AN INDEPENDENT REVIEW OF THE EFFICACY OF KILLING METHODS OF ANTARCTIC MINKE WHALES

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ABSTRACT

Video footage of the hunting of minke whales by the Japanese whaling fleet in the Southern Ocean taken by Greenpeace from independent observation platforms was analysed to estimate quantitative data relevant to animal welfare. Catches of 16 individual minke whales were analysed. Of these, 12 events allowed an estimation of minimum time to death or insensibility, and in 2 of these (17%) death could potentially have been instantaneous. For the remaining 10 observed kills where times could be estimated, the mean of the estimates of minimum time to death or insensibility was 10 minutes with a maximum of 33 minutes. These values are likely to be negatively biased due to difficulties of determining whether a whale that was not vigorously moving was indeed dead. Comparison with previous published data on the locations of harpoon impacts showed no evidence that the accuracy of shooting was affected by the presence of Greenpeace.

In 2 of the 16 events, asphyxiation appeared the most likely cause of death. These whales were harpooned aft of their midpoint and winched tight to the bow of the catcher with the head therefore forced underwater. Rifle shots were either not attempted or did not appear effective as a secondary killing method, since a clear shot of the head was not possible. The large proportion of harpoon impacts towards the tail from this and previous Japanese scientific and commercial whaling indicate that winching such whales tight to the bow on the harpoon line will likely result in a substantial proportion dying by asphyxiation. Thus asphyxiation appears to be the *de facto* secondary killing method in these situations.

A simple model was developed to estimate the relative shock to the brain caused by the penthrite grenade at different impact locations on the whale in relation to the likely position of the body relative to the sea surface. These calculations indicate that a harpoon which detonates deeper below the sea surface is likely to cause greater injury. This is consistent with reported differences between the effect of harpoons that hit ventral or dorsal regions. For whales shot during a high speed chase, the harpoons that hit closest to the brain are also likely to detonate close to the sea surface. These factors may contribute to the low instantaneous death rate reported and observed for this hunt.

INTRODUCTION

High quality video footage of the hunting of Southern Hemisphere minke whales (*Balaenoptera bonaerensis*) during the second phase of the Japanese Whale Research Program under Special Permit in the Antarctic (JARPAII) was taken by Greenpeace using helicopters and inflatable boats as observation platforms. The authors of this paper were not involved with the planning or execution of the Greenpeace anti-whaling campaign in the Southern Ocean. We make no judgment or comment about the campaign. The video footage was made available to us for analysis by Greenpeace.

The video footage we analysed is the first data source available from an independent platform which allows an assessment of the efficiency of killing techniques on Southern Hemisphere minke whales, and as such is germane to the deliberations of the workshop on whale killing methods.

Some of the footage was collected while Greenpeace was endeavouring to disrupt the hunting of whales. Our intent was to estimate welfare related parameters from the data that were representative of un-impeded hunting practice. In one case, an inflatable boat was in the direct line between the harpoon gun and the whale at the time of the shot and the line fell across the boat. This was excluded from further analysis because it was clearly an atypical event. In order not to prolong the deaths of harpooned whales, Greenpeace instituted a protocol where they kept clear of a harpooned whale that was still alive (S. Rattenbury, *pers. commn*.). This was visibly the case in the video footage we analysed.

This footage was analysed with the aim of determining a number of quantitative data items. These included the minimum time to death or insensibility, the location of the harpoon strike in the whale's body, the range at which the harpoon was fired, and development of a simple model to estimate properties of the shock wave exerted on the brain by the exploding grenade. Knudsen and Øen (2003) suggest that an instantaneous kill may be achieved by a sufficient shock to the brain. The shock to the brain caused by the detonation of the grenade will be a function of the distance of the explosion from the brain but also the propagation of the shock wave and interference caused by reflected waves. The main reflective boundaries are clearly the sea surface and any interface between the whales' body and the air for any part of the whale above the surface. As a general rule, Richardson (1995) notes that the impulse received from a given blast increases with charge depth and animal depth. These factors are explored further using video footage of minke whale surfacings at the time of harpoon impact.

In addition, the range to the animal at which the harpoon is fired will have a number of effects on the impact on the animal. The main effect will relate to the accuracy of the shot and where the harpoon hits the whale. Accuracy will decrease with greater ranges due to the effect of angular misalignment (roughly linear with distance) and animal movement. Øen (1992) notes that accuracy drops considerably as ranges exceed 60m and the recommended maximum range for harpoon shots in Norwegian hunts is 30m (Øen, 2003). The force of impact and penetration of the harpoon will also be lower at greater ranges.

METHODS

All the video footage analysed was taken between 22 December 2005 and 14 January 2006 (subsequently referred to as 05/06 footage). All sequences which either showed all or part of the sequence from harpoon shot to assumed death of the whale were analysed.

