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Vertebral compression syndrome in the Atlantic bonito, *Sarda sarda* (Bloch, 1793) from the Southwest Black Sea coasts of Türkiye

by

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Abstract

This study documents the first recorded case of vertebral compression syndrome (VCS) in an Atlantic bonito (*Sarda sarda*) from the southwestern Black Sea. The affected specimen exhibited distinct morphometric deviations, including a shortened vertebral column and an increased body depth, compared to a normal conspecific. Radiographic analysis revealed mild compression initiating at the 13th vertebra, which progressed to severe compression affecting vertebrae 21–40. Within this region, vertebrae showed a marked reduction in width and an increase in height, accompanied by localized dislocations and abnormal bulging along the spinal column. The deformity is consistent with a response to altered mechanical load, which likely disrupted bone growth zones and prompted the replacement of intervertebral tissue with cartilage. This study underscores the utility of high-resolution digital radiography as a nondestructive tool for detailed biological investigation. The exact etiology of the mechanical load, whether from an acute pressure event or chronic overexertion, remains unknown and warrants future investigation.

Key words: deformities, vertebral column, condition factor, radiography, malnutrition

1. Introduction

Fish specimens exhibiting morphological deformities are relatively uncommon but raise significant concerns when encountered, particularly among aquaculturists (Buckland, 1863), fishermen, and anglers (Fjelldal et al., 2015; Näslund & Jawad, 2022), as well as naturalists and scientists. Historically, such anomalies have been collected for both private and official collections, either due to scientific curiosity or for detailed examination (Heron et al., 1988; Hickey, 1972). Identifying these abnormalities is crucial, as they can serve as vital indicators of pollution or other detrimental environmental factors (Klumpp et al., 2002; Simon & Burskey, 2016). Consequently, many researchers argue that monitoring deformities in fish populations is essential for assessing the health of aquatic ecosystems (Jawad & Ibrahim, 2018; Lemly, 1993; Sfakianakis et al., 2015).

Among the most frequently, observed skeletal anomalies in various fish groups are ankylosis, lordosis, kyphosis, and pugheadedness. These deformities can range from mild to severe, occurring both in aquaculture settings and in natural habitats (Jawad & Ibrahim, 2018; Näslund & Jawad, 2022). Ankylosis, the fusion of vertebrae, can result in vertebral deformation, manifesting as compression or a combination of compression and fusion (Witten et al., 2006).

A compressed vertebra (vertebral compression syndrome [VCS]) typically retains a normal central region while exhibiting deformational changes in the anterior and posterior sections. In the central portion, the angle between the vertebral cone wall and the anterior-posterior axis is approximately 45°, whereas in the deformed sections, this angle increases to roughly 90° (Berg et al., 2006; Witten et al., 2006). Both descriptive and experimental studies suggest that compressions develop later in ontogeny (Berg et al., 2006; Witten et al., 2006). Ankylosis and compression are characterized by the fusion of two or more deformed vertebral bodies, often emerging during the parr stage (Wargelius et al., 2005; Witten et al., 2006). Interestingly, Witten et al. (2006) observed that in some cases, fused adjacent vertebrae may remodel into a single vertebra resembling a non-fused structure, albeit with supernumerary hemal and neural arches. However, whether vertebral compression is a precursor to ankylosis remains unresolved.

VCS arises from a complex interplay of nutritional, environmental, and genetic factors. A primary cause identified in aquaculture is nutritional deficiency, specifically a lack of phosphorus and an imbalance in the calcium-to-phosphorus ratio. Phosphorus is a critical component of hydroxyapatite, the mineral matrix of bone, and its deficiency disrupts normal vertebral mineralization, leading to weakened skeletal structures prone to compression. This was notably demonstrated in studies on Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), where diets deficient in available phosphorus resulted in high incidences of VCS and other spinal malformations (Baeverfjord & Shearer, 1998; Fjelldal et al., 2007). Furthermore, rapid growth rates, often promoted in intensive farming to maximize production, can exacerbate the condition if the diet is not perfectly balanced, as the skeleton cannot mineralize quickly enough to support the increasing mass of soft tissue.

