

文章编号: 1674-5566(2025)02-0333-08

DOI: 10.12024/jsou.20240704590

## 黄鳍金枪鱼仔鱼脊柱及附肢骨骼的发育

王晓东, 吕莉欣, 赵恒权, 钟俊生

(上海海洋大学 海洋动物系统分类与进化上海高校重点实验室, 上海 201306)

**摘要:**为了探明黄鳍金枪鱼(*Thunnus albacares*)脊柱及附肢骨骼的发育特征,基于2022年8月15日—9月9日在菲律宾海用大型仔稚鱼网(口径1.3 m、网目0.5 mm)进行表层水平拖网所采集的黄鳍金枪鱼仔鱼样本,采用软骨-硬骨双染色透明技术,观察了黄鳍金枪鱼仔鱼(前弯曲期9尾,弯曲期12尾,后弯曲期12尾,体长3.1~8.0 mm)脊柱及附肢骨骼的早期发育。结果显示,各鳍形成顺序是胸鳍、尾鳍、第一背鳍和腹鳍、第二背鳍和臀鳍,最后为小鳍;椎体由体前部向尾部逐渐形成;髓弓由体前部向尾部和由体中部向两端生长,脉弓由体中部向两端生长;尾下骨1和2先愈合为一个整体,随后侧尾下骨和尾下骨1+2的基部软骨联合,尾下骨3和4两端愈合,尾下骨5独立;体长8.0 mm个体形成躯椎18枚,尾椎21枚,侧尾下骨1枚,尾下骨5枚,尾上骨2枚。研究表明,侧尾下骨和尾下骨愈合为黄鳍金枪鱼提供了强劲的游泳动力。本研究可作为黄鳍金枪鱼早期阶段的鉴定依据,并为其仔鱼阶段的漂流机制形成提供参考。

**关键词:**黄鳍金枪鱼;骨骼发育;脊柱;附肢骨骼;软骨-硬骨双染色透明技术

**中图分类号:** Q 174      **文献标志码:** A

黄鳍金枪鱼(*Thunnus albacares*)隶属于鲭形目(Scombriformes)鲭科(Scombridae)金枪鱼属(*Thunnus*)。金枪鱼属鱼类为快速游泳的温带大洋性中上层鱼类,具有长距离洄游的习性,喜集群,广泛分布于印度洋、太平洋和大西洋的热带和亚热带海域<sup>[1]</sup>。其肉质鲜嫩、营养丰富,备受广大消费者喜爱。2022年太平洋中西部海域黄鳍金枪鱼捕捞量达69.53万t<sup>[2]</sup>。国内外对黄鳍金枪鱼已有大量研究,但主要集中在渔获量分析<sup>[3-4]</sup>、资源评估<sup>[5-6]</sup>、性腺发育<sup>[7-8]</sup>、基因转录组<sup>[9]</sup>、网箱养殖<sup>[10]</sup>等方面。仔稚鱼是鱼类个体发育过程中一个重要阶段,在此期间,鱼的个体形态、行为和生理等各方面都会有明显变化<sup>[11]</sup>。在自然条件下,很多鱼类在仔鱼期通常只有不到1%的存活率<sup>[12]</sup>。仔稚鱼时期鱼类的生长、死亡情况对种群的变化至关重要,仔稚鱼的存活量将直接影响到成鱼的补充量<sup>[13]</sup>。因此,对鱼类早期资源的研究是渔业资源可持续利用研究中心必不可少的工作。有关黄鳍金枪鱼仔稚鱼的研究主要包括仔稚鱼

鉴定<sup>[14]</sup>、早期发育和生长<sup>[15]</sup>、时空分布<sup>[16]</sup>、环境对其影响<sup>[17-18]</sup>等,而有关金枪鱼骨骼系统早期发育的研究较少。仅POTTHOFF<sup>[19]</sup>研究了黑鳍金枪鱼(*Thunnus atlanticus*)仔稚鱼脊柱及奇鳍骨骼的发育情况。有关黄鳍金枪鱼骨骼系统早期发育的研究尚未见报道。

本研究利用软骨-硬骨双染色透明技术,对黄鳍金枪鱼仔鱼脊柱与附肢骨骼的发育及其变化进行了观察和描述,旨在为黄鳍金枪鱼骨骼系统发育提供基础的科学依据,并为其早期发育阶段的移动趋向提供参考。

### 1 材料与方法

#### 1.1 材料来源

2022年8月15日至9月9日,在中西太平洋菲律宾海(11°N~19°N、129°E~138°E)的50个站位(水温29.66~30.60 °C,盐度33.40~34.65),采用大型仔稚鱼网(口径1.3 m,网目0.5 mm)以平均2 kn的船速进行表层水平拖网20 min。采集的样

收稿日期: 2024-07-01      修回日期: 2024-12-03

基金项目: 国家重点研发计划(2022YFC2804003);农业农村部公海渔业资源综合科学调查重大专项(D-8021-21-0109-01)

作者简介: 王晓东(1993—),男,博士,研究方向为仔稚鱼生态与资源学及鱼类早期生活史。E-mail:xiaodonwang@shou.edu.cn

通信作者: 钟俊生,E-mail:jszhong@shou.edu.cn

版权所有 ©《上海海洋大学学报》编辑部(CC BY-NC-ND 4.0)

Copyright © Editorial Office of Journal of Shanghai Ocean University (CC BY-NC-ND 4.0)

