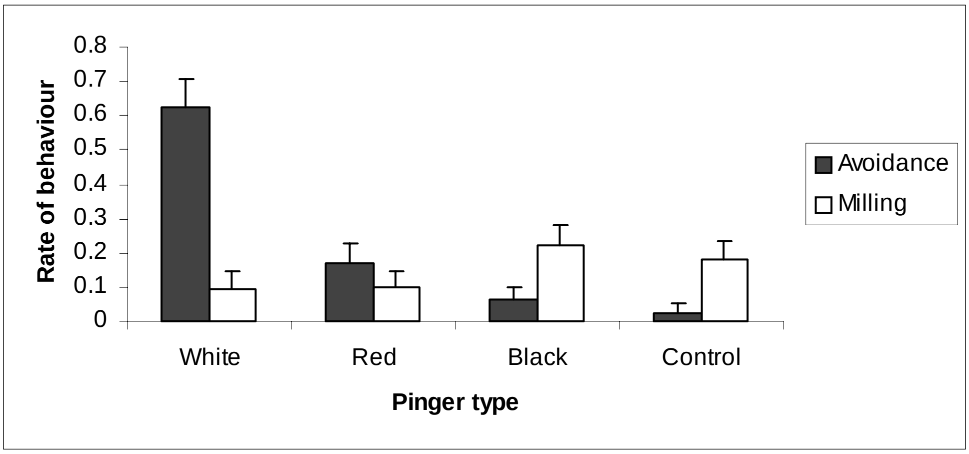

Figure 6. Rate of behavior observed in dolphin groups.

4.5 ECHOLOCATION CLICK ANALYSIS

There were no significant differences in the rate of clicks per dolphin, (F = 0.92, P = 0.44) or per dolphin group (F = 0.58, P = 0.63) under the four conditions (Table 4). There were no significant differences in the number of dolphin approaches, or in click rate per approach (Table 4). The click rate per approach was more variable for the control pinger (coefficient of variation, *cv* = 1.48). The *cv*s for the three other conditions were: white, 0.84; red, 1.03; and black, 1.09.

There were no significant differences among the frequencies (F = 1.58, P = 0.18) of the subset of clicks that were analysed for peak frequency and duration (Table 5, see Figs 6–13). The duration of the clicks from dolphins exposed to the black pinger and the dolphin associated with the dead calf were significantly longer than the other pinger conditions (F = 6.41, P = 0.0001).

TABLE 4. ECHOLOCATION CLICKS PER DOLPHIN, PER DOLPHIN GROUP, AND PER APPROACH. ALSO SHOWN IS THE TOTAL NUMBER OF APPROACHES UNDER THE FOUR PINGER CONDITIONS.

PINGER TYPE	CLICKS/ DOLPHIN*	CLICKS/DOLPHIN GROUP	NO. OF APPROACHES	CLICKS/ APPROACH
White	1.21 ± 0.29	4.35 ± 1.18	17	3.22 ± 0.66
Red	1.19 ± 0.21	4.39 ± 0.84	21	3.74 ± 0.88
Black	1.62 ± 0.20	5.71 ± 0.98	26	5.61 ± 0.23
Control	1.61 ± 0.28	5.57 ± 0.86	27	4.12 ± 1.18

* Clicks per dolphin were calculated by dividing the total number of recorded clicks by the number of dolphins in the group.

TABLE 5. FREQUENCY AND DURATION OF FULL RESOLUTION CLICKS RECORDED UNDER THE VARIOUS PINGER CONDITIONS.

PINGER TYPE	CLICK FREQUENCY (kHz)	CLICK DURATION (mS)
Control (*n* = 36)	124.17 ± 0.96	0.0613 ± 0.0030
Black (*n* = 32)	122.86 ± 0.94	0.0756 ± 0.0029
Red (*n* = 36)	125.38 ± 0.51	0.0643 ± 0.0014
White (*n* = 32)	123.73 ± 0.48	0.0675 ± 0.0020
Dead* (*n* = 12)	124.63 ± 0.46	0.0771 ± 0.0039

* Dead signifies clicks recorded from a female Hector's dolphin who was accompanying a dead calf.

