Original Article

A morphological analysis of the cervical spine of the dolphin

ABSTRACT

Objective: Morphology of bones of cervical vertebrae of dolphin was studied. When compared to human vertebrae the structural modifications in terms of functional needs are evaluated.

Material: Morphological analysis of duly prepared bones of species *D. delphis* was carried out.

Result: The craniocervical junction and cervical spine of the dolphin (*Delphinus dolphis*) has unique adaptations to allow for dorsoventrally undulating swimming movements as well as leaping out of water. The key differences from the human cervical spine include the absence of an odontoid process limiting rotatory movements, disproportionately short and wide vertebral bodies and a unilaterally elongated transverse process of the axis. Moreover, the cervical spine of the dolphin is disproportionally short compared to humans. These modifications give strength and stability to the cervical spine allowing maximal agility for flexion-extension movements of the lumbocaudal spine, which are keys for propulsion. The unilaterally elongated transverse process likely allows for rotatory spinning, suggesting possible lateral dominance of rotatory spin in this species.

Conclusions: Despite the skeletal adaptations, the cervical spine is strongly resonant of a mammalian heritage with a remarkably similar form and structure to house neurovascular contents and to allow muscular attachments.

Keywords: Atlas, axis, craniovertebral junction, dolphin, vertical axis rotation

INTRODUCTION

Functional necessity dictates the structural evolution of the skeletal system. Recognizing the anatomical differences between the bones of various species provides an insight into adaptations that allow for functional activity. In this article, we analyze the morphology of the bones of cervical spine of the dolphin (*Delphinus delphis*) and hypothesize on the significance of structural modifications in terms of functional movements of the dolphin.

Whales, dolphins, and porpoises constitute the *Cetacea*, mammals that cannot survive out of water. Despite their variations in size, all *Cetacea* share similar structural characteristics – a horizontal tail fluke for propelling movement, forelimbs as flippers, a short neck, and a stream-lined body.[1] Although their land ancestors made a transition to aquatic life about 50 million years ago,[1] developing specialized skeletal adaptations to suit their new way of life, they retain signs of their mammalian heritage in their vertebral anatomy.[2]

MATERIALS AND METHODS

We analyzed the morphology of the cervical vertebral

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bones of the species *D. delphis*. The maceration of the vertebrae of the dolphin was done by placing in water for several days and then fleshing them manually. After cleaning, the bones were degreased in trichloroethylene and bleached in the diluted hydrogen peroxide for the morphological analysis.

RESULTS

The cervical anatomy of dolphins

Like humans, dolphins have seven cervical vertebrae. The number of bones in each successive part of the vertebral column becomes progressively more numerous compared to humans: 13 thoracic, 17 lumbar, and 28 caudal vertebrae. The higher number of lumbar and caudal vertebrae attests to the importance of the tail fluke in generating a majority of swimming movement in dolphins. The dolphin head and neck, on the other hand, requires much less flexibility. In contrast to the extensive head and neck movements possible in humans, the dolphin head is said to move through only 45° on the vertical axis and an even lesser extent in the horizontal axis.

Atlas vertebra

The atlas bone of the dolphin is significantly larger and thicker than its human counterpart [Figure 1]. Unlike the human atlas, it is not in the form of an arch or a ring, and there is a well-defined vertebral body, transverse process, and elongated spinous process. In humans, the odontoid is the embryological body of atlas; however, in the dolphin, the atlas has its own distinct body, similar to the remaining vertebrae. Unlike the human axis which has two pairs of similarly sized superior and inferior facets for articulation with the occipital condyles and the axis, respectively, the dolphin atlas has a pair of very large facets for occipital condylar articulation, and two significantly smaller inferior articular facets for articulation with C2. In addition, it has a large smooth inferior surface for articulation with an intervertebral disc. The single caudal articulation at the intervertebral disc and two rostral articulations at the occipital condyle give the dolphin atlas a "Y"-shaped configuration. The vertebral artery foramina are located in the anterior aspect of the laminae-pedicle junction unlike their location in humans within the transverse process. The relative elongation of the spinous and transverse processes allows the attachment of powerful dorsal (epaxial) and ventral (hypaxial) muscles.

Axis vertebra

The axis vertebra is a peculiar bone in the dolphins. The absence of the odontoid is stark [Figure 2]. The spinous process is much shorter than that in the atlas and both superior and inferior facets are small and almost inconspicuous. There is no vertebral artery foramen. The most unusual feature, however, is the presence of a disproportionately elongated transverse process on the right side. The transverse process on the left side is also long but is significantly shorter when compared to the right. Marking on the bone suggests the relationship of large muscles with both transverse processes, more significantly on the right side.

