



Technical Support Information to the CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities

Module C. Decompression Stress

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C. Decompression Stress

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Decompression sickness (DCS, ‘the bends’) is a disease associated with gas uptake at pressure. As hydrostatic pressure increases with depth, the amount of nitrogen (N₂) that is absorbed by the blood and tissues increases, resulting in higher dissolved gas tensions that could at maximum reach equilibrium with the partial pressure of N₂ in the lungs. This is a long-known problem for human divers breathing pressurized air, but has often been discounted as a problem for breath-hold divers since they dive on only a single inhalation (Scholander 1940). However, for free-diving humans and other air-breathing animals, tissues can become highly saturated under certain circumstances depending on the iterative process of loading during diving and washout at the surface (Paulev 1967, Lemaitre *et al* 2009). During decompression, if the dissolved gas tension in the tissues cannot equilibrate fast enough with the reducing partial pressure of N₂ in the lungs, tissues will become supersaturated, with the potential for gas-bubble formation (Francis and Mitchell 2003).

Breath-hold diving vertebrates were previously thought to be relatively immune to DCS due to their multiple anatomical, physiological and behavioural adaptations (Fahlman *et al* 2006, Fahlman *et al* 2009, Hooker *et al* 2012). However, recent observations have shown that marine mammals and turtles may be affected by decompression sickness under certain circumstances (Jepson *et al* 2005, Dennison *et al* 2012, Van Bonn *et al* 2013, Garcia-Parraga *et al* 2014). Of most concern, however, are the beaked whales, which appear to be particularly vulnerable to anthropogenic stressors that may cause decompression sickness (Jepson *et al* 2003, Cox *et al* 2006, D'Amico *et al* 2009, Hooker *et al* 2009, Hooker *et al* 2012).

C.1.1. Bubble Formation

Among marine mammals, both acute and chronic gas emboli have been observed.

The formation of bubbles has been suggested as a potential explanation for lesions coincident with intravascular and major organ gas emboli in beaked whales that mass stranded in conjunction with military exercises deploying sonar (Jepson *et al* 2003, Fernandez *et al* 2005). There is some controversy about the proximate cause of the gas emboli (Hooker *et al* 2012) although it is widely agreed that it appeared to be linked to man-made acoustic disturbance. However, these types of lesions have also been reported in some single-stranded cetaceans for which they do not appear to have been immediately fatal (Jepson *et al* 2005, Bernaldo de Quirós *et al* 2012, Bernaldo de Quirós *et al* 2013). Looking at species-specific variability in bubble presence among stranded animals, the deeper divers (Kogia, Physeter, Ziphius, Mesoplodon, Globicephala, and Grampus) appeared to have higher abundances of bubbles, suggesting that deep-diving behaviour may lead to a higher likelihood of decompression stress (Bernaldo de Quirós *et al* 2012).

In addition, osteonecrosis-type surface lesions have been reported in sperm whales (Moore and Early 2004). These were hypothesized to have been caused by repetitive formation of asymptomatic N₂ emboli over time and suggest that sperm whales live with sub-lethal decompression induced bubbles on a regular basis, but with long-term impacts on bone health. Bubbles have also been observed from marine mammals bycaught in fishing nets, which died at depth (Moore *et al* 2009, Bernaldo de Quirós *et al* 2013). These bubbles suggested the animals' tissues were supersaturated sufficiently to cause bubble formation when depressurized (as nets were hauled). B-mode ultrasound has also shown bubbles in stranded (common and white-sided) dolphins, which showed normal behaviour after release and did not re-strand, and so appeared to tolerate this bubble formation (Dennison *et al* 2012). Cerebral gas lesions have also been observed using Magnetic Resonance Imaging in California sea lions,

Zalophus californianus, admitted to a rehabilitation facility (Van Bonn *et al* 2011, Van Bonn *et al* 2013).

It therefore appears that gas supersaturation and bubble formation may occur more routinely than previously thought. These cases highlight a growing body of evidence that marine mammals are living with blood and tissue N₂ tensions that exceed ambient levels (Moore *et al* 2009, Bernaldo de Quirós *et al* 2013). However, our understanding of how marine mammals manage their blood gases during diving, and the mechanism causing these levels to become dangerous is very rudimentary (Hooker *et al* 2012). Some perceived threats appear to cause a behavioural response that may override normal N₂ management, resulting in decompression sickness, stranding and death.

C.1.2. Sources of Decompression Stress

There is a documented association between naval active sonar exercises and beaked whale mass strandings (Frantzis 1998, Evans and England 2001, Jepson *et al* 2003). However, a comprehensive review of beaked whale mass strandings (D'Amico *et al* 2009) suggests that some strandings may be associated with other events. It therefore seems likely that other high-intensity underwater sounds may also present conservation concerns for these species (Taylor *et al* 2004). Indeed, ship-noise also appears to cause a behavioural response disrupting foraging behaviour in Cuvier's beaked whales, *Ziphius cavirostris* (Soto *et al* 2006).

The process of diving causes oxidative stress (Hermes-Lima and Zenteno-Savin 2002). Episodic regional lack of oxygen and abrupt reperfusion upon re-surfacing creates a situation where post-ischemic reactive oxygen species (ROS) and physiological oxidative stress are likely to occur. However, a link between oxidative stress and DCS has not yet been confirmed (Wang *et al* 2015).