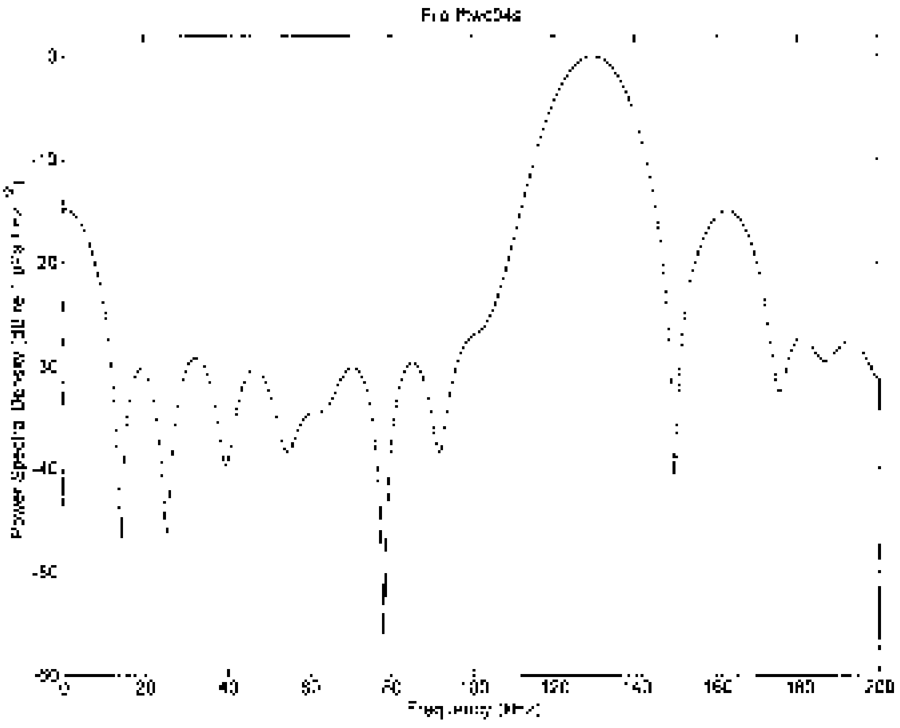

Figure 7. Hector's dolphin click recorded in the presence of white pinger.

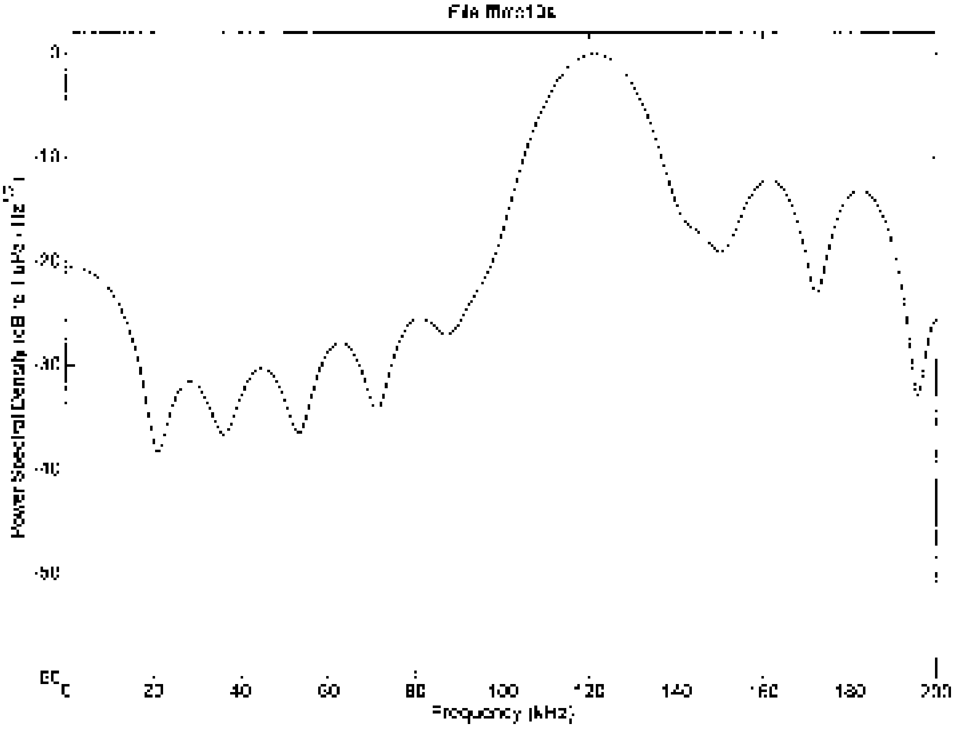

Figure 8. Hector's dolphin click recorded in the presence of red pinger.