In order to measure the location of the harpoon impact from photographs taken at unknown angles and distances with a zoom lens of unknown focal length, a number of reference points on the animal are required. Approximations are also needed by the analyst in an attempt to determine the relative viewing angle of the body and to correct for both presentation angle and perspective. In practice, human operators are relatively good at making judgements such as locating an imaginary centreline for the body as has been demonstrated by automated photo-identification matching systems where a 3D model is fitted to photographs based on the user identifying the location of a number of reference points (A.R. Hiby, *pers. commn*.). Measurements of external features on minke whales are given by Jonsgaard (1951) and van Utrecht and van der Spoel (1962). The measurements from Jonsgaard are for *Balaenoptera acutorostrata* in the North Atlantic, but these appear comparable with the single animal measured by van Utrecht and van der Spoel in the Southern Ocean (Table 1). These relative measurements were used to analyse the location of the harpoon impact as a proportion of body length depending on what features were present on the images. Knudsen *et al*. (1999 51/WK13) also describe the location of the brain. For a 5.25m minke whale, this was 55cm behind the blowhole and for an 8.5m whale this was 75cm behind the blowhole. If the centre of the blowhole is 13% of the whale's body length from the tip of the lower jaw then the brain will be at about 22-23% of the body length. This is consistent with the 23% estimated by Jonsgaard for the head length (Table 1).

There are several sources of previous data on the location at which minke whales were hit by harpoons. These include Best (1993) with data from Japanese commercial whaling during the 1978/79 seasons, McLachlan (1995) with data from the 1992/93 JARPA, Knudsen and Øen (2003) with data from Norwegian minke whale hunts 1998-2000 and Knowles and Butterworth (2006) based on combined data from Knudsen and Øen (2003) and Knudsen (2004).

To compare the locations of the hits obtained with those from commercial whaling, the minke whale was divided into 15 sections based on the proportion of the total body length body aft of the snout following the procedure used by Best (1993). Thus section 1 is from the snout to 6.7% of the body length, section 2 from 6.7% to 13.3% etc. The numbers of hits in each of these zones were calculated from data presented in Best (1993) for Japanese commercial whaling, Knowles and Butterworth (2006) for Norwegian commercial whaling and the 05/06 video footage for JARPAII whaling (Figure 1).

In order to model the likely shock wave to the brain, empirically derived equations from experiments with underwater explosives were used. When a high explosive detonates underwater, the peak pressure is given empirically by Urick (1983) as

$$P_{peak} = 5.24 \times 10^{13} (W^{1/3} / R)^{1.13} \quad \mu\text{Pa} \qquad (1)$$

Where W is the weight of the charge in kg and R is the range in metres.

However, equation 1 is limited to close distances and also assumes no interference from the surface, bottom or other boundaries. The limiting range R_0 for equation 1 to be representative is given by Richardson *et al.* (1995) as

$$R_0 = 4.76 W^{1/3} \quad \text{metres} \qquad (2)$$

For a 30g charge of a high explosive R_0 = 1.5m. Penthrite is classed as a high explosive that is slightly more powerful than TNT with a TNT equivalent of 1.77. For these calculations we use the weight of penthrite used rather than its TNT equivalent due to difficulties in using one single conversion factor for different explosive types (Richardson, 1995). Using the TNT equivalent for W (0.053kg) would increase the calculated peak pressures by 1.9dB. At greater distances than R_0 Richardson *et al.* (1995) give equations derived from weak shock theory where the peak pressure P_m is then given by

$$P_m = P_0 \left\{ \left[1 + 2(R_0 / L_0) \ln(R / R_0)\right]^{0.5} - 1 \right\} / \left[(R / L_0) \ln(R / R_0)\right] \qquad (3)$$

where the term L_0 in equation 3 is given by

$$L_0 = (\rho_0 c_0^{\,3} t_0) / (P_0 \beta) \qquad (4)$$

where ρ_0 is the density (1026kg/m^3 for water), c_0 is the speed of sound (1500m/s for water), β=3.5, P_0 is given by equation 1 and t_0 is given by equation 5 for $R = R_0$

The time constant for the pressure wave to decay exponentially to 37% of its initial value is given by t_c where

$$t_c = 92.5 W^{1/3} (W^{1/3} / R)^{-0.22} \quad \mu\text{s} \qquad (5)$$

These equations allow the peak pressure to be determined, but Richardson *et al.* (1995) note that in blast injuries to animals, the positive acoustic impulse is closely correlated with organ damage. The positive impulse is the integral over time of the initial positive pressure pulse. Calculating this can be problematic because a surface reflected blast may cancel out a directly received blast. In the simple case of a surface reflected blast from the sea surface, the integral may be calculated over a time Δt where this is the difference in travel times for the direct and reflected blasts. For a blast within a whale there is likely to be a surface reflection but also complex reflections within the body. Assuming Δt could be calculated, then Richardson *et al.* (1995) give the positive impulse I as

$$I = P_{peak} t_c (1 - e^{-\Delta t / t_c}) \quad \text{Pa.s} \qquad (6)$$

For ranges greater than R_0, t_c is given by equation 7.

$$t_c = t_0 \left[1 + 2(R_0 / L_0) \ln(R / R_0)\right]^{0.5} \qquad (7)$$

For reflections involving the sea surface, Δt can be given as

$$\Delta t = \left\{ \left[(d + S)^2 + H^2 \right]^{0.5} - R \right\} / c_0 \qquad (8)$$

Where *d* is the depth of the harpoon explosion, *S* is the depth of the brain at the time of the explosion, *H* is the distance between the harpoon and the brain in a horizontal plane and *R* is the slant distance between the harpoon and the brain.

