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An overview of the concentrations and effects of metals in cetacean species[1]

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ABSTRACT

Data are presented on the biomagnification rates, accumulation and concentrations of metals in cetacean species. Concentrations of metals predominantly occur in the soft tissues, although zinc and lead concentrate in the skin and bones. Rates of uptake are dependent upon metal availability, the species' dietary preference and chemical reactions between contaminants. Differences in concentrations occur according to the sex and age of the animal, with certain metals displaying age-related trends. Mercury is the only metal which shows both biomagnification at all levels of the food chain and a positive correlation with age at all stages during a cetacean's life. Differences in concentrations occur between baleen species and toothed cetaceans. Levels tend to be lower in baleen whales, primarily due to a shorter food chain (resulting in lower bioconcentration factors) and as the principal prey species are taken from lower parts of the food chain. A number of storage and detoxifying mechanisms have been recorded in many species that may alter the effects of high metal concentrations. Data on the effects of metal toxicity in cetacean species are sparse, but tolerance limits have been proposed for mercury and cadmium. These are compared with high concentrations recorded in certain species and possible effects extrapolated. Effects of toxicity may alter depending on the species, age and sex of the animal, but indications of toxic effects have been reported. Finally, the possibility of determining regional hot-spots, where background pollution levels are high, from concentrations of mercury reported in cetacean species, are examined.

KEYWORDS: POLLUTION; BIOACCUMULATION/MAGNIFICATION; HEAVY METALS; TOXICITY; REVIEW

INTRODUCTION

This paper is a review of the literature on the incidence of metals in cetacean species, and is intended to provide a focused addition to previous reviews by Wagemann and Muir (1984) and Law (1996) on metals in all species of marine mammals. The paper is intended to provide an overview of bioaccumulation rates, concentrations and effects of metals in cetacean species. Firstly, the major routes of uptake and site specificity of metal concentrations will be examined. A comparison will then be made between concentrations of metals on three levels: at an individual animal level; an intra-species level; and at the sub-order level between *Odontoceti* and *Mysticeti*. Known associated physiological effects of these concentrations on cetaceans will then be analysed following a review of the reported detoxification mechanisms.

However, difficulties arise in attempting to interpret data, particularly regarding the significance and possible effects of levels recorded. Firstly, data tend to be limited to certain species and certain metals. Although data are presented on levels of lead, cadmium, zinc, selenium, manganese, iron and copper, the majority of research has focused on mercury (see

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Appendix 1). Moreover, research has concentrated on particular species, such as toothed cetaceans, and in particular regions, for instance the Northwest Pacific and North Atlantic Oceans (Appendix 1). Secondly, it is problematic to compare data which have used different sampling, measuring and analytical techniques, and whose results are presented in different formats, such as wet or dry weight, original data, ranges, means or medians. Moreover, data may originate from samples of both freshly killed and stranded cetaceans, the latter likely to present altered levels of metal burdens. Thirdly, differences may occur in concentrations of metals due to factors such as the species' diet, age and sex, but this information is often lacking, particularly on the age of the sampled animal. Finally, as research on the effects of metal burdens on cetacean species is fairly recent, there are few long-term databases that can be used to depict trends and effects of metals on cetaceans.

As top predators, cetaceans can be affected by metals in two distinct ways. Firstly, they may suffer the direct effects from bioaccumulation through the marine food chain and, secondly, they may be indirectly affected by a reduction in prey availability caused by metal toxicity in species at lower trophic levels. This study will consider only the former.

Finally, the pattern of geographical variation in the metal levels found in cetaceans from different regions is examined.

OVERVIEW OF METALS

Two broad groups of metals are recognised: 'essential' and 'non-essential' metals. Essential metals are those which have a clearly documented and defined function in the body and life of a species. Species require relatively low levels of these metals as an integral part of certain biological and biochemical processes, and a deficiency in them will result in negative effects. Disease and other negative effects may also develop if the concentration of the metal exceeds the level that the species requires or is able to store. Essential metals tend to show less variation in concentrations and burdens within and between species because organisms are able to regulate them. Research has established that copper, iron, selenium and zinc all fulfil vital functions and can therefore be defined as essential metals (Thompson, 1990; Law, 1996).

Non-essential metals are those which have little or no known recorded biological function in a species. These metals, which include mercury, lead and cadmium, are often toxic even at relatively low concentrations.

Metal contamination occurs from natural and anthropogenic sources. The former include geological weathering and volcanic activity, e.g. high levels of mercury are expelled from sub-marine volcanic activities (Piotrowski and Coleman, 1980). Man-made sources of metals are predominantly from waste disposal, leakage from mining operations, the production, use and disposal of chemicals including pesticides, the burning of fossil fuels and the use of anti-fouling paints on shipping.

CONCENTRATION DIFFERENCES AT INTRA- AND INTER-SPECIES LEVELS

Levels of metals in cetaceans are the net difference between uptake of the metal and any subsequent loss, such as excretion of the metal. A number of factors affect rates of uptake and bioaccumulation. These include: the subject metal, its specification, inter-metal competition for available body sites, inter-metal synergistic effects; and the subject organism and its biological characteristics, particularly sex, age and diet.

There are three routes for the uptake of metals into cetacean bodies. The principal one is dietary, but accumulation has also been reported through the skin and into the lungs (Augier *et al.*, 1993; Law, 1996). The skin is probably of little importance as cetacean skin is an effective barrier and direct bioaccumulation by the cutaneous route probably only occurs when lesions are present (André *et al.*, 1990). The pulmonary route is also not that significant although direct incorporation of metals may also occur from those present in the atmosphere (André *et al.*, 1990; Augier *et al.*, 1993). The bioaccumulation and biomagnification of metal compounds in cetaceans primarily occurs through diet, and will vary on a species-specific and metal-specific basis.

Bioaccumulation rates

Muir *et al.* (1992) calculated bioaccumulation rates for mercury and cadmium from a relatively simple food web in the Arctic as shown in Table 1.

The data displayed in Table 1 show that only mercury has a consistently high biomagnification factor (BMF) throughout the marine food chain. BMFs from seawater to cetaceans for mercury have been reported in only two cases. These are from seawater to the liver of minke whales (4.3×10^4) in the Antarctic (Honda *et al.*, 1987), and from seawater to the livers of narwhals (3.5×10^5) from the Arctic (Muir *et al.*, 1992). However, Viale (1974) and Augier *et al.* (1993) calculated a lower mercury BMF of between 100-1,000 times in aquatic food chains, and their figure of a BMF of 4-8 times between fish and cetaceans is also considerably lower than that reported by Muir *et al.* (1992) who quote a value of 305 for fish to narwhal. The majority of mercury concentrations reported in marine species are of the organic form, methylmercury (Lindberg *et al.*, 1987; André *et al.*, 1990), which is highly lipophilic, therefore readily accumulated in the fatty tissues of fish and cetacean species, and consequently easily transferred along the food chain.

Cadmium BMFs have been reported from seawater to the liver of minke whales in Antarctica (5.5×10^5; Honda *et al.*, 1987) and to the liver of narwhals in the Arctic (4×10^6; Muir *et al.*, 1992). These high values are due to the species' reliance on prey which are rich in cadmium. However, as Table 1 shows, a high BMF does not occur at every stage in the food chain. This confirms other reports that the highest concentrations of cadmium are recorded at the phyto- and zooplankton trophic level (Furness and Rainbow, 1990).

There are few published BMFs for other metals, although Muir *et al.* (1992) stated that the BMF for lead was low between fish and small cetaceans (Table 1).