<http://www.shhydxxb.com>

本用5%的甲醛溶液固定。依据《日本产稚鱼图鉴》<sup>[20]</sup>筛选出黄鳍金枪鱼,参照KENDALL等<sup>[21]</sup>的研究结果划分鱼类早期发育阶段并计数。在Olympus SZX7解剖镜下利用目镜测微尺测量体长(Body length),前弯曲期和弯曲期仔鱼(尾下骨后缘尚未发育至与体轴垂直的个体)测量脊索长(Notochord length, NL),后弯曲期仔鱼(尾下骨后缘已发育至与体轴垂直的个体)测量标准体长(Standard length, SL)。选取形态大体完整的不同发育阶段(前弯曲期9尾、弯曲期12尾、后弯曲期12尾,体长3.1~8.0 mm,图1)的黄鳍金枪鱼仔鱼样本共33尾作为骨骼研究材料。

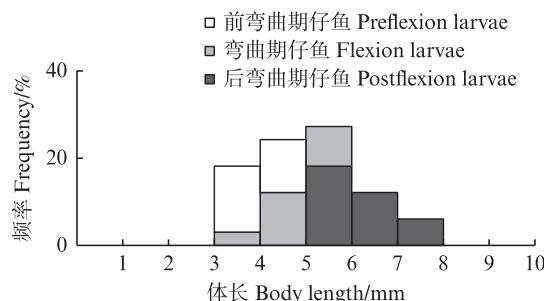


图1 黄鳍金枪鱼透明染色的样本体长分布  
Fig. 1 Body length frequency of stained and cleared *Thunnus albacares*

## 1.2 材料处理

参考DINGERKUS等<sup>[22]</sup>的软骨-硬骨双染色透明技术,对黄鳍金枪鱼仔鱼骨骼进行染色。具体步骤如下:(1)清洗,利用蒸馏水清洗甲醛保存的样品,浸泡2~3 d,中间更换1次蒸馏水;(2)软骨染色,将样品浸泡于软骨染色液(10 mg阿利新蓝 Alcian Blue 8GX + 80 mL纯乙醇 + 20 mL冰醋酸)中24~36 h,直至样品鳍条基部有明显蓝色;(3)梯度漂洗,将样品移入95%乙醇溶液中浸泡2~3 h,随后依次移入呈递减浓度(75%、40%、15%)的乙醇中直至沉底;(4)组织的消化与透明,将样品浸于胰蛋白酶消化液(1 g胰蛋白酶 Trypsin + 30 mL饱和硼砂水溶液 + 70 mL蒸馏水)中,直至样品透明;(5)硬骨染色,将样品移入硬骨染色液(茜素红 Alizarin Red 数粒 + 0.5% KOH溶液)中24~48 h,直至硬骨染上红色;(6)保存,将样品依次移入体积比为3:1、1:1、1:3的0.5% KOH-甘油混合试剂中直至沉底,最终将样品移入纯甘油中,并加数粒麝香草酚(Thymol)密封保存。

在Olympus SZX7解剖镜及描图装置(SZX-DA)下,对黄鳍金枪鱼仔鱼的脊柱和附肢骨骼形态进行连续观察(图2)并绘制发育图。各图中阴影区域为软骨,白色部分为硬骨。



图2 黄鳍金枪鱼透明染色样本(后弯曲期仔鱼,体长6.4 mm)

Fig. 2 Stained and cleared specimen *Thunnus albacares* (Postflexion larva, 6.4 mm SL)

## 2 结果

### 2.1 脊柱的发育

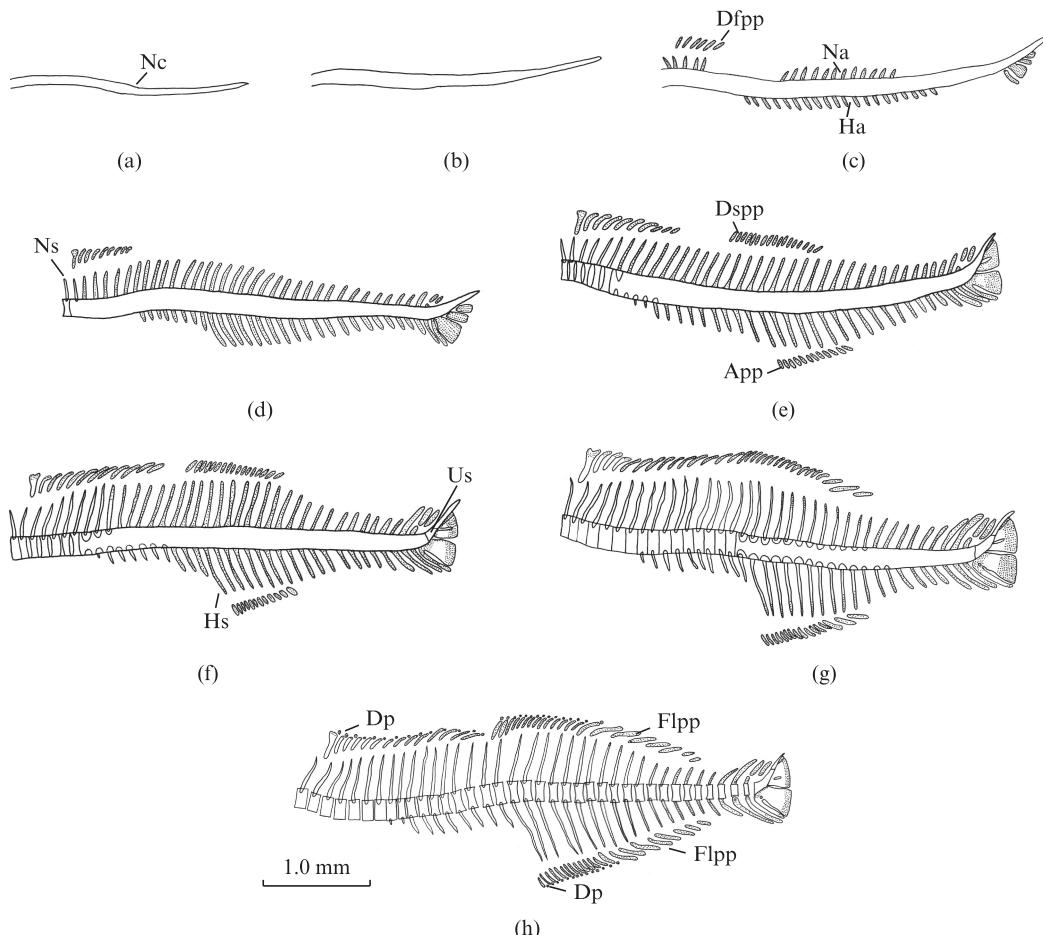
3.1 mm NL个体脊索透明,呈直管状,尚未分节(图3a);4.3 mm NL个体脊索末端上翘(图3b);4.9 mm NL个体髓弓在体前部和体中部出现,脉弓在体中部出现(图3c);5.3 mm NL个体髓弓和脉弓数量增多,第1、2枚椎椎体开始硬骨化,髓弓也开始硬骨化,末端愈合开始形成髓棘(图3d);6.0 mm SL个体硬骨环从体前部向尾部逐渐形成,髓弓和髓棘硬骨化数量增多(图3e);6.4 mm SL个体尾杆骨开始硬骨化,脉弓末端愈合形成脉棘(图3f);7.2 mm SL个体硬骨环数量增多,脉弓、脉棘开始硬骨化(图3g);8.0 mm SL个体所有椎体和尾杆骨进一步硬骨化,尾椎的部分髓弓髓棘、脉弓脉棘仍未硬骨化。椎骨总数为39枚,其中椎椎18枚,尾椎21枚(包含尾杆骨1枚,图3h)。

