

Consideration of factors affecting time to death for whales following entanglement in fishing gear

Russell Leaper¹, Vassili Papastavrou¹ and Laila Sadler²

¹International Fund for Animal Welfare, The Old Chapel, Fairview Drive, Bristol, BS6 6PW, UK.

²The Royal Society for the prevention of Cruelty to Animals, Southwater, West Sussex. RH13 9RS, UK.
contact email: russell@ivyt.demon.co.uk

(Submitted by the Government of the UK)

ABSTRACT

The death of cetaceans by asphyxiation following entanglement in fishing gear raises serious animal welfare issues. Although the physiological processes related to asphyxiation are relatively well understood from examination of carcasses, there are few data on the time duration over which these processes occur. The minke whale (*Balaenoptera acutorostrata*) is the large whale species most frequently reported as bycatch. This study reviews minke whale diving behaviour and estimates the likely theoretical aerobic dive limit in relation to body size. These estimates provide reference points to give some indication of likely times to death following entanglement for this species.

INTRODUCTION

Cetacean mortality in fishing gear is a global issue. Whales that become entangled in gear and cannot reach the surface to breathe will eventually die of asphyxiation. This fate is common for entangled small cetaceans that may not have the strength to break free, but is also frequently reported for whales. Whilst most larger cetaceans are more likely to swim away with the entangling fishing gear, which enables them to still reach the surface and breathe, the hindrance caused by the towed gear may result in long times to death. For example, there have been reported cases of North Atlantic right whales (*Eubalaena glacialis*) towing gear taking several months to die through starvation or injury related to the entanglement (IWC, 2003). Studies off the east coast of the USA indicate that around 71% of humpback whales (*Megaptera novaeangliae*) and 62% of North Atlantic right whales had been entangled at some stage in their lives, with an annual rate of entanglement of 10-31% for humpbacks (Robbins and Mattila, 2001) and 10-28% for right whales (Knowlton *et al.*, 2001). However, smaller species appear less likely to survive any entanglement and Lien (1994) estimated that 70% of minke whales that become entangled died compared to 16% of humpback whales. Many types of fishing gear may be involved in entanglement events. These include different types of gillnet and trap fisheries usually involving bottom set gear marked by surface floats. In the North Atlantic, at least, these are probably the two types of fishery involved in the largest number of whale entanglements. In Japan and Korea, set or trap net fisheries have the highest reported levels of large whale entanglement.

Measures to reduce the risk of death due to entanglement include gear modifications and acoustic alarms. Acoustic alarms are now part of regulatory measures designed to reduce bycatch of small cetaceans in several North Atlantic fisheries. Gear modifications are also included in measures to reduce entanglement of large whales off the east coast of the USA. Specifically, ground lines separating individual traps must be made of either sinking or neutrally buoyant line and a weak link must be placed at all surface buoys on vertical lines in certain high risk areas. The specification of the weak links varies between fisheries but involve a maximum breaking strength of between 272 and 500kg. In some areas disentanglement teams may be available to attempt to disentangle a snagged whale (IWC, 2003). However, in many fisheries disentanglement is not considered as an option and an entangled whale is either left to its own devices or killed by some other means.

Our understanding of the physiological processes that occur during sub-surface entanglement of a whale come from studies of diving physiology, and from examination of cetacean carcasses known to have died through asphyxiation. The diving behaviour of many species appears to be closely related to their aerobic dive limit (ADL). This is defined as the maximum dive duration that is possible without an increase in plasma lactate concentration (Kooyman, 1985) and indicates the point at which tissues switch from aerobic to anaerobic respiration. Aerobic dive limit is difficult to measure and direct measurements are limited to small cetaceans (e.g. Shaffer *et al.*, 1997).

Additionally, ADL appears to differ significantly between individuals of a species and even between dives for one individual since different dive strategies will lead to oxygen consumption at different rates. Various studies have estimated the theoretical aerobic dive limit (TADL) for a number of cetacean species based on estimating the oxygen (O₂) stores and diving metabolic rate. Estimates of TADL are usually based upon some function of body mass (e.g. Croll *et al.*, 2001).