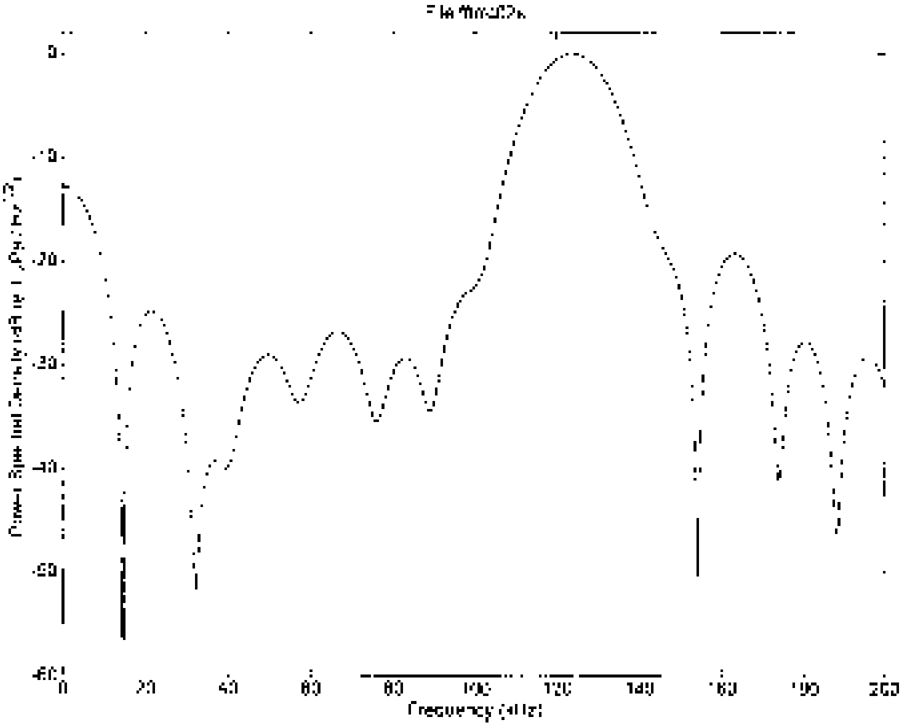

Figure 9. Hector's dolphin click recorded in the presence of black pinger.

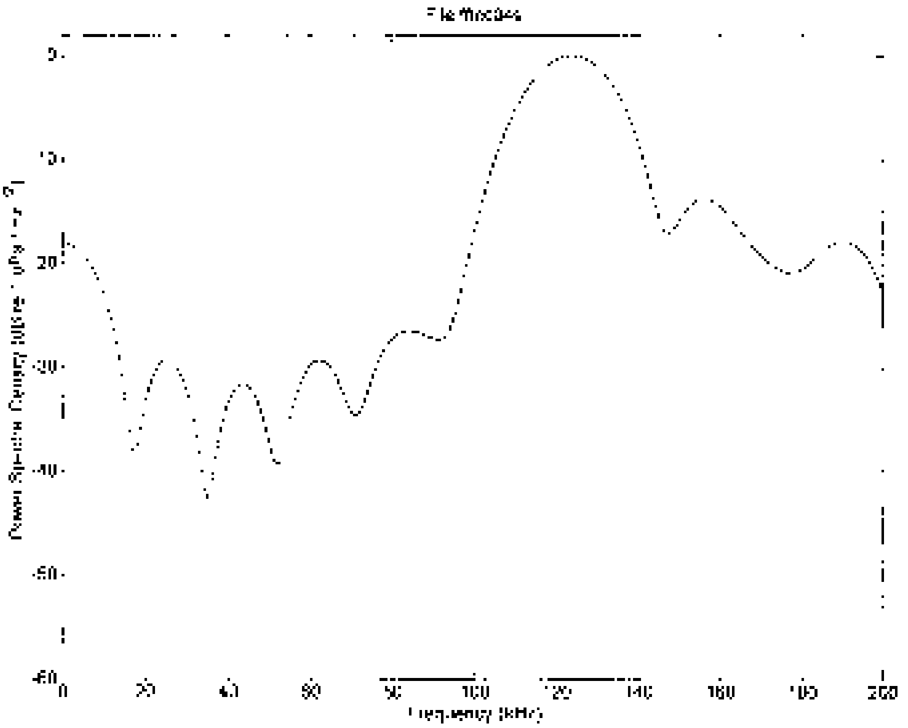

Figure 10. Hector's dolphin click recorded with no pinger.