Table 1

Biomagnification factors for certain metals in the Arctic food chain as calculated by Muir *et al.*, 1992.

	Water-algae	Algae-copepods	Amphipods-fish	Fish-small cetacean
Cadmium	2.4×10^5	1.1	0.04	80
Mercury	-	-	163.0	305
Lead	-	-	-	0.07

Site specificity of burden levels

As diet is the main source of uptake of metals in cetaceans, this will affect the pattern of site distribution of these concentrations recorded in the cetacean body. Metals ingested will be transported via the blood system to the soft tissues, so it is expected that these tissues would contain higher concentrations (André *et al.*, 1990).

Table 2 presents data recording the tissue or organ for fourteen species where the highest mean concentration of a particular metal was recorded. It shows that in the majority of baleen and toothed species, the liver consistently contained the highest concentrations of mercury,

Table 2

Tissue specificity for seven metals and thirteen species, showing the tissue containing the highest mean concentration. Li: Liver, Ki: Kidney, Sk: Skin, Bo: Bones, Bl: Blood, Mus: Muscle, ND: No data reported.

Species	Hg	Cd	Se	Zn	Cu	Fe	Pb
Spotted dolphin *Stenella attenuata*	Li[1]	ND	ND	ND	ND	ND	ND
Striped dolphin *Stenella coeruleoalba*	Li[2,6]	Ki[6,13]	Ki[11]	Li[6,13] Sk/Bo[17]	Li[6]	Li[6]	Li[6]
White whale *Delphinapterus leucas*	Li[9,14]	Ki[14,19]	Li[14,19]	Mus[14] Ki[19]	Li[19]	ND	Ki[19]
Narwhal *Monodon monoceros*	Li[3,14]	Ki[9,14]	Li[3,14]	Ki[14]	Li[3]	ND	Li[9]
Fransiscana *Pontoporia blainvillei*	Li[4]	Ki[4]	ND	Li[4]	Li[4]	ND	ND
Ganges river dolphin *Platanista gangetica*	ND	Ki[5]	ND	Li[5]	Li[5]	Li[5]	Ki[5]
Dall's porpoise *Phocoenoides dalli*	Li[10]	Ki[10]	ND	Sk[10]	Li[10]	Bl[10]	Sk/Bo[10]
Long-finned pilot whale *Globicephala melas*	Li[8]	Ki[8,12]	Li[8,12]	Li[8,12]	Li[12] Ki/Li[8]	ND	Li[8]
White-beaked dolphin *Lagenorhynchus albirostris*	Li[8]	Ki[8]	Li[8]	Li[8]	Li[8]	ND	Li/Ki[8]
Pygmy sperm whale *Kogia breviceps*	Li[4]	Ki[4]	ND	Ki[4]	Li[4]	ND	ND
Minke whale *Balaenoptera acutorostrata*	Li[14]	Ki[14]	Ki[14]	Li[14]	ND	ND	ND
Cuvier's beaked whale *Ziphius cavirostris*	ND	Li/Ki[18]	ND	Li/Ki[18]	Li[18]	Li[18]	ND
Fin whale *Balaenoptera physalus*	Li[7]	ND	ND	ND	ND	ND	ND
Harbour porpoise *Phocoena phocoena*	Li[15,16]	Ki[15,16]	Sk[16]	Sk[16]	Li[16]	ND	ND

[1] Andre *et al.*, 1990. [2] Augier *et al.*, 1993. [3] Wagemann *et al.*, 1983. [4] Marcovecchio *et al.*, 1990. [5] Kannan *et al.*, 1993. [6] Honda *et al.*, 1983. [7] Sanpera *et al.*, 1993. [8] Muir *et al.*, 1988. [9] Wagemann *et al.*, 1984. [10] Fujise *et al.*, 1988. [11] Itano *et al.*, 1984a. [12] Caurant *et al.*, 1993. [13] Honda and Tatsukawa, 1983. [14] Hansen *et al.*, 1990. [15] Teigen *et al.*, 1992. [16] Paludan-Muller *et al.*, 1993. [17] Honda *et al.*, 1986a. [18] Knap & Jickells, 1983. [19] Wagemann *et al.*, 1990.

iron and copper. In many of these species the second highest concentration was reported in the kidney.

André *et al.* (1990) and Augier *et al.* (1993) report that mercury concentrations in the striped dolphin (*Stenella coeruleoalba*) declined in the following order: liver ≥ spleen ≥ blubber, kidney, pancreas ≥ stomach, lungs ≥ skeletal muscles, intestine, heart, brain, skin ≥ melon fat, blood.

Differences in concentrations between tissues can be high. In a study of mercury levels in spotted dolphins (*Stenella attenuata*) in the Pacific Ocean, André *et al.* (1990) reported that 95% of the burden analysed in 18 different tissues and organs was in the liver, skeletal muscle and blubber; levels in the liver (62 $\mu g.g^{-1}$ the highest concentrations) were 170 times higher than those in the blood, which contained the lowest concentrations (0.36 $\mu g.g^{-1}$) and were six times higher than those in the spleen (which contained the second highest concentration). Similar differences have been reported for other species. In long-finned pilot whales (*Globicephala melas*) hepatic concentrations were ten times higher than those in the kidney, which contained the second highest concentration, and in white-beaked dolphins

(*Lagenorhynchus albirostris*) the concentations were three times higher than those in the kidney (Muir *et al.*, 1988). Similar differences in concentrations have been recorded between other body sites. For instance, mercury concentrations were 25 times lower in the melon than in the muscle of striped dolphins from the Mediterranean (André *et al.*, 1991).

The kidney contained the highest cadmium concentrations in all species recorded in Table 2. These concentrations were also significantly higher than those reported in the liver, which generally contained the second highest concentrations. For instance, mean renal cadmium concentrations were four times higher than those in the liver in striped dolphins from the west Pacific Ocean (Honda *et al.*, 1983), four times higher in harbour porpoises (*Phocoena phocoena*) from Greenland (Paludan-Muller *et al.*, 1993) and three times higher in narwhals (*Monodon monoceros*) from Greenland (Hansen *et al.*, 1990). The high concentration of cadmium in the kidney may be connected to the presence of certain storage mechanisms using cadmium metallothionein protein (Fujise *et al.*, 1988; Marcovecchio *et al.*, 1990). This will be discussed further under the section on detoxifying strategies.

Table 2 also shows that high concentrations of certain metals are reported in the skin, blood and bones. Zinc concentrations were highest in the skin and bones in studies where all the organs and tissues were analysed, and highest in the liver where only soft tissues were analysed. Only in white whales (*Delphinapterus leucas*) sampled around Greenland were the highest concentrations found in the muscle (Hansen *et al.*, 1990). Large differences were also reported between the organ or tissue containing the highest and second highest concentrations. In two Dall's porpoises (*Phocoenoides dalli*) from the western Pacific Ocean, over half the total body burdens of zinc recorded were in the skin and similarly zinc concentrations in the skin of harbour porpoises from Greenland were seven times higher than those found in the liver (Paludan-Muller *et al.*, 1993).

There are few comparative data between tissues for other metals (Table 2). High lead concentrations (40% of total burdens) were recorded in the skin and bones of Dall's porpoises (Fujise *et al.*, 1988), and high iron concentrations were reported in the blood and lungs of the same species. Selenium accumulation varies. Only one study has analysed selenium concentrations in all organs and tissues (Paludan-Muller *et al.*, 1993), and this found that the highest concentration occurred in the skin, five times greater than those in the kidney. Other studies, solely of soft tissues, recorded the highest concentrations to be in the liver, unsurprising in view of the strong correlation selenium displays with mercury concentrations.

