Ichthyol Res (2011) 58:291–294
DOI 10.1007/s10228-011-0220-8

NEWS AND COMMENTS

Are there habitat salinity markers of the Sr:Ca ratio in the otolith of wild diadromous fishes? A literature survey

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Received: 2 July 2010 / Revised: 30 March 2011 / Accepted: 7 April 2011 / Published online: 12 May 2011

Diadromous fishes may inhabit quite different water environments during their different life history stages. However, it is very difficult to precisely monitor these spatial and temporal dynamics because of the limitations of the most current research methods (e.g., catch analysis, biotelemetry, tagging). The basic water environments for fish can be categorized according to their salinity: fresh water, brackish water or seawater. The otoliths are calcified structures primarily composed of calcium carbonate (>90%) and located within the fish inner ear. They can be utilized as environmental markers because of their chemical properties such as the chronological signature in its concentric rings. The ambient environmental scalars and other characteristics in their isotopic and elemental composition (like a fingerprint) remain unmetabolized after deposition; they are derived from the habitat water, and the complete preservation of both spatial and temporal information in their aragonite mineralogy (Secor and Rooker 2000; Thorrold et al. 2001). Otolith microchemistry of trace elements is proving to be a powerful tool in reconstructing the migration chronology of diadromous teleosts in fresh water, estuarine and saltwater habitats (Campana 1999). Teleost fishes have three pairs of otoliths—the sagittae, lapilli and asterisci. The sagittae are usually chosen for element analysis because they are the largest of the three pairs. More recent studies have concentrated efforts on a smaller number of elements, including Ca, Sr, Mg, Mn, Ba and Pb (Thorrold and Swearer 2009). These elements, which are assimilated from the ambient water, accumulate in the body of the fish, including hard tissues including the otoliths. The otolith Sr:Ca ratio of concentrations has been especially used to describe diadromous migrations. Interestingly, Farrell and Campana (1996) reared Nile tilapia (*Oreochromis niloticus*) in fresh water and artificially enhanced Sr:Ca conditions to compare the incorporation of Sr and Ca from radioisotope-labeled food and water. Strontium and Ca in the otoliths were primarily derived from water (through gill uptake), with 75% of Ca and 88% of Sr derived from water rather than from food. Similarly, 83% of Sr in otoliths was derived from the surrounding water in marine species (Walther and Thorrold 2006). Consequently, patterns of Sr/Ca variability in fish otoliths have been widely applied as tracers of movement between freshwater and marine habitats, with a direct relationship between Sr/Ca in the otoliths and the water, across a range of estuarine salinities (Kraus and Secor 2004a). However, because all of the validation otolith Sr:Ca ratios in concentration studies to date have been derived separately by different authors even using different analytical approaches, e.g., EPMA, LA-ICPMS, PIXE and ion microprobe, it is difficult to assess the applicability of these varying Sr:Ca ratio results for other fish species, and, moreover, if these Sr:Ca ratio data can be summarized to a similar tendency for the habitats of freshwater, brackish water or seawater for diadromous fishes. As a result, interspecific variation in Sr incorporation can only be surmised based on comparisons of published studies. To fill the gap, in this study we reviewed the Sr:Ca ratios of diadromous species reported in the literature so far.

Fresh water, brackish water and seawater present significantly different salinity regimes. Secor and Rooker (2000) summarized that the regimes for freshwater,

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Table 1 Review of mean Sr:Ca × 1,000 data in the freshwater, estuarine (brackish water) and seawater habitat phases of otoliths for diadromous fishes (weight percent ratio)