A part of the dive response in marine mammals is a pronounced reduction in heart rate (bradycardia). Additionally, peripheral vasoconstriction shunts blood away from non-vital regions of the body to maintain perfusion of critical tissues (such as the brain and heart) with oxygenated blood. On deep dives, pressure reduces the volume of the lungs, forcing the small volumes of air into non-absorptive airways. With a cessation of lung ventilation, carbon dioxide (CO₂) no longer diffuses out of the blood, and, once ADL is reached and lactate begins to form as a by-product of anaerobic respiration, metabolic acidosis begins.

Various pathological changes have been noted in cetacean tissues associated with death from asphyxiation. These have been described by various authors, including Camps and Cameron (1971), Kuiken *et al* (1994) and Duignan *et al.* (2004). One key finding is fine, persistent whitish or blood-stained froth in the trachea and bronchi (DeMaster *et al* 1985, Kuiken *et al* 1994, Jepson *et al* 2000). Other potentially diagnostic findings include pulmonary oedema and congestion; multifocal intra-alveolar haemorrhage; bullae in lung parenchyma (Kuiken *et al*, 1994, Jepson *et al* 2000) alveolar or bullous emphysema, and pleural congestion. There may also be congestion of pericardial vessels and ecchymotic haemorrhages (haemorrhagic spots) on the endocardium or epicardium (Kuiken *et al* 1994). Histology shows hypercontraction, fibre fragmentation and fibre vacuolation of the myocardium. Such signs are indicative of physiological stress and a potentially protracted dying process.

A cetacean entangled underwater is in a potentially terminal forced dive situation. It may adopt one of two strategies: induce a rapid and profound dive response (though it is difficult to identify an adaptive explanation for such behaviour if the whale has been entangled and potentially perceives an opportunity to break free); or start to struggle. There is evidence of the latter behaviour from tissue damage to entangled marine mammals. For example harbour porpoises are known to struggle vigorously when they first feel contact with a net, frequently resulting in wrapping themselves tightly in a ball of net and sustaining internal and external damage (Kuiken *et al* 1994). Harp seals (*Phoca groenlandica*) have also been observed to struggle on becoming caught in a net and 'heavily scarred pelt and exposed muscle tissue that sometimes occur indicate a rather prolonged period of violent underwater activity' (Ronald, 1982).

For a whale that becomes entangled, there may be several conflicting responses. If the whale struggles frantically to free itself then this effort will require an increased oxygen supply to muscles whereas a whale that does not struggle may show the accentuated bradycardia seen in [forced] submergence. Some individuals of dolphin species trapped in nets appear to go into a catatonic state even when the sea surface is accessible (e.g. spotted dolphins in Eastern Tropical Pacific purse-seine fishery: Coe & Stunz, 1980; Oliveros & Maldonado, 2002), possibly indicating induction of a dive response in extreme stress situations. Observations of attempts to disentangle large whales (mainly right, gray and humpback whales) suggest that the response to entanglement may vary considerably between species (IWC, 2003).

When attempting to predict a whale's response to entanglement and the likely time to death for a sub-surface entangled animal, there are clearly a large number of unknowns. However, a useful reference point would appear to be TADL as this gives an approximate indication of the time likely to elapse before the animal experiences extensive anaerobic respiration.

CETACEAN CASE STUDY: ENTANGLED MINKE WHALE

The minke whale provides a useful model on which to examine possible times to death for sub-surface entangled whales, as a range of data are available on this species.

Minke whales typically exhibit a pattern of a long dive followed by several surfacings at shorter intervals. In the NW Pacific, Stern (1992) classified 'long dives' for minke whales as those dives longer than the upper 95% confidence interval of all dives. These long dives were 4.43 ± 2.37 minutes. In the NE Atlantic, Folkow and Blix (1993) found 'long' dives of 3.72 ± 1.6 at night and 2.89 ± 1.09 minutes during the day. Thus typical minke whale dives appear to be around 2-5 minutes.