Intra-species differences in concentrations

Two examples of intra-species differences in concentrations are given in Tables 3 and 4. Hepatic concentrations of mercury are several factors higher in minke whales from the Arctic than the Antarctic, the maximum concentrations in minke whales from the former region being 20 times higher than the maximum recorded in the Antarctic region. However, cadmium concentrations showed the reverse relationship. Maximum concentrations in Antarctic minke whales were about 20 times those recorded in the Arctic (Table 3).

The major difference between minke whale populations in the Arctic and Antarctic is their diet. Arctic minke whales feed principally on sand eels, *Ammodytes*, (Hansen *et al.*, 1990) whereas those in the Antarctic feed primarily on krill, *Euphasia* spp. (Honda *et al.*, 1987). Higher concentrations of cadmium and lower ones of mercury are found in krill when compared to fish (Honda *et al.*, 1987) and these differences are reflected in the concentrations outlined in Table 3. Honda *et al.* (1987) also stated that differences in the length of the food chain between the two regions may be relevant. The food chain in the Antarctic is short, providing less opportunity for biomagnification.

Table 3

Range and means of hepatic concentrations of cadmium and mercury in the minke whale population from three different areas (ng g^{-1} wet weight). ND: No data recorded. *The figure is the median, not the mean.

	Greenland[1]	Arctic[2]	Antarctic[3]
Cadmium	ND	500-1,450 900*	2,200-33,000
Mercury	70-410 180	140-2,680 390*	20-129 46.5*

[1]Johansen *et al.*, 1980 (*n*: 6). [2]Hansen *et al.*, 1990 (*n*: 24). [3]Honda *et al.*, 1987 (*n*: 135).

Table 4

Cadmium and mercury concentrations in the livers of harbour porpoises from two different areas ($\mu g\ g^{-1}$ wet weight).

	Greenland[1]	UK coast[2]
Mercury	range=0.48-20.7 mean=6.23	range=0.6-150 mean=13.8
Cadmium	range=0.06-11.7 mean=4.29	range=0.03-1.2 mean=0.18

[1]Paludan-Muller *et al.*, 1993 (*n*: 43). [2]Law *et al.*, 1991 (*n*: 20).

Table 4 shows differences in mercury and cadmium concentrations in two discrete populations of harbour porpoises. Cadmium levels in those from Greenland were significantly higher than those found around the UK (by more than 20 times) but mercury concentrations were about half those from UK porpoises. The reason for this is less apparent than the minke whale example shown above, but may be due to higher mercury levels found in the environment around the UK and the fact that porpoises from Greenland feed on fish which contain higher cadmium levels than fish species found around UK coasts (Paludan-Muller *et al.*, 1993).

Differences in concentration levels between toothed and baleen cetaceans

Table 5 shows differences in the cadmium and mercury bioconcentration factors between odontocetes and mysticetes. Both in the Arctic and Antarctic they were higher in odontocetes than in mysticetes. This is clearly reflected in the concentration of metals in tissues. Honda *et al.* (1983) recorded a range of mercury concentrations in the liver of striped dolphins from the western Pacific Ocean (Table 6) of 1.7 μg^{-1} to 485 $\mu g.g^{-1}$ (mean: 205 $\mu g.g^{-1}$) whereas Honda *et al.* (1987) reported concentrations in the livers of minke whales in the Antarctic from 0.02 $\mu g.g^{-1}$ to 1.3 $\mu g.g^{-1}$ (mean: 0.4 $\mu g.g^{-1}$), a difference of over 500 times. Other baleen whales, such as bowhead whales sampled in the Arctic, show similarly low mercury levels (Byrne *et al.*, 1985). Indeed generally, the minimum concentration of mercury in the liver of toothed cetaceans is higher than the maximum concentration recorded in baleen whales.

Three principal reasons explain these differences (Honda *et al.*, 1987): (1) diet: toothed cetaceans' greater reliance on fish as a prey species; (2) geography: toothed cetaceans' predominance in coastal areas; and (3) length of food chain: toothed cetaceans' position as a top predator in longer food chains than those found in baleen whales.

Table 5

Bioconcentration factors for three metals from sea water to cetaceans (concentrations measured in the livers of narwhals and minke whales). ND: No data recorded.

	Cadmium	Mercury	Lead
Odontoceti[1]	4.0×10^6	3.0×10^5	1.9×10^3
Mysticeti[2]	5.5×10^5	4.3×10^4	ND

[1] Arctic ecosystem: Muir *et al.*, 1992. [2] Antarctic ecosystem: Honda *et al.*, 1987.

Table 6

Tentative trends in the relationship of the concentrations of nine metals with age category in the liver of striped dolphins from the west Pacific Ocean. (data taken from Honda *et al.*, 1983.) +ve: increase in concentration in this age bracket; -ve: decrease in concentration in this age bracket; -: no discernible change in concentration recorded; ND: no data recorded.

Age of cetacean	Fe	Zn	Pb	Mn	Ni	Cd	Hg	Se	Cu
Gestation period	+ve	+ve	+ve	+ve	ND	-	+ve	ND	+ve
Suckling (calf)	-ve	+ve	+ve	+ve	+ve	+ve	+ve	ND	+ve
Up to 8 years	+ve	-ve	-	-ve	-	-	+ve	+ve	-ve
Adult	-	-	+ve	-	+ve	+ve	+ve	+ve	-

Focardi *et al.* (1992) reported levels of mercury in baleen and toothed cetaceans from the Mediterranean Sea, the geographical region where the highest burden of mercury in a small cetacean has been recorded. Levels of mercury and cadmium were on average 5-20 times lower in baleen whales and three times lower than those recorded in toothed cetacean species in the same locality (Focardi *et al.*, 1992). Indeed small cetaceans have recorded levels of mercury and selenium which are higher than in any other organism (Koeman *et al.*, 1973; André *et al.*, 1991).

Although accumulation rates and concentration levels for most metals are generally lower in baleen whales, as reported earlier, species-specific differences can occur as a result of diet. Cadmium levels are usually higher in krill than in fish (Thompson, 1990; Hapke, 1991) and this explains the comparatively higher cadmium levels present in the krill-eating minke whales from the Antarctic than in the fish-eating cetaceans from the Pacific Ocean (Honda *et al.*, 1987).

However, when cephalopod-eating odontocetes are compared with krill-eating mysticetes, concentrations are much higher in the former, again reflecting dissimilar cadmium richness in their diets. Caurant *et al.* (1993) recorded cadmium concentrations in the kidney of long-finned pilot whales in the North Atlantic to be up to 30 times higher than those recorded for minke whales. They reported a range of concentrations in the kidney from one school of pilot whales 1.4-158 $\mu g.g^{-1}$ (mean: 93.1 $\mu g.g^{-1}$) which compares with a range of 1.7-5.6 $\mu g.g^{-1}$ (median: 3.7 $\mu g.g^{-1}$) for cadmium concentrations in the kidneys of minke whales in the Arctic (Hansen *et al.*, 1990) and 2.2-33 $\mu g.g^{-1}$ in hepatic tissues of minke whales from the Antarctic (Honda *et al.*, 1987).

The greater reliance of baleen whales on krill may also be responsible for higher levels of nickel found in these species than in toothed whales (Honda *et al.*, 1987), although data on nickel levels in toothed cetaceans are sparse, making comparison difficult.