For the purposes of relating the likely impact on the brain with the location of the harpoon impact, the estimated distance from the harpoon location to the brain as a proportion of body length was multiplied by the length of a typical whale. Thus the peak pressure at the brain could be estimated from either (1) or (3) depending on whether the distance was less than or greater than R_0. In order to make some comparative estimates of the possible positive impulse on the brain in relation to the location of the harpoon strike, it was first assumed that the dominant reflected shock wave would be from the sea surface and not within the body tissues of the whale. This assumption was based on the fact that the differences in acoustic impedance between different types of body tissue within the whale are much smaller than the difference between air and water. Thus Δt was calculated using (8) and the positive impulse using (6). In order to estimate possible values for d and S, video footage of the actual moment of the strike in relation to the surfacing sequence of the minke whale was examined (figure 2). Based on photogrammetric measurements of the mean dimensions of the part of the body visible above the surface at various points in a surfacing (Leaper, 1996) a likely underwater profile of the whale was overlayed on captured video images of the visible body above the surface.

The calculations presented above only apply to situations where the explosion is sufficiently deep that surface venting does not occur. If surface venting does occur then energy is lost through the sea surface (in a visible plume of water) but the surface reflection will also be reduced. We were not able to quantify the extent of this effect but qualitatively it will also result in explosions at greater depth causing greater injury.

RESULTS

A total of 16 individual kill events were observed. These were each given an arbitrary two digit *Event Code* by which they are referred to in the text. Where more than one harpoon was fired the event code is given a single letter suffix *a, b …* to indicate the harpoon shot in the sequence.

The 05/06 video footage allowed the locations of 17 harpoon shots to be measured. These are shown in figure 1. Both sides of the whale have been combined for the purposes of this figure and only harpoon entry points are shown. Two cases are included where a whale was shot twice. In the case of event 4, the shot 4a wounded but did not tether the whale. Shot 4b was taken as the whale was still swimming freely and has been included in the comparison of hit locations. Shot 10b was made to a whale that was already tethered on the harpoon line. Because of the unusual circumstances, this shot was not included in the comparison of hit locations.

The mean location expressed as proportion of body length aft of the snout for these 16 hits was 0.48 (sd = 0.12). Based on observations of 7 hits made from whaling vessels during the 1992/93 JARPA reported in McLachlan (1995) we calculated an equivalent mean location of approximately 0.53 (sd = 0.17) of the body length. Thus the mean of observed hits in 05/06 was slightly closer to the optimum target area but the difference was not significant (Ttest, p=0.45)

Best (1993) used the criteria of whether the location was forward or aft of 40% of body length from the snout for comparison of hit locations between different catcher vessels. Using the same criteria of whether the whale was hit forward or aft of 40% body length from the snout there were significant differences between Japanese commercial whaling, Norwegian commercial whaling and the 05/06 video (Chi-squared = 17.7, df = 2, p<0.01). However, given the data in Knowles and Butterworth (2006) which shows a region extending aft to 49% of the body length at which instantaneous insensibility may be achieved, we also included one more of the 15 zones into the 'forward' category compared to Best. Thus the analysis was repeated with anything forward of 7/15 (47%) of the total length considered a hit to the forward part of the whale. In this case there were no significant differences between the three data sets (Chi-squared = 0.61, df =2, p=0.74).

One complication for this analysis is that Best included both entry and exit wounds noting that these were generally indistinguishable once the harpoon had been removed from the carcass. Thus he measured 152 wounds from 127 whales killed. Whales are generally harpooned as they are swimming away from the vessel. For example, Ishikawa and Shigemune (2005) report a mean harpoon entry angle of 36.7^{o} from to the midline of the whale as it swam away. As a result, exit wounds are almost invariably further forward than entry wounds and the mean distance from the Best data would be expected to be closer to the snout. Just comparing Norwegian commercial and the 05/06 video showed no significant differences (Chi-squared = 0.41, df = 1, p=0.52). Hence it seems most likely that the differences in the observations by Best and the other data which involve a number of hits a small but significant distance further forward on the body can be explained by the inclusion of exit wounds as well as locations of harpoon entry.

The video footage analysed had not been taken specifically for the purpose of measuring range and it was not possible to estimate accurate ranges at which all the whales were harpooned. Where photogrammetric measurements were obtained these were in the range 35 – 55m but this is not necessarily a representative sample from the observed shots. Some indication of range is given by the flight time of the harpoon which it was possible to measure for 8 shots (Table 3). However, measurements of the initial velocity at which the harpoon left the gun varied between 92 and 123ms^{-1}. Further measurements indicated that on average the velocity 0.6s after firing was about half the initial velocity. However, it cannot be determined how much of the variability in estimates of initial velocity was due to measurement error and how much is real variation. The Handbook for gunners (Tanaka, 1987) indicates an initial velocity of 113ms^{-1} with a velocity 0.6s after firing of 71ms^{-1} or 63% of the initial velocity. Within the likely measurement error, these values are consistent with those observed from the 05/06 video. Thus in order to estimate the range at which whales were shot, tabulated values of horizontal distance against flight time from the Handbook were interpolated for the measured flight times (Table 3). This gave a mean horizontal range of 44m and a maximum of 61m.

