The Phylogeny of Atherinomorphs: Evolution of a Novel Fish Reproductive System

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Abstract

The fishes commonly known in English as silversides, rainbowfishes, phallostethids, killifishes, ricefishes, halfbeaks, needlefishes, flying fishes, and sauries were combined by Rosen (1964), into one taxon, now known as the Atherinomorpha, largely using osteological and reproductive characters. Subsequent reviews have supported atherinomorph monophyly, adding characters to the diagnosis. Today atherinomorphs are diagnosed as monophyletic by derived characters of the testis, egg, reproductive mode, circulatory system, jaw musculature, olfactory organ, and various parts of the skeleton including the ethmoid region of the skull, gill arches, pelvic girdle, among others. Support for monophyly of each of the three included taxa, now classified as the orders Cyprinodontiformes, Beloniformes, and Atheriniformes, and the relationships among them, varies in quantity and quality. During the past twenty years, reproductive and molecular data used to infer atherinomorph relationships have grown significantly. In general, molecular data support hypotheses based on morphology, and, in some cases, provide novel hypotheses and unique challenges to morphological data. A growing body of data indicates that all atherinomorphs share a unique testis-type that is correlated with an array of reproductive modifications such as coupling during mating, relatively long developmental period, sperm-bundle formation, internal fertilization, superfetation, embryo retention, diapause, delayed hatching, hermaphroditism, and live-bearung. Corroboration of an atherinomorph sister group may include identification of some unique aspects of this reproductive system in other taxa.

Resumen

Los peces comúnmente conocidos en inglés como: silversides, rainbowfishes, phallostethids, killifishes, ricefishes, halfbeaks, needlefishes, flying fishes y sauries fueron integrados por Rosen (1964) en un taxon ahora conocido como Atherinomorpha, utilizando esencialmente caracteres osteológicos y reproductivos. Revisiones posteriores han sostenido que Atherinomorpha es un grupo monofilético y han agregado otros caracteres a la diagnóstico. Hoy, los aterinomorfos están definidos como monofiléticos por características derivadas del testículo, huevos, formas reproductoras, sistema circulatorio, musculatura de la mandíbula, órgano olfatorio, y varias partes del esqueleto, incluyendo la región etmoidea del craneo, arcos branquiales, y cintura pélvica, entre otros. El carácter monofilético de cada uno de los tres taxa incluidos actualmente, clasificados en los órdenes Cyprinodontiformes, Beloniformes, y Atheriniformes, se define en sus relaciones entre ellos, con variaciones de cantidad y calidad. Durante los últimos veinte años, ha aumentado significativamente el uso de datos sobre reproducción y moleculares para inferir relaciones en los aterinomorfos. En general, datos moleculares apoyan hipótesis basadas en la morfología y, en algunos casos, sustentan hipótesis nuevas y únicas referentes a los datos morfológicos. Un número creciente de datos indica que todos los aterinomorfos tienen un tipo testicular único, correlacionado con una serie de modificaciones reproductivas, tales como el apareamiento, un periodo relativamente largo de desarrollo, formación de paquetes de espermatozoides, fertilización interna, superfetación, retención de los embriones, diapausa, eclosión demorada, hermafroditismo y viviparidad. Corroborar que algún grupo de otro taxa, esté emparentado con los aterinomorfos, puede incluir la identificación de alguno de estos aspectos del sistema reproductor.
Introduction

In 1964, Donn E. Rosen, then curator in the Department of Ichthyology, American Museum of Natural History, New York, published a monograph as a Bulletin of the American Museum of Natural History, in which he brought together three disparate groups of teleost fishes in one order, the Atheriniformes (Rosen, 1964). The three suborders in Rosen’s Atheriniformes were the Atherinoidei (the silversides, rainbowfishes, and phallostethids), the Cyprinodontoidei (the killifishes and ricefishes), and the Exocoetoidei (the sauries, needlefishes, halfbeaks, and flying fishes). Support of this taxon included evidence largely from two systems, osteology and reproductive biology, which Rosen described in an essay, as was common then, rather than enumerating putative synapomorphies. Skeletal characters that Rosen considered diagnostic of his Atheriniformes included a disc-shaped dorsal and ventral ossified mesethmoid and decoupling of the rostral cartilage from the ascending processes of the premaxillae. Reproductive characters included a large, demersal egg with long, adhesive chorionic filaments and large oil globules (Rosen, 1964:253-255).

