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黄海常见鱼类体内汞含量的种内和种间差异研究

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摘要:海洋鱼类体内的汞含量及其影响因素是研究汞在海洋生态系统中生物放大效应的关键问题.为探明黄海鱼类体内汞含量的种内差异和种间差异,于 2012 年 8~10 月采集了 9 种共 164 条常见经济野生鱼类,用直接测汞仪测定了鱼体肌肉中的汞含量(总汞),同时测量了每个样品的体长、体重,并分析了不同种鱼类的食性和营养级. 164 条鱼类样品肌肉中汞含量(以干重计)变化范围为 0.025~0.526 μg·g⁻¹,平均值为(0.124±0.096)μg·g⁻¹.同一种鱼类,汞含量与体长、体重显著正相关.营养级大于 2.8 的捕食性鱼类体内汞含量高于营养级小于 2.8 的滤食性 鱼类.此外,体重增长快的鱼类在生长稀释作用下,肌肉中的汞含量也较低.结果表明,体长、体重是影响黄海常见鱼类体内汞含量种内差异的重要因素,食性、营养级水平和体重增长速率的差异是影响黄海常见鱼类汞生物累积种间差异的重要因素.

关键词:汞; 鱼类; 生物累积; 生物放大; 黄海

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Inner- and Inter-Species Differences of Mercury Concentration in Common Fishes from the Yellow Sea

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Abstract: Mercury concentration in marine fishes and its influencing factors are the key problems in the study of mercury biomagnification in marine ecosystems. In order to understand the inner- and inter-species differences of mercury concentration in fishes from the Yellow Sea, a total of 164 marine wild fishes covering nine different species were collected from the area from August to October, 2012. Mercury (total mercury) concentration in fish muscle tissue was measured by a direct mercury analyzer. Body length and wet weight of each sample were also determined. Moreover, feeding habit and trophic level of different species were examined. Hg concentrations (dry weight) in the muscle tissues of the 164 individuals ranged from 0.025 μg·g⁻¹ to 0.526 μg·g⁻¹, with an average of (0.124 ±0.096) μg·g⁻¹. By an inner-species analysis, log₁₀ Hg concentration was significantly correlated to their body length and wet weight. Predator fishes with trophic level >2.8 were more readily to be contaminated by Hg than the filter feeder with trophic level <2.8. Furthermore, species with higher increasing rate of weight had lower Hg concentration in the muscle due to growth dilution. The results suggest that length and weight are the main factors affecting the inner- species difference of mercury concentration in common fishes from the Yellow Sea, while dietary preference, trophic level and increasing rate of weight are the main factors affecting the inter-species difference from the Yellow Sea.

Key words: mercury; fishes; bioaccumulation; biomagnification; the Yellow Sea

汞是备受世界关注的全球性污染物,对人类和生态系统有重要威胁. 在汞的物质循环过程中,最突出的方面是它在水生生态系统中的生物累积和生物放大^[1],致使食用海水或淡水鱼类成为人类暴露于汞的最普遍途径^[2]. 汞在鱼体内的生物累积和生物放大受鱼体大小^[3-5]、营养级水平^[1,5]和生活史^[6]等因素的影响. 此外,鱼体内的汞含量还存在地域差异^[7,8]. 因此,汞在水生生态系统中的含量和行为引起了学者们广泛的兴趣和重视. 与淡水鱼类和淡水生态系统相比,关于海洋鱼类和海洋生态系

统中汞污染的监测数据和系统研究较少^[9,10]. 我国 20 世纪 80 年代对近岸野生鱼类体内的重金属有过全国范围的调查研究^[11,12],之后对浙江沿岸、大亚湾和海南红树林区野生鱼类体内汞含量也有研究报道^[13-15]. 但关于海洋野生鱼类对汞的生物累积和

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生物放大的种内差异和种间差异研究较少,尚未见到黄海海区的相关报道.对于我国沿海居民而言,食用海洋鱼类是主要的汞暴露途径^[16].掌握不同种海洋鱼类体内的汞含量差异能为沿海居民汞暴露评估以及消费建议的提出提供依据.

汞在海洋食物链中有明显的生物放大效应^[17],明确海洋鱼类体内汞含量的种内差异和种间差异,是研究汞在海洋生态系统中生物放大效应的关键问题之一. 本研究的主要目的是通过对黄海多种常见经济鱼类体内汞含量及其体长、体重、食性和营养级的分析,探讨影响汞在黄海野生经济鱼类体内累积的生物学和生态学因素.