Species	Order	Freshwater	Brackish water	Seawater	Analytical method	Reference
Coilia mystus	Clupeiformes			8.1	EPMA	Yang et al. (2006)
Coilia nasus	Clupeiformes	1.7	4.3		EPMA	Yang et al. (2006)
Coilia nasus	Clupeiformes	1.6			EPMA	Yang et al. (2006)
Anchoa mitchilli,	Clupeiformes			7.4	EPMA	Secor and Rooker (2000)
Anchoa mitchilli	Clupeiformes	1.7	5.4		EPMA	Kimura et al. (2000)
Anchoa mitchilli	Clupeiformes	1.3				Summarized by Secor et al. (1995)[a]
Anguilla japonica	Anguilliformes	2.5	5	6	EPMA	Tsukamoto and Arai (2001)
Anguilla australis; *A. dieffenbachii*	Anguilliformes	2.5		6	EPMA	Arai et al. (2004a)
Anguilla japonica	Anguilliformes			6	EPMA	Tzeng et al. (2003)
Anguilla rostrata	Anguilliformes		5		EPMA	Jessop et al. (2002)
Anguilla japonica	Anguilliformes			5.1	EPMA	Tzeng et al. (2002)
Anguilla japonica	Anguilliformes			6.57	EPMA	Tzeng (1996)
Anguilla anguilla	Anguilliformes			3.3		Summarized by Secor et al. (1995)[a]
Anguilla rostrata	Anguilliformes	0.7		5.9		Summarized by Secor et al. (1995)[a]
Pogonias cromis	Perciformes	5.1		6.7	EPMA	Rooker et al. (2004)
Morone americana	Perciformes	2.5			EPMA	Kraus and Secor (2004b)
Morone americana	Perciformes	3.2	6.7		EPMA	Kraus and Secor (2004b)
Stizostedion lucioperca	Perciformes	1			EPMA	Kafemann et al. (2000)
Arripis trutta	Perciformes			4.6		Summarized by Secor et al. (1995)[a]
Trachurus declivis	Perciformes			11.4		Summarized by Secor et al. (1995)[a]
Nemadactylus macropterus	Perciformes			6.4		Summarized by Secor et al. (1995)[a]
Pseudolabrus tetricus	Perciformes			8.5		Summarized by Secor et al. (1995)[a]
Acanthopagrus butcheri	Perciformes			12		Summarized by Secor et al. (1995)[a]
Thyrsites atun	Perciformes			7.2		Summarized by Secor et al. (1995)[a]
Thunnus thynnus thnnus	Perciformes	2.4				Summarized by Secor et al. (1995)[a]
Nemadactylus macropterus	Perciformes			5.7		Summarized by Secor et al. (1995)[a]
Thunnus maccoyii	Perciformes			3.9		Summarized by Secor et al. (1995)[a]
Morone saxailis	Perciformes		5	10.5		Summarized by Secor et al. (1995)[a]
Morone americana	Perciformes	2.8	6.8	7.4	EPMA	Kerr et al. (2007)
Gasterosteus aculeatus	Gasterosteiformes		5.6		EPMA	Arai et al. (2003a)
Gasterosteus aculeatus	Gasterosteiformes	0.96			EPMA	Arai et al. (2003a)
Gasterosteus aculeatus	Gasterosteiformes	2.1			EPMA	Arai et al. (2003a)
Gasterosteus aculeatus	Gasterosteiformes	0.85			EPMA	Arai et al. (2003a)
Salvelinus leucomaenis	Salmoniformes	3		6	EPMA	Arai and Morita (2005)
Salangichthys microdon	Salmoniformes	7.6		26.9	EPMA	Arai et al. (2003b)
Oncorhynchus tshawytscha	Salmoniformes	2.5	5.9	19.2	Ion microprobe	Bacon et al. (2004)
Oncorhynchus mykiss	Salmoniformes		4.4		EPMA	Zimmerman and Reeves (2000)
Hucho perryi	Salmoniformes	4.6		6.36	EPMA	Arai et al. (2004b)
Hucho perryi	Salmoniformes	2.96			EPMA	Arai et al. (2004b)
Hypomesus nipponensis	Salmoniformes	4.21		6.94	EPMA	Katayama et al. (2007)
Salmo trutta	Salmoniformes			6.8		Summarized by Secor et al. (1995)[a]
Oncorhynchus mykiss	Salmoniformes	1.8		6.8		Summarized by Secor et al. (1995)[a]
Mugil cephalus	Mugiliformes	3		7	EPMA	Chang et al. (2004)
Abramis brama	Cypriniformes	3.6			EPMA	Kafemann et al. (2000)
Gadus morhua	Gadiformes	2				Summarized by Secor et al. (1995)[a]
Helicolenus papillosus	Scorpaeniformes			9.2		Summarized by Secor et al. (1995)[a]

