

ON THE MORPHOLOGY OF THE VERTEBRAL COLUMN OF THE FRIGATE TUNA, *AUXIS THAZARD* (LACEPEDEA, 1800) (FAMILY: SCOMBRIDAE) COLLECTED FROM THE SEA OF OMAN

LAITH A. JAWAD

Auckland War Memorial Museum, Natural Sciences, Tamaki Paenga Hira, The Domain, Private Bag 92018, Victoria Street West, Auckland 1142, New Zealand; e-mail: laith_jawad@hotmail.com

LUQMAN AL-HASSANI

LUBNA H. AL-KHARUSI

Marine Science and Fisheries Centre, Ministry of Agriculture and Fisheries Wealth, P.O. Box 427, Postal Code 100, Muscat, Oman



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Abstract. Based on morphometric studies, the vertebral column of the frigate tuna, *Auxis thazard*, can be divided into three morphologically distinct regions; postcranial, middle and ural. Biometrical measurement of the length, height and width of the vertebral column of *Auxis thazard* allows vertebral profiles with characteristic features to be drawn. The differences in length of vertebrae present in different regions of the vertebral column cause regionalization in this structure. These morphologically descriptive parameters express a morphotype which seems to have a functional link with the frigate tuna's thunniform mode of swimming.

■ Morphology, vertebrae, regionalization, frigate tuna, *Auxis*, The Sea of Oman.

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Introduction

Vertebrates show variation in the degree of regionalization of the vertebral column. Such differences in the morphology of vertebrae in different regions of the vertebral column can be revealed by biometrical studies (Kubo and Asano 1987, 1990, Desse et al. 1989). The vertebral column of actinopterygian fishes has two basic regions: the pre-anal abdominal region and post-anal caudal region (Grande and Bemis 1998), with remarkable diversity in vertebral form within these regions (Ford 1937, Pietsch 1978, Grande and Bemis 1998, Bemis and Forey 2001). The abdominal region may include, from anterior to posterior, occipital vertebrae that are incorporated into the skull through ontogeny, middle region vertebrae that are highly modified (e.g. the Weberian apparatus in Ostariophysi and fused vertebrae in Syngnathoidei), and vertebrae that usually bear abdominal ribs. The ural region includes vertebrae that bear haemal spines and ural vertebrae that bear hypurals. Locomotory function is linked to this regional pattern in vertebral structure along the vertebral column (Ramzu et al. 1992).

Among the important mechanical tasks of the vertebral column is locomotion (Learn 1976, Lindsey 1978, Weihs 1989). During development, this structure is subjected to different types of biological strains which seem to be reflected by local and specific morphological peculiarities

(Kubo and Asano 1987, 1990, Desse et al. 1989). Due to the strong anatomical and functional relationship with the trunco-caudal musculature (Le Danois 1958, Lindsey 1978, Vronskii and Nikolaitchouk 1989), studying the morphological characteristics of the vertebral column can reveal such relationships.

The frigate tuna *Auxis thazard* is one of the most commercially important fish species in Oman. Landings in the Sultanate of Oman have shown a dramatic increase to several hundred tons (Ministry of Agriculture and Fisheries Wealth 2011).

The aim of the present paper is to study the diversity of vertebrae and the morphological divisions in the vertebral column of the frigate tuna, *A. thazard*, collected from the Sea of Oman. Studying the morphology of the vertebral column of a teleost species such as *A. thazard* will enable us to check the validity of the morpho-functional hypothesis in this species.