The new taxon, classified as the series Atherinomorpha by Greenwood et al. (1966), was not accepted readily by all systematic ichthyologists. In particular, Gosline (1971, Fig. 28B) argued that Rosen had brought together fishes from different evolutionary grades that did not share an evolutionary history. Atherinoids (now classified as the order Atheriniformes following Dyer and Chernoff, 1996; Table 1) were considered by Gosline to be “higher teleosts” because they have characters such as two dorsal fins, both with anterior spines or thickened rays, and an I,5 pelvic-fin ray formula. In contrast, the Cyprinodontoidei and Exocoetoidei (Cyprinodontiformes and Beloniformes, following Greenwood et al., 1966) were considered by Gosline to be “intermediate teleosts.” Both have a single, soft-rayed dorsal fin and may have more than six pelvic-fin rays, among other characters, that they share with taxa that Gosline thought to be less advanced (see review by Parenti, 1993). Cyprinodontiformes and Beloniformes were not considered closely related by Gosline (1971), who postulated that they were derived from, or most closely related to the Beryciformes and Myctophiformes, respectively.

Monophyly of atherinomorphs and monophyly and relationships of the three included taxa was reviewed by Rosen and Parenti (1981) in conjunction with a phylogenetic analysis of Cyprinodontiformes by Parenti (1981). The first explicitly cladistic analyses of atherinomorph phylogeny were presented in these two papers. Atherinomorph monophyly was supported by ten characters, again largely those of the skeleton, but also including two reproductive characters (Rosen and Parenti, 1981:20), one of the egg (“a large demersal egg with long adhesive and short filaments and many lipid globules that coalesce at the vegetal pole”), and one of the testis (“the spermatogonia forming only at the blind end of the tubule near the tunica albuginea”).
Table 1.

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<td>Family Notocheiridae (including Isonidae)</td>
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<td>Infraorder Atherines</td>
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<td>Family Melanotaeniidae (including Bedotiidae, Pseudomugilidae)</td>
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<td>Family Atherionidae</td>
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<td>Family Atherinidae</td>
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<td>Order Cyprinodontiformes [= Cyprinodontoidea of Rosen, 1964]</td>
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<td>Suborder Aplocheiloidei</td>
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<td>Family Aplocheilidae</td>
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<td>Family Poeciliidae</td>
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<td>Order Beloniformes [not recognized by Rosen, 1964]</td>
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<td>Suborder Adrianichthyoidae [= Adrianichthyoidae of Rosen, 1964]</td>
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<td>Family Adrianichthyidae (including Horaichthyidae and Oryziidae)</td>
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The many, unique characteristics of the atherinomorph egg are correlated with reproductive and developmental modifications. Filaments are derived from the secondary or outer layer of the zona pellucida which is secreted by follicle cells (Wourms, 1976; Wourms and Sheldon, 1976; Loureiro and deSá, 1996). Filaments vary in number, shape, and relative length (e.g., Able, 1984; Collette et al., 1984; White et al., 1984; Loureiro and deSá, 1996). Oil globule number ranges from one to over 100 (White et al., 1984: table 93). The relatively long developmental period in both oviparous and viviparous taxa is correlated with direct development, that is, loss or reduction of a distinct larval stage, most notably in cyprinodontiforms and beloniforms (Rosen, 1964:253).

The long developmental period and relatively large, desiccation-resistant egg is correlated with the evolution of delayed hatching (Martin, 1999) or diapause (Wourms, 1972). Delay of hatching of fertilized eggs has been reported in the atheriniform grunions of the genus Leuresthes, and the cyprinodontiforms Fundulus heteroclitus, F. confluentus, and Adinia xenica (Martin, 1999). Delay of hatching in these taxa is facultative; fertilized, fully-developed eggs can hatch, but are stranded in relatively dry habitats and must await waves, tides, or rains to stimulate hatching (Martin, 1999; Griem and Martin, 2000). This is in contrast to fertilized eggs of annual killifishes, which undergo diapause and for which delay of hatching is obligatory (Wourms, 1972). Stranding of fertilized eggs out of water has been reported also in the Baja California endemic, Fundulus lima, by Brill (1982). Facultative delayed hatching of teleost eggs has been reported outside atherinomorphs only in the lower teleost osmeroid Galaxias maculatus (Martin, 1999).