Table 1 continued

Species	Order	Freshwater	Brackish water	Seawater	Analytical method	Reference
Platycephalus bassensis	Scorpaeniformes			6.1		Summarized by Secor et al. (1995)[a]
Neosebastes scorpaenoides	Scorpaeniformes			8.5		Summarized by Secor et al. (1995)[a]
Hoplostethus atlanticus	Beryciformes			8.1		Summarized by Secor et al. (1995)[a]
Galaxias argenteus	Osmeriformes			15	PIXE	David et al. (2004)
Osmerus mordax	Osmeriformes	3.8	7.8	11	LA-ICP-MS	Bradbury et al. (2008)
Mean ± SD		2.7 ± 1.5	5.6 ± 1.1	8.3 ± 4.5		

[a] The Sr:Ca × 1,000 data summarized by Secor et al. (1995) in this table are converted from molar ratio basis

estuarine and marine are 0–5, 5–25 and >25 ppt, respectively. In another study, Kraus and Secor (2004b) documented that the salinity of freshwater and oligohaline brackish habitats was <3 and 3–15 ppt, respectively, in the Patuxent River estuary, Maryland, USA. Surge and Lohmann (2002) believed that 34 ppt is a normal marine salinity. Although Sr uptake in otoliths of diadromous fish may be influenced to some degree by temperature, growth rate, age, diet and stress, the salinity of the ambient water is the most consistent and prominent factor influencing Sr uptake and may often mask the effects of other factors. Temperature and growth rate seem not to be major factors; likewise, age, stress and diet are likely unimportant (Howland et al. 2001). Actually, positive functional relationships between the otolith Sr:Ca ratio and habitat salinity were reported by Secor et al. (1995) in Japanese eel, by Tzeng (1996) in *Anguilla japonica* and by Zenitani et al. (2003) in *Engraulis japonicas*. In contrast, the relationship between Sr:Ca ratio and temperature has been reported as either negative, positive, non-existent (Pontual and Geffen 2004) or inconsistent (Kawakami et al. 1998; Pontual and Geffen 2004; Yang et al. 2006). In the up to date literature, we found that the mean Sr:Ca ratios (i.e., Sr:Ca × 1,000) of the 37 teleosts were highly variable, and most of them belonged to Clupeiformes, Salmoniformes, Anguilliformes, Mugiliformes, Perciformes, Gasterosteiformes, Cypriniformes, Gadiformes, Scorpaeniformes, Beryciformes and Osmeriformes. Nevertheless, it is noteworthy that the values of Sr:Ca × 1,000 are significantly different between the certain concentric zones in otoliths, reflecting the freshwater (mean ± SD, 2.7 ± 1.5), brackish water (5.6 ± 1.1) and seawater habitat (8.3 ± 4.5) phases of these aforementioned fishes (Kruskal-Wallis H test, $P < 0.01$; SPSS Inc., Chicago, IL) (Table 1). Similarly, Secor and Rooker (2000) once reported a significant difference ($P < 0.01$) in Sr:Ca × 1,000 among fish taxa collected from three different salinity regimes: freshwater 0.9, estuarine 2.3 and marine 3.4. The results of both Secor and Rooker (2000) and ours suggest that Sr:Ca × 1,000 among fishes from freshwater, brackish and sea habitats must be a significant difference, although Sr:Ca ratio studies to date have been conducted separately by different authors even using different analytical methods with known differences in performance from each other (Campana et al. 1997; Pontual and Geffen 2004). Noteworthily, the summarized Sr:Ca ratio results by Secor and Rooker (2000) were much lower than ours. In accordance with many recent studies, including our own (Table 1), the former seems to be too low, probably because limited literature was available at that time. Actually, research on otolith chemistry (including Sr, Ca) has increased quickly since the 2000s. Campana (2005) indicated that the papers on otoliths on annual age and growth accounted for 80% of all otolith papers before 1999, but then the portion dropped to 40%, while those of otolith chemistry, microstructure and non-aging application each accounted for 15–20% of the total between 1999 and the early months of 2004. We believe that Sr:Ca ratios are highly variable among species; nevertheless, the difference in mean data of Sr:Ca ratios may possibly be used as a reference to separate the otolithic salinity markers of freshwater, brackish water and seawater habitats of wild diadromous fishes, although these ratio data are reported by different authors who even use different analytical approaches. Future continuous studies involving more data on wild diadromous species are required to thoroughly understand the connection between the otolith Sr:Ca ratio and ambient salinity regime.

Acknowledgments This work was supported by the National Natural Science Foundation of China (grant no. 30871920) and 973 project (2010CB429005).

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