

Anatomical Description of an Infant Bottlenose Dolphin (*Tursiops truncatus*) Brain from Magnetic Resonance Images

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Abstract

Cetacean brains are among the least studied mammalian brains because of the formidable histological preparations of such relatively rare and large specimens. Although the bottlenose dolphin, *Tursiops truncatus*, has been the most extensively studied cetacean species, there have been relatively few studies of the brain of the infant bottlenose dolphin. In this study, we present the first magnetic resonance imaging (MRI)-based study of the brain of an infant bottlenose dolphin. Magnetic resonance images in the coronal plane were originally acquired and used to digitally generate a set of resectioned virtual images in orthogonal planes. A sequential set of images in all three planes was anatomically labeled and reveals major neuroanatomical features. Some of the distinctive features of cetacean brains are already evident in the infant bottlenose dolphin brain, while other features may represent differences that deserve further study.

Key Words: bottlenose dolphin, *Tursiops truncatus*, brain, neuroanatomy, magnetic resonance imaging

Introduction

Cetacean brains have been of interest to mammalogists and comparative neuroanatomists for decades because cetaceans are highly divergent from other mammals, and their unusual brains represent a striking blend of conservative and highly derived characteristics (Glezer et al., 1988; Manger et al., 1998; Ridgway, 1986, 1990). For this reason, the study of cetacean brains, particularly in comparison with the brains of primates and other large-brained mammals, is important for a complete understanding of the range of forms mammalian brain evolution can take. Non-adult brains offer

insight into the developmental patterns that may be recruited for evolutionary change.

There are several published studies on adult brains from the cetacean suborder Odontoceti (toothed whales, dolphins, and porpoises). These include Kojima's (1951) description of the sperm whale (*Physeter macrocephalus*) brain and MRI-based descriptions of the adult bottlenose dolphin (*Tursiops truncatus*) brain (Marino et al., 2001c), the adult beluga whale (*Delphinapterus leucas*) brain (Marino et al., 2001b), and the adult common dolphin (*Delphinus delphis*) brain (Marino et al., 2002). Several studies document the differences between odontocete and other mammalian brains at the level of cortical cytoarchitecture and immunohistochemistry (Garey & Leuba, 1986; Garey et al., 1985; Glezer & Morgane, 1990; Glezer et al., 1990, 1992a, 1992b, 1998; Hof et al., 1992, 1995), cortical surface morphology (Haug, 1987; Jacobs et al., 1979; Morgane et al., 1980), and noncortical structures and features (Glezer et al., 1995; Tarpley & Ridgway, 1994). There also have been quantitative descriptions of the brains of the Ganges River dolphin (*Platanista gangetica*) (Kamiya & Pirlot, 1980) and the franciscana dolphin (*Pontoporia blainvillei*) (Schwerdtfeger et al., 1984). The most comprehensive description of the adult cetacean brain in comparison to the brains of other marine mammal species is the recent review by Oelschlager & Oelschlager (2002).

Relatively few papers have focused on the developmental features of cetacean brains. Many of these involve descriptions of postnatal growth patterns for the whole brain, rather than for more specific morphological features (Marino, 1995—bottlenose dolphin; Marino, 1998—Franciscana dolphin; Marino, 1999—harbor porpoise [*Phocoena phocoena*] and Pacific white-sided dolphin [*Lagenorhynchus obliquidens*]; Pirlot & Kamiya, 1975—franciscana dolphin and

striped dolphin [*Stenella coeruleoalba*]; Ridgway & Brownson, 1984—bottlenose dolphin, killer whale [*Orcinus orca*], and common dolphin). Other studies have primarily focused on prenatal brain development (Holzmann, 1991—Narwhal [*Monodon monoceros*]; Kamiya & Pirlot, 1974—striped dolphin; Marino et al., 2001a—common dolphin; Oelschläger & Kemp, 1998—sperm whale; Buhl & Oelschläger, 1988—harbor porpoise [*Phocoena phocoena*]; Wanke, 1990—spotted dolphin [*Stenella attenuata*]).

Until the present study there have been no detailed descriptions of the overall morphology of the bottlenose dolphin brain during early infancy. In this study, we present the first morphological description of an infant bottlenose dolphin brain based upon magnetic resonance imaging (MRI) in all three spatial planes. In addition, these images are compared with MRI scans of the brain of an adult bottlenose dolphin from a previously published study. The 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 histology methods.

Materials and Methods

Specimen

The specimen was the postmortem brain of an infant male bottlenose dolphin (*Tursiops truncatus*) that stranded deceased on 20 July 2000 on Virginia Beach (Field#VMSM20001031). The carcass was in fresh condition (Smithsonian Institution Condition Code 2; Geraci & Loundsbury, 1993) and was frozen immediately for later necropsy. The dolphin was thawed in 25° C water on 20 January 2001, and during necropsy, the brain was extracted from the skull, weighed, and placed in 10% neutral buffered formalin. The brain mass at necropsy was 766 g. The anterior-posterior length of the brain was 132 mm. The bitemporal width was 155 mm. The height of the brain was 96 mm.