### 2.2 背鳍和臀鳍支鳍骨的发育

4.9 mm NL个体第一背鳍近端支鳍骨最先出现,仍为软骨质(图3c);5.3 mm NL个体第一背鳍近端支鳍骨数量增多,从体前部向尾部依次形成(图3d);6.0 mm SL个体第二背鳍和臀鳍近端支鳍骨出现(图3e);6.4 mm SL第一背鳍的第1、2枚近端支鳍骨开始硬骨化(图3f);7.2 mm SL个体第二背鳍和臀鳍近端支鳍骨数量增多,第一背鳍近端支鳍骨从底端向顶端,由体前部向尾部依次硬骨化(图3g);8.0 mm SL个体第一背鳍和臀

鳍出现远端支鳍骨,第一背鳍的第1~7枚近端支鳍骨基部硬骨化,其余近端支鳍骨均为软骨,此时可区分出小鳍支鳍骨。第一背鳍近端和远端支鳍骨各14枚,第二背鳍近端和远端支鳍骨各

14枚,背鳍小鳍近端支鳍骨8枚,远端支鳍骨1枚,臀鳍近端和远端支鳍骨14枚,臀鳍小鳍近端支鳍骨8枚(图3h)。



(a)体长3.1 mm;(b)体长4.3 mm;(c)体长4.9 mm;(d)体长5.3 mm;(e)体长6.0 mm;(f)体长6.4 mm;(g)体长7.2 mm;(h)体长8.0 mm;App. 臀鳍近端支鳍骨;Dfpp. 第一背鳍近端支鳍骨;Dp. 远端支鳍骨;Dspp. 第二背鳍近端支鳍骨;Flpp. 小鳍近端支鳍骨;Ha. 脉弓;Hs. 脉棘;Na. 髓弓;Nc. 脊索;Ns. 髓棘;Us. 尾杆骨。

(a) 3.1 mm NL; (b) 4.3 mm NL; (c) 4.9 mm NL; (d) 5.3 mm NL; (e) 6.0 mm SL; (f) 6.4 mm SL; (g) 7.2 mm SL; (h) 8.0 mm SL; App. Anal fin proximal pterygiophores; Dfpp. The first dorsal fin proximal pterygiophores; Dp. Distal pterygiophores; Dspp. The second dorsal fin proximal pterygiophores; Flpp. Finlet proximal pterygiophores; Ha. Haemal arches; Hs. Haemal spines; Na. Neural arches; Nc. Notochord; Ns. Neural spines; Us. Urostyle.

图3 黄鳍金枪鱼脊柱、背臀鳍支鳍骨的发育

Fig. 3 Development of vertebral column, dorsal and anal pterygiophores in *Thunnus albacares*