PHYSIOLOGICAL EFFECTS

Toxicity occurs in a species when the accumulation of a metal is not matched by the body's storage, excretory, metabolic and detoxification mechanisms (Underwood, 1977; Piotrowski and Coleman, 1980). Once this stage is reached, spill-over of the metal occurs to other cells, particularly in soft tissues such as the liver and kidney (Underwood, 1977; Piotrowski and Coleman, 1980).

A number of factors will determine the actual toxic effects on a species. These will include the levels of metal ingested; the period of ingestion; any storage, metabolic, excretory or detoxifying mechanisms; synergistic interactions with concentrations of other metals; the tissue site; relationships and effects resulting from failure at other different tissue sites (Langston, 1990). Synergistic effects from high concentrations of other pollutants such as polyaromatic hydrocarbons have also been reported (George, 1990).

Little research has been undertaken on the effects of metals in cetacean species. The capacity for excretion of mercury appears to be low, so most ingested mercury remains in the animal (Nigro and Leonzio, 1993). Probably because mercury occurs naturally in the environment, to compensate for poor excretory mechanisms, storage and detoxifying strategies have evolved in many cetaceans. These allow metals to be stored in an inert state in tissues. Thus, the presence of high concentrations of a metal is not necessarily correlated with toxicity.

Detoxifying strategies

In many cetacean species, correlations have been reported between metal concentrations in the tissues and organs analysed (Table 7). Some of these relate to detoxification mechanisms.

Mercury

Most mercury available in the ecosystem is inorganic, but is converted by micro-organisms present in freshwater and marine sediments to methylmercury, a more toxic and readily bioaccumulative form (Law, 1996). The effect of detoxification can be seen in the high values of inorganic mercury recorded in cetaceans, despite the fact that most mercury is ingested in its organic form.

A decline in the ratio of methylmercury to total mercury has been recorded in the soft tissues of harbour porpoises (Joiris *et al.*, 1991), pilot whales (Julshamn *et al.*, 1987; Caurant *et al.*, 1993), narwhals (Wagemann *et al.*, 1984), striped dolphins (Itano *et al.*, 1984b) and common dolphins (Joiris *et al.*, 1992b) and in the hard tissues of striped dolphins (Honda *et al.*, 1986b), confirming that a de-methylating process occurs within the tissues of the animal. In one adult narwhal examined by Wagemann *et al.* (1984), methylmercury only represented 7% of total mercury values in the liver and 11% in the kidney.

Joiris *et al.* (1992b) interpreted mercury detoxification in common dolphins as follows: methylmercury concentrates in the fatty areas of the animal, where it is mineralised and re-mobilised to accumulate as inorganic mercury in the liver. Here it is detoxified by binding to selenium or metallothionein proteins.

The binding of mercury to selenium can be seen in the high levels of selenium that have been widely reported in conjunction with high levels of mercury in a number of cetacean species (Table 6), but appears to only occur on specific tissues in certain species and only after a certain age. It has been reported in the bone, kidney, liver and muscle of striped dolphins (Itano *et al.*, 1984b; Honda *et al.*, 1986b; Leonzio *et al.*, 1992), and the livers of pilot whales (Muir *et al.*, 1988; Caurant *et al.*, 1993), narwhals (Wagemann *et al.*, 1990) and harbour porpoises (Paludan-Muller *et al.*, 1993). However, no relationship was found in the

Table 7

Inter-metal correlations reported in cetaceans. Key = Ki: Kidney, Li: Liver, Mu: Muscle, Bo: Bone, Blu: Blubber; +ve: positive correlation recorded; -ve: negative correlation recorded.

	Tissue	Species	Reference
Mercury-selenium +ve	Li; Ki; Mu	White whale	Wagemann *et al.*, 1990
	Li; Ki	Narwhal	Wagemann *et al.*, 1983
	Li	Common dolphin	Joiris *et al.*, 1992b
	Li	Bottlenose dolphin	Nigro & Leonzio, 1993
	Li; Bo	Striped dolphin	Nigro & Leonzio, 1993
			Honda *et al.*, 1986a
	Li	Harbour porpoise	Teigen *et al.*, 1992
	Li	Minke whale	Hansen *et al.*, 1990
	Li; Ki	Pilot whale	Caurant *et al.*, 1993
	Li	Cuvier's beaked whale	Martoja & Viale, 1977
Cadmium-selenium +ve	Ki	Beluga	Wagemann *et al.*, 1990
	Li; Mu	Pilot whale	Caurant *et al.*, 1993
	Li	White whale	
		Minke whale	Hansen *et al.*, 1990
		Narwhal	
Cadmium-mercury -ve	Ki	Beluga	Wagemann *et al.*, 1990
Cadmium-mercury +ve	Li; Blu	Narwhal	Wagemann *et al.*, 1983
	Li; Ki; Mu	Pilot whale	Caurant *et al.*, 1993
Cadmium-zinc +ve	Li; Ki	Striped dolphin	Honda & Tatsukawa, 1983
	Li; Ki	Beluga	Wagemann *et al.*, 1990
	Li; Ki	Narwhal	Wagemann *et al.*, 1983
	Ki	Harbour porpoise	Paludan-Muller *et al.*, 1993
	Li	Minke whale	Honda *et al.*, 1987
	Li; Ki	Pilot whale	Caurant *et al.*, 1993
Lead-cadmium +ve	Ki	Narwhal	Wagemann *et al.*, 1983
Zinc-mercury -ve	Ki	Beluga	Wagemann *et al.*, 1990
Zinc-mercury +ve	Mu	Beluga	
	Li	Minke whale	Honda *et al.*, 1986b
	Ki	Pilot whale	Caurant *et al.*, 1993
Zinc-selenium +ve	Ki	Beluga	Wagemann *et al.*, 1990
Silver-mercury +ve	Li	Beluga	Becker *et al.*, 1995
		Pilot whale	

muscle of harbour porpoises (Schnapp, 1993) or in the liver of long-finned pilot whale foetuses (Caurant and Navarro, 1994).

The interactions between selenium and mercury are still poorly understood. Detoxification could occur due to competition for binding sites, or a formation of a less toxic and more easily storable complex such as mercury selenide (Koeman *et al.*, 1973; Augier *et al.*, 1993). The occurrence of mercury selenide granules within phagocytic cells reported by Nigro and Leonzio (1993) in bottlenose dolphins suggests that the production of mercury selenide, and thus the detoxification of methylmercury, is performed by phagocytosis. As mercury selenide granules have been reported in the liver (Martoja and Viale, 1977; Nigro and Leonzio, 1993), lungs (Augier *et al.*, 1993) brain and muscle (Nigro and Leonzio, 1993) of cetacean species, it appears that storage and detoxification of mercury occurs at different sites. However, cetaceans cannot excrete mercury selenide (Martoja and Berry, 1980; Caurant *et al.*, 1994), so particles will accumulate in their cells.

By binding mercury to metal-binding proteins, damage is reduced and the storage of certain metals regulated. The actual toxic effects of the metal will only occur once the binding capacity of the metallothionein becomes saturated and a spillover of excess ions occurs to other cells (Langston, 1990). Metallothioneins have been found in long-finned pilot whales (Caurant *et al.*, 1993), narwhals (Wagemann *et al.*, 1984) and common dolphins (Joiris *et al.*, 1992b).

Other metals

The sequestration of free ions of metals by metallothionein has been recorded in a number of species for other metals, including, in descending order of binding affinity, copper, cadmium and zinc; no sequestration of lead has yet been reported (Eisler, 1984; Quarterman, 1986; Tohyama *et al.*, 1986; Law, 1996).