Of a total of 16 kills analysed, 12 allowed some estimation of time to death. The whale was judged to be certainly still alive if there were signs of strong, distinctive, movements involving either fluke strokes or blows. If neither of these were visible it was assumed that the whale was likely to be insensible and may be dead. Hence the time from the harpoon shot to the time at which the whale was last definitely seen alive can give a conservative estimate of the minimum time to death (Table 3). In several cases there was a discontinuity, either because of a break in the footage or because the whale submerged, between the last time that the whale was seen alive and the time that it was subsequently observed with no sign of movement and assumed to be dead. Where times could be determined, the time from harpoon shot to first footage at which whale appeared dead is shown in Table 3.

In two instances the actual harpoon shot was not observed, but it is believed that the footage commenced within a few seconds judged from the movement of the catcher vessel. If all kills which could have potentially been instantaneous (when the whale was first observed subsequent to being shot it showed no sign of life) were given a time to death of 0 and the times for the two cases where the harpoon shot was not observed were taken from when the footage started, then the mean time to death was 498s (sd = 661s). The median was 210s. The mean and median will be negatively biased for a number of reasons. Firstly, these are times to the last time the whale was seen alive. Although the mean of the difference between the time of 'first believed to be dead' and 'last time seen alive' was only 91s, there was one occasion when the whale was secured alongside the catcher by the tail still clearly alive. Once the catcher started steaming it was impossible to tell how much longer the whale remained alive due to the motion of the body resulting from the moving water. A second cause of negative bias might be if some of the whales that were assumed to be dead were not in fact dead. The IWC criteria of a slack mouth, a slack flipper and all movements to cease (IWC, 1980) were not easy to apply to video footage and thus only very clear signs were used to indicate that the whale was still alive. A whale that was only moving weakly, or was insensible, but still alive, might well be classified as assumed dead in this analysis whereas the movements might be detected by an experienced observer on the vessel.

The instantaneous death rate has been shown to be closely related to the location of harpoon impact on Norwegian hunts (Knudsen and Øen, 2003; Knowles and Butterworth, 2006). Based on the analysis of Knowles and Butterworth, 5 of the observed impacts (Event codes 02, 07, 12, 17, 18) and possibly 10b would have been expected to result in instantaneous death. Of these, no data on time to death could be obtained for 07, but 02 and 17 could potentially have been instantaneous. Event codes 12 and 18 had minimum times to death of 2:48 and 1:04 respectively, which were shorter than the median.

The effects of reflection of the blast may be a possible explanation for some of the differences in damage to the brain between harpoons that strike in the ventral area compared to the dorsal region, noted by Knowles and Butterworth (2006) based on data in Knudsen (2004). Based on these equations, the larger the Δt (the time between the initial shock wave and the interference from its reflection), the larger the positive impulse. If the main reflection is from the sea surface then increasing either the distance from the sea surface at which the harpoon explodes or the depth of the brain will increase the positive impulse. This is illustrated in figure 2. This figure shows a still image captured from the video of a minke whale surfacing during a high speed chase and the harpoon just about to hit the whale. This has been overlaid with a drawing of the expected position of the whales' body based on what is visible above the surface. Based purely on reflection from the sea surface and ignoring the complexities of reflection within the whales' body and surface venting, the two harpoon locations illustrated might be expected to have the same positive impulse on the brain (338 Pa-s). If the overall length of this whale was 7.5m then in this case the actual harpoon strike (hit location 1) is estimated to be 0.5m below the sea surface and 1.60m from the brain that is at a depth of 0.56m. This would give the equivalent positive impulse to a strike in the head (hit location 2) at 0.04m below the sea surface only 0.9m from the brain.

Although this is a highly simplified model it would provide an explanation consistent with the observed data on locations of strikes presented in Knowles and Butterworth (2006) in terms of reaching a critical positive impulse in order to achieve instant insensibility. The video footage showed that some surface venting does occur in that there was a visible plume of water following the impact of the harpoon. However, we were not able to quantify the energy lost in this manner. It might be assumed that surface of the whale that is above the water in contact with the air will have similar reflective properties to the surface of the sea. However, the amount of surface venting that might occur through the skin of the whale is complex and has not been considered within this model.