The evolutionary relationship between facultative and obligatory delay of hatching in atherinomorphs is unknown. Phylogenetic analyses based on molecules (e.g., Murphy and Collier, 1997) or morphology (e.g., Costa, 1990, 1998a) have led to various, sometimes conflicting, conclusions concerning single or multiple origins of developmental diapause. A molecular phylogenetic analysis of the family Rivulidae by Hrbek and Larson (1999: Fig. 4) supported the hypothesis that diapause was present in two distantly related groups of South American killifishes. Rather than interpret the cladogram literally, they considered it unlikely that diapause had originated twice, but that presence or absence of diapause results from “...developmental switches between alternative stabilized pathways” (Hrbek and Larson, 1999:1200). This was said another way by Parenti (1981:364): “...the annual habit is no more than an exaggeration, due to extreme environmental fluctuations, of a capability of all cyprinodontiforms to survive stress that involves desiccation”. Now, with our increased knowledge of delayed hatching patterns, I would rewrite that sentence by substituting “atherinomorphs” for “cyprinodontiforms” (see also Parenti, 1993). Delayed hatching patterns of atherinomorphs, whether facultative or obligatory, may be homologous and represent another atherinomorph synapomorphy.

The testis character proposed as an atherinomorph synapomorphy by Rosen and Parenti (1981) had been described just the year before by Harry Grier and colleagues (Grier et al., 1980; Fig. 1) who reported this distinctive testis-type in 31 atherinomorph species representing each of the three orders. Since Grier et al. (1980), the atherinomorph testis has been reported or confirmed in a total of 79 atherinomorph species (Parenti and Grier, 2004), including the beloniform Adrianichthys Hropaichthys setnai (Grier, 1984), seven species of atheriniform phalostethids (Grier and Parenti, 1994), an anablepid, Jenynia multi- dentata (Martínez and Monasterio de Gonzo, 2002), the internally-fertilizing halfbeak genus, Zenarchopterus (Grier and Collette, 1987), and the viviparous halfbeaks, Dermogenys, Hemirhamphodon and Nonnorhamphus (Downing and Burns, 1995; Meisner and Burns, 1997a). A possibly similar testis-type in viviparous sur- sperches, family Embiotocidae, was noted by Grier et al. (1980) but dismissed a year later by Grier (1981).
Evolution of viviparity is considered independent in atherinomorphs and embiotocids (see Lydeard, 1993). The phylogenetic significance of reproductive characters in emiobtocids, including both egg and testis, are evaluated relative to those of atherinomorph fishes elsewhere in this volume (Grier et al., this volume). The derived testis and egg are correlated in atherinomorphs with a vast array of reproductive modifications including coupling during mating, relatively long developmental period, sperm-bundle formation, internal fertilization, superfetation, embryo retention, diapause, delayed hatching, hermaphroditism, and live-bearing. Understanding the phylogeny of atherinomorph fishes will be enhanced by an understanding of their derived reproductive modifications and evolution of this novel reproductive system.

The purpose of this paper is to review the current state of our knowledge of atherinomorph phylogeny, with a focus on live-bearing taxa, summarizing molecular and morphological cladistic analyses published during the past two decades. Some phylogenetic analyses of solely oviparous taxa are cited but not discussed in detail. It is not my goal to summarize all cladistic analyses of atherinomorph taxa, which is well beyond the scope of this review.

**Atherinomorph Monophyly**

Atherinomorph monophyly was reviewed by Parenti (1993) who listed 14 diagnostic characters, five of which were of reproduction and development (Fig. 2, node A). The atherinomorph testis-type and associated reproductive modifications remain among the strongest evidence for monophyly, as argued above.