There is also a relatively large amount of information available on bycatch mortality for the minke whale, the largest number of reported entanglements coming from fisheries in the NW Pacific around the coasts of Japan and Korea. Body length data are available for a sample of animals that died in fishing gear in the East Sea/Sea of Japan. Between 1998 and 2004, body lengths of 337 minke whales (178 females and 159 males) were examined (Kim *et al.*, 2005). The body length of the minke whales ranged from 3.2m to 8.5m for females and from 3m to 8m for males. Mean body length for females and males were 4.98m (± 0.90 m) and 5.40 (± 1.08 m), respectively.

When investigating diving capability and ADL for the minke whale, work carried out by Croll *et al.* (2001) calculating TADL for large mysticetes can help to provide insight into the oxygen storage capacity and likely TADL for minke whales. Their study estimated TADL for blue and fin whales based on estimates of the oxygen stored in lungs, blood and muscle, and the diving metabolic rate. This study carries out the same analyses on the available minke whale data, after first converting the body length data from Kim *et al.* (2005) into body mass.

Trites and Pauly (1998) derived regressions for mean mass against maximum length for a number of marine mammals, including mysticetes. These were :

$$\ln(M_{mean}) = -7.347 + 2.329 \ln(L_{max}) \text{ for males} \quad (1)$$

$$\ln(M_{mean}) = -7.503 + 2.347 \ln(L_{max}) \text{ for females} \quad (2)$$

Equation (1) and (2) provide average body mass for the minke whale dataset of 3720kg for males (based on a maximum observed length 8m) and 4138kg for females (based on a maximum observed length 8.5m). For the purposes of this analysis we assumed that a 7.5m minke whale would have a body mass of 5250kg and that the body mass to length relationship could be expressed as:

$$M = 18.6 L^{2.8} \quad \text{where } M \text{ is in kg and } L \text{ is in metres.} \quad (3)$$

This gives a range of body mass from 400kg to 6300kg for minke whales from 3m to 8m in length.

The same allometric relationships used by Croll *et al.* (2001) were applied to the minke whale converted body mass data. It was assumed that the minke whales would show similar dive/glide behaviours, and a similar percentage muscle mass (39.4% of body mass) to the blue whale calculations used by Croll *et al.* Total O₂ in the lungs was assumed to be $0.0113M^{0.96}$ litres. Total O₂ in the muscle was assumed to be $0.0174M$ litres and O₂ in the blood was assumed to be $0.0282M$ litres. Total oxygen store was assumed to be the sum of the amounts stored in the lungs, muscle and blood. Basal metabolic rate (BMR) was assumed to be $3.51M^{0.75} \text{ Js}^{-1}$, equivalent to $0.0105M^{0.75}$ litres of oxygen per minute. Diving metabolic rate was assumed to be $4 \times \text{BMR}$ with the same savings as assumed by Croll *et al.* for gliding behaviour giving an O₂ requirement of $0.0298 M^{0.75}$ litres of oxygen per minute. TADL was then assumed to be the total oxygen stored divided by the requirement, thus

$$TADL = (0.0113M^{0.96} + 0.0456M) / 0.0298M^{0.75} \quad (4)$$

This produced the values for TADL in Figure 1, for the range of body lengths from 3m to 8m.

The same authors also derived a relationship between body mass and dive time for large vertebrates diving between 150-200m. They obtained a significantly better fit if *Balaenopteridae* (blue and fin whales) were excluded from the regression. We have also used the regression with the *Balaenopteridae* excluded on the assumption that the short dive times of these species is a behavioural rather than a physiological trait. Anecdotal evidence given in Leatherwood *et al.* (1982) does suggest dive times slightly in excess of TADL for both blue and fin whales that found themselves in life threatening situations.

This relationship can be applied to the minke whale body length data using the following:

$$D = 2.23 + 1.785 \ln(M) \quad (5)$$

Where D is dive duration in minutes and M is body mass in kg

It is used to generate a distribution of dive durations for the minke whale based on body length data (Fig. 1). The values of TADL obtained and the expected mean dive times based on equation (4) are similar. For example for a 5m whale, TADL is 11.6 minutes compared to 11.1 minutes for expected dive time. This similarity is not surprising given that many species frequently dive for durations close to or just beyond their TADL. However, it shows a marked difference from dive durations recorded in the field (Stern, 1992; Folkow and Blix, 1993), indicating that minke whales, like other Balaenopterids, appear to dive for shorter times than might be expected. Body length data from Kim *et al.* (2005) were then used to calculate a distribution of predicted TADLs (Fig. 2).