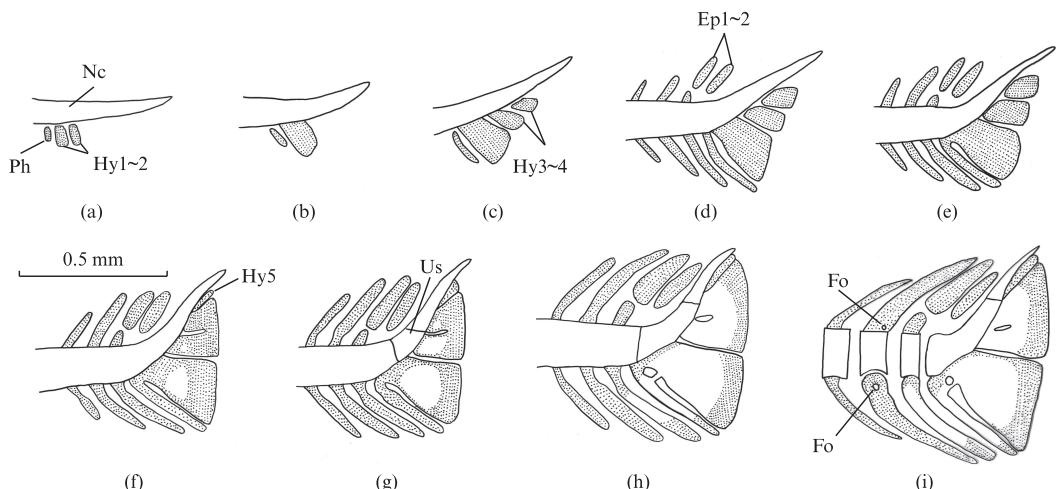
### 2.3 尾鳍支鳍骨的发育

4.4 mm NL个体脊索末端下方出现1枚侧尾下骨(Ph)和2枚尾下骨(Hy1、2, 图4a);4.5 mm NL个体第1和第2枚尾下骨愈合(Hy1+2, 图4b);4.9 mm NL个体第3和第4枚尾下骨(Hy3、4)出现(图4c);5.3 mm NL个体脊索末端上方出现2枚尾上骨(Ep1、2, 图4d);5.7 mm NL个体侧尾下骨与尾下骨1+2基部软骨联合(图4e);6.0 mm SL个体尾下骨末端与体轴垂直,第3和第4

枚尾下骨末端愈合(Hy3+4),第5枚尾下骨(Hy5)出现,尾下骨1+2、3中间出现骨化点,向四周硬骨化(图4f);6.4 mm SL个体尾下骨1+2、3+4进一步硬骨化,尾杆骨由底部向顶端硬骨化(图4g);7.2 mm SL个体侧尾下骨和最后一枚脉弓从中间向两端开始硬骨化,尾下骨3+4基部开始愈合,除第5枚尾下骨外,其余尾下骨进一步硬骨化(图4h);8.0 mm SL个体尾杆骨、侧尾下骨和尾下骨1+2、3+4进一步硬骨化,尾上骨1、2

和尾下骨5仍为软骨。最后3枚髓弓脉弓扁平，倒数第二枚髓弓和脉弓基部有孔。尾鳍共有尾

上骨2枚、尾杆骨1枚、侧尾下骨1枚、尾下骨5枚(图4i)。



(a)体长4.4 mm; (b)体长4.5 mm; (c)体长4.9 mm; (d)体长5.3 mm; (e)体长5.7 mm; (f)体长6.0 mm; (g)体长6.4 mm; (h)体长7.2 mm; (i)体长8.0 mm; Ep. 尾上骨; Fo. 孔; Hy. 尾下骨; Nc. 脊索; Ph. 侧尾下骨; Us. 尾杆骨。  
(a) 4.4 mm NL; (b) 4.5 mm NL; (c) 4.9 mm NL; (d) 5.3 mm NL; (e) 5.7 mm NL; (f) 6.0 mm SL; (g) 6.4 mm SL; (h) 7.2 mm SL; (i) 8.0 mm SL; Ep. Epurals; Fo. Foramen; Hy. Hypurals; Nc. Notochord; Ph. Parhypural; Us. Urostyle.

图4 黄鳍金枪鱼尾鳍支鳍骨的发育

Fig. 4 Development of caudal pterygiophores in *Thunnus albacares*

## 2.4 胸鳍支鳍骨的发育

3.1 mm NL个体软骨质的匙骨、乌喙骨-肩胛骨软骨出现(图5a);3.9 mm NL个体软骨质的上匙骨出现,匙骨从中间向两端硬骨化(图5b);4.3 mm NL个体软骨质的后颞骨出现,上匙骨完全硬骨化,匙骨底端仍为软骨(图5c);4.5 mm NL个体后颞骨完全硬骨化(图5d);5.3 mm NL个体出现已基本硬骨化的后匙骨,后颞骨顶端形成尖棘,底端逐渐增宽(图5e);5.7 mm NL个体支鳍骨原基中间出现2条明显的裂缝(图3f);8.0 mm SL个体支鳍条原基出现3条裂缝,匙骨变宽并向后弯曲,肩胛骨孔出现,肩胛骨和乌喙骨部分硬骨化(图5g)。

## 2.5 腹鳍支鳍骨的发育

4.9 mm NL个体腹鳍出现软骨质的细小支鳍骨原基(图6a);5.3 mm SL个体支鳍骨原基伸长(图6b);6.1 mm SL个体支鳍骨原基从中间向两端硬骨化(图6c);7.2 mm SL个体支鳍骨除两端外均已硬骨化,出现内侧翼和外侧翼(图6d);8.0 mm SL个体支鳍骨内侧翼和外侧翼扩大(图6e)。