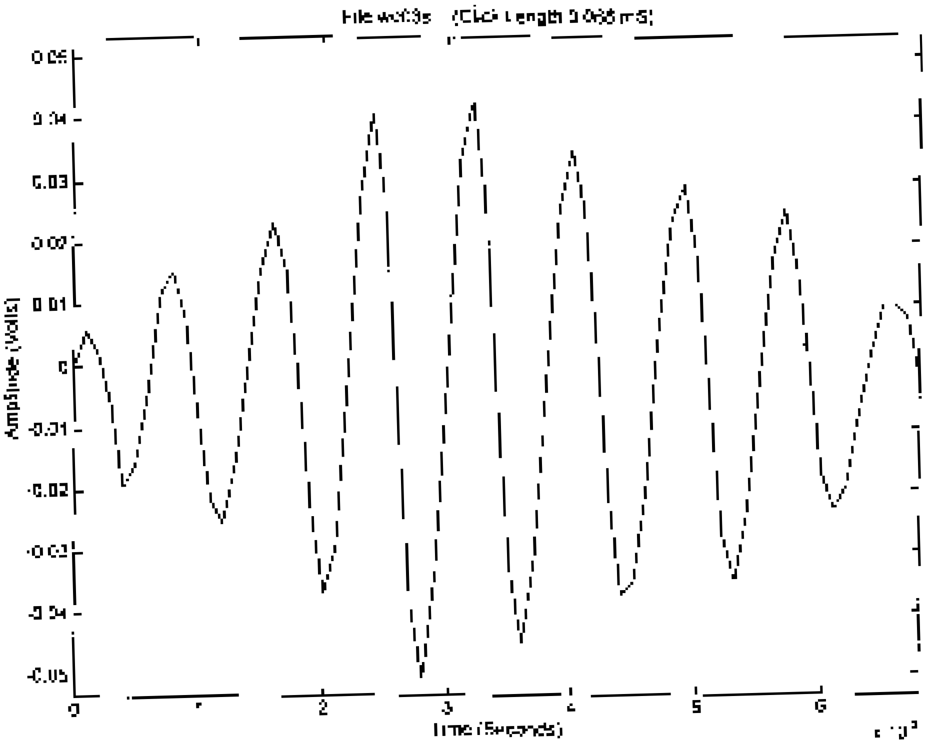

Figure 11. Duration of Hector's dolphin click in the presence of white pinger.

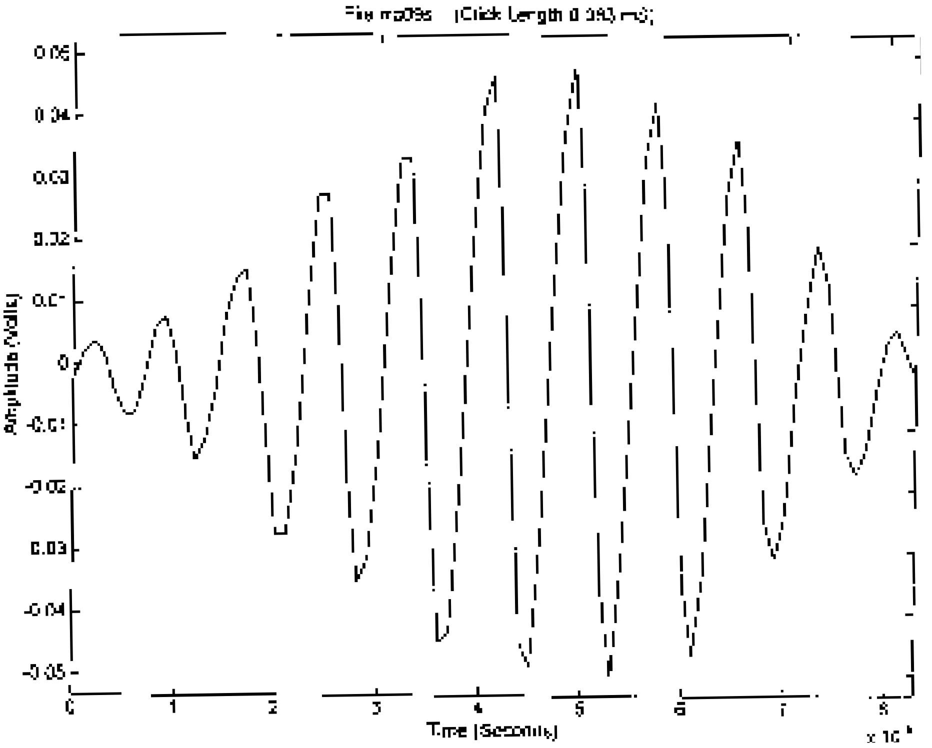

Figure 12. Duration of Hector's dolphin click in the presence of red pinger.