1 材料与方法

1.1 鱼类样品采集

2012 年 8 ~ 10 月,通过渔民捕捞采集到黄海常见的 9 种鱼类:黑棘鲷(Acanthopagrus schlegeli)、白姑鱼(Argyrosomus argentatus)、鲬鱼(Platycephalus indicus)、焦氏舌鳎(Arelicus joyneri)、少鳞鱚(Sillago japonica)、少鳞舌鳎(Cynoglossus oligolepis)、六丝矛尾鰕虎鱼(Chaeturichthys hexanema)、绿鳍马面鲀(Cantherines modestus)和小黄鱼(Pseudosciaena polyactis),每种收集了 14 ~ 22条(表 1).样品放置在 - 20℃内保存直至分析.

表 1 黄海 9 种常见鱼类食性、营养级、体长、体重及其体内的汞含量

Table 1 Feeding type, trophic level, body length, weight and mercury concentration in 9 common fish species from the Yellow Sea

中文名	拉丁名	食性 ¹⁾	营养级1)	数量	体长 ²⁾ /cm	体重 ²⁾ /g	汞含量 ²⁾
		(主要食物)					/μg•g ⁻¹
绿鳍马面鲀	Cantherines modestus	滤食(浮游生物)	2. 2 ~ 2. 79	14	15. 6 ± 4.6	117.9 ± 130.9	0.038 ± 0.020^{a}
少鳞舌鳎	Cynoglossus oligolepis	_	_	18	26.5 ± 1.8	109. 3 ± 21.5	0.046 ± 0.016^{ab}
六丝矛尾鰕虎鱼	Chaeturichthys hexanema	捕食	>2.8	22	13. 3 ± 1.5	26.2 ± 9.5	$0.072 \pm 0.022^{\rm abc}$
黑棘鲷	$A can tho pagrus\ schlegeli$	捕食(软体类、多毛类等)	> 2.8	16	19.9 \pm 0.7	186. 1 ± 19.0	$0.\ 081 \pm 0.\ 014^{\rm bc}$
小黄鱼	Pseudosciaena polyactis	捕食(甲壳类、磷虾和十足类)	>2.8	16	16.0 ± 1.0	69. $3 \pm 14. 1$	0. 084 $\pm0.$ 011 $^{\rm bc}$
焦氏舌鳎	Arelicus joyneri	捕食(幼鱼、软体类、甲壳类)	_	20	16. 2 ± 1.4	25.5 ± 8.2	$0.097 \pm 0.022^{\circ}$
鲬鱼	Platycephalus indicus	捕食(底栖动物)	> 2.8	16	26.3 ± 4.0	133. 8 ± 62.5	0. 178 \pm 0. 063 ^d
少鳞鱚	Sillago japonica	捕食(底栖动物)	>2.8	22	15. 2 ± 1.1	38.9 ± 8.6	$0.\ 197 \pm 0.\ 129^{d}$
白姑鱼	Argyrosomus argentatus	捕食(小鱼、无脊椎动物)	>2.8	20	12. 3 ± 0.7	33.4 ± 5.6	0.285 ± 0.055^{e}

1)信息主要来自 www. fishbase. org; 2)数值为平均值 ± 标准差; 上标字母表示经 Duncan 差异显著性检验结果,字母不同表示有显著种间差异 (P<0.05)

1.2 汞含量分析

实验室内测量每一条鱼样的标准体长和体重(湿重)后,用不锈钢解剖刀取背部白肌并将其冻干,同时称量每一个样品冻干前后的重量用于干湿重换算. 将冻干的肌肉研磨成粉末,每一个样品 称取约 0.02~g 用 DMA-80 直接测汞仪(Milestone Srl, Italy)测定汞含量(总汞). QC 和QA的方法为测定 20% 的平行样(SD < 10%)和测定参考物质 NIST SRM 1566b(Hg 含量: 37.1 ng·g⁻¹ ± 1.3 ng·g⁻¹)和 IAEA 2976(Hg 含量: 61.0 ng·g⁻¹ ± 3.6 ng·g⁻¹),测定过程中的回收率为 97%~103%. 本研究中的鱼体肌肉中的汞含量以干重含量表示,在与湿重数据比较时则换算成湿重含量.

1.3 数据统计

数据的统计分析采用 SPSS 16.0 (SPSS Inc., USA),数据取常用对数. 鱼体肌肉内的汞含量与体长、体重的相关性采用 Pearson 相关分析,当 *P* < 0.05 时认为显著相关. 鱼体汞含量的种间差异是否

显著采用方差分析(ANOVA)法和 Duncan 差异显著性检验法进行判断.