For a 30g explosive charge, equation 1 gives a peak pressure of 263 dB re 1µPa at 1m. The exponent of $R^{-1.13}$ is an empirically derived figure based on the properties of seawater. Transmission within a whale will vary between tissues but for the sake of this analysis has been assumed equivalent to sea water based on the similar density and acoustic properties. Regardless of the issues of reflection of the shock wave, the basic relationship between peak pressure and distance is consistent with larger whales receiving a reduced impact on the brain for a harpoon that strikes in the body in the same relative location. Knowles and Butterworth (2006) suggest a target area as a proportion of body length from the tip of the lower jaw for which data indicate there is a high probability of instantaneous death. They suggest that on average this area extends backwards on the whale to 30% of total length dorsally and 49% ventrally for North Atlantic minke whales. Assuming the brain is 22% of the body length behind the lower jaw then if these values are for a mean whale length of 7.5m then the equivalent proportions of body length for a mean whale length of 8.5m giving the same distance from the brain would be approximately 29% and 46% dorsally and ventrally respectively (Figure 1). The fact that a relatively small change in average body length results in a measurable change in instantaneous death rate could suggest that the threshold between the shock exerted by the grenade explosion between instant insensibility and injuries that are not immediately fatal may be quite sharp.

Two instances (Event codes 3 and 10) were observed where the harpoon lodged in the dorsal area close to the head such that the blowhole remained out of the water even when the line was winched tight to the bow (Figure 4). Continuous sections of video footage could then be examined for blow rates. For Event code 3, 9 blows were observed over a period of 246 seconds (mean interval 30.8s, sd = 23.0s) with whale tethered at bow but able to get its head out of the water. For Event code 10, 16 blows were observed in 200 seconds (mean interval 13.3s, sd = 4.4s). These intervals are much shorter than any mean rates reported for freely swimming minke whales (Joyce, 1982; Folkow and Blix, 1993; Stokin *et al*., 2001).

DISCUSSION

The kills where the first harpoon lodged in the whale can be divided into two categories, either where the harpoon delivered an injury which was fatal before the whale could be winched tight to the bow of the catcher or where the whale was winched tight to the bow still alive. In the latter case some whales were observed killed by rifle shots that appeared to have instant effect. However in one case, event code 4, the whale was observed still alive even after being shot at least twice with the rifle. In this instance it is believed that the whale was not able to get a breath between being harpooned and being winched to the bow by the tail. There was continuous, wide angle video footage from the harpoon shot until the whale appeared tail first at the bow of the catcher with no sign of the whale at the surface 4m 47s later. The footage was then continuous until 12m 54s after the harpoon shot at which point there was a break of 16s. During this time the whale was suspended by a tight line and there appeared no possibility for it to get its head above water. It thus appeared to survive without a breath for 14m 02s but appeared to be dead by 16m 44s, possibly due to asphyxiation. It is perhaps not surprising that the injuries from the harpoon blast in this case did not appear to damage the brain to cause immobilisation since the peak pressure would be around 250dB, or 8dB lower than event code 7 for example.

Once harpooned, whales are winched tight to the bow of the catcher on the harpoon line. If the harpoon hits aft of the midpoint of the whale, as was the case in nearly 50% of these events, it is likely to be very difficult for the whale to get its blowhole above the sea surface when the harpoon line is tight (Figure 5). Thus blows were only observed in these cases before the line was tight and the whale still had greater opportunity for reaching the surface. The rapid blow rates of whales that could get their blowholes above the surface may be a response to injury and stress, or a response to an extended chase at high speed. It seems likely that they indicate low oxygen stores in relation to physical demands, suggesting that asphyxiation may also be a relatively common cause of death for whales that are secured by the harpoon line in such a way that they cannot get their blowhole to the surface. For these whales it also appears that secondary killing by rifle is not effective because it is not possible to get a clear shot of the head. It is not possible to estimate the likely times to death of whales that die of asphyxiation because this is likely to depend on the oxygen supplies used up in the chase. Nevertheless the longest survival time without a breath we are aware of reported for a minke whale was 17 minutes (Katona *et al*., 1993) and so any whale that cannot get a breath within that time and has not died of other causes may well die of asphyxiation and asphyxiation may well occur at much shorter times bearing in mind typical minke whale dive times of 2-5 minutes (see Leaper *et al*. 2006 for review). Thus for at least 2/16 (12.5%) of all the observed kills in this study, asphyxiation seems the most likely cause of death. Video footage taken by M. Votier of the 1992/93 JARPA also shows similar situations of whales winched tight to the bow so that they were not able to breathe. Given the observed distributions of harpoon hit locations for all the minke whale hunts considered, it seems likely that any hunting practice which involves winching whales tight to the bow on the harpoon line will result in a substantial proportion of whales dying of asphyxiation.

Ishikawa (2003) and Ishikawa and Shigemune (2005) report a strong correlation between body size and time to death (TTD). However, Ishikawa and Shigemune (2005) found no correlation between body length and instantaneous death rate except for the smallest whales of less than 6m length. If a substantial proportion of whale die from asphyxiation then times to death for larger whales might be expected to be longer since theoretical aerobic dive limit (TADL) tends to increase with body size. For example, Leaper *et al.* (2006) estimated TADLs of 15.3 minutes and 16.7 minutes for 7.5m and 8.5m minke whales respectively. Based on these estimates of TADL in relation to body size, the observed increase in mean TTD with body size reported by Ishikawa and Shigemune (2005) could be fully explained by 40% of whales dying of asphyxiation. However, it seems likely that there are also several other factors that would result in a longer TTD for larger whales.