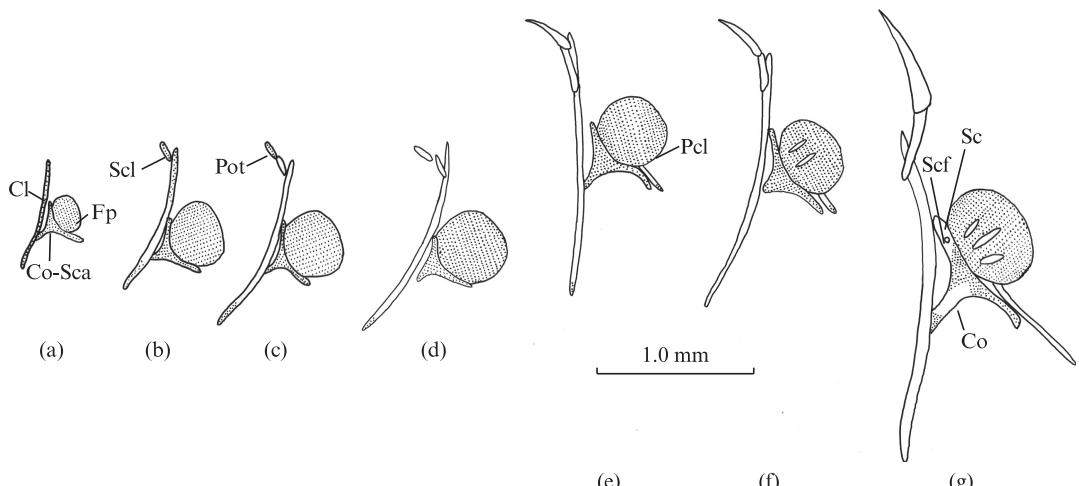
## 3 讨论

### 3.1 黄鳍金枪鱼仔鱼骨骼系统发育的适应性

仔稚鱼脊柱与附肢骨骼的发育与其形态结构、生态适应和功能需求以及运动方式密切相关<sup>[23]</sup>。胸鳍是黄鳍金枪鱼最早发育的鱼鳍,在前弯曲期个体可观察到匙骨、乌喙骨-肩胛骨软骨和支鳍骨原基,可为黄鳍金枪鱼提供基础的移动和平衡能力。进入弯曲期后,尾下骨和侧尾下骨最先出现,并发生愈合。同时脊索上也开始出现硬骨环、髓弓和脉弓,背臀腹鳍支鳍骨相继形成,游泳能力得到初步建立。后弯曲期随着个体增大,脊椎和各鳍支鳍骨数量增多,硬骨化程度进一步提高,且尾下骨进一步愈合,相似的尾下骨联合情况在大泷六线鱼(*Hexagrammos otakii*)<sup>[24]</sup>、大黄鱼(*Larimichthys crocea*)<sup>[25]</sup>、长颌拟飞鱼(*Parexocoetus mento mento*)<sup>[26]</sup>中也有被观察到。而在同属鲭科(Scombridae)的鲔(*Euthynnus affinis*)<sup>[27]</sup>和青干金枪鱼(*Thunnus tongol*)<sup>[28]</sup>成鱼中,所有尾下骨进一步愈合成一块。后弯曲期仔鱼最后3枚髓弓和脉弓扁平,可

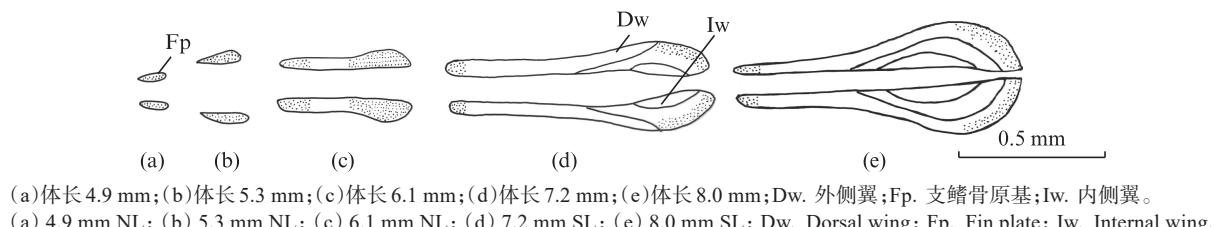
能为身体外侧肌肉组织的附着提供了更大的表面积和更强的基底<sup>[29]</sup>。这都为快速游泳提供了

强劲动力,提升个体的捕食效率,增加躲避天敌的能力,提高了早期阶段的存活率。



(a)体长3.1 mm;(b)体长3.9 mm;(c)体长4.3 mm;(d)体长4.5 mm;(e)体长5.3 mm;(f)体长5.7 mm;(g)体长8.0 mm;Cl. 匙骨;Co. 乌喙骨;Co-Sca. 乌喙骨-肩胛骨软骨;Fp. 支鳍骨原基;Pcl. 后匙骨;Pot. 后颞骨;Sc. 肩胛骨;Scf. 肩胛骨孔;Scl. 上匙骨。  
(a) 3.1 mm NL; (b) 3.9 mm NL; (c) 4.3 mm NL; (d) 4.5 mm NL; (e) 5.3 mm NL; (f) 5.7 mm NL; (g) 8.0 mm SL; Cl. Cleithrum; Co. Coracoid; Co-Sca. Coracoid-scapula cartilage; Fp. Fin plate; Pcl. Postcleithrum; Pot. Posttemporal; Sc. Scapula; Scf. Scapula foramen; Scl. Supracleithrum.

图5 黄鳍金枪鱼肩带的发育  
Fig. 5 Development of pectoral girdle in *Thunnus albacares*



(a)体长4.9 mm;(b)体长5.3 mm;(c)体长6.1 mm;(d)体长7.2 mm;(e)体长8.0 mm;Dw. 外侧翼;Fp. 支鳍骨原基;Iw. 内侧翼。  
(a) 4.9 mm NL; (b) 5.3 mm NL; (c) 6.1 mm NL; (d) 7.2 mm SL; (e) 8.0 mm SL; Dw. Dorsal wing; Fp. Fin plate; Iw. Internal wing.

图6 黄鳍金枪鱼腰带的发育  
Fig. 6 Development of pelvic girdle in *Thunnus albacares*

### 3.2 黄鳍金枪鱼仔鱼骨骼系统发育的独特性

脊椎骨是支撑鱼体的重要组成部分,不同鱼类的脊椎骨数目有所差异。同属鲭科的日本鲭(*Scomber japonicus*)31枚,狐鲣(*Sarda sarda*)50枚,大耳马鲛(*Scomberomorus cavalla*)51枚,沙氏刺鲅(*Acanthocybium solandri*)63枚<sup>[30]</sup>。金枪鱼属脊椎骨总数虽为39枚,但其躯椎和尾椎的组成也有一定差异:蓝鳍金枪鱼(*Thunnus thynnus*)、长鳍金枪鱼(*Thunnus alalunga*)有18枚躯椎和21枚尾椎,与黄鳍金枪鱼组成一致;但黑鳍金枪鱼有19枚躯椎和20枚尾椎<sup>[30]</sup>。本研究中最大个体(8.0 mm)的倒数第二枚髓弓和脉弓上的孔推测