Paludan-Muller *et al.* (1993) reported that the relationship between zinc and cadmium concentrations in the kidneys of harbour porpoises was due to cadmium binding to zinc-metallothionein. This correlation has also been recorded in the liver of narwhals and white whales (Hansen *et al.*, 1990) and in the liver and kidney of other marine mammals (Wagemann and Stewart, 1994). Wagemann *et al.* (1984) reported that in the liver of a narwhal, a high percentage of both cadmium and copper were thionein-bound, whereas for mercury it was lower. Similarly, in the livers of common dolphins, Joiris *et al.* (1992b) reported that 50% of inorganic mercury was not thionein or selenium-bound and was thus potentially toxic.

Other synergistic effects have been reported. A deficiency in levels of iron and zinc, for example, can increase the absorption rate of lead in certain species (Honda and Tatsukawa, 1983; Kostial, 1986; Quarterman, 1986). Honda and Tatsukawa (1983) also reported that cadmium accumulation may inhibit detoxification rates for zinc and copper in striped dolphins. Other variables can increase the toxic potential of a metal. High water temperature and low salinity have been reported to react with metals such as cadmium, mercury and zinc to result in an increase in the metal's toxic potential (Langston, 1990).

Effects of metals in cetacean species

Mercury

The high toxicity, long biological half-life, lipophilicity and biomagnification of mercury in the food chain make this metal one of the most threatening. In their review, Wagemann and Muir (1984) proposed that tolerance limits for mercury in mammals may be in the range of 100-400 $\mu g.g^{-1}$ in hepatic tissue, although the evidence for this is unclear. Table 8 shows that seven studies of three species have reported concentrations above this limit.

Despite the assertion in Wagemann and Muir (1984), studies to ascertain the effects of these concentrations in cetaceans are rare, although in certain non-cetacean species, mercury poisoning has resulted in serious disorders in the liver, kidney and brain, and methylmercury poisoning resulted in behavioural defects, loss of coordination and loss of vision. In other marine mammal species, high hepatic and renal mercury concentrations have caused liver and kidney failure (Law, 1996). Samples of six of the seven case studies of cetaceans shown in Table 8 were taken from stranded dolphins, suggesting a possible causal link with high mercury concentrations (Augier *et al.*, 1993).

Rawson *et al.* (1993) reported toxic effects of mercury in a pod of bottlenose dolphins stranded off the USA coast. Nine of the 18 animals sampled had extensive deposits of a granular pigment within the livers' portal areas. These animals also contained the highest mercury liver concentrations which ranged from 61-433 $\mu g.g^{-1}$. Furthermore, four of the nine animals with pigmentation deposits also had active liver disease, including necrosis and fat globules among the hepatocytes adjacent to the portal areas. The presence of fat globules revealed that the animals' fat metabolism had been affected, and may have led to cell death. In the absence of any correlation with age, Rawson *et al.* (1993) suggested that the pigment accumulation was related to the toxic effect of mercury.

Table 8

Concentrations of mercury recorded in the liver of cetaceans which exceed the proposed tolerence limits suggested by Wagemann & Muir, 1984 (100-400μg.g^{-1}). All figures are μg.g^{-1} wet weight except *=dry wt.

	Range of concentrations	Mean/median concentration	Geographical area	Reference
White whale				
(*n*: 30)	1.42-756*	126*	St Lawrence, Canada[2]	Wagemann *et al.*, 1990
False killer whale				
(*n*: 38)	41-479	249	New South Wales, Australia[2]	Kemper *et al.*, 1994
Bottlenose dolphin				
(*n*: 12)	0.1-443	134.6	US[2]	Rawson *et al.*, 1993
(*n*: 4)	12.2-13,155.6*	med: 270.4*	Mediterranean[2]	Leonzio *et al.*, 1992
Striped dolphin				
(*n*: 45)	1.7-475	205	West Pacific[1]	Honda *et al.*, 1983
(*n*: 25)	1.2-1,544	346.1	Mediterranean[2]	Andre *et al.*, 1991
(*n*: 13)		med: 327		
(*n*: 19)	48-1,613	474	Mediterranean[2]	Augier *et al.*, 1993
	324.4-4,400*	med: 324.4*	Mediterranean[2]	Leonzio *et al.*, 1992

[1] Samples taken from freshly killed animal. [2] Samples taken from dead animal.

The effects of anthropogenic pollutants have also been studied extensively over a nine year period on the population of white whales in the St Lawrence River, Canada. Pathological abnormalities such as bladder cancer, severe lesions and tumours have been reported (Martineau *et al.*, 1985; 1988; 1994). Twenty-four neoplasms were found in 18 of the 45 animals necropsied in the nine year study, eight neoplasms being malignant (Béland *et al.*, 1993). The population has a high level of bacterial infections, pneumonia and tooth loss, about 2% have spinal deformities and its reproductive rate is only half that found in other white whale populations (Martineau *et al.*, 1988; Béland *et al.*, 1993). Although mercury levels are extremely high in white whales from the St Lawrence (Table 8), it is difficult to attribute specific effects to mercury poisoning as the concentrations of lead (Wagemann *et al.*, 1990) and other anthropogenic pollutants, notably organochlorines (Béland *et al.*, 1992; 1993), are also high. Wagemann *et al.* (1990) believed that the adverse effects reported in this population are likely to be a combination of all the toxic elements acting over a long time period (see also the review by Martineau *et al.* in the present volume).

So, for certain species, there is some evidence that high levels of mercury may have resulted or contributed to chronic illness in disease and mortality in die-offs (Wagemann *et al.*, 1990; Béland *et al.*, 1992; Augier *et al.*, 1993; Law, 1996). However, equally high mercury levels in mature striped dolphins from the North Pacific have apparently not resulted in any side effects (Itano *et al.*, 1984a). This difference may be due to interspecific differences in susceptibility to the effects of metals or that the rate of bioaccumulation of mercury is more important than its actual burden level.

Other metals

Wagemann and Muir (1984) were unable to suggest tolerance limits for metals other than mercury. In the absence of any specific marine mammal values for cadmium tolerance limits in the kidney, Law (1996) has used the figures suggested for humans where renal damage occurs above concentrations of 200-400 μg.g^{-1} (Piotrowski and Coleman, 1980). From research on the association of cadmium concentrations in the kidney and liver, Fujise *et al.* (1988) proposed that concentrations of cadmium higher than 20 μg.g^{-1} in the liver would result in renal dysfunction. Taking the tolerance figure for the kidney, Law (1996) proposed that this corresponded to a liver tolerance figure in the range of 40-200 μg.g^{-1}. Maximum and mean concentrations reported in cetaceans above these proposed tolerance limits are shown in Table 9.

According to Caurant *et al.* (1994), renal cadmium levels varied considerably among schools of Faroese long-finned pilot whales, with several having levels higher than 100 μg.g^{-1}, possibly approaching critical levels. Cadmium concentrations in the blood were also higher than the minimum levels established for adverse effects in humans. Caurant *et al.* (1993), whilst suggesting that high levels might reflect an adaptive response of pilot whales, qualified this by noting that those animals which contained high cadmium concentrations had less efficient regulation of copper and zinc (cadmium is bound to available metallothionein thus reducing its function of ensuring homeostasis of copper and zinc). Wagemann *et al.* (1983) also reported high cadmium concentrations in narwhals from the Arctic. They did not examine metal damage in the narwhals' kidneys but reported that concentrations were high enough to cause renal dysfunction. In non-cetacean species, cadmium poisoning has resulted in adverse effects on reproduction, growth and bone structure (Kostial, 1986), but to date no causal relationship between cadmium and physical effects have been reported in cetaceans, although Caurant *et al.* (1994) associated gastric erosion and ulcers in pilot whales with high cadmium levels.