Material and methods

Vertebral columns from 54 specimens of *A. thazard* were studied. The fish ranged in length from 290 to 380 mm SL and were caught in the vicinity of Muscat City in the Sea of Oman during August 2009. To prepare the vertebral column, the specimens were boiled to enable the flesh to be

stipped off the bone. Each vertebral column was rinsed in running water. After drying, the vertebrae were separated and numbered then measured with a digital 1/100 caliper. Three vertebral parameters were selected: the length of the vertebra (VL), which represents the distance along the left mid-ventral line; the anterior height (VH), which corresponds to the maximum vertical distance on the anterior side of the vertebrae; and width of the vertebra (VW), which represents the maximum horizontal width on the anterior side of the vertebrae. From these three measurements, it is possible to establish a vertebral profile which reflects the variation within these parameters along the vertebral axis (Desse et al. 1989, Ramzu 1994, Kacem et al. 1998, Ramzu and Meunier 1999). To compensate for individual variation and to facilitate future comparisons with other samples or other species, each vertebral measurement was converted into a vertebral index V_i :

$$V_i = P/SL$$

where P represents the vertebral parameters (VL, VH and VW) and SL is the standard length. Profiles of the vertebral column were drawn by plotting VL, VH and VW against the ordinal number of the vertebrae.

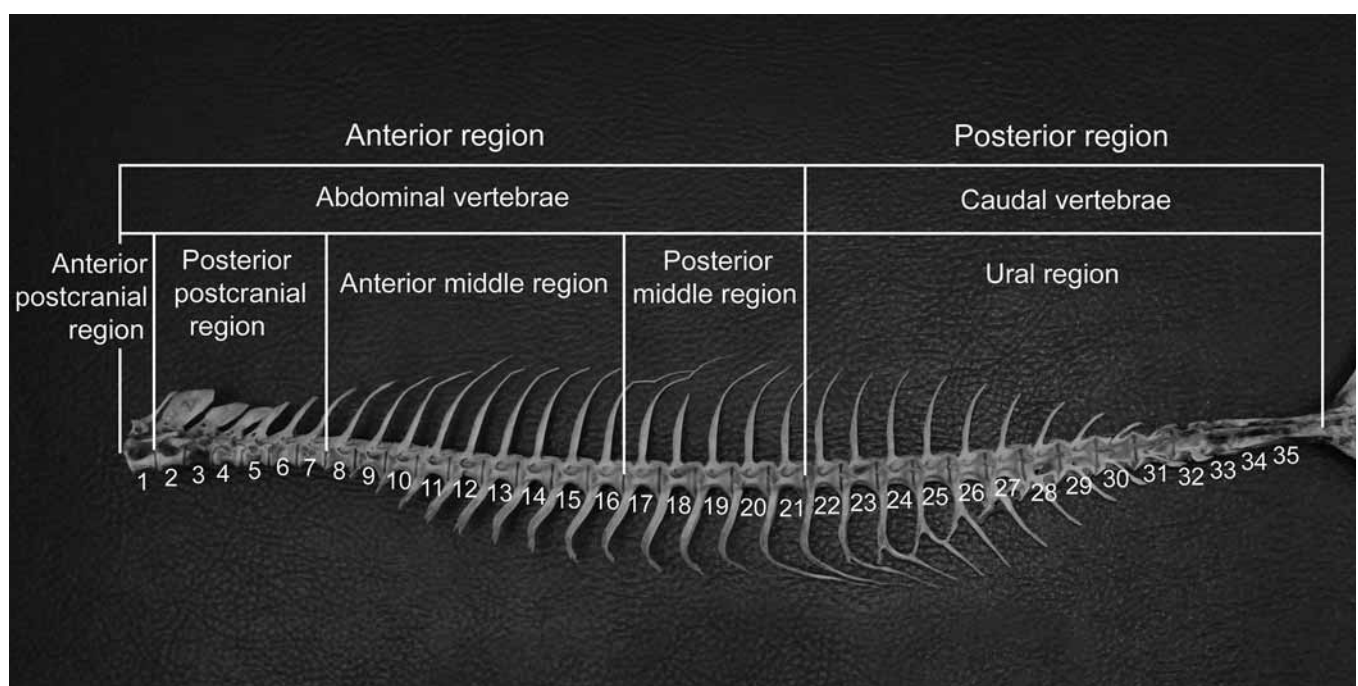
The abdominal and caudal vertebrae were counted and the mean values for each region were calculated for each individual, then the species means were calculated for abdominal vertebral number (AVN) and caudal vertebral number (CVN). Abdominal vertebrae were defined as those that were cranial to the vertebrae with separated haemal arches. The caudal region was defined as the region from the first fused haemal arch posterior to the last centrum including the ural centrum. The mean vertebral aspect ratio (AR= centrum length/ centrum width) for each region was calculated for each individual. The means were then calculated for abdominal aspect ratio (AAR) and caudal aspect ratio (CAR).