There was no evidence from comparisons with other minke whale hunts that the observed shooting accuracy was any less good in the observed kills from the 2005/06 JARPA II compared to either Japanese commercial whaling, previous observations of JARPA or Norwegian commercial hunts. Thus the instantaneous death rate (IDR) would be expected to be similar to the reported figures for JARPA in the range 25-44% (Ishikawa, 2003). However, of 12 kills observed where footage allowed at least an estimate of minimum time to death only 2 (17%) could have been instantaneous. Determining the proportion of whales which are instantly immobilised by the harpoon shot is not easy in practice. In several instances the catcher continued forward such that the whale and harpoon line were pulled taut astern of the bow of the catcher by the motion of the vessel. At this point the whale was usually underwater but the body would be accelerated forwards as the line came tight. The drag effect on the body made determination of whether the whale was still alive extremely difficult. It is not clear how such cases were classified in the statistics for instantaneous death rate reported in Ishikawa (2003) and Ishikawa and Shigemune (2005). Of the other 10 observed kills the mean of the minimum estimates of TTD was 598s (10 minutes). This is roughly double the mean of the non-instantaneous kills reported for the 2001/02 and 2002/03 JARPA hunts (Ishikawa, 2003). However, the mean for whales that were not killed instantly is slightly less but comparable to about 12 minutes in Norwegian commercial hunts Øen (2003) based on the assumption that all whales killed instantaneously were included in the calculations of the mean time to death but with a time of 0. When the differences in the IDR proportions are accounted for, the overall median values for the non-instantaneous kills are comparable with those reported by Ishikawa (2003). The two kills with the longest times to death (27m 25s and 33m 12s) were events where the whale was injured by the first harpoon hit but not secured. If these are excluded then the mean time to death for the remaining 8 events (292s) is comparable with the figures from Ishikawa of 302s and 263s for the 2001/02 and 2002/03 JARPA respectively. Ishikawa and Shigemune (2005) indicate that events where the whale was not secured by the first harpoon were not included in the reported mean times to death. It is also not clear in the reported times to death how time to death is estimated in cases where a live whale is tied by the tail alongside a moving vessel since it is likely that movement of the whale caused by being dragged through the water may be confused with signs of life. Times to death of up to 90 minutes for whales that were injured but not secured have been reported from Norwegian hunts Øen (2003). However, following the introduction of penthrite harpoons the proportion of whales that were harpooned more than once in Norwegian hunts was around 4% (Øen, 2003). The two whales in this study that were observed to have been struck and injured but not tethered were both killed eventually but it is not known what the struck and lost rate was. A total of 61minke whales were reported struck and lost in the years 1997-2002 in Norwegian hunts, averaging about 1.7% of the landed catch (SC/56/ProgRepNorway).

The observed locations and effect of the observed harpoon hits are consistent with the target area described by Knowles and Butterworth (2006) for which instant immobilisation is likely to be achieved. This area extends further from the brain ventrally compared to dorsally. The explanation given by Knowles and Butterworth is due to differing transmission through different types of tissue. Based on video footage of the harpoon hitting the whale, the current analysis has suggested a possible alternative hypothesis based on reflection of shock waves as to why harpoon hits in the dorsal region are less likely to cause instantaneous death than those in the ventral region. Although the model used based on reflections from the sea surface is clearly an oversimplification of a complex series of reflective boundaries both inside and outside of the whale, the results do provide quantitative estimates of the shock to the brain that are consistent with the observed data. In situations where substantial surface venting of the explosion occurs, surface reflection effects will be reduced. However, in these situations considerable energy will have been dissipated through the sea surface. Thus the general principle that the deeper the charge the greater the effect will still hold. Ishikawa and Shigemune (2005) note that hunting minke whales during JARPA requires pursuit at high speed and this was also observed to be the case on the 05/06 video. The combined effect of minke surfacing behaviour at high speed and the aiming of the harpoon appears to result in harpoon hits that are closest to the brain also detonating close to the surface. This would contribute to the low instantaneous death rates of around 33% reported by Ishikawa and Shigemune (2005) for JARPA and 17% observed in this study.

SUMMARY AND CONCLUSIONS

Our analysis of the video footage of the killing of 16 minke whales show that the location of harpoon strikes and time to death are similar to data reported for non-impeded whale hunts, and are thus likely to representative of normal hunting practice in JARPA and JARPA II. Less than one in five of the filmed whales are estimated to have died instantaneously and the remaining whales took an average of 10minutes to be killed. Only a quarter of harpoon hits were located in the forward 40% of the whale (i.e. most likely to have entered the thorax or skull region), with almost half the hits being in the rear half of the body. The estimated shooting ranges of 44-60m are beyond the optimum 30m recommended for Norwegian hunts, and may have contributed to the poor accuracy and substantially higher welfare costs for the whales.

Whales tethered to the catching vessels by the rear half of their bodies have difficulty in surfacing to breathe once the harpoon line has been tensioned. This removes the head from access for effective secondary killing with rifle shots and on at least two occasions appears to have resulted in asphyxiation being the secondary killing method.