3rd cervical vertebra

As shown in Figure 3, the C3 vertebra of the dolphin is relatively thin, flat, and wide. Similar to the axis, the vertebra has thin laminae, small facets and a short spinous process. Unique to the C3 is the presence of two large discrete transverse processes [Figure 3]. The anterior transverse

Figure 1: Images of the atlas vertebra of the dolphin as viewed in the erect position. (a) Inferior view of the atlas. (b) Superior view of atlas. (c) Dorsal view of atlas

Figure 2: Images of the axis vertebra of the dolphin as viewed in the erect position. (a) Inferior view of axis-note the large transverse process. (b) Dorsal view of axis. (c) Superior view of axis

process is large, thick, and "horn-like." The posterior transverse process is an extension of the pedicle and small facets. The markings on the bones suggest attachment with large muscles over the anterior transverse process and anterior aspect of the vertebral body. There are no foramina for the vertebral arteries.

4th cervical vertebra

Like the C3, the vertebral body is small in height but large in the transverse direction. The anterior transverse process is relatively thin compared to C3 and curved posteriorly to form a partially enclosed vertebral artery foramen [Figure 4]. The delicate facets, laminae, and spinous process of these vertebrae and the lower cervical vertebrae are in stark contrast to the large, circular vertebral bodies.

5th cervical vertebra

While the overall structure of C5 is similar to C4, the anterior and posterior transverse processes are now seen to fuse, housing a vertebral artery foramen [Figure 5].

6th cervical vertebra

The overall structure of C6 is very similar to C4 with unfused anterior and posterior segments of the transverse process that provide a partially enclosed foramen for the vertebral artery [Figure 6].

7th cervical vertebra

The 7th cervical vertebra is morphologically distinct compared to the more rostral cervical vertebrae. It has a single, large transverse process, thick pedicles, and an elongated and thick spinous process [Figure 7].

DISCUSSION

The musculoskeletal design of the dolphin has been adapted to create propulsive force. In cetaceans, the vertebral column is the primary scaffold to which muscles that generate the swimming movement attach.[3] These dorsoventral undulations of their tail flukes are powered by the large epaxial and hypaxial muscles which primarily attach to the spinous processes of the vertebral column. Dolphins demonstrate a method of travel called "porpoising," long parabolic ballistic jumping alternating with periods of gliding during which no swimming occurs and an acceleration phase characterized by high thrust swimming.[4,5] The reduced drag due to motion in air is greater than the energy cost of leaping, making this an energy efficient technique. Apart from travel, this leaping behavior in dolphins is thought to allow orientation, social displays, nonverbal communication, parasite dislodgment, and entertainment. Dolphins propel themselves by vertical oscillation of their tail flukes, which

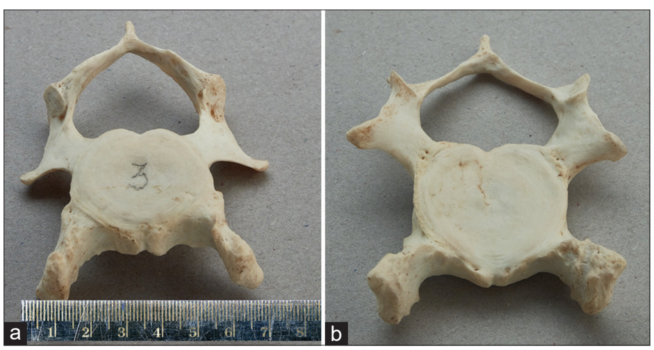

Figure 3: Images of the C3 vertebra of the dolphin as viewed in the erect position. (a) Inferior view of C3 vertebra. (b) Superior view of C3 vertebra

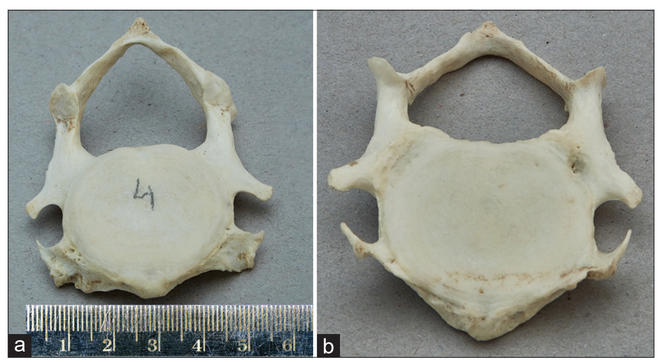

Figure 4: Images of the C4 vertebra of the dolphin as viewed in the erect position. (a) Inferior view of C4 vertebra. (b) Superior view of C4 vertebra

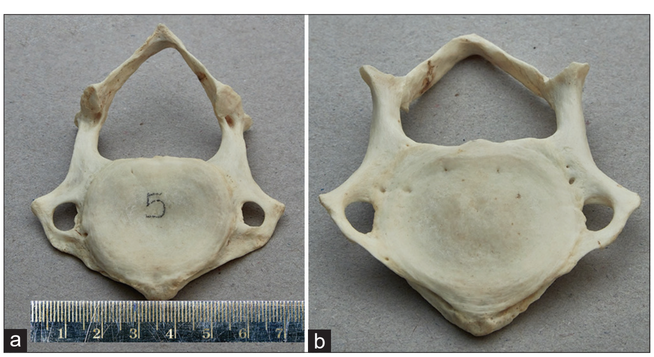

Figure 5: Images of the C5 vertebra of the dolphin as viewed in the erect position. (a) Inferior view of C5 vertebra. (b) Superior view of C5 vertebra