是神经孔和血管孔(图3i),在体长20 mm以上的长鳍金枪鱼、黑鳍金枪鱼和蓝鳍金枪鱼的20多枚髓弓和10多枚脉弓上有类似孔<sup>[19]</sup>,体长更小的黑鳍金枪鱼仔稚鱼(体长5.1~17.6 mm)未能观察到这类孔<sup>[31]</sup>。黄鳍金枪鱼在体长8.0 mm就已经出现这两个孔,相比同属其他种类出现较早,也可能是个体具有缺陷,需要收集更多样本进行比较。不同种类的硬骨环形成方向也有所差异,本研究中黄鳍金枪鱼硬骨环是从体前部向尾部形成,尖吻鲈(*Lates calcarifer*)的脊柱则是由首尾两端向中间发生骨化<sup>[32]</sup>。刀鲚(*Coilia nasus*)是单一起点从中间向两侧进行<sup>[33]</sup>。大黄鱼<sup>[25]</sup>和棘头

梅童鱼(*Collichthys lucidus*)<sup>[34]</sup>则是多起点向两侧发生。有明银鱼(*Salanx ariakensis*)未能观察到硬骨环形成,可能受其“幼态持续”的影响<sup>[35]</sup>。

鱼类各鳍早期发育的顺序一般是胸鳍最先形成,其次是尾鳍,背臀鳍,腹鳍最后形成。例如,有明银鱼<sup>[35]</sup>、褐菖鲉(*Sebastiscus mamoratus*)<sup>[36]</sup>、鳓(*Siniperca chuatsi*)<sup>[37]</sup>、大黄鱼<sup>[25]</sup>、棘头梅童鱼<sup>[34]</sup>、矛尾虾虎鱼(*Chaeturichthys stigmatias*)<sup>[23]</sup>等。刀鲚胸鳍最先形成,而背臀鳍早于尾下骨的形成<sup>[33]</sup>。鲭科的日本鲭第二背鳍和臀鳍先于第一背鳍形成,第一背鳍支鳍骨由中间向两端形成;狐鲣、沙氏刺鲅、大耳马鲛和金枪鱼属的第一背鳍和臀鳍先于第二背鳍形成,第一背鳍支鳍骨由体前部向尾部形成<sup>[30]</sup>。黄鳍金枪鱼各鳍形成顺序依次是胸鳍、尾鳍、第一背鳍和腹鳍、第二背鳍和臀鳍、小鳍。腹鳍提前形成可能由于其栖息于大洋中,比起前后移动的需求,优先需要在流速较高洋流中保持平衡。此外小鳍作为鲭科的一大分类特征,其支鳍骨在后弯曲期仔鱼中表现出面积较大和间距更宽的特点,可与普通背臀鳍支鳍骨相区分。

作者声明本文无利益冲突。

## 参考文献:

- [1] 伍汉霖,钟俊生.中国海洋及河口鱼类系统检索[M].北京:中国农业出版社,2021: 1172.  
WU H L, ZHONG J S. Key to marine and estuarial fishes of China [M]. Beijing: China Agriculture Press, 2021: 1172.
- [2] ISSF. Status of the World fisheries for tuna [R]. Pittsburgh: International Seafood Sustainability Foundation, 2024: 40.
- [3] SAMBAH A B, NOOR'IZZAH A, INTYAS C A, et al. Analysis of the effect of ENSO and IOD on the productivity of yellowfin tuna (*Thunnus albacares*) in the South Indian Ocean, East Java, Indonesia [J]. Biodiversitas Journal of Biological Diversity, 2023, 24 (5): 2689-2700.
- [4] 刘志强,郭绍健,王禹程,等.中西太平洋金枪鱼延绳钓钩深度分布及其影响因素[J].上海海洋大学学报,2024,33(4):1020-1030.  
LIU Z Q, GUO S J, WANG Y C, et al. Hook depth distribution and influencing factors of tuna longline fishing in Western and Central Pacific Ocean [J]. Journal of Shanghai Ocean University, 2024, 33(4): 1020-1030.
- [5] 李秀超,林琴琴,陈作志,等.基于LeMaRns模型评估印度洋金枪鱼渔业对大洋生态系统的影响[J].上海海洋大学学报,2023,32(1):203-216.  
LI X C, LIN Q Q, CHEN Z Z, et al. Impact of Indian Ocean tuna fisheries on pelagic ecosystem based on LeMaRns model [J]. Journal of Shanghai Ocean University, 2023, 32 (1): 203-216.
- [6] 崔明远,麻秋云,田思泉,等.自然死亡和亲本补充关系对黄鳍金枪鱼资源评估的影响[J].海洋学报,2023,45(3): 40-51.  
CU M Y, MA Q Y, TIAN S Q, et al. Influence of natural mortality and stock-recruitment relationship on yellowfin tuna (*Thunnus albacares*) stock assessment [J]. Haiyang Xuebao, 2023, 45(3): 40-51.
- [7] 黄雯晓,符文雅,潘帅,等.南海黄鳍金枪鱼性腺发育形态观察和组织学研究[J].水产学杂志,2024, 37 (2): 98-106.  
HUANG W X, FU W Y, PAN S, et al. Morphology and histology characteristics of gonads of yellowfin tuna (*Thunnus albacares*) at different developmental stages in South China Sea [J]. Chinese Journal of Fisheries, 2024, 37(2): 98-106.
- [8] PACICCO A E, BROWN-PETERSON N J, MURIE D J, et al. Reproductive biology of yellowfin tuna (*Thunnus albacares*) in the northcentral U. S. Gulf of Mexico [J]. Fisheries Research, 2023, 261: 106620.
- [9] 闫路路,郭杰匀,赵超,等.不同规格黄鳍金枪鱼红肌转录组比较分析[J].海洋渔业,2024, 46(1): 1-10.  
YAN L L, GUO J Y, ZHAO C, et al. Comparative analysis of transcriptome in red muscles of *Thunnus albacares* of different sizes [J]. Marine Fisheries, 2024, 46(1): 1-10.
- [10] 戴世明,周胜杰,于刚,等.金枪鱼养殖研究进展[J].中国渔业质量与标准,2023, 13(1): 51-59.  
DAI S M, ZHOU S J, YU G, et al. Research progress on the culture of tuna [J]. Chinese Fishery Quality and Standards, 2023, 13(1): 51-59.
- [11] D'ALESSANDRO E K, SPONAUGLE S, COWEN R K. Selective mortality during the larval and juvenile stages of snappers (Lutjanidae) and great barracuda *Sphyraena barracuda* [J]. Marine Ecology Progress Series, 2013, 474: 227-242.
- [12] OVERTON A S, JONES N A, RULIFSON R. Spatial and temporal variability in instantaneous growth, mortality, and recruitment of Larval River herring in Tar-Pamlico River, North Carolina [J]. Marine and Coastal Fisheries Dynamics Management, and Ecosystem Science, 2012, 4(1): 218-227.
- [13] LEIS J M. Vertical and horizontal distribution of fish larvae near coral reefs at Lizard Island, Great Barrier Reef [J]. Marine Biology, 1986, 90(4): 505-516.
- [14] MATSUMOTO W M, AHLSTROM E H, JONES S, et al.