The effects of VCS are profound, impacting both the biological integrity of the fish and the economic viability of aquaculture operations. The most direct effect is a significant reduction in slaughter yield and fillet quality, as the compressed spine leads to abnormal body shape, making automated processing difficult and resulting in substantial product downgrading or rejection. Beyond these economic losses, VCS has severe welfare implications for the affected fish. The spinal compression can impinge on the spinal cord and associated nerves, leading to impaired swimming performance, reduced feeding ability, and chronic pain or neurological dysfunction. For instance, in severely affected Atlantic salmon, the deformity can compromise the vertebral canal, potentially causing compression of the spinal cord, which is associated with nociception and a reduced ability to evade predators or compete for resources (Fjelldal et al., 2012). Consequently, VCS not only represents a production bottleneck but also a critical animal welfare issue that necessitates mitigation through optimized nutrition and breeding strategies.

A review by Yılmaz et al. (2024) identified 34 published studies documenting fish anomalies in Türkiye's waters, reporting 62 affected individuals spanning 38 species and 20 families. Notably, vertebral compression has been previously described in *Serranus hepatus* from the Sea of Marmara (Jawad et al., 2022), as well as in *Mullus barbatus* and *Sphyraena sphyraena* (Linnaeus, 1758) along the İzmir coast in the northeastern Aegean Sea (Jawad & Akyol, 2023; Jawad et al., 2018).

To the authors' knowledge, no prior studies have reported skeletal deformities in *S. sarda* (Atlantic bonito). Recently, Ortega et al. (2024) investigated the role of water temperature—a critical abiotic factor—in shaping early fish development. Their study focused on larvae of two tuna species, Atlantic bluefin tuna (*Thunnus thynnus*, Linnaeus 1758) and Atlantic bonito (*S. sarda*), revealing that temperature fluctuations significantly influence deformity occurrence. Although

Ortega et al. (2024) noted an abnormal *S. sarda* larva; they did not specify the nature of the deformities.

Thus, this study presents the first documented case of a skeletal anomaly in *S. sarda*, offering a detailed description of severe vertebral compression affecting both the abdominal and caudal regions of the vertebral column. The specimen was collected along the southwestern Black Sea coast of Türkiye, marking a novel contribution to the understanding of skeletal deformities in this species.

2. Materials and methods

One abnormal and one normal specimen of *S. sarda* (Fig. 1) were collected from the Southwestern Black Sea (Latitude 41° 16′ 15″ N and Longitude 29° 01′ 41″ E) (Fig. 2) on 24 October, 2024. Fish specimens were collected using a pair midwater trawl at a depth of 25 meters. The normal specimen was used for comparison. The total length (TL) was measured from the tip of the snout to the posterior end of the upper and the lower lobes of the caudal fin grouped, fork length (FL) measured from the tip of the snout to the point separating the upper and the lower lobes of the caudal fin, and standard length (SL) was measured from the tip of the snout to the distal edge of the hypural bones. The length of the fish was measured using a digital calliper to the nearest 0.01 mm. Specimens' bodies and fins were examined carefully for malformations, deletions, and any other morphological anomalies. The specimens were fixed in 70% ethanol and deposited in the fish collection of the Department of Fisheries Technologies and Management, Faculty of Aquatic Sciences, Istanbul University, Istanbul, Türkiye. The skeletons of both normal and abnormal specimens were examined using an X-ray machine model FCR Prima T2 (Digital Imaging System, Fujifilm Corporation) compact digital imaging system connected to the Hasvet 838 HF50 (High-Frequency Generator Hasvet 838 HF50 Hasevetsan (Historical Turkish brand)) high-frequency X-ray device available at the Sarıyer Municipality Safiye Kaya temporary shelter for stray animals. The length of the vertebral column of both the normal and the abnormal specimens was measured from the anterior edge of the 1st abdominal vertebra to the urostyle to calculate the ratio between the length of the vertebral column and the SL of the fish. Both the vertebral length and height were measured for each vertebra of both the abnormal and the