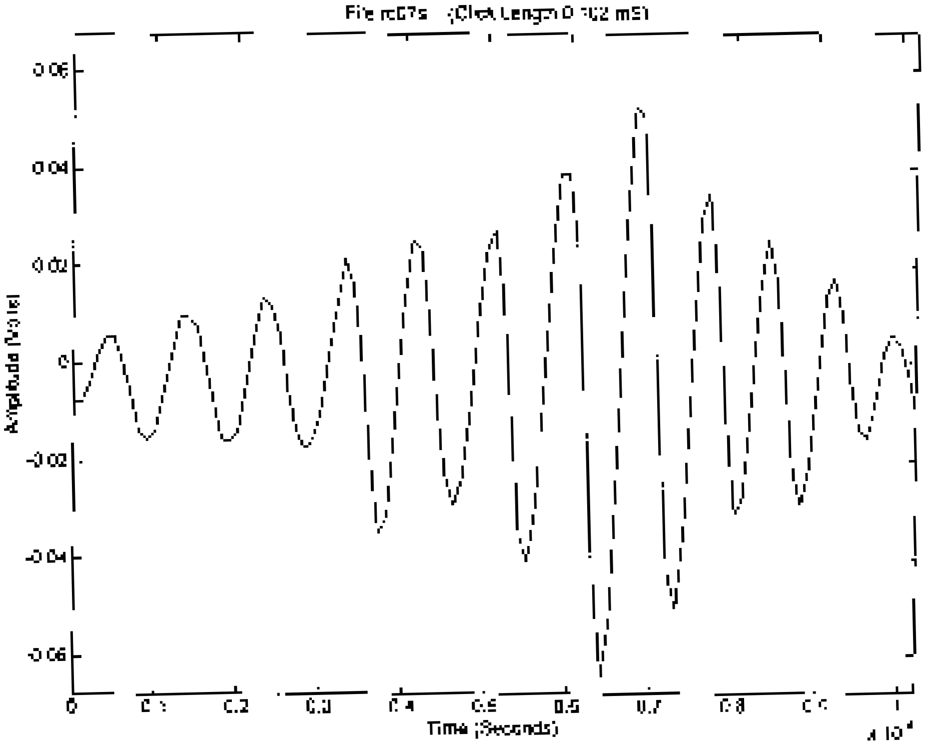

Figure 13. Duration of Hector's dolphin click in the presence of black pinger.