Total body length of the dolphin was 127 cm, and total body weight was 29.2 kg. Body length is consistent with an estimated postnatal age of less than six months, but not a newborn (Harrison, 1969; Harrison et al., 1972; Mead & Potter, 1990; Perrin & Reilly, 1984; Read et al., 1993; Sergeant et al., 1973). The specimen did not have fetal folds, but possessed a healed umbilicus, relatively flexible flukes, and five to six erupted upper teeth on both tooth rows of the rostrum. Information

on patterns of abundance and distribution for neonates in the same nearshore waters as the present specimen was obtained from Barco et al. (1999). Taken together, the body weight and length and other physical features lead us to estimate that the postnatal age of the present specimen was two to three months.

MRI Protocol

Magnetic resonance (MR) 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, TR = 3,000 msec, TE = 13 msec, field of view = 160 mm, and matrix = 256 X 256 pixels. The specimen was scanned with the ventral side down in the human head coil. Approximate scan time for the coronal series was 20 min. The period of time between brain extraction and scanning was 77 days. Whereas the clarity of MRI scans and the integrity of brain tissue can potentially be disrupted by freezing and thawing, we saw no evidence of any detrimental effects on the tissue or scans in the present specimen.

Three-Dimensional Reconstruction and Reformatting

A computer-generated 3D model was created 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 (145 0.6-mm thick virtual sections) and sagittal (255 0.5-mm thick virtual sections) planes.

Volume Measurements

Whole brain volume was measured manually with the image analysis software program *Scion IMAGE for Windows* (PC version of *NIH IMAGE*), using manually defined areas from successive slices that were integrated to arrive at a volume estimate. The entire volumetric estimate was converted to weight units by multiplying the volume by the specific gravity of brain tissue or 1.036 g/cm³ (Stephan et al., 1981).

Anatomical Labeling and Nomenclature

All identifiable brain structures of the specimen were labeled 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 MR images of the dolphin brain were compared with the published photographs and illustrations of the adult bottlenose dolphin

brain from Morgane et al. (1980), as well as published neuroanatomical atlases based on MR scans of an adult bottlenose dolphin brain (Marino et al., 2001c). Nomenclature is based upon Marino et al. (2001c) and Morgane et al. (1980). Additionally, scans also were compared with several complete alternate series of sections of the adult bottlenose dolphin brain, which were stained, respectively, for cell bodies (Nissl method) and for myelinated fibers 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 at Madison.

Results

Volumetric Measurements

The measured whole brain volume of the specimen from MR scans was 705.3 cc. 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 730.69 g. The MRI-based value is similar to the measured brain weight of 766 g at the time of necropsy. A previously published value for average whole brain volume in newborn bottlenose dolphins was 713.0 cc (Marino, 1995). Average adult brain weight for bottlenose dolphins is 1,824 g (Marino, 1998). The estimated brain weight for the present specimen is 40.1% of the published average adult brain weight. This is consistent with Ridgway & Brownson (1984) who found that neonatal brain weight averaged 42.5% of the average adult brain weight in bottlenose dolphins. The present estimated brain weight is also consistent with the estimated age

of the specimen and within the published range of brain weights 676-750 g for infant bottlenose dolphins of similar age (Marino, 1995).

Anatomical Description

Figures 1a and b shows a photograph of the specimen and an image of a reconstructed adult bottlenose dolphin brain from MR scans from Marino et al. (2001c). Figure 1, in general, shows that the infant bottlenose dolphin brain resembles the adult in overall shape and structure.

Figure 2 (a-h) displays a posterior-to-anterior sequence of originally acquired 2.0 mm-thick coronal MR brain sections at 10-mm intervals and a labeled schematic illustration of each section. Figure 3 (a-h) displays a dorsal-to-ventral sequence of reconstructed "virtual" 0.6-mm thick horizontal sections at 6-mm intervals and a labeled schematic illustration of each section. Figure 4 (a-h) displays a midline-to-lateral sequence of reconstructed 0.5-mm thick "virtual" sagittal sections through the left hemisphere at 3-mm intervals and a labeled schematic illustration of each section.

The MR scans reveal, not unexpectedly, that the internal structure of the infant bottlenose dolphin brain resembles that of the adult bottlenose dolphin brain. Some of the specific features unique to cetaceans are observable in the infant brain. Many of these features involve the relative size of various structures and regions. The proportionately large size of the inferior colliculus in Figures 2d, 3e and f, and 4c and d; the thalamus in Figures 2f, 3c, and 4d-f; the cerebellum in Figures 2b and c, 3f and g, and 4c-e; and the pons in Figures 2e, 3h, and 4b is evident. Likewise, the relatively diminutive size of the corpus callosum in Figures 2h and 4a-c and the hippocampal region