Results

There are in total 35 vertebrae in the vertebral column of *A. thazard*. The general appearance of each vertebra is cylindrical. The centrum comprises two inverted cones joined by their tips (amphicoelic vertebrae), and whose chordal cavities are connected by a narrow hole. Around these chordal cavities, there are no bony deposits masking the structure (text-fig. 1).

It is possible to divide the vertebral column of *A. thazard* into three regions: postcranial, middle and ural. The postcranial region can be further subdivided into two regions, the anterior and posterior postcranial regions. Similarly, the middle region can be divided into the anterior and posterior middle regions. The boundary between the abdominal and caudal vertebrae is located at V11. The 15 vertebrae of the middle region (V8-V21) define the abdominal or truncal region, delimited by the presence of the gut. Here, the two haemal arches are separate and there is absence of haemal spines. In the caudal vertebrae (V22-V35) the haemal arches are fused from V22 and prolonged by a haemal spine. This latter spine shows variation in both its length and shape. The haemal arch increases in length posteriorly and reaches its maximum length at V21. The left and right sides of the haemal arch in V21-V25 are not fused. There are small anterior bony projections on V24-V28. These projections become wider and shorter posteriorly until vertebra number 28. The anterior surface of the haemal arch is smooth and no concavity is present. There is no noticeable intraspecific variation in vertebral shape.

The vertebral column of *A. thazard* shows characteristic regionalization (Table 1). Firstly, the postcranial region, immediately behind the skull, provides articulation and is composed of four vertebrae that exhibit relatively important variation. The first vertebra is small, with a fine neural spine. There are no anterior zygapophyses on the first vertebra as this vertebra supports the skull; instead, it has



Text-fig. 1. Vertebral column of *Auxis thazard* showing different regions

Table 1. Average values (M) (mm) of length (LV), height (LH) and anterior width (LW) for the successive vertebrae of the vertebral column of *Auxis thazard* (SD = standard deviation).

No. of Vertebrae	VL	VH	VW
1	6.18		
2	5.11	5.55	5.35
3	4.81	5.10	6.73
4	4.79	5.09	7.09
5	4.33	5.21	6.66
6	4.75	6.81	6.25
7	4.89	7.32	6.04
8	6.52	5.53	6.47
9	6.02	5.59	6.65
10	7.64	5.34	6.84
11	7.04	6.21	7.07
12	8.05	6.43	7.28
13	6.90	6.30	7.43
14	6.69	6.23	7.46
15	6.34	6.15	7.60
16	6.38	6.62	7.96
17	7.52	6.73	7.04
18	6.82	7.02	5.76
19	6.39	6.58	6.64
20	6.35	6.51	6.00
21	7.56	6.75	7.46
22	6.29	6.3	7.96
23	6.63	6.68	7.66
24	6.81	6.37	7.27
25	6.50	6.40	7.87
26	7.03	6.25	7.71
27	7.64	6.33	7.76
28	7.77	6.78	7.35
29	7.32	6.83	7.29
30	7.08	6.87	7.34
31	6.86	7.99	7.45
32	6.56	9.25	7.23
33	8.49	8.14	6.82
34	5.93	6.08	6.40
35	3.92	5.49	5.57

two facets for the skull to rest on. The lateral processes of V1-V4 are well developed and lie parallel to the axis of the vertebral column. The development of the lateral paraphysis decreases posteriorly. V3-V8 can be considered as transitional vertebrae that form a connection between the first four vertebrae and the trunk because their biometrical parameters increase or decrease in a regular manner (text-fig. 2). Secondly, the middle region appears to be made up of two morphological entities: the anterior middle region (V8-V16) and the posterior middle region (V17-V21). Here, the length of the trunk vertebrae starts to fluctuate and reaches its

maximum at V2 (text-fig. 1). V17-V21 bear ribs that extend along the sides of the body. Thirdly, the ural region which starts almost at the vertebrae V22-V35. It corresponds with the caudal peduncle and is characterized by sharp increases and decreases in vertebral length, height and width. Vertebral parameters decrease between V31-V35.

