Magnetic Resonance Images of the Brain of a Dwarf Sperm Whale (Kogia simus)

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ABSTRACT

Cetacean (dolphin, whale and porpoise) brains are among the least studied mammalian brains because of the difficulty of collecting and histologically preparing such relatively rare and large specimens. Among cetaceans, there exist relatively few studies of the brain of the dwarf sperm whale (Kogia simus). Magnetic resonance imaging (MRI) offers a means of observing the internal structure of the brain when traditional histological procedures are not practical. Therefore, MRI has become a critical tool in the study of the brain of cetaceans and other large species. This paper represents the first MRI-based anatomically labelled three-dimensional description of the dwarf sperm whale brain. Coronal plane sections of the brain of a sub-adult dwarf sperm whale were originally acquired and used to produce virtual digital scans in the other two orthogonal spatial planes. A sequential set of images in all three planes has been anatomically labelled and displays the proportions and positions of major neuroanatomical features.

Introduction

Cetaceans (dolphins, whales and porpoises) are a highly modified group of mammals that are closely tied to artiodactyla, the ‘even-toed’ ungulates. Recent morphological evidence supports the view that early whales diverged from an artiodactyl terrestrial ancestor approximately 55–60 million years ago (Gingerich et al. 2001; Thewissen et al. 2001). Some of the most significant evolutionary changes that occurred among cetaceans were in brain morphology and relative size. Modern cetacean brains represent an unusual blend of early mammalian characteristics and uniquely derived features (Ridgway, 1986; Glezer et al. 1988; Manger et al. 1998). This constellation of neuroanatomical features displayed by cetaceans has been the focus of considerable interest within the field of comparative mammalian brain evolution.

The brains of a select few cetacean (and mostly Odontocete) species have been studied. In particular, the bottlenose dolphin (Tursiops truncatus), a member of the family Delphinidae, has received the most scientific attention. But there exist relatively few studies of the brains of species outside Delphinidae. One such species is the dwarf sperm whale (Kogia simus), a member of the family Physeteridae that also includes the pygmy sperm whale (Kogia breviceps) and the much larger sperm whale (Physeter macrocephalus). Both Kogia species resemble Physeter, including the possession of a large spermaceti organ in the forehead, an underslung lower jaw and an asymmetrical blowhole. Kogia, like Physeter, are found almost exclusively in deep-water environments. Kogia are not as numerous as Physeter and have
not been hunted, so data that would normally derive from capture do not exist as they do for their larger counterpart. Our knowledge of *Kogia* comes primarily from examination of stranded specimens. Therefore, there is a need for data on essentially every aspect of *Kogia* physiology and behaviour, with brain anatomy being no exception.

There are a handful of existing studies of the brain of *P. microcephalus*. These studies are mainly of brain size (Kojima, 1951; Pilleri & Gihr, 1970; Ridgway & Brownson, 1984) or of brain morphogenesis during fetal development (Oelschlager & Kemp, 1998). There are only two existing studies of the brain of *Kogia*. Both of these focus on brain size in *K. breviceps* (Ridgway & Brownson, 1984; Marino, 1998) and in *K. simus* (Marino, 1998). There have been no studies of neuroanatomical structure in either *Kogia* species. The present study is the first description of brain anatomy in the dwarf sperm whale (*K. simus*). Furthermore, this study represents the first magnetic resonance imaging (MRI)-based anatomically labelled three-dimensional description of the brain of any of the Physeterids. MRI offers a means of observing the internal structure of these large brains where traditional methods of embedding, sectioning, staining, mounting and microscopic examination are not practical. Furthermore, MRI offers the opportunity to observe internal structures in their precise anatomical positions because the fixed whole brain is kept intact during the scanning, therefore minimizing the spatial distortions associated with many histological processing methods. MRI therefore has become a valuable method for examining cetacean brains (Marino et al. 2001a,b,c, 2002, 2003).

**Materials and methods**

**Specimen**

The specimen is the post-mortem brain of a 166-cm, 107-kg female dwarf sperm whale (*K. simus*) that stranded alive on 27 March 2001 in Cape Fear, North Carolina, USA (WAM 566). The animal was considered subadult as the reproductive tract was determined to be immature. Few data exist on length/weight growth curves for this species. The animal was transported from the beach and an initial health assessment determined that euthanasia was required. The animal was euthanized and a necropsy and tissue collection were conducted, during which the brain was removed from the skull and placed immediately in 10% buffered formalin. The necropsy was performed at the University of North Carolina at Wilmington. The brain was immersion fixed in formalin for 30 days prior to scanning.

The anterior–posterior length of the brain was 120 mm. The bitemporal width was 131 mm. The maximum height of the brain was 75 mm. Fresh brain weight was 544 g.

**MRI protocol**

Magnetic resonance images of the entire brain were acquired in the coronal plane with a 1.5-T Philips NT scanner (Philips Medical System, the Netherlands) at Emory University School of Medicine. Imaging protocol parameters were: slice thickness = 2 mm, slice interval = 0 mm, Time to repetition = 3000 ms, Time to echo = 13 ms, field of view = 150 mm, matrix = 256 × 256 pixels. The specimen was scanned with the ventral side down in the human head coil.