Our analyses demonstrate that killing methods for Antarctic minke whales in JARPA II are inefficient and raise serious welfare issues concerning low instantaneous death rates, protracted times to death and the occurrence of asphyxiation as a secondary killing method. Given that mean times to death increase with body size in hunted minke whales it is likely that the inclusion of fin whales in the JARPA II hunt, will lead to even more substantial welfare concerns in relation to killing methods.

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Table 1. Measurements of minke whale as a proportion of body length used to create scale drawing (figure 1).

Measurements	Proportion of body length (7.35m female) Jonsgaard (1951)	Utrecht and Spoel (8.41m whale)
Tip of snout to blowhole	13%	13%
Tip of snout to tip of flipper	43%	
Notch of flukes to posterior emargination of dorsal fin	29%	
Flukes notch to tip	14%	15%
Dorsal fin vertical height	3.6%	4.5%
Flipper, tip to axilla	10%	
Flipper tip to head of humerus	17%	
Length of flipper		17%
Head length condyle to tip of snout	23%	
Tail depth at dorsal fin	13%	
Tip of snout to basis of dorsal fin		65%

Table 2. Number of hits forward or aft of specified body length

	Japanese commercial (Best, 1993)	JARPAII 05/06 video	Norwegian commercial (Knowles and Butterworth, 2006)
Forward of 40% body length	92	4	21
Aft of 40% body length	60	12	42
Forward of 47% body length	100	9	40
Aft of 47% body length	52	7	23

Table 3

Event code for harpoon shot	Date	Catcher	Time from first harpoon hit to point at which whale was last seen alive	Time from harpoon shot to first footage at which whale appeared dead	Proportion of body length from snout to harpoon impact point	Distance from brain as proportion of body length	Harpoon flight time (s)	Horizontal range, metres (based on Tanaka, 1987)	Notes
01	22/12/2005	YM			0.36	0.18			No footage of shot or estimate of time to death
02	22/12/2005	KM1	00:00:00	00:04:25	0.41	0.19	0.75	61.1	
03	22/12/2005	YM2	00:13:53		0.32	0.10	0.6	50.8	No time when whale could be observed believed dead due to being secured alongside moving catcher.
04a	07/01/2006	YM			0.72	0.50			
04b			00:33:12	00:35:54	0.71	0.49	0.6	50.8	
05	06/01/2006	YM2	>00:02:06	>00:03:56	0.44	0.22			No footage of shot but footage appeared to start soon after
06	12/01/2006	YM2			0.55	0.33			No footage of shot or estimate of time to death
07	12/01/2006	YM2			0.43	0.21			No footage of shot or estimate of time to death
08	13/01/2006	YM2	00:03:05	00:03:29	0.46	0.24			
09	13/01/2006	YM			0.55	0.33			No footage of shot or estimate of time to death
10	14/01/2006	YM2					0.16	17.2	Shot appeared to miss
10a					0.53	0.31	0.64	53.6	
10b			00:07:26	00:09:36	0.29	0.08	0.4	36.1	
12	21/12/2005	KM1	00:02:48		0.31	0.10	0.44	39.1	No footage of whale when it was believed to be dead
13	05/01/2006	KM1	00:04:41	00:04:45	0.53	0.31	0.52	45.0	
14a	07/01/2006	YM2							Harpoon location could not be accurately determined
14b			00:27:25						Harpoon location could not be accurately determined No footage of whale when it was believed to be dead
15	12/01/2006	YM2	00:03:56	00:04:31	0.51	0.30			
17	13/01/2006	KM1	00:00:00	00:02:43	0.41	0.20			
18	05/01/2006	KM1	>00:01:04	>00:01:20	0.30	0.10			No footage of shot but footage appeared to start soon after

> indicates that the time of the shot was not measured

Vessel codes (KM1 = Kyo Maru No.1, YM = Yushin Maru, YM2 = Yushin Maru No. 2)