The profiles corresponding to the three parameters measured on all the vertebrae were the same in all the specimens studied (text-fig. 2).

The vertebral profile given by the variation in the vertebral length along the axis shows two maxima: one anteriorly at V12, the other posteriorly at V20. Between V1 and V12, the vertebral length steadily increases between V1 and V7 and dramatically increases between V8 and V12; then it fluctuates slightly between V12 and V20. After that, the value decreases sharply, reaching its first minimum value at V25, rising again until V33, then dropping significantly at V35.

The vertebral profile revealed by the vertebral height shows the following changes along the axis of the vertebral column: there are two maxima, one anteriorly at V18 and one posteriorly at V33; two minima, anteriorly at V10 and posteriorly at V35. Between V1 and V2 the vertebral height increases, then decreases with slight fluctuations between V2 and V10. A significant increase and fluctuation in value are observed between V10 and V30. A further increase is noticed between V3 and V33; beyond V33 the value drops dramatically, reaching a minimum value at V35.

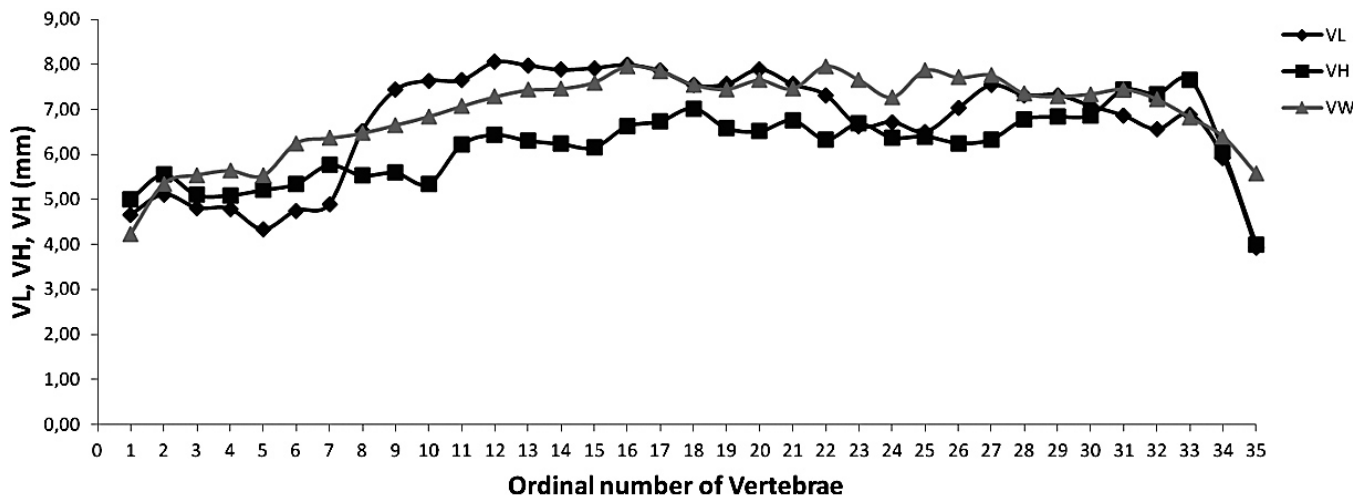
There are two minima and two maxima shown in the vertebral width profile, V1, V35 and V16, V25 respectively. An increasing trend in the vertebral width value is seen between V1 and V6. A significant increase occurs between V6 and V16. The width value fluctuates greatly between V17 and V32, then drops dramatically at V35.

The total number of vertebrae in *A. thazard* is 35. Within this number there are 21 abdominal vertebrae and 14 caudal vertebrae. The vertebral aspect ratio is 0.92 and 0.94 for the abdominal and caudal regions respectively.