**Three-dimensional (3D) reconstruction and reformatting**

A computer-generated 3D model was created from 60 2-mm-thick originally acquired coronal scans using the software program *VOXELVIEW* (Vital Images, Inc.) at the Laser Scanning Microscopy Laboratory at Michigan State University. The 3D rendered model was then digitally resectioned in orthogonal planes to produce corresponding virtual section series in the horizontal (75 0.52-mm-thick virtual sections) and sagittal (254 0.52-mm-thick virtual sections) planes.
**Volume measurements**

Whole brain volume was measured with the image analysis software program SCION IMAGE for Windows (PC version of NIH IMAGE) using manually defined areas from successive slices, which were integrated to arrive at a volume estimate. Volumetric estimates were converted to weight units by multiplying the volume of the structure by the specific gravity of brain tissue or 1.036 g cm\(^{-3}\) (Stephan et al. 1981).

**Anatomical labelling and nomenclature**

All identifiable brain structures of the specimen were labelled in the originally acquired coronal plane images as well as in the images from the virtual sectioned brain in the sagittal and horizontal planes. The magnetic resonance images of the whale brain were compared with the published photographs and illustrations of the bottlenose dolphin brain from Morgane et al. (1980), published neuroanatomical atlases based on MRI scans of an adult bottlenose dolphin brain and an adult common dolphin brain (Marino et al. 2001c, 2002), and published neuroanatomical studies of the sperm whale (*P. macrocephalus*) brain (Kojima, 1951; Oelschlager & Kemp, 1998). Nomenclature follows Marino et al. (2001c) and subsequent anatomical papers by Marino and colleagues. Additionally, scans were also compared with a complete alternate series of sections of the bottlenose dolphin brain stained, respectively, for cell bodies (Nissl method), and for myelinated fibres in the same three orthogonal planes (coronal or transverse, sagittal and horizontal). These stained section series are from the Yakovlev-Haleem collection at the National Museum of Health and Medicine and the Welker collection at the University of Wisconsin-Madison.

**Results**

**Volumetric measurements**

The measured whole brain volume of the specimen from MRI scans was 467.63 mL. When converted to weight by multiplication with the value of the specific gravity of water, the estimate of whole brain weight from the MR images was 484.46 g. The MRI-based estimate was not appreciably different from fresh brain weight. A previously published value for average whole brain volume in the adult dwarf sperm whale was 622 mL (Marino, 1998). Therefore, the fresh and MRI-based estimated brain weights for the present specimen are consistent with that of a subadult individual.

**General morphology**

Figure 1(a–h) displays a posterior-to-anterior sequence of originally acquired 2.0-mm-thick coronal magnetic resonance brain sections at 10-mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section was taken in three orthogonal planes and a computer-generated 3D reconstruction of the whole brain showing the brain digitally ‘cut’ at the level of the section. Figure 2(a–h) displays a ventral-to-dorsal sequence of reconstructed ‘virtual’ 0.52-mm-thick horizontal sections at 5.2-mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section was taken in three orthogonal planes and a computer-generated 3D reconstruction of the whole brain showing the brain digitally ‘cut’ at the level of the section. Figure 3(a–h) displays a midline-to-lateral sequence of reconstructed virtual 0.52-mm-thick sagittal sections through the left hemisphere at 5.2-mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section was taken in three orthogonal planes and a computer-generated 3D reconstruction of the whole brain showing the brain digitally ‘cut’ at the level of the section. The figures reveal the excellent level of preservation of the spatial relationships among the brain’s structures in the originally acquired magnetic resonance images and also in the digitally reconstructed images.
As is the case for cetaceans in general, the largest gross morphological difference between cetacean brains and non-cetacean brains lies in the overall shape and cortical sulcal configuration. These images show that the *K. simus* brain generally possesses the same configuration of gross morphological features noted in the brains of other odontocete species (Morgane et al. 1980; bottlenose dolphin, Marino et al. 2001c; beluga whale, Marino et al. 2001a; common dolphin, Morgane et al. 1980; Marino et al. 2002; harbor porpoise, Marino et al. 2003). *K. simus* skulls are highly asymmetrical but there is no gross morphological evidence that skull asymmetry is replicated in the brain.

As is typical of odontocete brains, the *Kogia* brain is wider than it is long. However, the coronal images in Fig. 1(c–h) suggest that the separation, or diastasis, between the dorsal aspect of the orbital lobes is wider in the *K. simus* brain than in many other odontocete brains examined, i.e. bottlenose dolphin, common dolphin, beluga whale and even sperm whale (*P. microcephalus*). Many authors have noted the unusually short rostrum and concave shape of the *Kogia* cranium (see Caldwell & Caldwell, 1989, for a review). Therefore, it may be that in *Kogia* the extreme width of the brain is due both to neural elaboration in the lateral axis and to compression in the anterior–posterior axis.