Little work has been done on the effects of the other metals in cetaceans. Levels of lead tend to be low although Wagemann *et al.* (1990) reported that the St Lawrence River white whale population had very high levels, reaching 2.13 μg.g^{-1} dry weight in the liver (mean: 0.59 μg.g^{-1} dry weight; n:30). These concentrations, about 10 times higher than those found in Arctic white whales, were attributed to high aquatic levels of lead resulting from anthropogenic sources (Wagemann *et al.*, 1990). A young bottlenose dolphin stranded along the South Australian coast had levels of 61 μg.g^{-1} in the bone, which Kemper *et al.* (1994)

Table 9

Concentrations of cadmium in the liver and kidney which exceed the range of tolerance limits proposed by Piotrowski & Coleman (1980), Fujise *et al.* (1988) and Law (1996) (200-400 μg g^{-1} in the kidney and 20-200 μg g^{-1} in the liver). x: mean value. All concentrations are wet weight except ^{1} converted from dry weight (Law, in press) and ^{2} dry weight. All samples analysed from freshly killed animals.

		Hepatic concentration ≥20-200μg g^{-1}	Renal concentration ≥200-400μg g^{-1}	Geographical region	Reference
Narwhal	(*n*: 98)	0.02-73.7	-	Greenland	Hansen *et al.*, 1990
	(*n*: 38; Li) (*n*: 55; Ki)	1.28-130.8 x: 34.1	1.0-205.4 x: 63.5	Canadian Arctic	Wagemann *et al.*, 1983
	(*n*: 55)	2.44-137 x:29.7	-	Canadian Arctic	Wagemann *et al.*, 1996
White whale	(*n*: 109)	0.03-97^2 x: 12.5^2	0.05-277^2 x: 48.2^2	Canadian Arctic	Wagemann *et al.*, 1990
Minke whale	(*n*: 27)	2.2-33	-	Antarctic	Honda *et al.*, 1987
False killer whale	(*n*: 27)	14.3-75.8^2 40.4^2	-	Australia	Kemper *et al.*, 1994
Pilot whale	(*n*: 52)	0.1-94	-	Atlantic Ocean	Caurant *et al.*, 1993
		x: 41			Julshamn *et al.*, 1987
		0.74-125	-		
			1.4-962 x: 78		Caurant & Amiard-Triquet, 1995
	(*n*: 13)	0.03-118.9^1 x: 54.2^1	-	Canada	Muir *et al.*, 1988 Law, 1996

attributed to contamination from a lead smelter in the area. In non-cetacean species, lead poisoning is associated with the inhibition of enzyme systems, renal damage and cardiac disease (Quarterman, 1986).

REGIONAL DIFFERENCES IN BIOCONCENTRATIONS

The regional concentration of a metal, and thus its availability to marine biota, is dependent on the source of the metal and its method of transportation to and within the marine environment. Any localised high concentrations of metals will be important in determining levels of transfer to species whose range includes such regions. Thus, metals derived from anthropogenic sources in the form of fossil fuel combustion emissions (e.g. lead) show higher concentrations in areas close to the shoreline source (Davis, 1993; Herut *et al.*, 1993). Coastal concentrations are also high for those metals deposited by riverine transportation (e.g. manganese, aluminium and copper), which tend to show high levels close to and a rapid decrease away from the source.

Only a comparison of metal concentrations from the same tissues or organs and from similar species and comparable habitats, can provide data for a preliminary analysis of geographical differences in metal levels. Even attempts to identify 'hot spots' from metal concentrations in cetaceans can only be tentative due to the other, often uncontrolled, factors that affect concentration levels, particularly the influence of diet. For instance, cadmium concentrations in narwhals from Baffin Bay were 100 times higher than those for white-beaked dolphins from Newfoundland, whilst lead concentrations were 40 times lower; dietary rather than higher background pollution levels were considered responsible for these differences (Muir *et al.*, 1988). Lima and Sequeira (1993) also showed that mercury concentrations in common dolphins from the Portuguese coast were lower than those found in the Mediterranean, where the main prey species, sardines *(Sardinus pilchardus)*, contained very low mercury levels.

Differences have also been reported in concentrations of mercury from species caught in the same place. As Table 10 shows, mean liver concentrations of mercury in adult long-finned pilot whales (*Globicephala melas*) caught in the Faroe Islands in 1977 was 280.2 $\mu g.g^{-1}$ but data from animals caught in 1978 showed a decline to a fifth of the previous years figure, 53.4 $\mu g.g^{-1}$ (Julshamn *et al.*, 1987). This decline is also reflected in the mean muscle levels of mercury which in 1978 averaged 1.8 $\mu g.g^{-1}$, almost half the mean of 3.3 $\mu g.g^{-1}$ recorded in the previous year. The cause of this discrepancy may be due to discrete populations of pilot whales feeding on different prey items rather than a change in the background pollutant levels of mercury (Julshamn *et al.*, 1987). Further differences were reported by Caurant *et al.* (1993) on two schools of pilot whales caught in the same place both in 1986. These showed large differences in mean mercury concentrations in the liver (52.1 $\mu g.g^{-1}$ compared to 84.1 $\mu g.g^{-1}$). Differences in mercury concentrations from the same geographical area have also been reported for striped dolphins (Itano *et al.*, 1984b).

Despite recognising these sources of variation, Table 10 presents data on the hepatic concentrations of mercury in seven cetacean species from eight regions in an attempt to tentatively identify certain 'hot spots' where reported concentrations of mercury are significantly higher.

Extremely high levels of mercury have been recorded in stranded striped (1,544 $\mu g.g^{-1}$ ww) and bottlenose (3,828 $\mu g.g^{-1}$ ww) dolphins from the Mediterranean Sea (André *et al.*, 1991; Leonzio *et al.*, 1992; Law, 1996). The reasons for the high levels recorded in cetaceans from the Mediterranean Sea is likely to be a combination of anthropogenic causes and the high level of background geological mercury levels present in the area (Augier *et al.*, 1993).

Table 10

A geographical comparison of mercury concentrations in the liver of eight toothed cetacean species ($\mu g.g^{-1}$). *= median value, ND: no data reported. All values are dry weight except ^{1} which has been converted from dry weight and ^{2} which is dry weight.

Species	Region	Range (where known)	Mean	Study
Striped dolphin (*n*: 35)	Mediterranean	48-1,613	474.0^1	Augier *et al.*, 1993
Striped dolphin (*n*: 45)	NW Pacific	1.7-485	205.0	Honda *et al.*, 1983
Pantropical spotted dolphin (*n*: 44)	ET Pacific	0.18-218	62.7	André *et al.*, 1990
Long-finned pilot whale (*n*: 14)	Faroe islands	ND	280.0	Julshamn *et al.*, 1987
Narwhal (*n*: 98)	Arctic	0.01-42.8	5.26*	Hansen *et al.*, 1990
Harbour porpoise (*n*: 36)	Irish Sea	0.6-190	20.5	Law *et al.*, 1992
Bottlenose dolphin (*n*: 1)	SW Atlantic	ND	86.0	Marcovecchio *et al.*, 1990
White-beaked dolphin (*n*: 27)	NW Atlantic	0.13-1.6	3.0^2	Muir *et al.*, 1988

Similarly there appears to be a relationship between the high levels recorded and anthropogenic sources in the western North Pacific. Mercury input into the ocean from Japanese chlor-alkali production in 1970 alone amounted to 650 tons, and a correlation has been reported between the increasing amount of industrial waste inputs into the marine environment and the levels of metals present in the sediments (Goto, 1973; André *et al.*, 1991).