Discussion

The vertebral column of *A. thazard* is a complex structure composed of three main regions. Biometric study suggests a division of the vertebral column into three main regions: 1) a postcranial regions (anterior truncal), subdivided into anterior and posterior postcranial regions; 2) a middle region, subdivided into anterior and posterior middle regions; 3) a ural region. Regions 1 and 3 are characterized by significant variation in vertebral parameters; in region 2, these variations are more regular and characterized by increases in the length, height and width of the vertebrae.

The post-cranial region, immediately behind the head, provides articulation with the skull. The first four vertebrae form a morphological set with similar vertebral length and width. However, these four vertebrae do not show completely different morphological characteristics compared to the other vertebrae (except for the first vertebra). In *A. thazard*, the first vertebra has an anterior ventral concavity which articulates with the basioccipital. This first post-cranial vertebra is designed to articulate with the posterior region of the skull, and together with the next vertebra forms a link



Text-fig. 2. Vertebral profiles of *Auxis thazard*. VL, central length; VH, central height; VW, central width.

between the two main elements of the axial skeleton, which is a function which requires morphological specificity (Videler 1993). The five vertebrae beyond V4 could be considered as transitional vertebrae because they show a regular increase in vertebral biometric parameters (Ramzu and Meunier 1999).

The middle region includes the boundary between the truncal and caudal regions (V8-V16 and V17-V21) which corresponds with closing of the haemal arch. It is therefore composed of truncal vertebrae and caudal vertebrae and forms morphological units. In these regions the increase in the three parameters is regular until a maximum value is reached, then there is a progressive decrease.

The ural region starts at the 22nd vertebra. It corresponds to the tail and is characterized by a decrease in the values of the three analyzed parameters. The ural vertebra has different anatomy as it lacks real haemal arches, but it has hypural elements which support the lepidotriches of the caudal fin.

As in other teleost fishes (Ramzu et al. 1992), the substitution of the classical anatomical truncal- and caudal region by more than two regions, as in the case of *A. thazard*, is probably linked to the mechanical constraints of swimming. Moreover, the antero-posterior characteristics seen in the three morphological parameters studied, with the abrupt variation in the postcranial and ural regions on one hand, and the maximum values in the middle region on the other, support this hypothesis (Ramzu et al. 1992). The frigate tuna is known to present a thunniform mode of swimming (Breder 1926, Lindsey 1978, Webb 1978) in which the vast majority of movement is concentrated in the very rear of the body and tail. Thunniform movement involves lateral movement in the tail and the region connecting the main body to the tail (the peduncle). The tail itself tends to be large and crescent-shaped. The fact that the maximum values in the three parameters considered occurs around the 25th–33rd vertebrae could be a structural response in these vertebrae to the local presence of maximal mechanical constraints.

Regarding the third region, its specific parametrical variation might reflect the major role performed by the caudal vertebrae in the motor process of swimming. The caudal skeleton responds to the alternate contraction of the intrinsic muscles on the lateral sides of this region, thus torsion of the caudal peduncle is created, which slightly

increases or decreases the surface area of the caudal fin during different phases of one beat (Bainbridge 1963), thereby exerting force on the water.

Morphometric analysis of the vertebral column revealed no significant difference in variation within vertebral length, height and width of each vertebra in *A. thazard*. Therefore, characterization of one vertebra along the vertebral column would be sufficient if it was based on only one of these three parameters (Desse et al. 1989). Furthermore, the morphology of male and female vertebrae are similar. This result is similar to that of Kacem et al. (1998) on the skeletal morphology of *Salmo salar*.

Regionalization in the vertebral column of *A. thazard* could have developed due to the difference in length of vertebrae in different regions of the vertebral column. This in turn is due to different mechanisms which regulate vertebral growth in each region (Fjellidal et al. 2005). On the other hand, the similarity in the value of the aspect ratio of both the abdominal and caudal region in this study may indicate that the changes in the vertebral length in the abdominal and caudal regions are closely linked (Ward and Brainerd 2007).

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