Here, I add a fifteenth character to the atherinomorph diagnosis: absence of the saccus vasculosus, a hypothalamic circumventricular organ of unspecified function (Tsuneki, 1992). The saccus vasculosus has been reported to pro-

duce a parathyroid hormone-related protein in the perciform sea bream, *Sparus aurata* (Devlin et al., 1996). Approximately 200 teleost species, both freshwater and marine, representing all major teleost lineages, were surveyed by Tsuneki (1992) for presence or absence of the saccus vasculosus and extent of its development when present. A well-developed saccus vasculosus was considered to be a generalized condition, present in some Osteoglossiformes, Anguilliformes, and ostariophysans among lower teleosts, and Mugiliformes, Gasterosteiformes, Scorpaeniformes, Perciformes, Pleuronectiformes, and Tetradontiformes among higher teleosts. The saccus vasculosus is reduced or absent in a variety of taxa, including atherinomorphs, African cichlids, some anabantoids, and a synbranchid eel among higher teleosts.

The most “clear-cut” result of this survey, according to Tsuneki (1992:74), is that absence of the saccus vasculosus is characteristic of atherinomorphs, and I agree. Fifteen atherinomorphs surveyed, representing all three orders, from both freshwater and marine habitats unambiguously lack the saccus vasculosus. Its absence is proposed here as an atherinomorph synapomorphy.

A sixteenth atherinomorph synapomorphy, of the oocyte, was proposed and illustrated by Parenti and Grier (2004: Figs. 3,4). Atherinomorph yolk is fluid, rather than granular, throughout vitellogenesis.

**Atherinomorph Sister Group**

The Series Atherinomorpha was classified as sister to the Series Percomorpha by Rosen and Parenti (1981) without an explicit proposal of relationship to any particular percomorph taxon. In diagnosing atherinomorphs, Rosen (1964) made deliberate comparisons with taxa such as mullets (Mugilidae) or percopsiform fishes that had at one time been proposed as closely related to one or another atherinomorph order (see Parenti, 1993). In discussing atherinomorph sister-group relationships, Parenti (1993: Fig. 1c) could come to no firm conclusion, arguing that evidence linked atherinomorphs to paracanthopterygians on one hand and to percomorphs on the other.

The close relationship of mullets to atherinomorphs was proposed by Stiassny (1990) and explored further by Stiassny (1993) who, although she concluded that there was good evidence for a sister group relationship, discussed numerous characters that contradicted that proposal. Of seven characters in support of a mul-
let-atherinomorph sister-group relationship (Stiassny, 1993: Fig. 1), four were of the pectoral girdle, two of the branchial muscles, and one of the vertebral column. Three pelvic fin characters were considered to have reversed in atherinomorphs (via Stiassny and Moore, 1992). The study was not intended as an exhaustive review of acanthomorph relationships, however, because, for example, another reversal in atherinomorphs would be loss of transforming pyloric caeca.

The hypothesis of a close mullet-atherinomorph relationship was taken a step further by Johnson and Patterson (1993) who proposed a new taxon, the Smegmamorpha, to include synbranchoid eels, mastacembeloid eels, the new taxon, the Smegmamorpha, to include morph relationship was taken a step further by ctenoid scales (Roberts, 1993).

Rinomorphs would be loss of transforming cause, for example, another reversal in atherinomorph sister taxa. Broader surveys of morphology, as well as molecules, are needed to further test monophyly of smegmamorphs and evaluate the hypothesis of a sister group relationship of mullets and atherinomorphs.

Cyprinodontea

Relationships among the three groups of atherinomorph fishes were unspecified by Rosen (1964). Monophyly of each group and the relationships among them were considered by Rosen and Parenti (1981:21-23) who proposed a sister group relationship between Cyprinodontiformes and Beloniformes, together called Division II atherinomorphs. Four characters were proposed to support monophyly of Division II (Rosen and Parenti, 1981:21; Fig. 2, node B). A fifth character may be added from Li (2001:585): absence of a stomach, including absence of pyloric caeca and a pneumatic duct.