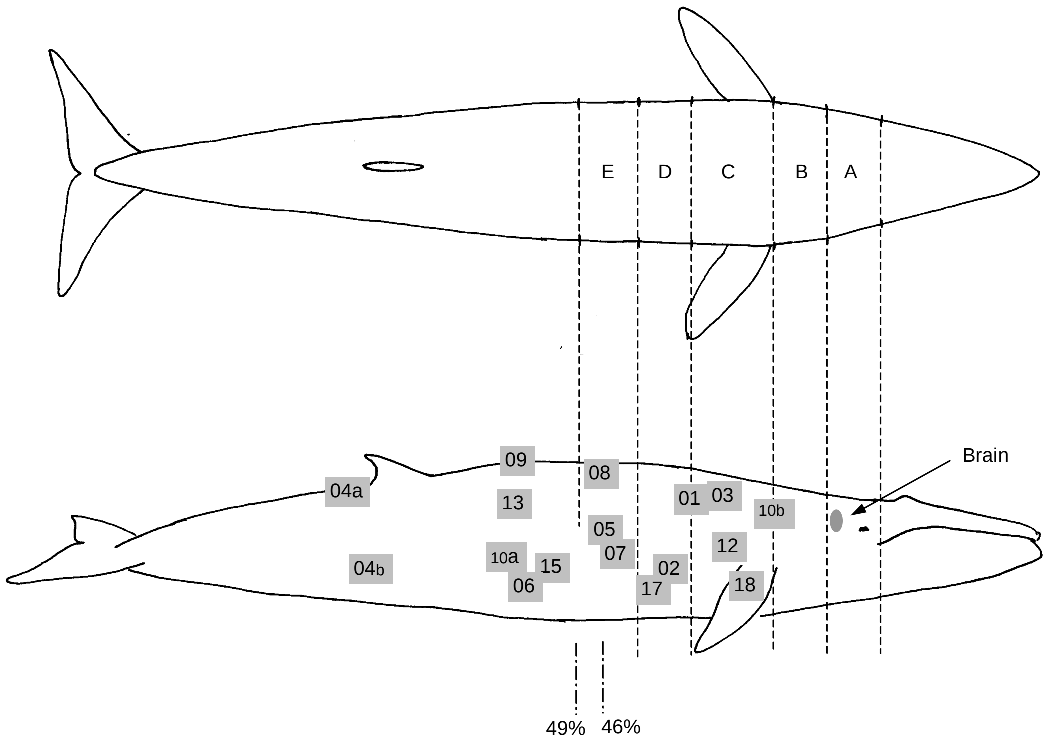

Figure 1. Locations of harpoon hits. Zones A-E are equivalent to the notation used by Knudsen and Øen (2003). The lines at 46% and 49% indicate the relative location of these proportions of total body length aft of the snout.

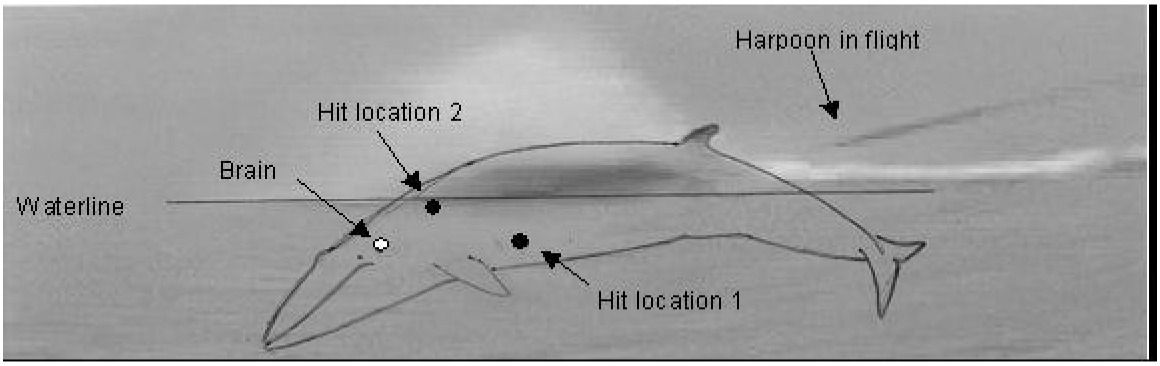

Figure 2. Image captured from video of harpoon just about to hit minke whale. Drawing overlay indicates assumed position of whale's body underwater based on tracing outline above surface from photograph. Hit location 1 (the actual shot) and hit location 2 (a hypothetical shot) would exert the same positive impulse on the brain based on the simple surface reflection model.

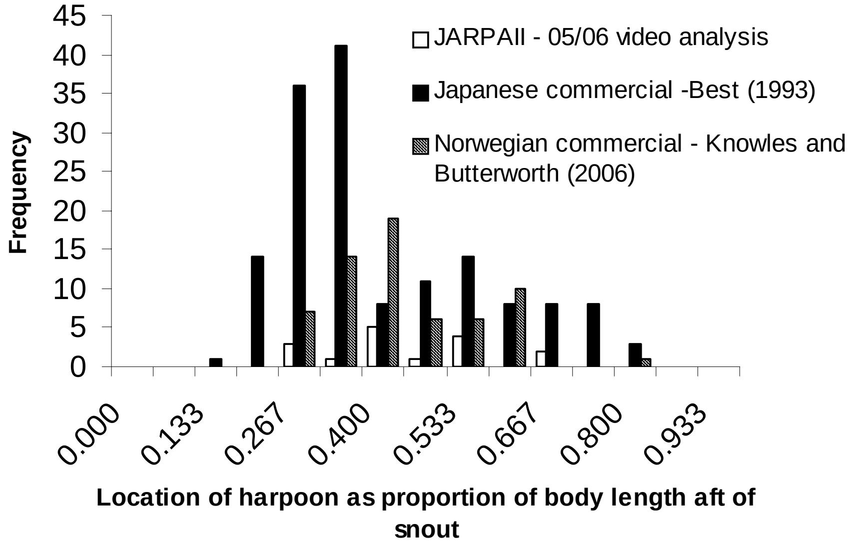

Figure 3. Locations of harpoon hits expressed as a proportion of body length.

Figure 4. Event code 3 showing harpoon location that allowed whale to get blowhole above surface even when line was tight at bow.

Figure 5. Event code 4. Harpoon location (4b) does not allow whale to get head out of water to breathe once the line is tight at the bow.