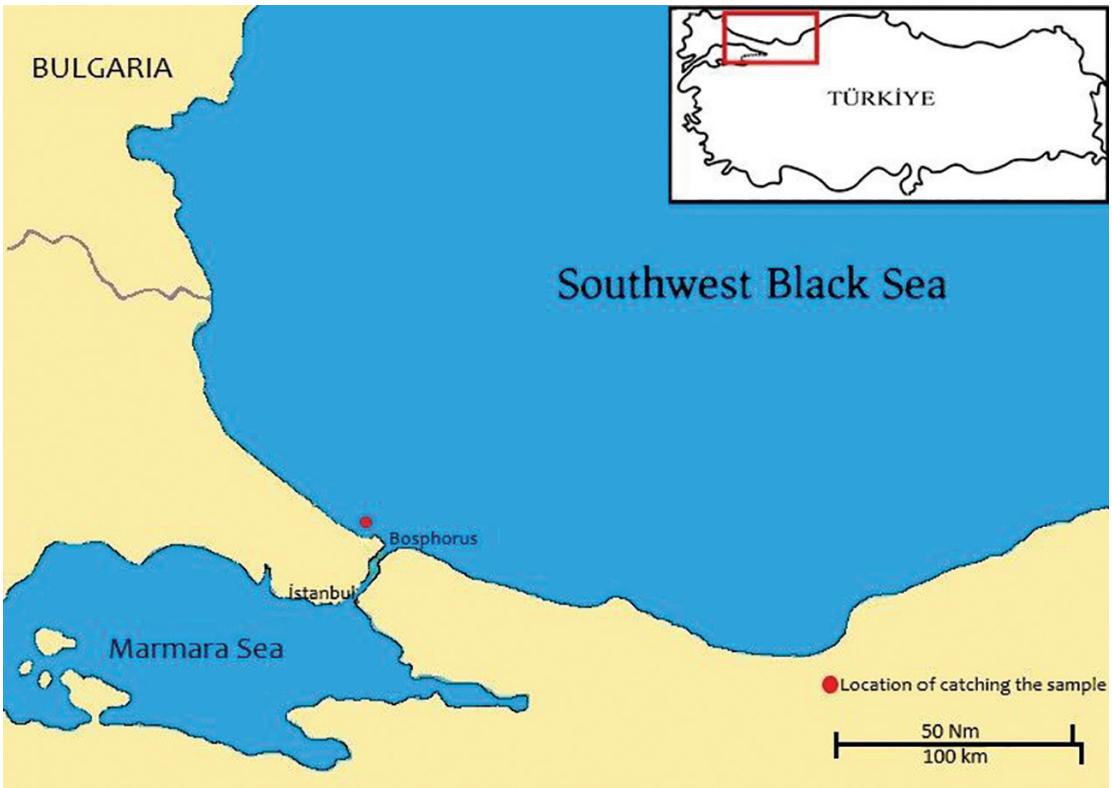

Figure 1

Map of the geographic location where the abnormal *S. sarda* specimen was collected.

Figure 2

Specimens of *S. sarda* collected from the Southwest Black Sea coast of Türkiye. **(A)** Abnormal specimen (271 mm TL, 236 mm FL, 213 mm SL); **(B)** Normal specimen (of 265 mm TL, 238 mm FL, 221 mm SL). FL, fork length; SL, standard length; TL, total length.

normal specimens examined. To assess the degree of abnormality in the anomalous specimen, the ratios between the height and width of the anomalous vertebrae and the SL of the abnormal specimens were measured to the nearest 0.1 mm and compared with those of the normal specimen. All measurements were made by the same person using the same instrument to increase the accuracy of the measurements and reduce variability owing to measurement error. The skeletal terminology used here is according to Harder (1975). The vertebral number of the affected vertebrae and the type of deformity were determined. According to the classification of compressed vertebrae of Fjelldal et al. (2007), adjacent vertebrae that were compressed in the anterior–posterior direction with intervertebral spaces were classified as compression. The condition factor (CF) of both the abnormal and the normal specimens was calculated using the formula of Le Cren (1951):

$$CF = [\text{weight (g)}/\text{FL (cm}^3)] \times 100$$

3. Results

VCS was identified in a single *S. sarda* specimen with a TL of 265 mm, a FL of 238 mm, and a SL of 221 mm. These measurements were compared to those of a normal specimen of similar size (271 mm TL, 236 mm FL, 213 mm SL) (Figs.1A and 1B). The ratio of FL to TL was 89.8% for the normal specimen and 87.1% for the abnormal specimen, while the ratio of maximum body depth to TL was 22.3% for the normal specimen and 28.7% for the abnormal one. A full summary of the morphometric characteristics for both specimens is provided in Table 1.