Law *et al.* (1992) have identified another 'hot spot' in the Irish Sea. Inputs from a variety of industrial sources, particularly from local phosphate plants, raised levels of cadmium in seawater in the area to about 50 times higher than that found in the open ocean, and levels of zinc and lead to ten times higher (Forstner, 1980). This explains the relatively high concentrations of metals in cetaceans from the eastern Irish Sea, for example those found in harbour porpoises (Table 10), which continue to remain high despite a reduction in inputs in the past 10 years (Law *et al.*, 1991; 1992).

CONCLUSIONS

In the first published overview of metals in marine mammals, Wagemann and Muir (1984) reviewed 16 different studies on 14 cetacean species. In the ten years subsequent to this review this database has increased to over 70 studies on 26 different species (the major ones are shown in Appendix 1). Some of the difficulties outlined at the start of this review continue to apply. Studies still tend to be limited to odontocetes, mercury concentrations and soft tissues. Comparison of concentrations between different species is still difficult because of the number of uncontrolled variables that can affect the levels reported. Different analytical techniques increase the difficulty, although there have been calls to establish a more standardised and coordinated approach (Kuiken and Hartmann, 1991; Kemper *et al.*, 1994) and several long-term studies using consistent techniques have recently been published (Law, 1994; Marcovecchio *et al.*, 1994; Miyazaki, 1994).

The increase in data has resulted in definite trends being established for the accumulation of many metals within the cetacean body. There is a large database on the site specificity of metal concentrations within the animal. Most metals accumulate in the soft tissues, particularly in the liver and kidney. Since 1984, new information has shown that the highest concentrations of zinc and lead have been found in hard tissues such as the skin and bone, and that concentrations of certain metals are transferred between the female and her young. New data have also been recorded on bioaccumulation rates throughout the food chain. Although this is limited to certain metals, studies to date show that only mercury biomagnifies at each level of the food chain.

Wagemann and Muir (1984) stated that systematic differences were not apparent in metal concentrations but, since then, new data have revealed both regional and species differentiation in concentrations of metals. Many of these are due to differences in background levels of metals and diet. Baleen whale species have lower concentrations of the majority of metals due to a shorter food chain and the fact that they feed lower in the trophic chain than odontocetes (O'Shea and Brownell, 1994).

In the past decade, information on detoxification has improved. It is now known that the positive correlation between mercury, probably the most toxic metal, and selenium results in a detoxification of the organic mercury into a storable compound. Metallothioneins can also reduce damage to cells by binding the toxic metals. Toxicity will occur in a species when the accumulation rate is greater than the combined detoxification, excretion or storage rates, but the actual levels of concentration needed for toxicity to occur are still unknown for most metals or species. Tentative ranges have been proposed for tolerance levels of hepatic and renal mercury and cadmium concentrations, and there are several examples of species which have concentrations exceeding these limits. A possible causal link between high mercury levels and liver disease has been suggested in two study groups of animals (Rawson *et al.*, 1993; Caurant *et al.*, 1994). There may also be a causal link between high levels of metals and 'die-offs' (André *et al.*, 1991; Béland *et al.*, 1992; 1993). Although the effects of these concentrations according to variables such as the species, age and sex, have yet to be established. the available data suggests that high levels of metals have an impact on at least some cetacean species.

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Editors' note: The paper of Henry and Best (pp. 177-94 in this volume) arrived too late for inclusion in this review.

Appendix 1

Summary of species, metals and geographical areas covered in this review.

Species	Metal	Tissue/Organ	Area	No.
MYSTICETI				
Minke whale,	Hg, Cd, Zn, Cu, Pb, Fe, Mn	Li	Ant	1
Balaenoptera acutorostrata	Hg, Cd, Se, Zn	Li, Ki, Mu	GD	2
	Cd	Li, Ki, Blu	GD	32
	Hg	Li, Mu	GD	6
	Hg	Li, Ki, Mu	GD	34
	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	11
	Hg	Mu	NWP	49
	Hg	Mu	NWP	50
Sei whale,	Hg	Mu	SP	5
Balaenoptera borealis	Hg	Mu	NWP	49
Bowhead whale,	Hg, Cd, Se, Zn, Cu, Pb, Ni, Ag	Li, Ki, Mu, Blu	AS	17
Balaena mysticetus	Hg	Li, Ki, Mu, Blu	AS	62
	Hg, Cd, Se, Zn, Cu, Pb, Fe	Li, Ki, Mu, Blu	AS	71
	Ag	Li	AS	75
Bryde's whale,	Hg	Mu	NWP	50
Balaenoptera edeni				
Fin whale,	Hg	Li, Ki, Mu	NEA	3
Balaenoptera physalus	Hg, Cd, Pb	Sk	Med	4
	Hg	Mu	SP	5
Pygmy right whale,	Hg, Cd, Pb	Li, Mu, Blu, Bo	Aust	69
Caperea marginata				
Gray whale,	Hg, Cd, Se, Zn, Cu, Pb, Fe, Ni, Ag	Li, Ki, Sto, Br	AS,	71
Eschrichtius robustus			ETP	
ODONTOCETI				
Sperm whale,	Hg	Mu	Sp	5
Physeter macrocephalus	Hg	Mu	Ant	5
	Hg	Li, Mu	NS	25
	Hg	Mu	NWP	49
	Hg	Mu	NWP	50
	Hg, Cd	Li	NWP	63
	Hg, Cd, Pb	Li, Ki, Mu, Blu	Aust	72
	Hg	Mu	Aust	73
	Hg,Cd, Se, Zn, Cu, Pb, As, Ni, Cr	Li	UK	76
Pygmy sperm whale,	Hg, Cd, Zn, Cu	Li, Ki, Mu, Blu	SWA	8
Kogia breviceps	Hg, Cd, Pb	Li, Mu, Blu, Bo	Aust	72
Ganges river dolphin,	Hg, Cd, Zn, Cu, Pb, Fe, Ni, Cr	Li, Ki, Mu	ID	7
Platanista gangetica				
Franciscana,	Hg, Cd, Zn, Cu	Li, Ki, Mu, Blu	SWA	8
Pontoporia blainvillei				
White whale,	Hg, Cd, Se, Zn	Li, Ki, Mu	GD	2
Delphinapterus leucas	Hg, Cd, Pb	Li, Ki, Mu	GD	34
	Hg	Li, Ki, Mu	CA	32
	Hg	Li, Ki, Mu	CA	42
	Hg	Li, Mu, Blu	CA	44
	Hg, Cd, Se	Li	SLA	27
	Hg	Li, Ki, Mu	SLA	60
	Hg, Cd, Se, Zn, Cu, Pb	Li, Ki, Mu	SLA/C	33
	Hg, Se, Ag	Li	A	75
	Hg, Cd, Se, Zn, Cu, Pb	Li, Ki, Mu, Sk	AS	78
			CA	