- al. On the clarification of larval tuna identification particularly in the genus *Thunnus* [J]. Fishery Bulletin, 1972, 70(1): 1-12.
- [15] KAJI T, TANAKA M, OKA M, et al. Growth and morphological development of laboratory-reared yellowfin tuna *Thunnus albacares* larvae and early juveniles, with special emphasis on the digestive system [J]. Fisheries Science, 1999, 65(5): 700-707.
- [16] BOEHLERT G W, MUNDY B C. Vertical and onshore-offshore distributional patterns of tuna larvae in relation to physical habitat features [J]. Marine Ecology Progress Series, 1994, 107: 1-13.
- [17] BROMHEAD D, SCHOLEY V, NICOL S, et al. The potential impact of ocean acidification upon eggs and larvae of yellowfin tuna (*Thunnus albacares*) [J]. Deep Sea Research Part II : Topical Studies in Oceanography, 2015, 113: 268-279.
- [18] KIM Y S, DELGADO D I, CANO I A, et al. Effect of temperature and salinity on hatching and larval survival of yellowfin tuna *Thunnus albacares* [J]. Fisheries Science, 2015, 81(5): 891-897.
- [19] POTTHOFF T. Osteological development and variation in young tunas, genus *Thunnus* (Pisces, Scombridae), from the Atlantic Ocean [J]. Fishery Bulletin, 1974, 72(2): 563-588.
- [20] OKIYAMA M. An atlas of the early stage fishes in Japan [M]. 2nd ed. Kanagawa: Tokai University Press, 2014: 1385-1046.
- [21] KENDALL JR A W, AHLSTROM E H, MOSER H G. Early life history stages of fishes and their characters [M]// MOSER H G, RICHARDS W J, COHEN D M, et al. Ontogeny and Systematics of Fishes. The American Society of Ichthyologists Herpetologists. Lawrence: Allen Press Inc., 1984: 11-22.
- [22] DINGERKUS G, UHLER L D. Enzyme clearing of alcian blue stained whole small vertebrates for demonstration of cartilage [J]. Stain Technology, 1977, 52(4): 229-232.
- [23] 黄洁丽, 胡芬, 宋小晶, 等. 矛尾虾虎鱼仔稚鱼脊柱及附肢骨骼系统的发育观察 [J]. 上海海洋大学学报, 2022, 31(1): 71-85.
- HUANG J L, HU F, SONG X J, et al. Development of the vertebral column and appendicular skeleton in larvae and juveniles of *Chaeturichthys stigmatias* [J]. Journal of Shanghai Ocean University, 2022, 31(1): 71-85.
- [24] 于超勇, 官曙光, 于道德, 等. 大泷六线鱼仔稚鱼脊柱及附肢骨骼系统的发育观察 [J]. 大连海洋大学学报, 2020, 35(1): 47-55.
- YU C Y, GUAN S G, YU D D, et al. Development of vertebral column and appendicular skeleton in larvae and juveniles of fat greenling *Hexagrammos otakii* [J]. Journal of Dalian Ocean University, 2020, 35(1): 47-55.
- [25] 王秋荣, 倪玥莹, 林利民, 等. 大黄鱼仔稚鱼脊柱、胸鳍及尾鳍骨骼系统的发育观察 [J]. 水生生物学报, 2010, 34(3): 467-472.
- WANG Q R, NI Y Y, LIN L M, et al. Development of the vertebral column and the pectoral and caudal fins in larvae of the large yellow croaker *Larimichthys crocea* (Richardson) [J]. Acta Hydrobiologica Sinica, 2010, 34(3): 467-472.
- [26] DASILAO J C, YAMAOKA K. Development of the vertebral column and caudal complex in a flyingfish, *Parexocoetus mento mento* (Teleostei: Exocoetidae) [J]. Ichthyological Research, 1998, 45(3): 303-308.
- [27] 周胜杰, 杨蕊, 于刚, 等. 鲔脊椎骨与附肢骨骼描述 [J]. 南方水产科学, 2022, 18(1): 84-89.
- ZHOU S J, YANG R, YU G, et al. Description of *Euthynnus affinis* vertebrae and appendages [J]. South China Fisheries Science, 2022, 18(1): 84-89.
- [28] 杨蕊, 于刚, 胡静, 等. 青干金枪鱼骨骼系统研究 [J]. 南方水产科学, 2021, 17(2): 36-43.
- YANG R, YU G, HU J, et al. Research on skeleton system of *Thunnus tonggol* [J]. South China Fisheries Science, 2021, 17(2): 36-43.
- [29] FIERSTINE H L, WALTERS V. Studies in locomotion and anatomy of scombroid fishes [J]. Memoirs of the Southern California Academy of Sciences, 1968, 6: 1-31.
- [30] POTTHOFF T, KELLEY S, JAVECH J C. Cartilage and bone development in scombroid fishes [J]. Fishery Bulletin, 1986, 84(3): 647-678.
- [31] POTTHOFF T. Development and structure of the caudal complex, the vertebral column, and the pterygiophores in the blackfin tuna (*Thunnus atlanticus*, Pisces, Scombridae) [J]. Bulletin of Marine Science, 1975, 25(2): 205-231.
- [32] 李仲辉, 杨太有. 大口黑鲈和尖吻鲈骨骼系统的比较研究 [J]. 动物学报, 2001, 47(s1): 110-115.
- LI Z H, YANG T Y. Studies on osteology of *Micropterus salmoides* (Lacepede) and *Lates calcarifer* (Bloch) [J]. Acta Zoologica Sinica, 2001, 47(s1): 110-115.
- [33] 陈渊戈, 夏冬, 钟俊生, 等. 刀鲚仔稚鱼脊柱和附肢骨骼发育 [J]. 上海海洋大学学报, 2011, 20(2): 217-223.
- CHEN Y G, XIA D, ZHONG J S, et al. Development of the vertebral column and the appendicular skeleton in the larvae and juveniles of *Coilia nasus* [J]. Journal of Shanghai Ocean University, 2011, 20(2): 217-223.
- [34] 吴尘艳, 唐鹏彦, 钟俊生, 等. 棘头梅童鱼仔稚鱼脊柱及附肢骨骼的早期发育 [J]. 中国水产科学, 2022, 29(10): 1500-1509.
- WU C Y, TANG P Y, ZHONG J S, et al. Development of vertebral column and appendicular skeleton in