The results showed that the CF ratio of the abnormal and the normal specimens were 1.95 and 1.24 respectively.

The ratio of vertebral column length (from the first vertebra to the urostyle) to SL was 0.75 in the affected fish, compared to 0.87 in the normal specimen. Externally, the ratios of minimum and maximum body depth to SL were 2.99% and 2.79%, respectively, for the abnormal specimen. In contrast, the corresponding ratios for the normal specimen were 2.25% and 2.31%. Although the abnormal specimen had a greater TL, its subsequent morphometric measurements were all proportionally larger.

Radiographic analysis revealed that the abnormal specimen possessed 52 vertebrae, while the normal specimen had 51. A variable degree of compression was observed in abdominal vertebrae 21–25 and caudal vertebrae 26–44. Table 2 presents the vertebral length and height for both the abnormal and normal specimens, with vertebrae grouped in sets of 10 for comparison. Both

Table 1

Morphometric characteristics of the abnormal and the normal specimens of *S. sarda* collected from the Southwest Black Sea coasts of Türkiye.

Morphological measurements	Abnormal fish	Normal fish
TL (mm)	271	265
FL (mm)	236	238
SL (mm)	213 mm	221
Weight (g)	256.59	166.71
Head length (mm)	72.5	61.2
Eye diameter (mm)	10.6	9.6
Preocular distance (mm)	28.2	20.6
Postocular distance (mm)	37.5	31.8
First dorsal fin length (mm)	76.2	74.6
Second dorsal fin length (mm)	28.3	26.5
Anal fin length (mm)	16.5	19.4
Pectoral fin Length (mm)	37.8	26.4
Ventral fin length (mm)	22.9	16.2
Predorsal distance (mm)	72.2	60.3
Prepectoral distance (mm)	72.3	63.8
Preventral distance (mm)	79.8	66.1
Max. body depth (mm)	61.1	49.2
Caudal fin length (mm)	57.9	40.1

FL, fork length; SL, standard length; TL, total length.

Table 2

Vertebral length and height of the abnormal and normal specimens of *S. sarda* collected from the Southwest Black Sea coasts of Türkiye.

Vertebrae	Vertebral length (mm)	Vertebral height (mm)
Abnormal specimen		
1–10	2.93–4.31	3.48–4.31
11–20	2.40–4.31	3.83–5.27
21–30	1.68–2.40	4.79–5.27
31–40	1.44–2.40	4.79–5.27
41–50	2.40–3.83	3.35–5.75
51, 52	1.92, 1.44	2.40, 1.92
Normal specimen		
1–10	2.12–3.64	2.42–3.33
11–20	3.33–3.94	3.03–3.64
21–30	3.33–3.94	3.64–4.24
31–40	3.33–3.64	3.64–4.36
41–50	1.82–3.64	2.42–4.24
51	1.21	1.82

vertebral length and height exhibited a decreasing trend in the second and third groups.

A mild compression began at abdominal vertebra No. 13, where the vertebral length decreased from 40.3 mm in vertebra No. 12 to 29.8 mm. Severe compression commenced at vertebra No. 21, which had a length of 21.6 mm compared to 24 mm in vertebra No. 20. This severe compression continued through vertebra No. 40 (Figs. 3A and 3B). The length and width of vertebrae 1–12 appeared normal compared to the control. From vertebra 13 onward, a noticeable decrease in width and overall compression was observed, accompanied by an increase in vertebral height, making these vertebrae appear longer than they were broad. This compressed morphology continued through vertebra 40, after which vertebral dimensions returned to normal.