The overall double-flexed shape of the brain, particularly in the mesencephalic and cervical regions, is detectable in the *K. simus* brain in Fig. 3(a–c). This flexion is characteristic of adult cetacean brains and is found in non-cetacean mammals only in fetal stages.

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**Fig. 1** (a–j) Posterior-to-anterior sequence of originally acquired 2.0-mm-thick coronal magnetic resonance brain sections at 10-mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section was taken in three orthogonal planes and a computer-generated three-dimensional reconstruction of the whole brain showing the brain digitally ‘cut’ at the level of the section.
Fig. 2 (a–j) Ventral-to-dorsal sequence of reconstructed ‘virtual’ 0.52-mm-thick horizontal sections at 5.2-mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section was taken in three orthogonal planes and a computer-generated three-dimensional reconstruction of the whole brain showing the brain digitally ‘cut’ at the level of the section.
Fig. 3 (a–j) Midline-to-lateral sequence of reconstructed virtual 0.52-mm-thick sagittal sections through the left hemisphere at 5.2-
mm intervals, a labelled schematic illustration of each section, computer-generated images showing the level at which the section
was taken in three orthogonal planes and a computer-generated three-dimensional reconstruction of the whole brain showing the
brain digitally ‘cut’ at the level of the section.
Forebrain anatomy

The great degree of cortical convolution in the hemispheres is most evident in Figs 1(c–j) and 2(g–j), and in all of the sagittal images. The *K. simus* brain also exhibits the uniquely cetacean three-tiered arrangement of limbic, paralimbic and supralimbic arcuate cortical lobules divided by the deep limbic and paralimbic clefts. This arrangement can best be seen in Figs 1(c–f) and 3(b–e). The extreme depth and density of cortical sulci are particularly evident in Figs 1(d–f), 2(g,h) and 3(e–g).

As is typical of adult odontocete brains, olfactory structures are absent. Also consistent with findings in other odontocete species (Morgane et al. 1980; Marino et al. 2001a,c, 2002, 2003) basal ganglia structures, such as the caudate, putamen, pallidum and internal capsule, are easily visualized in Figs 1(g,h), 2(f–h) and 3(b–e). As is the case in the forebrain of other odontocete species (Morgane et al. 1980; Marino et al. 2001a,c, 2002, 2003) limbic structures, particularly the hippocampus, are either highly reduced or did not undergo enlargement in *K. simus*. By contrast, the amygdala (see Figs 1f and 3f) in *K. simus* is not as diminutive as one would expect given the small paleocortex. This condition also exists in other odontocetes (Morgane et al. 1980; Marino et al. 2001a,c, 2002, 2003).

The diencephalon of other odontocetes is substantial (Marino et al. 2001a,c, 2002, 2003) and *K. simus* is no exception. The thalamus, and specifically the pulvinar, is massive (see Figs 1f, 2g and 3c,d) and the hypothalamus is clearly visible (see Fig. 1g).

As is the case in other odontocetes (Marino et al. 2001a,c, 2002, 2003; Oelschlager & Oelschlager, 2002), the corpus callosum in *K. simus* appears relatively thin compared with the mass of the hemispheres. This feature is observable in Figs 1(e–h), 2(g,h) and 3(a,b). Despite the reduced corpus
callosum the adjacent cortical field, i.e. the limbic lobe, does not appear to be reduced in *K. simus* (Fig. 1e–g).

**Midbrain anatomy**

Most of the profound differences between cetacean and non-cetacean brains exist at the cortical level. However, in the midbrain there are differences in size proportions and in spatial arrangement of several systems and structures between cetaceans and noncetaceans. For instance, whereas the cerebral peduncle lies on the ventral surface of the midbrain in most mammals, the cerebral peduncle is located high on the lateral surface of the ventral midbrain in odontocete brains. This configuration is observable in *K. simus* in Fig. 1(f) and is also found in other odontocetes (Marino et al. 2002, 2003).

**Hindbrain anatomy**

As is characteristic of cetacean brains, the *K. simus* cerebellum is large relative to the hemispheres. This is most evident in Figs 1(b,c), 2(c) and 3(a–d). Typical of cetacean brains is the massive inferior colliculus (see Figs 1d, 2d and 3b), which is over four times more massive than the superior colliculus. Also visible caudal to the thalamus is the large pons (see Fig. 3a,b).

**Discussion**

This paper presents the first series of MRI-based anatomically labelled sectioned images of the brain of the dwarf sperm whale, *K. simus*. The present study displays the usefulness of imaging-based analyses of post-mortem brain tissue in cetaceans. Such analyses are critical for building a normative database of neuroanatomical images for cetaceans and for crucial comparative studies among cetaceans and across cetaceans and non-cetaceans. In the present study these images allowed us to visualize the distinctive features of the dwarf sperm whale brain from various orientations by preserving the gross morphological and internal structure of the specimen.

The results show that the *K. simus* brain shares many of the distinctive features of cetacean brains with other odontocetes. However, there is some suggestion that there are differences in the morphology of the hemispheres.

These images can also serve as the basis for specific morphological and volumetric comparisons that should reveal further differences across species and families of cetaceans.

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**References**