- Collichthys lucidus* larvae and juveniles [J]. Journal of Fishery Sciences of China, 2022, 29(10): 1500-1509.
- [35] 王晓东, 何鸣笛, 曾娇, 等. 杭州湾北部明银鱼仔稚鱼脊柱和附肢骨骼发育研究[J]. 上海海洋大学学报, 2018, 27(6): 930-937.
- WANG X D, HE M D, ZENG J, et al. Development of the vertebral column and the appendicular skeleton in the larvae and juveniles of *Salanx ariakensis* in the north of Hangzhou Bay [J]. Journal of Shanghai Ocean University, 2018, 27(6): 930-937.
- [36] 邓平平, 严银龙, 施永海. 褐菖鲉仔稚鱼脊柱及附肢骨骼系统的早期发育[J]. 浙江大学学报(农业与生命科学版), 2018, 44(6): 735-742.
- [37] DENG P P, YAN Y L, SHI Y H. Early development of the vertebral column and appendicular skeleton in *Sebastiscus marmoratus* larvae [J]. Journal of Zhejiang University (Agriculture & Life Sciences), 2018, 44(6): 735-742.
- 田文斐. 鳜鱼骨骼早期发育以及主要摄食器官发育与摄食行为的适应性研究[D]. 上海: 上海海洋大学, 2012.
- TIAN W F. Study on the development of skeleton and feeding apparatus and their adaption to feeding in *Siniperca chuatsi* (Perciformes: Sinipericinae) [D]. Shanghai: Shanghai Ocean University, 2012.

## Development of vertebral column and appendicular skeleton in larvae of *Thunnus albacares*

WANG Xiaodong, LYU Lixin, ZHAO Hengquan, ZHONG Junsheng

(Shanghai Universities Key Laboratory of Marine Animal Taxonomy and Evolution, Shanghai Ocean University, Shanghai 201306, China)

**Abstract:** To understand its osteological development during early stage, 33 larval specimens of *Thunnus albacares* (9 preflexion larvae, 12 flexion larvae, 12 postflexion larvae, body length: 3.1–8.0 mm) were collected by horizontal trawling at the surface layer by a larval net (1.3 m in diameter, 0.5 mm in mesh size) in the Philippine Sea from August 15th to September 9th, 2022. The specimens were stained and cleared for both cartilage and bone to evaluate their vertebral column and appendicular skeleton development in *T. albacares*. The results show that the fins were developed in following sequence: pectoral fin, caudle fin, the first dorsal fin and pelvic fin, the second dorsal and anal fin, and finally, finlets. Centrum was formed in a posterior direction. Neural arches were formed in a posterior direction at anterior part of the body and in both anterior and posterior at the middle part of the body. Haemal arches proceeded both anteriorly and posteriorly. Hypural 1 and 2 were fused, and then jointed with the parhypural by cartilage. Hypural 3 and 4 were fused at both ends. Hypural 5 was dissociated. There are 18 precaudal vertebrates, 21 caudal vertebrates, 1 parhypural, 5 hypurals and 2 erpurals in 8.0 mm specimen. The fusions of parhypural and hypurals could enhance the swimming ability for *T. albacares*. This study can be used as a basis for the fish identification and provides an evidence for the formation of the drift mechanism of *T. albacares* larvae.

**Key words:** *Thunnus albacares*; osteological development; vertebral column; appendicular skeleton; staining and clearing technique of cartilage and bone