Specific dislocations were also noted: the anterior side of vertebrae 14 and 15 bulged posteriorly; the posterior ventral ends of vertebrae 22–24 were tilted posteriorly; the posterior ventral ends of vertebrae 26–28 were curved posteriorly; the abdominal edge of vertebra 35 bulged posteriorly; in vertebra No. 38, the dorsal ends of the anterior and posterior sides were close to each other, while the ventral ends were widely separated; in vertebra No. 39, the ventral ends of the anterior and posterior sides were close to each other, while the dorsal ends were normally separated compared to the normal specimen; and in vertebra No. 40, the ventral end of the anterior side was tilted anteriorly.

4. Discussions

This study documents the first case of VCS in the Atlantic bonito (*S. sarda*), characterized by anteroposterior shortening of the vertebral column. In teleosts, such deformities can manifest as spinal curvatures (lordosis, kyphosis) or as a more subtle vertebral compression, the latter often-requiring radiographic examination for detection (Gavaia et al., 2002; Madsen et al., 2000). The phenotype observed in our specimen, a reduced FL relative to TL, coupled with an increased body depth and an elevated CF, closely aligns with the classic 'short tail' deformity described in Atlantic salmon (Vågsholm & Djupvik, 1998). This suggests a common morphological outcome across phylogenetically distant species.

The deformity was complex, involving not only compression but also vertebral distortion and altered intervertebral spaces, a combination consistent with previous reports (Baeverfjord et al., 1996; Kvellestad et al., 2000). The etiology of

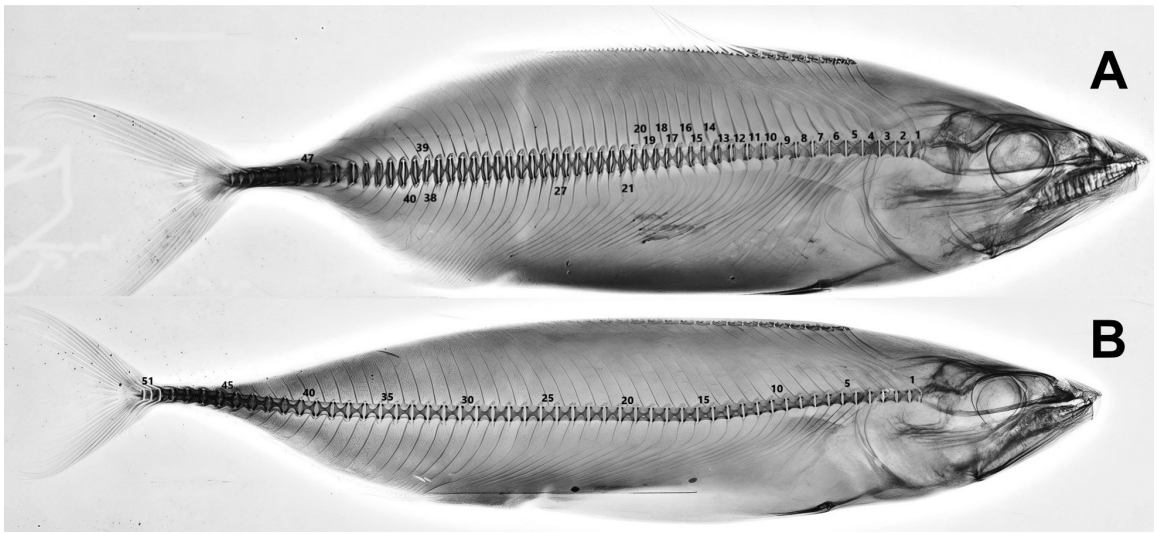

Figure 3

Radiograph of specimens of *S. sarda* collected from the Southwest Black Sea coasts of Türkiye. **(A)** Abnormal specimen (of 271 mm TL, 238 mm FL, 221 mm SL); **(B)** Normal specimen (265 mm TL, 236 mm FL, 213 mm SL). FL, fork length; SL, standard length; TL, total length.

such malformations is often multifactorial, with proposed causes including nutritional imbalances, infectious agents, pollution, genetic predisposition, and elevated water temperature (Kvellestad et al., 2000; Madsen et al., 2001; Scott, 2001). The latter two factors are of particular relevance to the Black Sea, the origin of our specimen. This region is subject to significant anthropogenic stress, including chemical pollution and thermal discharge (Bat et al., 2018), and models project a substantial warming of its coastal waters (Nacar et al., 2024).