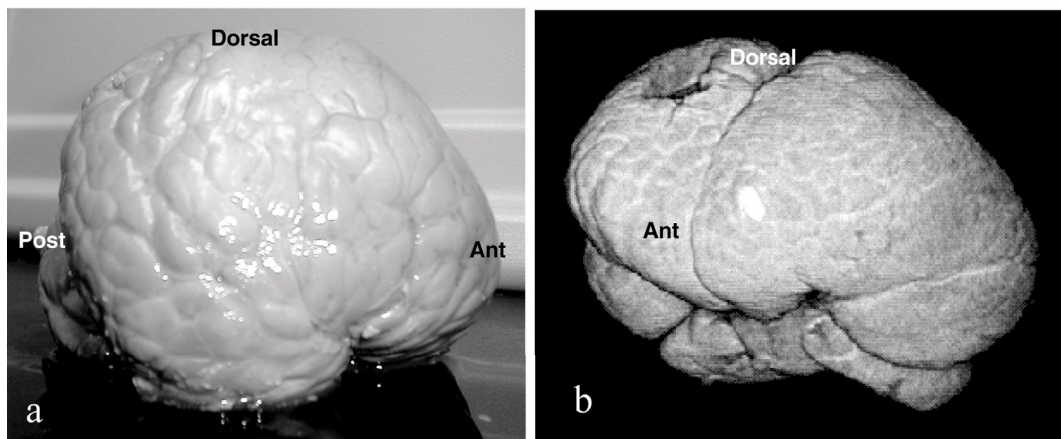


Figure 1. (a) Photograph of the infant bottlenose dolphin brain, and (b) adult bottlenose dolphin brain reconstructed from MRI scans

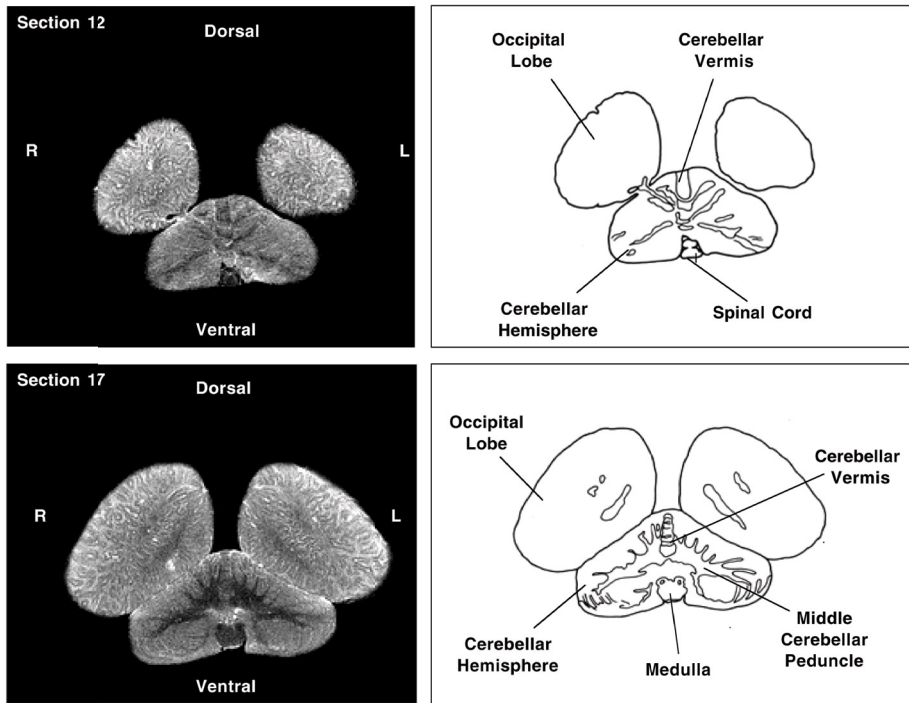


Figure 2 a-b

Figure 2 (a-h). Posterior-to-anterior sequence of originally acquired 2.0-mm thick coronal MR brain sections at 10-mm intervals and a labeled schematic illustration of each section

in Figure 2f is apparent. Furthermore, the present specimen possesses distinctive cetacean features regarding the spatial arrangement of subcortical structures. For instance, in most other mammals the cerebral peduncle lies on the ventral surface of the midbrain. In the present specimen (see Figure 2f) and other cetacean species (Marino et al., 2002; pers. obs.), the cerebral peduncle is located high on the lateral surface of the ventral midbrain.

One of the ways in which the present specimen appears different from the adult bottlenose dolphin brain is in the degree of myelination of the thalamo-cortical radiations. As evident in Figures 2 c-h and 3 b-e, the degree of branching of myelinated

fibers (which appear dark grey) does not seem to be as extensive as in the adult bottlenose dolphin brain (Marino et al., 2001c). Furthermore, those radiations that are most visible (of the darkest shade of grey) appear to be concentrated in the dorsal medial gyri of the parietal lobes. This observation must be interpreted with caution, however, because it is not clear whether this pattern is due to limits in contrast and spatial resolution of the MR scans or whether it represents a real difference in myelination patterns between the infant and adult bottlenose dolphin. Further analyses of both MR scanned and histologically prepared infant bottlenose dolphin brains are required to differentiate between these two possibilities.