2 结果与讨论

2.1 鱼体内汞含量及其种内差异

2.1.1 鱼体内汞含量

采自黄海的 9 种常见经济鱼类肌肉中的汞含量在 0.025 ~ 0.526 $\mu g \cdot g^{-1}$ 之间, 平均值为 (0.124 ± 0.096) $\mu g \cdot g^{-1}$. 表 1 列出了每一种鱼类的特征及其体内的汞含量,各种鱼类的平均汞含量变化范围为 0.038 $\mu g \cdot g^{-1}$ (绿鳍马面鲀)至 0.285 $\mu g \cdot g^{-1}$ (白姑鱼). 差异显著性检验结果表明,白姑鱼、少鳞鱚和鲬鱼(0.178 ~ 0.285 $\mu g \cdot g^{-1}$)的汞含量显著高于其它鱼类(0.038 ~ 0.097 $\mu g \cdot g^{-1}$),绿鳍马面鲀的汞含量(0.038 $\mu g \cdot g^{-1}$)显著低于上述 3 种鱼类和焦氏舌鳎、小黄鱼、黑棘鲷(0.081 ~ 0.285 $\mu g \cdot g^{-1}$).

鱼体中的汞绝大部分是以甲基汞的形式存在的^[18],这与一些海洋贝类(如:牡蛎)的状况不同^[19].本研究所有样品的汞含量(以湿重计)均低

于我国水产品汞的限量标准(肉食性鱼类为甲基汞 $1.0 \, \mu g \cdot g^{-1}$,其他鱼类为甲基汞 $0.5 \, \mu g \cdot g^{-1}$) ^[20] 和世界卫生组织的限量标准 $0.50 \, \mu g \cdot g^{-1}$ (表 2).

与历史资料相比(表 2),目前黄海野生经济鱼 类体内的汞含量低于1989年的水平.与20世纪80 年代初各岸段的研究结果相比,除略高于山东岸段外,均低于其他岸段.与其他海区相比,除高于大亚湾外,均低于其他海区.尽管对不同种类鱼类的研究得出的结果有所差异,但总体而言,黄海野生经济鱼类体内的汞含量处于较低水平.

表 2 中国近海野生经济鱼类体内的汞含量比较(以湿重计算)/µg·g-1

Table 2 Comparison of mercury concentration in wild economic fish species in coastal areas of China (wet weight)/µg·g⁻¹

年份	海区	部位	平均值	变化范围
	河北岸段	整体	_	0. 020 ~ 1. 34
	天津岸段		_	0. 023 ~ 0. 116
	山东岸段		_	0.006 ~ 0.082
20 世纪 80 年代初[11]	浙江岸段		_	0.04 ~ 1.10
	福建岸段		_	0.016 ~ 0.195
	广东、海南岸段		_	0. 027 ~ 0. 045
	广西岸段		_	0. 024 ~ 0. 75
	渤海	肌肉	0.06	0. 02 ~ 0. 09
1989 年 ^[12]	黄海		0. 19	0.05 ~ 0.32
1989 4	东海		0.07	0.00 ~ 0.21
	南海北部		0. 19	0. 01 ~ 0. 36
2001、2007年[14]	大亚湾	肌肉	0. 019	0. 002 ~ 0. 050
2006年[13]	浙江	肌肉	0.047	0.008 ~ 0.084
2009年[15]	海南东寨港红树林区	肌肉	0.068	0. 035 ~ 0. 155
2012 年(本研究)	黄海	肌肉	0.026	0.005 ~ 0.113

2.1.2 鱼体内汞含量与体长、体重的相关关系

本研究采集的黄海9种常见鱼类的标准体长和 体重的变化范围分别为 11.2~32.4 cm 和 13.3~ 466.3 g. 除了黑棘鲷,其余种类的体长和体重均显 著相关(包括幂函数和线性相关,P<0.0001),见 图 1. 鱼体肌肉中汞含量和鱼类体长、体重(取对 数)的相关分析结果表明,鲬鱼、少鳞鱚和绿鳍马面 鲀肌肉中的汞含量与体长、体重呈显著正相关(P< 0.0001),焦氏舌鳎和少鳞舌鳎肌肉中的汞含量与 体长呈较显著的正相关(P < 0.05,图 2、图 3). 黑 棘鲷、白姑鱼和小黄鱼体内汞含量与体长相关性不 显著,可能与所采样品的体长差异较小(变异系数 CV 值为 3.75~6.50) 有关, 它们是所采集的 9个种 类中个体间体长差异最小3种,其它种类体长 CV 值在 7.47~29.67 之间. 而六丝矛尾鰕虎鱼虽然个 体间体长差异较大(CV 值为 10.94),但其体内汞含 量与体长的相关性不显著,其原因有待进一步研究. 此外,鲬鱼和绿鳍马面鲀是采集到的个体间体重差 异最大的种类, CV 值分别为 46.70 和 111.04, 其体 内汞含量与体长有显著正相关关系. 其余种类体重 的 CV 值在 9.93~36.06 之间,这些种类中只有少 鳞鱚体内汞含量与体重(CV 值为 22.24)呈正相关. 体重差异较小是影响汞含量和体重变化之间关系分