In the absence of pathological, metabolic, or genetic analysis for our specimen, the exact cause remains speculative. However, the morphological evidence points toward a mechanism involving altered vertebral growth. Witten et al. (2006) proposed that vertebral compression in salmon results from the fusion of mirror-image growth zones, leading to bone deposition that increases vertebral height at the expense of length. This process is intimately linked to the notochord, a critical tissue for inducing and maintaining vertebral morphogenesis (Hall, 2005; Hunter et al., 2003; Smits & Lefebvre, 2003). A failure of notochord cells to sustain proper development can lead to vertebral compression (Hall, 2005; Oegema, 2002), and it is plausible that notochordal changes precede the observed bone alterations.

The presentation of VCS in this single *S. sarda* specimen aligns with established morphological patterns observed in other marine fish species within its distribution range, yet exhibits a notable severity. The significant reduction in the vertebral column length to SL ratio (0.75 in affected vs 0.87 in normal) and the increased body depth are classic external indicators of VCS, frequently reported in species like the Atlantic bluefin tuna (*T. thynnus*) (Matsuoka, 2003). Studies on captive-reared bluefin tuna have documented similar body shortening and lordosis, often linked to nutritional imbalances or trauma during handling. The radiographic findings of severe compression across a long series of vertebrae (from vertebra 21–40) and the complex dislocations mirror the spinal pathologies described in farmed Southern bluefin tuna (*Thunnus maccoyii*), where such deformities are a major production constraint (Fjelldal et al., 2012). The increased CF (1.95% vs 1.24%) further suggests that the fish's mass was disproportionately packed into a shorter frame, a common consequence of vertebral body fusion and compression (Woo et al., 2006). This case confirms that the pathological mechanisms leading to VCS are consistent across scombrids, from wild-caught *S. sarda* to aquacultured *Thunnus* species.

A particularly intriguing finding in this *S. sarda* specimen is the presence of 52 vertebrae compared to 51 in the normal conspecific. Vertebral number is generally considered a stable meristic character in teleosts, and deviations can indicate developmental disruptions during embryogenesis. While direct

studies on *Sarda* spp. are scarce, research on other species, such as Atlantic salmon (*S. salar*), has shown that environmental stressors like temperature fluctuation during early development can induce vertebral number anomalies, which subsequently predispose the spine to compression later in life (Fjelldal et al., 2007). The fact that the compression initiated at vertebra 13, a point potentially corresponding to a developmental somite boundary, supports the hypothesis of an early developmental insult (Partridge and Flake, 2012). This distinguishes the present case from VCS caused solely by nutritional deficiencies in later life stages, as documented in gilthead sea bream (*Spams aurata*) from Mediterranean aquaculture, where deformities occur without a change in vertebral count (Paperna, 1978). Therefore, this specimen suggests a potential embryonic or larval origin for the syndrome, which was then exacerbated by biomechanical forces during growth, leading to the observed severe and widespread compression.

In conclusion, we hypothesize that the vertebral compression in this *S. sarda* specimen was initiated by an altered mechanical load, which subsequently transformed the bone growth zones and led to the replacement of intervertebral notochord tissue with cartilage. This is supported by the established role of mechanical loading in intervertebral disc integrity (Lotz et al., 2002). Whether the damaging mechanical load was an acute event (Kihara et al., 2002) or a result of chronic overexertion cannot be determined from the present data and represents a key question for future research.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability statement

The data supporting these study findings are available from the corresponding author upon reasonable request.

Ethics statement

This work is based on personal fish catch. Therefore, ethical aspects are not applicable.

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Author Contributions

İsmail Reis: Observation, collecting fish specimens, formal analysis, methodology, performing X-ray and specimens imaging, project administration, validation, visualization, reading the first draft of the manuscript.

Firdes S. Karakulak: Observation, formal analysis, methodology.

Laith Jawad: Conceptualization, formal analysis, investigation, methodology, project administration, supervision, validation, visualization, writing original draft, writing review and editing.

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