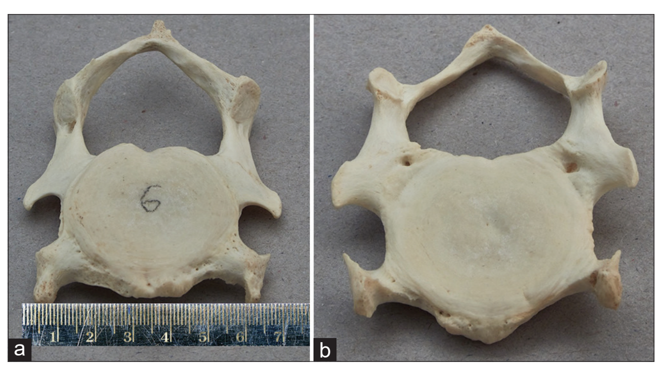

Figure 6: Images of the C6 vertebra of the dolphin as viewed in the erect position. (a) Inferior view of C6 vertebra. (b) Superior view of C6 vertebra

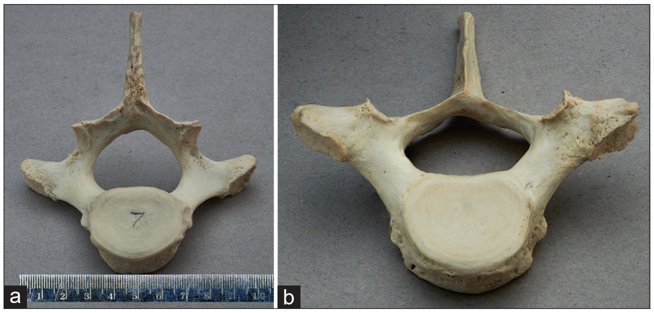

Figure 7: Images of the C7 vertebra of the dolphin as viewed in the erect position. (a) Inferior view of C7 vertebra. (b) Superior view of C7 vertebra

provides hydrodynamic thrust. The relatively elongated spinous and transverse processes compared to humans, especially in lower cervical vertebrae act as lever arms for muscle attachment. This allows for the amplification of forces compared to that which would be generated by muscle insertions closer to the vertebral bodies.[6]

The craniovertebral junction of the dolphin appears to be designed for strength of attachment rather than rotation. The absence of the odontoid process limits circumferential movements at the atlanto-axial joint which are arguably less important in a dolphin where strong dorsoventral movements are key to swimming. The large superior facets for articulation with the occipital condyles, the large surface area for articulation with the intervertebral disc and the small facet joints between the C1–C2 likely allow for strength and stability, rather than agility of neck movements in a species where caudal rather than cervical flexibility is key to its swimming movements. Moreover, we argue that the relative "flatness" of the cervical vertebrae and the large articular surface area of the vertebral bodies allows for stable attachment and more space for more numerous lumbo-caudal vertebrae that are key for dorsoventral undulations. The need for a stable and rigid neck is further highlighted in reports that describe cervical vertebral fusion in some dolphins, possibly as an adaptation to aid stability.[7,8] The large discs may serve a further adaptive role as the greater fluid content between bones, along with the relatively light and porous nature of the dolphin vertebrae most likely aid buoyancy in this large cetacean.

Perhaps, the most unusual and interesting feature noted during this morphological study was the presence of a disproportionately elongated right-sided transverse process in the axis vertebra. We were unable find other reports of this feature. The edges of transverse processes on both sides of C2 were smooth and rounded and did not indicate any fracture points. This unilaterally placed large transverse process perhaps provides a fulcrum for muscles that are involved in a special rotatory or spinning movement of the dolphin. The contraction and sudden relaxation of these muscles may allow slingshot-like propulsion and spinning leap on a vertical axis. The space for muscle attachment is provided by horn-like anterior transverse process of the C3 and large transverse process of the C7. Further studies to evaluate the consistency of this unique anatomical feature are required to ascertain the plausibility of a one sided-dominant spinning theory.

CONCLUSION

In conclusion, the architecture of the cervical spine of the dolphin is adapted in multiple ways to allow for swimming movements. The thin and wide vertebral bodies allow for a stable and strong articulation with neighboring vertebrae and allow buoyancy. The relative elongation and bifid nature of transverse process allows for lever-like amplification of power required for propulsion. In humans, there is a posterior-prominence of extensor spinal muscles due to the need for standing and weight-bearing. However, the cervical spine of the dolphin has evolved to allow for a circumferential attachment of upstroke and down stroke muscles which provide equal power, allowing for strong dorsoventral undulations.[6]

In this article, we looked at cervical vertebrae from a single dolphin only. In reality, vertebral anatomy does tend to vary with anomalies seen in over 50% of individual dolphins, representing developmental anomalies or adaptations to variable environments.[3] However, attention has been paid to gross features and their likely adaptive significance in comparison to that of humans. A more detailed morphological analysis and modeling of swimming movements will further elucidate the complex swimming mechanisms in this remarkable species.

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Conflicts of interest

There are no conflicts of interest.

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