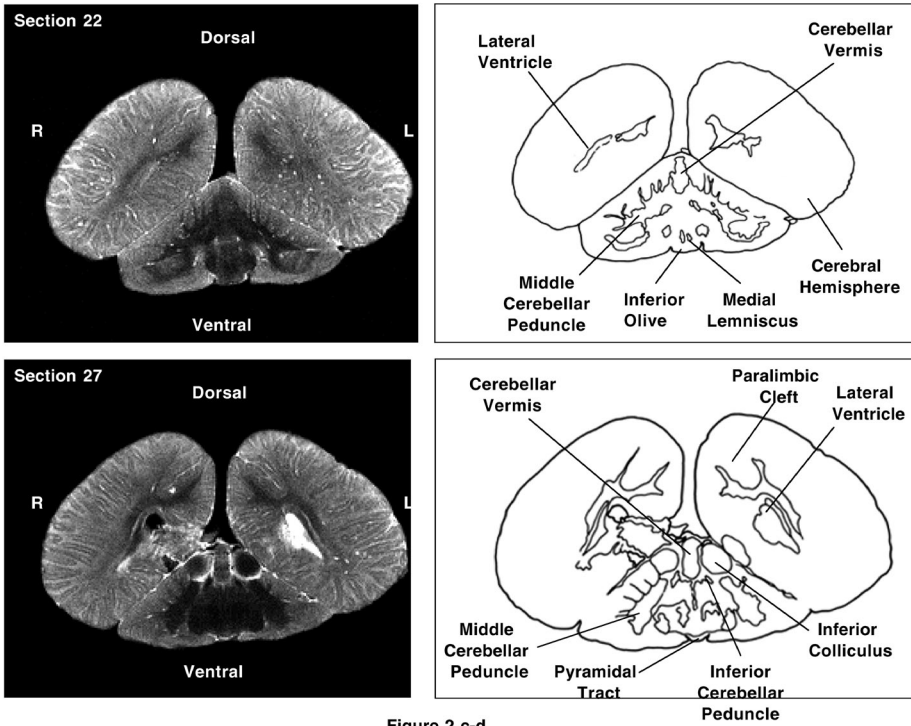


Figure 2 c-d

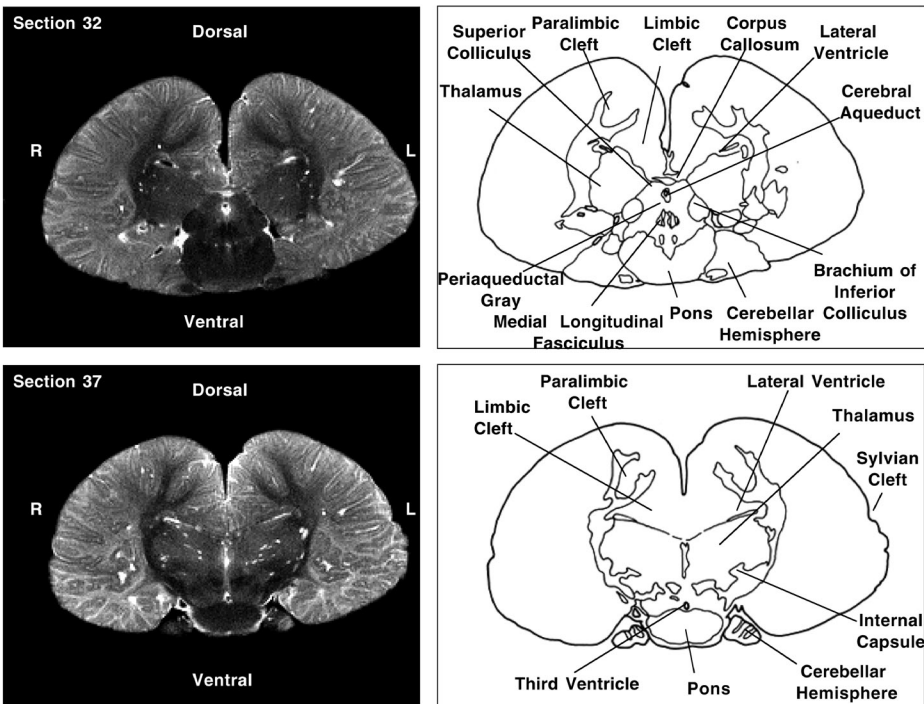


Figure 2 e-f

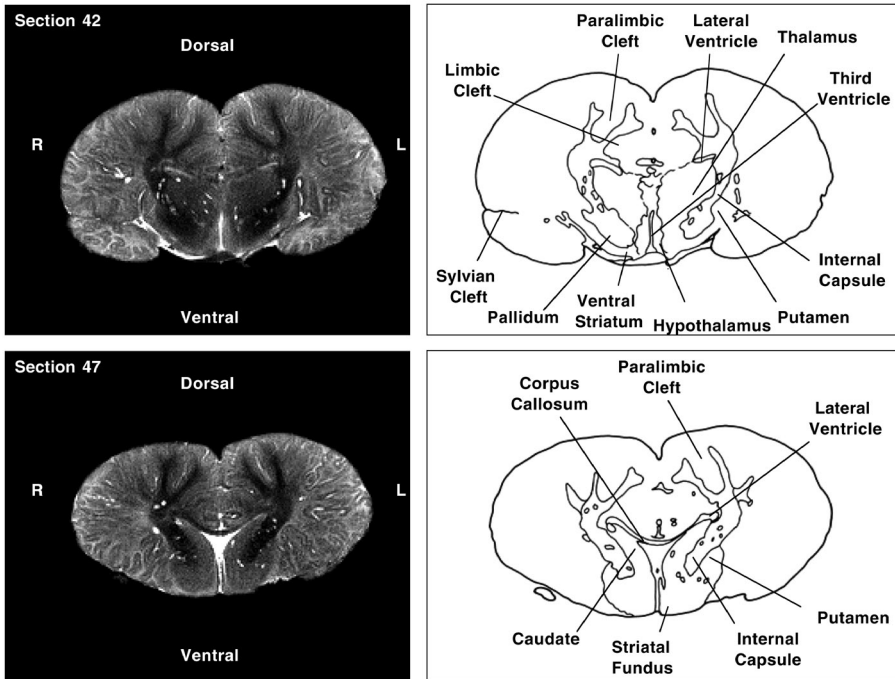


Figure 2 g-h

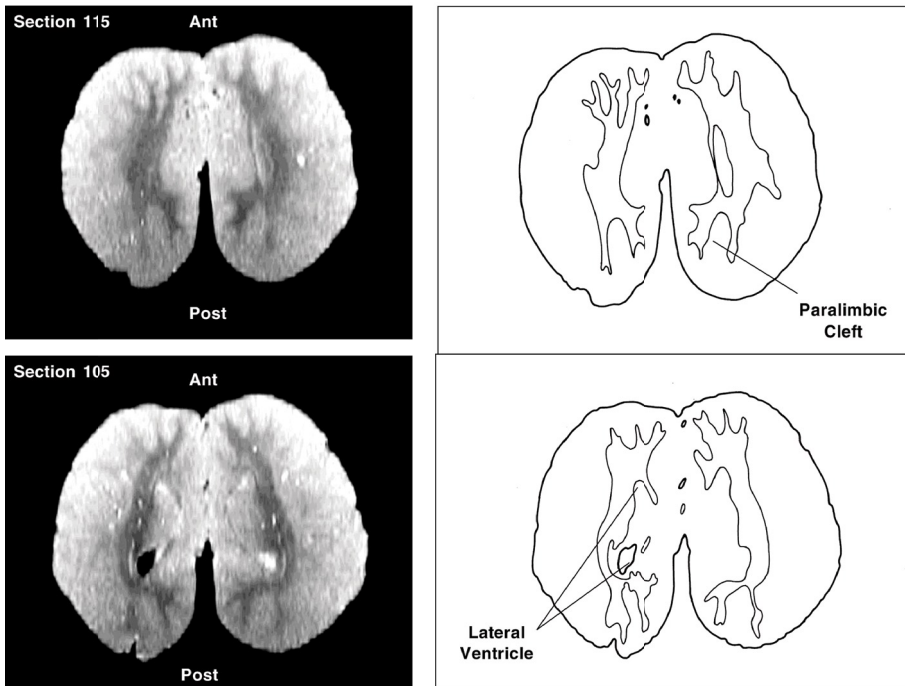


Figure 3 a-b

Figure 3 (a-h). Dorsal-to-ventral sequence of reconstructed “virtual” 0.6-mm thick horizontal sections at 6-mm intervals and a labeled schematic illustration of each section