The sister group relationship between Cyprinodontiformes and Beloniformes has been corroborated (Stiassny, 1990; Saeed et al., 1994; Dyer and Chernoff, 1996; Wiley et al., 2000; Li, 2001). The relationship was recognized by Nelson (1984:214) who in his second edition of *Fishes of the World* synonymized the two orders in an expanded Cyprinodontiformes. This decision was reversed in the third edition (Nelson, 1994:264, with the three orders Atheriniformes, Beloniformes, and Cyprinodontiformes recognized without inter-ordinal relationships expressed). The current edition of *Fishes of the World* is used worldwide as a standard reference for teleost classification, however, and an enlarged order Cyprinodontiformes, including beloniforms, was incorporated into numerous publications, particularly during the decade between 1984 and 1994 (e.g., Tsuneki, 1992; Kottelat et al., 1993). The superorder Cyprinodontea was proposed by Dyer and Chernoff (1996) as a formal name for Rosen...
and Parenti’s (1981) Division II, the Cyprinodontiformes and Beloniformes, and is adopted here (Table 1).

**Cyprinodontiformes**

The first explicitly cladistic analysis of cyprinodontiform fishes was based largely on osteological characters (Parenti, 1981; Fig. 3). Cyprinodontiform monophyly was corroborated by six complex characters (Parenti, 1981: Fig. 9, node a), and it has been challenged only by Li (2001; see comments below under Beloniformes). One cyprinodontiform character of Parenti (1981), prolonged embryonic development, is discussed above as an atherinomorph synapomorphy (see also Parenti, 1993). A major conclusion of Parenti’s (1981) study that refuted earlier notions of cyprinodontiform relationships was that viviparity had evolved at least three times within the order, not once. That is, oviparous sister groups of each group of viviparous taxa were hypothesized. Also, cyprinodontiforms were divided into two monophyletic suborders, the Aplocheiloidei and Cyprinodontoidei. This proposal of relationships was tested by Meyer and Lydeard (1993; Fig. 4) using partial DNA sequences of the tyrosine kinase gene \textit{X-src}, an oncogene chosen in part because cyprinodontiforms of the genus \textit{Xiphophorus} have long been known to inherit melanomas (see Schartl, 1995). No non-cyprinodontiform taxon was used as an outgroup by Meyer and Lydeard, so their analysis was not a test of cyprinodontiform monophyly. Also, at least one pivotal taxon, the oviparous \textit{Oxyzygonectes}, sister to the viviparous \textit{Anableps} and \textit{Jenynsia} in the Anablepidae, according to Parenti (1981), was not included. Nonetheless, the maximum parsimony phylogenetic hypothesis of Meyer and Lydeard (1993) corroborated Parenti’s (1981) conclusions that viviparity had evolved at least three times within cyprinodontiforms, in anablepids, goodeids, and poeciliids. Further, the analysis recovered the controversial sister group relationship of the viviparous goodeids and their oviparous relatives, \textit{Empetrichthys} and \textit{Crenichthys} (see also Grant and Riddle, 1995).

Cyprinodontiforms were used as a test taxon by Parker (1997) to evaluate the consequences of combining morphological and molecular data in a phylogenetic analysis. Morphological characters described by Parenti (1981, 1984a) are listed and character states coded in a detailed appendix (Parker, 1997:184-185). Although this study was not intended as a thorough re-analy-
sis of Parenti’s (1981) hypothesis, some of Parker’s results anticipated those of other studies. For example, *Tomeurus*, the ovoviviparous poeciliine, had been considered primitive to viviparous poeciliines since Rosen and Bailey’s (1963) classic review, and this relationship was corroborated by Meyer and Lydeard (1993; Fig. 4). In contrast, a partitioned X-src dataset of first and second codon positions only, analyzed under maximum parsimony (Parker, 1997: Fig. 2), supported the sister group relationship of *Tomeurus* and *Cnesterodon*, a viviparous poeciliine, together considered derived, not basal, poeciliines. This relationship was corroborated by an array of synapomorphies in a parsimony analysis of morphological characters by Ghedotti (2000; Fig. 5), including neural arch of first vertebra open dorsally, lateral processes on ventral portion of seventh, eighth, and ninth proximal anal-fin radials in adult males present and in contact, and distal tip of the gonopodium with elongate, bony processes. These morphological characters were of course known to Rosen and Bailey (1963) who likely accepted the constraint that an ovoviviparous taxon such as *Tomeurus* was basal to a group of viviparous taxa. This constraint was relaxed by Parker (1997) and Ghedotti (2000) who independently recovered a novel hypothesis of relationships of *Tomeurus*.