DISCUSSION

A 5m whale that becomes entangled at the bottom of a planned dive may be between 1-4 minutes from leaving the surface. Based on estimates of TADL it appears that the whale may survive without physical trauma for a further 7-10 minutes. After that it is likely that physical stress will become acute. However, as already noted, the times are likely to show a wide variation between individuals.

Many species can routinely exceed TADL by as much as 3 times (Boyd and Croxall, 1996), though many baleen whales tend to make dives that are much shorter than TADL (Croll *et al.*, 2001). Although there is no evidence that minke whales voluntarily dive exceeding TADL it is possible that they might survive without oxygen for periods of some multiple of TADL. Although for studies with large amounts of data on diving behaviour, maximum observed dive duration might be a better reference point than TADL there is some evidence that minke whales can stay submerged for much longer than their typical dive times. For example, Katona *et al.* (1993) report a single observation of a minke whale in the North Atlantic surviving submerged for 17 minutes as it was being freed from a fish weir. Whilst this time falls within the range of TADLs calculated in this paper, it is clearly exceptional in terms of normal dive durations.

For fishing gear that spans the whole depth of the water column, the entanglement is assumed equally likely to occur at any point in the dive cycle. If fishing gear is at the surface and only extends to a depth less than the whales dive depth then entanglement is likely to occur at the start or end of a dive. In this case the distribution of times from entanglement to TADL is likely to be bimodal, although because the average dive time is relative small compared to TADL the point at which a whale becomes entangled in a dive will likely have a relatively small influence on total time to death.

This paper provides some examples for calculating likely times for an entangled minke whale to reach its TADL, though there are clearly uncertainties surrounding these estimates. Schreer *et al.* (2001) found that generic calculations of TADL are 'problematic and that estimates of diving metabolic rate can drastically influence TADL and resultant findings'. Metabolic rates following entanglement will be heavily influenced by the amount of physical activity as a whale tries to break free. Although our predictions are that larger individuals will survive longer, this may not always be the case. For example, MacArthur *et al.* (2001) found no evidence that the diving abilities of muskrats increased with age or body size, despite large differences in TADL.

Some uncertainties inherent in predicting time to death relate to the physiological processes once TADL has been exceeded. Though minke whales would be unlikely to die of asphyxiation in a shorter time than TADL, given the typically short dive durations of this species it seems possible that death could occur within minutes of reaching TADL. On the other hand, it is also possible that death may only occur at some multiple of TADL. Nevertheless it is likely that minke whales dive well within their TADL, and that therefore the time from entanglement to unconsciousness, and to subsequent death, can be considerably greater than the species' average dive times of two to five minutes.

REFERENCES

- Boyd and Croxall, 1996. Dive Duration in pinnipeds and seabirds. *Can. J. Zool.* 74, 1696-1705.
- Butler, P.J. and Jones, D. R. 1997. Physiology of diving of birds and mammals. *Physiological Reviews* 77(3):837-899
- Camps, F.E. & Cameron, J.M. (1971) Practical Forensic Medicine. Hutchinson Medical Publications. London. 2nd Edn. p. 164, 316.
- Coe, J.M. and W.E. Stunz. 1980. Passive behavior by the spotted dolphin, *Stenella attenuata*, in tuna purse seine nets. *Fish. Bull.* 78(2): 535-537.