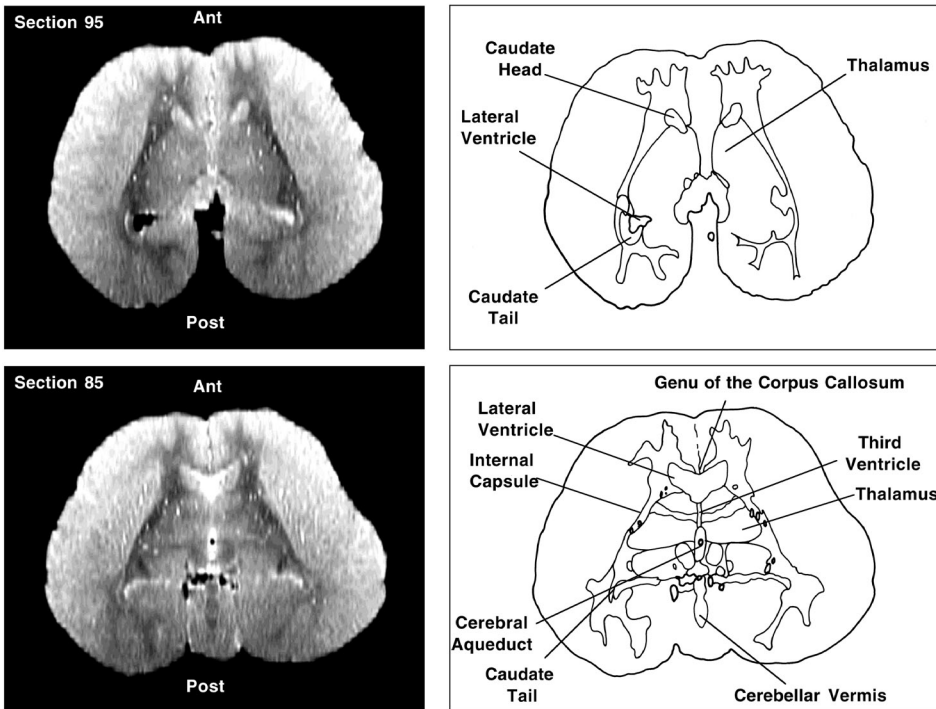


Figure 3 c-d

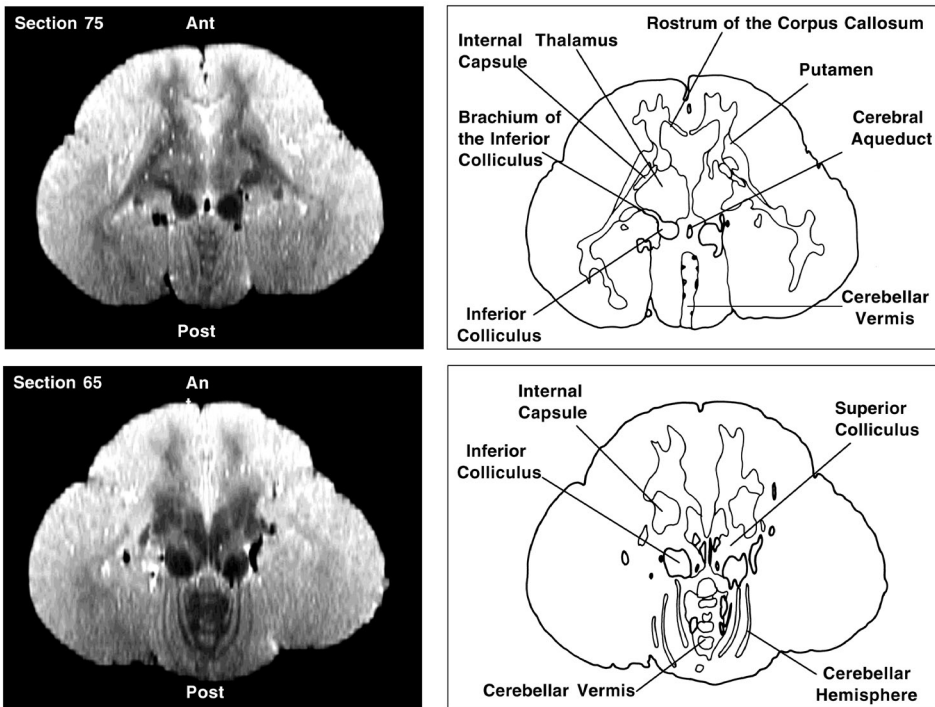


Figure 3 e-f

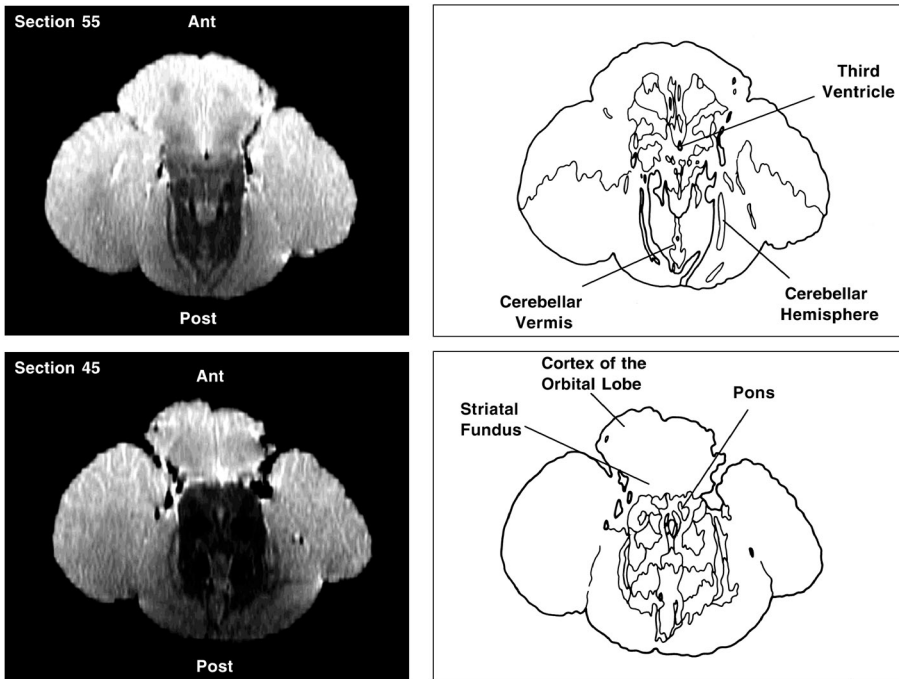


Figure 3 g-h

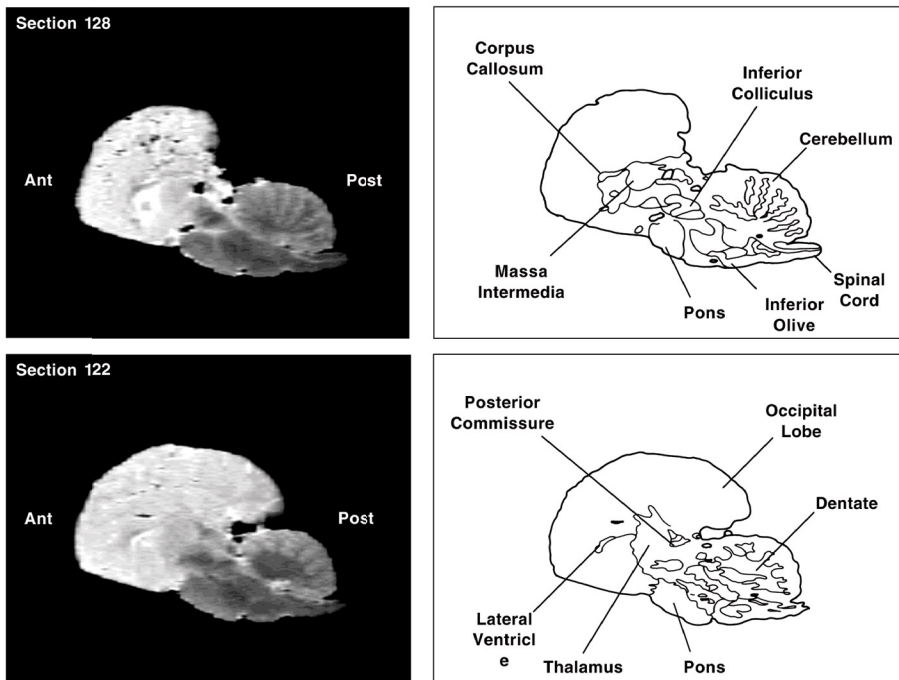


Figure 4 a-b

Figure 4 (a-h). Midline-to-lateral sequence of reconstructed 0.5-mm thick “virtual” sagittal sections through the left hemisphere at 3-mm intervals and a labeled schematic illustration of each section