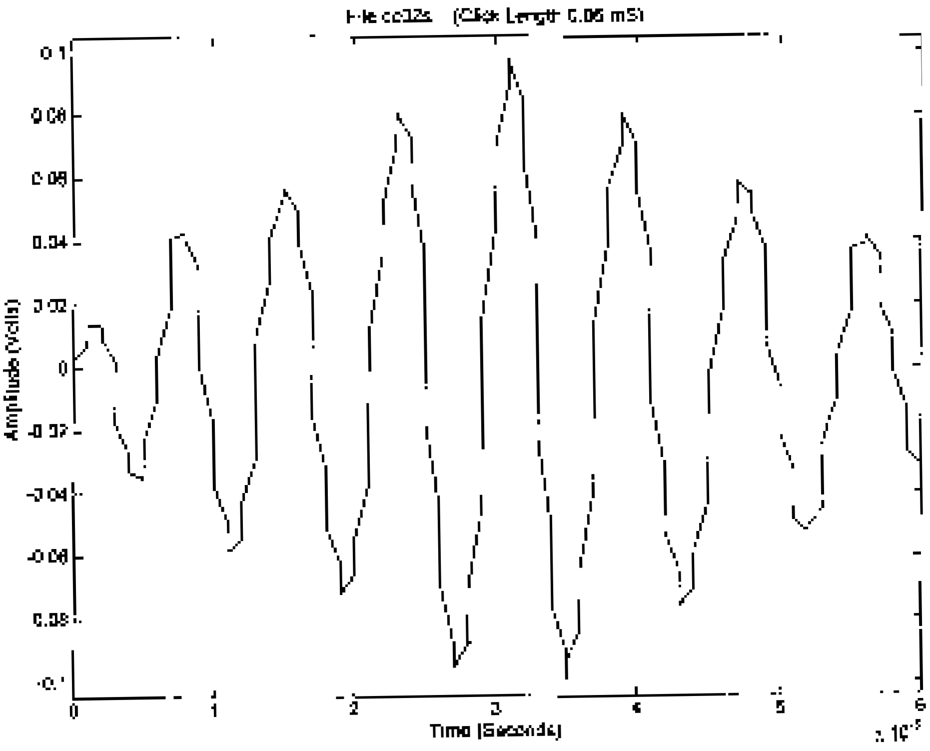

Figure 14. Duration of Hector's dolphin click with no pinger.

5. Discussion

The primary goal of this study was to determine what characteristics an acoustic device should have for use in gillnet fisheries in the Canterbury region of New Zealand for the purpose of reducing entanglement of Hector's dolphin. The study pursued this goal by comparing *in situ* acoustic and behavioural reactions of Hectors' dolphins to three different pingers and a control. Our data showed that the acoustic device which elicited the strongest response from Hector's dolphins was the white Dukane pinger, which had steady and evenly spaced harmonic peaks at approximately 10, 40, 60, 80, 100, 110, 130, 150 kHz. This conclusion is based on the behavioural reaction of the dolphins to the white Dukane pinger. The statistically significant increase in avoidance behaviour to this pinger (see Fig. 5) was the most dramatic result of this study.

The black pinger, which showed no measurable effect on the animals had, on average, a lower spectral output and more random pattern than the white Dukane pinger. It is not recommended as a pinger for this species.

It is puzzling that the red Dukane pinger has a very similar spectral output to the white Dukane pinger, but the dolphins reacted differently. Perhaps the dolphins reacted differently because white pinger has evenly spaced harmonic peaks to its spectral output up to 150 kHz. The red pinger had less evenly spaced spectral outputs and was not as strong or defined in the upper range of 150–160 kHz. One possible explanation is that the dolphins are sensitive to the combined effect of the harmonic peaks of a pinger or that the slightly higher output (at 150 kHz) is important. There may also be other subtle differences in pinger outputs that the dolphins can sense, but the instruments used to evaluate the pingers cannot. It must be stressed that these are empirical results and that we do not understand the mechanisms or reason for the dolphin reactions, but the animals were deterred from the area by the sounds of the relatively high frequency white pinger. It should also be noted that we only tested one type of each white and red pingers. If there is enough variation in red and white pinger outputs, it is possible that red and white pingers may have similar results if many are tested and compared.

It is not surprising that Hector's dolphins may be particularly sensitive to the higher frequencies. The frequency of sound made and used by an animal tends to scale with the body size of the animal (Popper et al. 1997). Hector's dolphin is one of the smallest cetaceans in the world. One of the major differences in the structure of odontocete ears when compared to terrestrial mammals is the larger mass of the inner ear bones and structural complexity of the cochlea (Ketten 1997).

In March 1998 a mature female Hector's dolphin was flown to the United States under the co-operative research program between DOC and the New England Aquarium (Stone et al. 1998). The specimen was autopsied and subjected to topographic studies (Computerised Topography and Magnetic Resonance Imaging) at the Massachusetts General Hospital, Boston, MA, USA. The CT scanning comprised a full body series at 3 mm, followed by an ultra-high resolution (UHRCT) spiral scan series with a 1 mm continuous acquisition (Fig. 15). The