Division of Cyprinodontiformes into two suborders, Aplocheiloidei and Cyprinodontoidae, was corroborated by Costa (1998a; Fig. 6) who re-analyzed killifish phylogenetic relationships using morphology. The hypothesis of Costa (1998a; Fig. 6) differs from that of Parenti (1981; Fig. 3) in the placement of Goodeidae as sister to Profundulidae, not Cyprinodontidae, and the resolution of the relationships of Valenciidae. Both studies used osteology as a principal source of data, but differed in interpretation of significance of character states of the premaxilla, among others. The sister group relationship of Goodeidae and Profundulidae was recovered also in the molecular hypotheses of Meyer and Lydeard (1993) and Parker (1997). The close relationships of fundulids, goodeids, and profundulids is reflected in the written classification of Cyprinodontiformes (Table 1).

Monophyly of each of the nine families recognized by Parenti (1981) was corroborated by Costa (1998a) and the terminal taxa of Meyer and Lydeard’s (1993; Fig. 4) hypothesis are also consistent with Parenti’s hypothesis. Monophyly of the Anablepidae and Poeciliidae (*sensu* Parenti, 1981) was corroborated in Ghedotti’s

Figure 5. Phylogenetic relationships among the poecilioid fishes, simplified from Ghedotti (2000: Fig. 20). Species listed are members of the subfamily Poeciliinae

Figure 6. Phylogenetic relationships among families of Cyprinodontiformes as proposed by Costa (1998a)

The genus Xiphophorus, the swordtails and platyfishes, serves as a model taxon in analyses of congruence of phylogenetic pattern with behavior, development, morphology, and molecules (see, for example, Basolo, 1991; Haas, 1993; Meyet et al., 1994, Marcus and McCune, 1999, and Morris et al., 2001).

Beloniformes

Beloniform monophyly was supported by seven synapomorphies (Rosen and Parenti, 1981:17), including absence of the interhyal bone, reduction or loss of the interarcual cartilage, presence of only a single, ventral hypohyal bone, modifications of the gill arch skeleton, as well as a distinctive caudal skeleton characterized by the lower caudal lobe with more principal rays than in the upper caudal lobe.

Beloniform relationships were reviewed by Collette et al. (1984; Fig. 7) who accepted a monophyletic Beloniformes including Rosen and Parenti’s (1981) proposal that ricefishes (family Adrianichthyidae) are more closely related to exocoetoids (families Exocoetidae, Hemiramphidae, Belonidae, and Scomberesocidae) than to cyprinodontiforms. This proposal has been criticized recently by Li (2001) who argued that adrianichthyoids are more closely related to Cyprinodontiformes than to exocoetoids. In particular, Li (2001) claimed that some characters proposed as diagnostic of Beloniformes sensu lato, although absent in the primitive cyprinodontiform suborder Aplocheiloidei, are present in the derived suborder Cyprinodontiformes. For example, Li (2001:584) rejected Rosen and Parenti’s (1981) beloniform synapomorphy of a single, ventral hypohyal because cyprinodontoids have a single hypohyal. If we accept cyprinodontiform monophyly, however, which is supported by a symmetrical caudal fin skeleton, absent in adrianichthyoids, and first pleural rib on the second, rather than
the third vertebra, among other characters, then similarities between cyprinodontoids and adrianichthyoids must be interpreted as convergent rather than indicative of close relationship. Cyprinodontiforms and beloniforms, sensu Rosen and Parenti (1981), are readily distinguished by their distinct caudal fin skeletons. Finally, both cyprinodontiforms and adrianichthyoids were characterized by Li (2001) as lacking elongate jaws, whereas Parenti (1987, 1989a) argued that the elongate jaws of the large-bodied adrianichthyoids of Sulawesi, some of which have been called ‘duck-billed’ represented additional support for their close relationship to exocoetoids. Despite rejection of Li’s (2001) hypothesis, I appreciate his comments as they call for continued critique of the monophyly of clades within the Atherinomorpha as recognized herein.