- Croll, D. A., Acevedo-Gutierrez, A., Tershy, B. R. and Urban-Ramírez, J. 2001. The diving behavior of blue and fin whales: is dive duration shorter than expected based on oxygen stores? *Comparative Biochemistry and Physiology Part A* 129: 797-809.
- DeMaster, D., Miller, D., Henderson, J.R. & Coe, J.M. (1985) Marine Mammals and Fisheries. Eds. J. Beddington, R.J.H. Beversion, D.M. Lavigne. George Allen & Unwin, London. P.111
- Duignan, P.J., Gibbs, N.J. and Jones, G.W. 2004. Autopsy of cetaceans incidentally caught in fishing operations 1997/98, 1999/2000, and 2000/01 Doc Science Internal Series 119
- Folkow, L. P. and Blix, A. S. 1993. Daily Changes in Surfacing Rates of Minke Whales (*Balaenoptera acutorostrata*) in Norwegian Waters. *Rep. Int. Whal. Commn* 43: 311-361.
- IWC. 2003. Report of the intersessional working group on large whale entanglement. *J. Cetacean. Res. Manage.* 5(Suppl):353-358
- Jepson, P.D., Baker, J.R., Kuiken, T., Simpson, V.R., Kennedy, S. & Bennett, P.M. (2000) Pulmonary pathology of harbour porpoises (*Phocoena phocoena*) stranded in England and Wales between 1990 and 1996. *Vet Record*, 146, 721-728.
- Katona, S.K., Rough, V. and Richardson, D.T. 1993. A field guide to whales, porpoises and seals from Cape Cod to Newfoundland. Smithsonian Institution Press. Washington.
- Kim, Z.G., Na, J.H. and ZHANG, C.I. 2005. Body length and sex of minke whale *Balaenoptera acutorostrata*, bycaught in Korean waters from 1996 to 2004. Paper SC/57/NPM12 presented to IWC Scientific Committee, Ulsan, Korea.
- Knowlton, A.R., Marx, M.K., Pettis, H.M., Hamilton, P.K. and Kraus, S.D. 2001. Scarification analysis of North Atlantic right whales (*Eubalaena glacialis*): monitoring rates of entanglement interaction. Report to the U.S. National Marine Fisheries Service under contract 43EANF030107. Available from New England Aquarium, Central Wharf, Boston, MA 02110.
- Kooyman, G.L. 1985. Physiology without restraint in diving mammals. *Mar Mammal Sci* 1: 166-178
- Kuiken, T., Simpson, V.R., Allchin, C.R., Bennett, P.M., Codd, G.A., Harris, E.A., Howes, G.J., Kennedy, S., Kirkwood, J.K., Law, R.J., Merrett, N.R., Phillips, S. (1994) Mass mortality of common dolphins (*Delphinus delphis*) in south west England due to incidental capture in fishing gear. *Vet Record*, 134, 81-89
- Lien, J. 1994. Entrapments of large cetaceans in passive inshore fishing gear in Newfoundland and Labrador (1979-1990). *Rep. int. Whal. Commn.* (Special Issue) 15, 149-157.
- Lockyer, C. 1976. Body weights of some large whales. *ICES J. Cons.* **36**:259-273
- MacArthur, R. A. 1990. Seasonal changes in the oxygen storage capacity and aerobic dive limits of the muskrat (*Ondatra zibethicus*). *Journal of Comparative Physiology B* 160: 593-599.
- MacArthur, R. A., Humphries, M. M., Fines, G. A. and Campbell, K. L. 2001. Body oxygen stores, aerobic dive limits, and the diving abilities of juvenile and adult muskrats (*Ondatra zibethicus*). *Physiological and Biochemical Zoology* 74(2): 178-190.
- E.S Oliveros and F G Maldonado. 2002. Coping behaviors of spotted dolphins during fishing sets. Report for SW Fisheries Science Center, NMFS Administrative Report LJ-02-36C
- Robbins, J. and Mattila, D.K. 2001. Monitoring entanglements of humpback whales in the Gulf of Maine on the basis of caudal peduncle scarring. SC/53/NAH25.
- Ronald, K. 1982. A study of the underwater response of harp seals to nets. *Annual report to Canadian Scientific Authority, Fisheries Research Branch* .
- Schreer, J. F. and Kovacs, K. M. (1997). Allometry of diving capacity in air-breathing vertebrates. *Can. J. Zool.* 75, 339-358.
- Schreer, J.F., Kovacs, K.M. and R. J. O'Hara Hines. 2001. Comparative Diving Patterns of Pinnipeds and Seabirds. *Ecological Monographs*: Vol. 71, No. 1, pp. 137-162.