C.1.3. Source Frequency, Level and Duration

Understanding the responses of cetaceans to noise is a two-stage process: (1) understanding the noise required to cause the behavioural modification and (2) understanding the physiological mechanism by which that behavioural modification causes harm to the animal. At present, almost all research has focussed on the first of these, i.e. work evaluating playback and response, and

almost nothing is known about how this response then leads to decompression stress.

Several recent studies have found similar behavioural responses of a small number of beaked whales to sonar signals (Tyack *et al* 2011, DeRuiter *et al* 2013, Stimpert *et al* 2014, Miller *et al* 2015). These studies have shown that beaked whales respond behaviourally to sonar and other human and natural stimuli, typically showing a combination of avoidance and cessation of noise-production associated with foraging (Table 8). Responses to simulated sonar have started at low received levels. These types of behavioural changes were also documented in work monitoring vocal activity using Navy range hydrophones (Tyack *et al* 2011, Moretti *et al* 2014). This type of 'flight' response could, if catastrophic, disrupt the normal physiological mechanisms of these animals, leading to DCS.

C.1.4. Assessment Criteria

At the planning stage, the primary mitigation method to reduce issues of decompression stress would be to reduce the interactions of stressor and animals (i.e. to reduce the number of "takes"). This can be done by placing any high-intensity noise into areas without high densities of species of concern. Thus proposals should take account of all survey and modelling information sources to predict areas of likelihood of high/low species density, and attempt to reduce the number of impacted animals by designing operations only for areas of low animal density.

To supplement this, or in areas in which such species densities are unknown, baseline studies should be conducted. Beaked whales are particularly difficult to monitor visually (surfacing for as little as 8 per cent of the time), but have more reliable detection acoustically (vocalising for 20 per cent of the time, de Soto *et al* 2012). Hydrophone arrays can detect animals at 2-6km distances (Moretti *et al* 2010, Von Benda-Beckmann *et al* 2010).

During the activity, real-time monitoring of animal presence should be conducted. This can be done using visual and acoustic monitoring, with detections within a specified range of the activity resulting in cessation of the sound source. On-board visual or towed hydrophone monitoring allows only limited detection distance and thus limits mitigation effectiveness.

Monitoring over a wider area can be achieved using hydrophone arrays placed on the seafloor (Moretti *et al* 2010). Such hydrophone arrays allow detection over a wide

but static area. Dynamic monitoring over a wide area could potentially be achieved using acoustic drones, allowing near real-time hydrophone arrays to be placed over a greater area to ensure more effective assessment of species presence prior to any disturbance event.

Modelling of animal likelihood and distance from the source should be carried out in order to aim to minimize received levels (Table 1), thus reducing the risk of animals receiving too high a dose which might incur DCS/death.

C.1.5. Species not listed on the CMS Appendices that should also be considered during assessments

Beaked whales, *Ziphius cavirostris* (Appendix I) and *Hyperoodon* spp and *Berardius* spp (Appendix II) require additional consideration. These species appear particularly vulnerable to noise impacts. 20 species of *Mesoplodon* are currently missing from the CMS Appendices and yet are likely to also be vulnerable to noise impacts. All of these species are likely to be particularly sensitive to decompression stress.

Of other deep diving species which may potentially be at increased risk of decompression stress, *Kogia* are currently not listed on either of the CMS Appendices, *Physeter* is listed on Appendices I and II, *Globicephala* on Appendix II, and *Grampus* should also be considered during assessments.

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Table 8: Responses of beaked whales to sound sources

Species	Sound source	Response observed as received level (dB re. 1µPa)
Cuvier's beaked whale, <i>Ziphius cavirostris</i> (DeRuiter <i>et al</i> 2013)	30 min playback of 1.6s MFA sonar signal repeated every 25 sec. Initial source level of 160 dB re 1 mPa-m was increased ('ramped up') by 3 dB per transmission to a maximum of 210 dB re 1 mPa-m.	89-127
Cuvier's beaked whale, <i>Ziphius cavirostris</i> (Soto <i>et al</i> 2006)	Maximum broadband (356 Hz–44.8 kHz) level received during the ship passage was 136 dB rms re 1 µPa, approx. 700m away.	106 (in click frequency range)
Northern bottlenose whale, <i>Hyperoodon ampullatus</i> (Miller <i>et al</i> 2015)	104 1-s duration 1–2 kHz upswing pulses (naval sonar signals) at 20s intervals. The source level of the sonar pulses increased by 1 dB per pulse from 152 to 214 dB re 1 µPam over 20min (61 pulses), and the remaining pulses were transmitted for 15min at a source level of 214 dB re 1 µPa m.	107
Baird's beaked whale, <i>Berardius bairdii</i> (Stimpert <i>et al</i> 2014)	Simulated mid-frequency active (MFA) military sonar signal at 3.5-4 kHz, transmitting 1.6 s signal every 25 s. The initial source level of 160 dB re: 1 mPa was increased by 3 dB per transmission for the first 8 minutes to a maximum of 210 dB for 22 additional minutes (72 transmissions total over 30 minutes).	127
Blainville's beaked whale, <i>Mesoplodon densirostris</i> (Tyack <i>et al</i> 2011)	Simulated 1.4 s MFA sonar, killer whale and noise signals. MFA sonar had both constant frequency and frequency modulated tonal components in the 3–4 kHz band repeated every 25 s. Initial source level of 160 dB re 1 mPa-m was increased ('ramped up') by 3 dB per transmission to a maximum of 210 dB re 1 mPa-m.	138

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