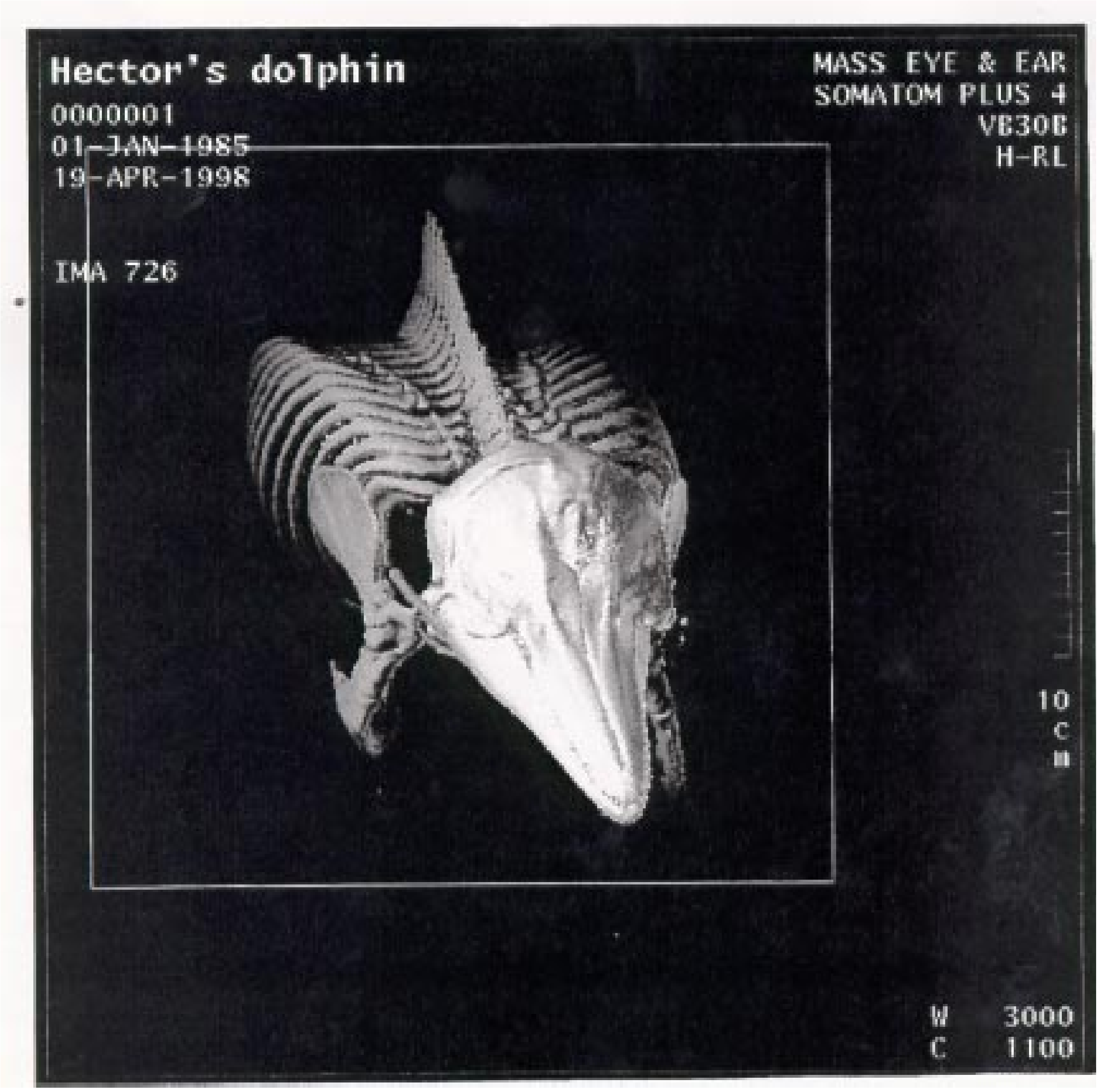

Figure 15. Three dimensional scan of Hector's dolphin skeleton reconstructed from whole body CT scans.

cochlea had distinct well-separated lobes and substantial outer osseous lamina, which is a hallmark of high frequency hearing. Ketten (1998) determined that observations from this specimen indicate Hector's dolphin's hearing ability are a Type I odontocete. Type I odontocetes can hear to 200 kHz and have best sensitivities above 100 kHz. Ketten (1998) estimated that this specimen would have relatively good frequency hearing with peak sensitivity >>80 kHz.

These cochlea data may help explain the reaction of Hector's dolphins to the pingers, and supports the selection of a relatively high frequency pinger for mitigation measures, perhaps as high as 200 kHz. In addition to high frequency, the pinger design should also consider the relatively evenly spaced harmonics in the spectral output of the white pinger. In the Canterbury region with Hector's dolphin, it appears that pingers with high frequency outputs and even harmonic are desirable for use and that they may deter the animals from nets. It may be possible for different pingers to have different effects. In our case the white pinger seemed to act as a deterrent to the dolphins, but this does not discount the possibility of another type of acoustic device alerting the animals to the nets.