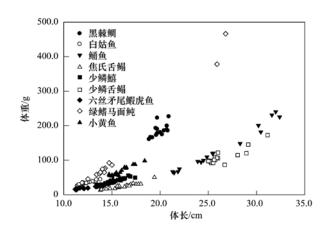


图 1 黄海 9 种常见鱼类体长与体重的关系

Fig. 1 Relationship between the body length and body weight for 9 common fish species in the Yellow Sea

析的因素之一,其它因素有待进一步研究.

2.1.3 体长、体重对鱼体内汞含量的影响

在本研究中,有5种鱼体内的汞含量与其体长呈显著的正相关,3种鱼体内的汞含量与其体重呈显著的正相关.这与前人的研究结果表明鱼体内的汞含量随鱼体的增大而增加一致(体长和体重)^[5,22,23]. Storelli等^[24]报道了地中海剑鱼(Xiphias gladius)和蓝鳍金枪鱼(Thunnus thynnus)体内的汞含量与其个体大小显著相关. Walters等^[25]指出鱼

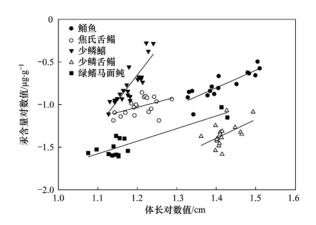


图 2 黄海 5 种常见鱼类肌肉中汞含量对数值与标准体长对数值的关系

Fig. 2 Relationships of log-transformed mercury concentrations in 5 common fish species with the log-transformed body lengths in the Yellow Sea

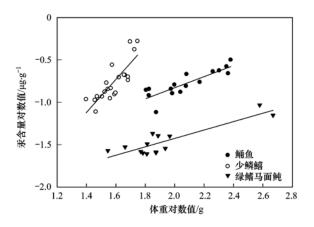


图 3 黄海 3 种常见鱼类肌肉中汞含量对数值与体重对数值的关系

Fig. 3 Relationships of log-transformed mercury concentrations in 3 common fish species with the log-transformed body weights in the Yellow Sea

体的大小和营养级能很好地指示鱼体内的汞含量水平,个体大的顶级捕食者体内汞含量最高. 本研究表明,体长和体重是黄海常见鱼类体内汞含量种内差异的重要因素.

关于体长和体重对同种鱼类体内汞含量的影响,一种可能的解释是在鱼类的生长过程中,对汞的吸收速率大于排泄速率,导致即使食物中汞的含量不变,鱼体内的汞含量仍然会随着个体的增长而增加^[18,26].最近,Dang等^[27]利用黑鲷(Acanthopagrus schlegeli)幼体研究了海洋鱼类体内汞含量随个体增大而升高的生物动力学因素.他们定量计算了关键的生物动力学参数,包括有机汞(甲基汞)和无机汞的溶解态吸收速率常数、食物相同化效率、排泄速率常数以及鱼体生长速率常数随鱼体个体大小的变

化. 其中,鱼体的生长速率和汞的排泄速率的差异能很好地解释鱼类个体大小与其体内汞含量的关系. 随着鱼类个体的增大,鱼类的生长速率和汞的排泄速率下降,导致大个体鱼类体内累积的汞含量较高. Trudel 等^[28]也报道了汞的排泄速率与鱼类的个体大小呈负相关关系. 此外,鱼类生长过程中,会出现食性转换的过程,使其营养级升高,从而导致体内的汞含量增加^[29].