Species	Metal	Tissue/Organ	Area	No.
Narwhal,	Hg, Cd, Se, Zn,	Li, Ki, Mu	GD	2
Monodon monoceros	Hg	Li, Ki, Mu	GD	34
	Hg, Cd, Se, Zn, Cu, Pb, As	Li, Ki, Mu, Blu	CA	20
	Hg	Li, Ki, Mu	CA	42
	Hg, Cd, Zn, Cu	Li, Ki	CA	64
	Hg, Cd, Se, Zn, Cu, Pb	Li, Ki, Mu, Sk	CA	78
Harbour porpoise,	Hg	Li, Mu	CA	19
Phocoena phocoena	Hg	Li, Ki, Mu	CA	24
	Hg, Cd, Se, Zn, Cu	Li, Ki, Mu, Sk	GD	10
	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	11
	Hg, Cd, Zn, Cu, Pb, Ni, Cr	Li	UK	15
	Hg, Cd, Se, Zn, Cu, Pb, Ni	Li, Ki	UK	66
	Hg, Cd, Zn, Cu, Pb	Li, Ki, Br	UK	18
	Hg, Cd, Zn, Cu, Pb, Ni, Cr	Li, Mu, Blu	UK	35
	Hg, Cd, Pb	Li, Ki, He, Sp, Br	UK	22
	Hg, Se	Mu	UK	53
	Hg	Li, Ki, Mu	NS	25
	Hg	Li, Mu	NS	43
	Hg, Cu, Pb, Zn	Li, Mu,Blu	NS	45
	Hg, Cd, Zn, Cu, Pb	Li, Ki, Mu	NS	46
	Hg, Cd, Zn	Li, Ki, Blu	NS	54
	Hg, Se	Li, Ki	NY	14
	Ag	Li	AS	75
	Hg, Cd	Ki	NEA	79
	Hg	Li, Ki	NEA	80
	Hg, Cd, Se, Zn, As	Li, Br	NEA	81
	Hg	Li, Ki, Mu, Blu, Br	UK	82
	Hg, Cd, Cu, Zn, Pb, Ni, Mn	Li	UK	83
Dall's porpoise, *Phocoenoides dalli*	Hg, Cd, Zn, Cu, Pb, Fe, Mn	Li, Ki, Mu, Sk, Bl	NWP	13
White beaked dolphin,	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li, Ki	UK	66
Lagenorhynchus albirostris	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	11
	Hg, Cd, Se, Zn, Cu, Pb	Li, Ki, Mu	AC	9
White sided dolphin, *Lagenorhynchus acutus*	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li	UK	66
Bottlenose dolphin,	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li, Ki	UK	66
Tursiops truncatus	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	11
Tursiops gephyreus	Hg, Cd, Zn, Cu	Li, Mu, Blu	UK	35
	Hg	Li, Ki, Mu	NS	25
	Hg	Li	WA	26
	Cu	Li, Ki, Mu	WA	57
	Hg, Cd, Zn, Cu, Pb	Bo	WA	59
	Hg, Cd, Zn, Cu, Pb, Ni, Cr	Li, Ki, Mu, Blu	SWA	8
	Hg, Cd, Se, Zn, Pb	Li, Ki, Mu	Med	37
	Hg, Se	Li, Ki, Mu, Br	Med	51
	Hg, Cd, Pb	Li, Ki, Mu, Blu, Bo	Aust	72
Pantropical spotted dolphin,	Hg	Li, Ki, Mu, Sk, Bo, Blu	ETP	39
Stenella attenuata	Hg, Se	Mu	NWP	41
Striped dolphin,	Hg, Cd	Li, Ki, Mu	NWP	12
Stenella coeruleoalba	Zn, Cu, Pb, Fe, Mn	Li, Ki, Mu, Sk, Bo	NWP	30
	Hg, Se	Li, Ki, Mu	NWP	21
	Cd, Zn	Bo	NWP	29
	Hg, Se, Zn, Cu, Pb, Fe, Mn	Li, Mu, Blu	NWP	31
	Hg, Se	Li, Ki, Mu	NWP	41
	Hg, Se	Li	UK	66

Species	Metal	Tissue/Organ	Area	No.
	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li	UK	11
Striped dolphin, *Stenella coeruleoalba* (cont.)	Hg, Cd, Zn, Cu, Pb, Fe, Mn	Li	Med	16
	Hg	Li, Ki, Mu, Sk, Blu	Med	23
	Hg	Sk	Med	4
	Hg, Cd, Pb	Li, Ki, Mu	Med	37
	Hg, Cd, Se, Zn, Pb	Li, Ki	Med	47
	Hg, Se	Li, Ki, Mu, Br	Med	51
	Hg, Se	Li, Ki, Mu, Sk	Med	55
	Hg, Cd, Pb	Li, Ki, Mu, Blu	Aust	72
Common dolphin, *Delphinus delphis*	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	11
	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li, Ki, Sto	UK	66
	Hg	Li, Ki, Mu	NS	25
	Hg	Li, Mu, Blu	NS	65
	Hg	Li, Ki, Mu, Blu, Br	EA	52
	Hg, Cd, Zn, Cu	Li, Ki, Mu, Blu	EA	59
	Cd, Zn	Li, Ki, Mu	SWA	58
	Hg, Cd, Pb	Li, Ki, Mu, Blu, Bo	Aust	72
Risso's dolphin, *Grampus griseus*	Hg, Cd, Zn, Cu, Pb, Cr	Li	UK	66
Long-finned pilot whale, *Globicephala melas*	Hg, Cd, Se, Zn, Cu, Pb	Li, Ki, Mu	CA	9
	Hg, Cd, Se, Zn, Cu	Li, Ki, Mu	NEA	28
	Hg, Cd, Se, Zn, Cu	Li, Ki, Mu	NEA	38
	Hg	Blu	NEA	41
	Cd	Li, Ki, Mu, Bl	NEA	74
	Hg, Se	Mu	NWP	41
	Hg, Cd, Se, Zn, Cu, Pb, Cr	Li	UK	66
Short-finned pilot whale, *Globicephala macrorhynchus*	Hg, Cd, Se	Li, Ki	USA	32
	Hg	Li, Ki	WI	40
	Hg, Pb	Li, Ki, Mu	Aust	72
Killer whale, *Orcinus orca*	Hg, Cd, Pb	Li, Ki	Aust	72
False killer whale, *Pseudorca crassidens*	Hg, Cd, Pb	Li, Ki, Mu, Blu	Aust	72
Cuvier's beaked whale, *Ziphius cavirostris*	Hg, Se	Li	NEA	67
	Hg, Cd	Li, Ki, Mu, Blu	WA	36
	Hg, Zn, Cu, Pb,, Fe, Mn, Ni	Li, Ki, Mu	SWA	68
Beaked whale, *Mesoplodon* spp	Hg, Cd, Pb	Li, Ki, Mu, Blu, Bo	Aust	72
Bottlenose whale, *Hyperoodon ampullatus*	Hg	Li, Mu	NS	43

SITES

Li: Liver; Ki: Kidney; Mu: Muscle; Blu: Blubber; Bl: Blood; Sk: Skin; Bo: Bone; Br: Brain; Sp: Spleen; He: Heart; Sto: Stomach

GEOGRAPHICAL AREAS

Ant: Antarctic; AS: Alaska; Aust: Australia; CA: Canada; EA: East Atlantic Ocean; ETP: Eastern Tropical Pacific Ocean; GD: Greenland; ID: India; Med: Mediterranean Sea; NEA: North East Atlantic Ocean; NS: North and Baltic Seas; NWP: North West Pacific Ocean; NY: Norwegian coast; SLA: St Lawrence Seaway, Canada; SP: South Pacific Ocean; SWA: South West Atlantic Ocean; UK: UK coastline; WA: West Atlantic Ocean; WI: West Indies

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