Shaffer, S.A., Costa, D.P., Williams, T.M. and Ridgway, S.H. 1997. Diving and swimming performance of white whales, *Delphinapterus leucas*: An assessment of plasma lactate and blood gas levels and respiratory rates. *J. exp. Biol.* 200, 3091-3099.

Sigurjónsson, J. and Víkingsson, G. A. 1997. Seasonal abundance of and estimated food consumption by cetaceans in Icelandic and adjacent waters. *Journal of the Northwest Atlantic Fisheries Sciences* 22: 271-287.

Stern, S. J. 1992. Surfacing Rates and Surfacing Patterns of Minke Whales (*Balaenoptera acutorostrata*) off Central California, and the Probability of a Whale Surfacing Withing Visual Range. *Rep. Int. Whal. Commn* 42(SC/43/Mi2): 379-385.

Trites, A. W. and Pauly, D. 1998. Estimating mean body masses of marine mammals from maximum body lengths. *Canadian Journal of Zoology* 76: 886-896.

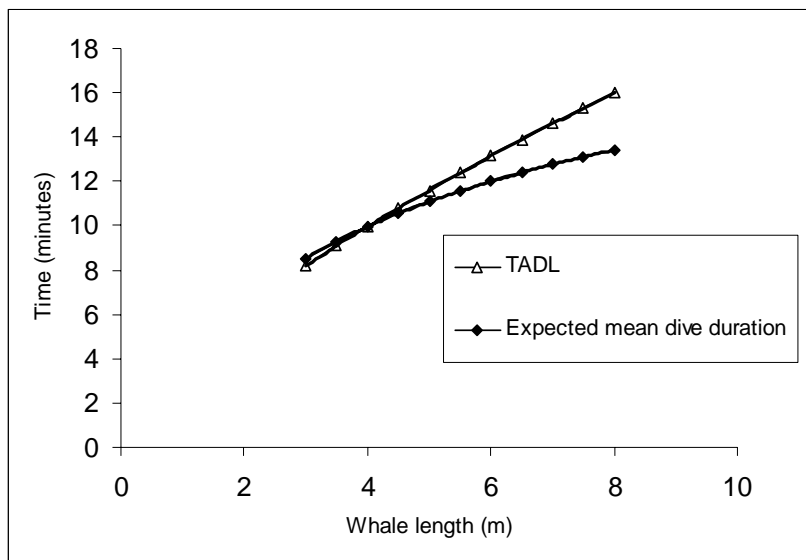


Figure 1. Expected time to theoretical aerobic dive limit TADL (triangles), and calculated mean dive duration (circles) for a range of minke whale lengths.

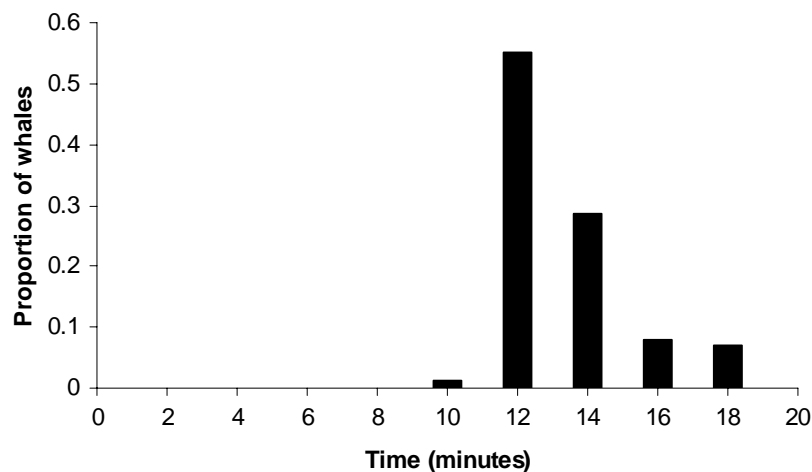


Figure 2. Distribution of expected time to TADL based on length distribution of entangled minke whales (Kim *et al.*, 2005).