2.2 鱼体内汞含量的种间差异

2.2.1 食性和营养级对鱼类体内汞含量的影响

鱼体内汞含量的变化与其食性有关. 一方面, 本研究中不同种类的鱼类食性不同,包括捕食和滤 食两种类型,主要食物种类有浮游生物、底栖动物、 甲壳类、软体类、多毛类和鱼类等. 其中,滤食性鱼 类(如绿鳍马面鲀,0.038 μ g·g⁻¹) 明显低于捕食性 鱼类(如黑棘鲷、白姑鱼、鲬鱼、少鳞鱚、六丝矛尾 鰕虎鱼和小黄鱼)体内汞含量(0.072~0.285 μg·g⁻¹). 以浮游生物为主要食物的鱼类(绿鳍马面 鲀,0.038 μg·g⁻¹) 明显低于以鱼类、底栖动物为主 要食物的鱼类(白姑鱼、鲬鱼、少鳞鱚)体内汞含量 (0.178~0.285 μg·g⁻¹). 上述结果表明, 汞对鱼类 的暴露途径主要是由食性决定的营养级. 对河口和 海洋中的鲸研究表明,食性的种间差异影响其对汞 的累积^[30]. Hall 等^[31]研究指出: 鱼类体内汞的含量 与其食物种类密切相关,鱼类的食性转换也会影响 其体内的汞含量.

对于鱼类而言,食物中汞的吸收占了总汞吸收的 90% ^[26],不像贝类(如:牡蛎)会从海水中吸收大量的无机汞^[19]. Hall 等^[31]研究表明鱼类体内汞的累积主要来自食物中的吸收. 海水鱼类对食物中甲基汞和无机汞的同化效率分别在 56% ~ 100% 和 5% ~ 51% 之间^[18,27,32,33],并受食物种类的影响^[18,32].

很多研究证实了汞在海洋食物链中的放大效应. 如 Campbell 等^[34] 研究发现汞在北极的 Northwater Polynya 海区的食物网中有生物放大效应,鱼体肌肉中汞的含量与氮同位素丰度 δ¹⁵ N (表征营养级的高低)呈显著正相关关系. 近期, Coelho 等^[35] 利用氮同位素的研究证实了汞在受汞污染的河口区有明显的生物放大. 此外,有研究表明营养级较高的鱼类对汞的累积速率较高^[26]. 汞在海洋食物链中放大与生物体对食物中汞的吸收效率大于排泄效率是其中的重要原因^[36]. 本研究中,营养级高于 2.8 的黑棘鲷、白姑鱼、鲬鱼、少鳞鱚、六丝

矛尾鰕虎鱼和小黄鱼体内的总汞含量 $(0.072~0.285~\mu g \cdot g^{-1})$ 高于营养级小于 2.8 的绿鳍马面鲀 $(0.038~\mu g \cdot g^{-1})$,表明营养级对鱼体类汞含量有重要影响,汞在黄海常见鱼类体内有生物放大效应.

2.2.2 体重增长速率对鱼类体内汞含量的影响

一些鱼类的快速生长可以对体内的汞含量形成生长稀释效应[5.37]. Balshaw 等[38]研究发现养殖的蓝鳍金枪鱼(Thunnus maccoyii)体内的汞含量低于野生的蓝鳍金枪鱼,主要与养殖过程中的生长稀释作用有关,养殖 136 d 后由于生长稀释作用,汞含量从 $0.51~{
m mg\cdot kg^{-1}}$ 下降至 $0.33~{
m mg\cdot kg^{-1}}$. 本研究中,各种鱼类体重随体长的增加速率(用体重-体长斜率 S 表示)的变化范围在 $5.43\sim28.09$ 之间,平均值为 12.2. 其中,绿鳍马面鲀体重增加最快(S=28.09),其体内的汞含最低;而白姑鱼、少鳞鱚和焦氏舌鳎体重增加较慢(S<7.5),体内的汞含量也较高.这一结果表明,体重增加的快慢也可能是影响黄海常见鱼类体内汞含量的因素之一:体重快速增加对鱼体内的汞含量有一定稀释作用,而体重增加缓慢则有利于汞在鱼体内的累积.

3 结论

- (1) 对黄海 9 种常见鱼类体内的汞含量及其种内和种间差异进行了研究. 结果表明,体长、体重变化是影响黄海常见鱼类体内汞含量种内差异的重要因素,而食性、营养级和体重的增长速率是影响其种间差异的重要因素.
- (2)对于同一种鱼类而言,体内汞含量随体长、体重的增加而增加.对于不同种类的鱼类而言,捕食性鱼类体内的汞含量高于滤食性鱼类,以鱼类和底栖动物为主要食物的鱼类体内汞含量高于以浮游生物为主要食物的鱼类.
- (3) 营养级高的鱼类体内汞含量较高,表明汞 在黄海鱼类体内有生物放大效应. 此外,体重的快 速增长对鱼体内的汞含量有一定的稀释作用.
 - (4) 黄海常见的9种鱼类未见受到汞的污染.

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