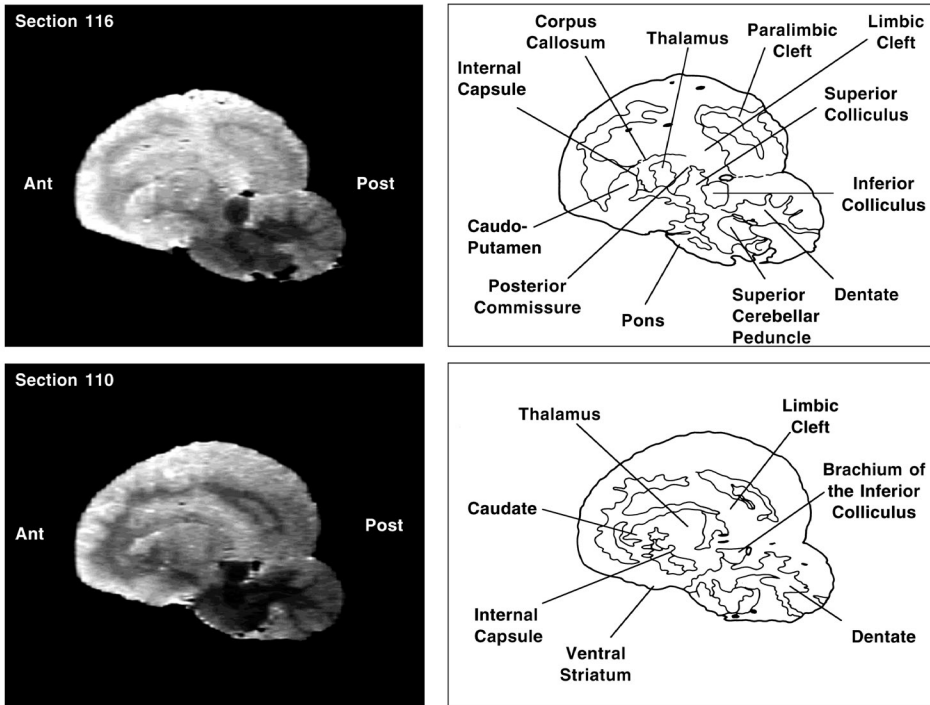


Figure 4 c-d

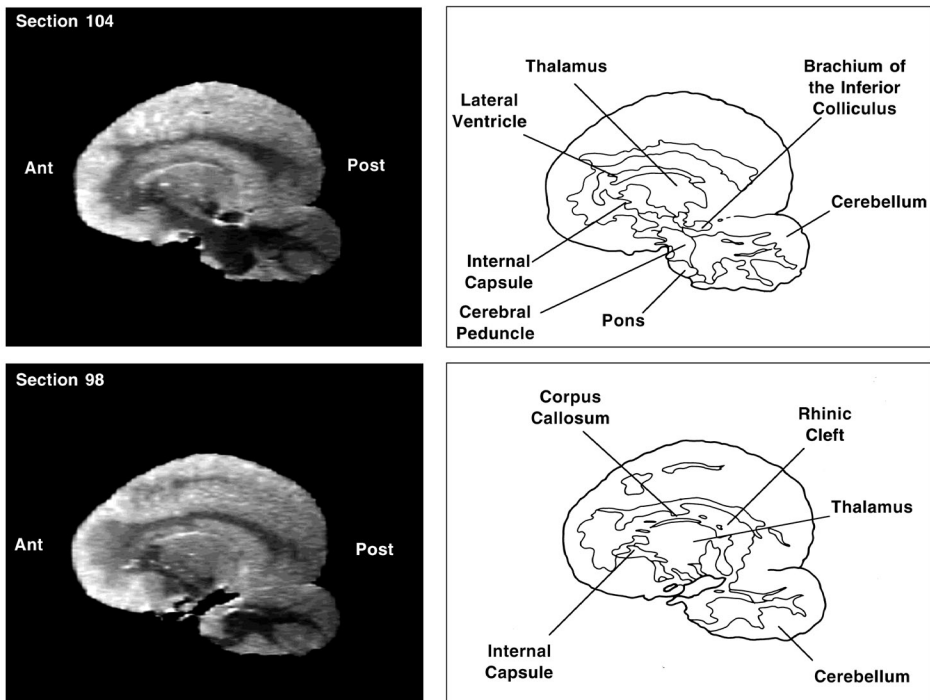


Figure 4 e-f

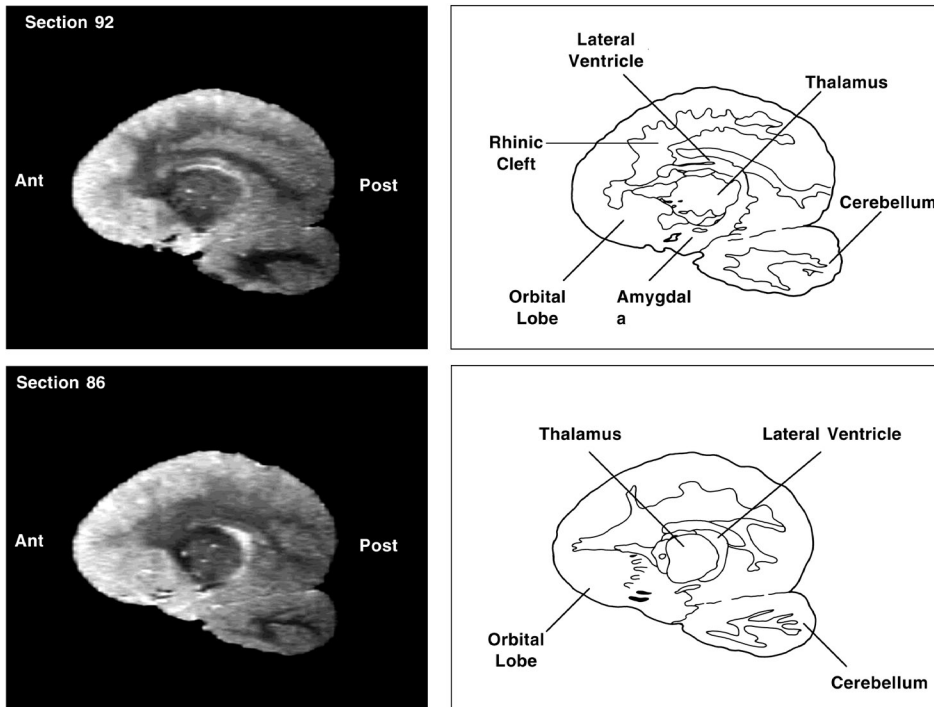


Figure 4 g-h

Discussion

The present study displays anatomically labeled MR images of a postmortem infant bottlenose dolphin brain. The findings reveal that the infant brain is very similar in many morphological respects to that of the adult bottlenose dolphin brain and displays a number of features unique to cetacean brains. These include the gross morphological characteristics, the relative size proportions of various structures, and the peculiar spatial arrangement of some of the structures. There is an intriguing suggestion that myelination patterns in the infant brain may be different from those in the adult brain. Further quantitative analyses will determine whether this observation is accurate and will allow for these patterns to be described in more detail.

This study represents one of a handful of studies of early brain development in the bottlenose dolphin. The study of early postnatal (and prenatal) cetacean brain development has been constrained by the lack of data. This situation can be resolved by using an MRI to analyze the numerous post-mortem specimens available in museums and similar facilities. The present study demonstrates that MR images of early postnatal dolphin brains can be obtained to formulate a database on the normative range of morphometric values for whole

brains and substructures in cetaceans. The MRI also allows for the preservation of spatial aspects of internal structures and their relationship to one another. This enables accurate three-dimensional reconstruction, which then offers the flexibility to view any part of the brain from any angle and in any plane of sectioning while maintaining the intactness of the specimen. This study is part of a larger effort towards the study of developmental morphometrics in cetaceans as a way to elucidate not only ontogeny but potential evolutionary patterns as well.

Comparative analyses of neuroanatomical developmental patterns in and among cetaceans and other mammals are critical for elucidating the history of phylogenetic divergence among cetacean species and between cetaceans and other mammals. Studies of cetacean brain development provide valuable data that will assist efforts to reconstruct the evolutionary history of cetaceans since their divergence from terrestrial ancestors.

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