Also supporting this deterrent effect with the white pinger was the finding that there were significantly more approaches to the control condition. The dolphins approached the area more often with no sound in the water. While this study was not designed to measure the fine scale distance between the pingers and the dolphins, it might be, based on significantly fewer approaches to all three pingers when compared to the control, that all the pingers had some deterrent effect. There is no doubt, however, that the dolphins reaction was strongest when exposed to the white pinger.

An assumption at the beginning of this study, and one that has been widely considered, is that pingers may affect the echolocation of dolphins. The hypothesis is that the pinger sound will stimulate the dolphin to begin echolocating or echolocate at a higher rate, detect the net, and then avoid it. The alternate hypothesis is that the pinger would deter a dolphin from the area and cause a corresponding decrease in echolocation. This study found no change in echolocation under the four conditions, indicating that the avoidance of pingers may not be related to the echolocation habits of the dolphins. Under all conditions echolocation rates were the same, showing that in our experiment the dolphins used their sonar equally for all situations encountered. Perhaps the constant use of sonar by Hector's dolphins in this experiment suggests that avoidance of a sound is not related to their choice to echolocate or not, or to increase or decrease the echolocation rate, but rather to their choice of where to locate themselves relative to that sound.

This does not mean that Hector's dolphins could not detect and avoid a net by echolocating. Au & Jones (1991) showed that echolocating dolphins (*Tursiops truncatus*) should be able to detect gillnets at ranges that would allow the animal to avoid entanglement. They point out that dolphins may not always have their sonar on and may not perceive the net as a threat, even if they do echolocate and detect it. For oceanic dolphins with rare encounters of nets, they may not perceive a net as a threat, especially if it is their first encounter. However, when this study was conducted, the use of nets in the Canterbury region had been on going for many years. It is likely that the dolphins have encountered nets.

In our situation, the dolphins were echolocating under all conditions. If a net had been in the water, they probably would have sensed it with their sonar. It is also possible that the research boat or the hydrophone stimulated the dolphins to echolocate. We must also consider the situation cited by Au & Jones (1991), that is, how would a dolphin swimming through the ocean with their sonar off react to a net. It is likely that Hector's dolphins swim through waters of the Canterbury region with no boats in the area and with their sonar off; and during these times they may encounter nets. How would a dolphin react to a pinger in these conditions? Unfortunately it is difficult to duplicate this study without the potential effect of the research boat and hydrophone stimulating the dolphins to echolocate. The use of boats and hydrophone are the standard way to record *in situ* dolphin sounds. But based on this study, if a non-echolocating dolphin encountered a white pinger, it would probably avoid the area. Because the dolphins in our study were acoustically active, we do not know if a previously silent dolphin would begin echolocating when encountering a pinger.

The use of acoustic pingers to reduce entanglement continues to stimulate lively discussion with varied opinions on their efficacy (Kraus 1999; Dawson et al. 1998; Kraus et al. 1997). Two studies have shown pingers reduced the level of bycatch in harbour porpoise (Kraus et al. 1997; Gearin et al. 1996). Pingers are also being used in a number of uncontrolled situations throughout the world, where their effectiveness is not known. In all examples where they have been tested and proven effective through a controlled situation, the question still remains as to the mechanism that keeps the dolphins out of the nets. Are they alerted to the presence of nets by pingers, stimulating them to echolocate and thus avoid the net, or are they deterred by the frequency and leave the area of the net? Data in this study actually support both hypotheses in the case of Hector's dolphins. The animals were acoustically active around the pingers, but also showed clear avoidance from the white pinger.

The strength of this study is that it is the first experiment to look at the *in situ* acoustic and behavioural response of the dolphins to pingers. Throughout all the previous discussion and experimentation with pingers there have been few studies on *in situ* behavioural and acoustic reactions of the dolphins. This paper is the first report of underwater sounds produced by dolphins in the presence of pingers.

6. Management recommendation

Based on this study, a higher frequency pinger would be the first choice for Hector's dolphin. The white Dukane pinger had strong harmonics right up to and probably over 150 kHz. The upper limit of reliability for the experimental hydrophone was 160 kHz, but it is likely that the harmonic outputs of the pinger extended beyond this range. A pinger of similar power, but with harmonics up to 200 kHz is probably best for deterring Hector's dolphin.

It must also be stressed that pingers are not the only or the final solution to dolphin bycatch. All options need to be considered. Pingers are only one of the tools available to address the widespread problem throughout the world. We must also keep exploring new net designs, area closure options, and research into new and unexplored mitigation approaches.

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