Higher-order beloniform sensu lato relationships were reviewed by Lovejoy (2000; Fig. 8) who combined data from nuclear and mitochondrial gene sequences with morphology in a total evidence analysis. The families Exocoetidae (flyingfishes) and Scomberesocidae (sauries) were considered monophyletic by both Collette et al. (1984; Fig. 7) and Lovejoy (2000; Fig. 8). The families Hemiramphidae (halfbeaks) and Belonidae (needlefishes), considered monophyletic by Collette et al. (1984), were hypothesized to be paraphyletic by Lovejoy (2000).

No non-beloniform taxon was included in Lovejoy’s analysis and a single adrianichthyid species (Oryzias matanensis) was an outgroup to the ingroup exocoetoids. Therefore, the analysis was not a test of beloniform or of exocoetoid monophyly. Further, some intriguing taxa were not included in the study, such as the southern African needlefish, Petalichthys, which remains in a “halfbeak stage” of development for a relatively long time before both upper and lower jaws become elongate (Collette et al., 1984:342; Boughton et al., 1991). Also missing was the hemiramphid Oxyporhamphus recently reclassified as a flyingfish, family Exocoetidae, based on a re-analysis of morphology (Dasilao et al., 1997). Nonetheless, Lovejoy’s (2000; Fig. 8) hypothesis offers a novel reinterpretation of traditional beloniform morphology and invites further study of the relationship between morphological and molecular data as used in phylogenetic analyses. Molecular sequences and morphology were combined in a total evidence analysis of phylogenetic relationships of New World needlefishes by Lovejoy and Collette (2001).

Monophyly of the internally-fertilizing halfbeaks, genera Zenarchopterus, Hemirhamphodon, Dermogenys, and Nomorhamphus, was supported by the morphological studies of Anderson and Collette (1991), Downing and Burns (1995), Meisner and Burns (1997b), Meisner and Collette (1999), and Meisner (2001). Petalichthys and Oxyporhamphus were included in a reanalysis of beloniform phylogeny by Lovejoy et al. (2004) and paraphyly of hemiramphids and belonids corroborated. The last three halfbeak genera are viviparous and together form a monophyletic group as corroborated by these analyses. A fifth genus, the monotypic Tondanichthys, described from the type series of ten specimens that does not include a mature male, is inferred to be internally fertilizing (Collette, 1995; Meisner and Collette, 1999).

Reproductive biology has been used to infer phylogenetic relationships among live-bearing halfbeaks. Dermogenys is diagnosed by large sperm bundles and intrafollicular development; whereas, Nomorhamphus is diagnosed by small sperm bundles and a long intraluminal developmental period (Downing and Burns, 1995; Meisner and Burns, 1997b; Meisner and Collette, 1999; Meisner, 2001). These generic limits are in contrast to those of Brembach (1991).

Ricefish females are known to carry bundles of fertilized eggs until hatching (Fig. 9), rather than depositing them on over-hanging vegetation or the substrate. Aquarium-maintained O.
nigrimas females reportedly carry large bundles of eggs, but deposit them among plants or on the substrate soon after spawning (Kottelat, 1990a:54). In spawning in open water, ricefishes are similar to the above mentioned Fundulus lima (Brill, 1982). Embryos in the clusters are relatively well developed, with large, well-formed eyes and pigmented bodies, and appear near hatching (Fig. 10). Because these fertilized eggs may be carried until hatching, Kottelat (1990a:62) proposed that ricefishes be considered a distinct reproductive guild for which he coined the term “pelvic brooders.” This represents one of the few cases of parental care in oviparous atherinomorphs. Females carrying clusters of fertilized eggs, long known in the medaka, Oryzias latipes (Yamamoto, 1975:7), has been reported in at least eight other ricefish species, O. dancena (Fig. 9), O. nigrimas (Kottelat, 1990a:54) X. oophorus (Kottelat, 1990a: Fig. 6), X. sarasinorum (Fig. 10), O. marmoratus (Kottelat, 1990b: Fig. 5), O. matanensis (Kottelat, 1990b:161), O. javanicus (BMNH 1970. 7.22:38-39), O. luzonensis (Blanco, 1947) and is likely to occur in others.

The Indian ricefish, Horaichthys setnai, is internally fertilizing and lays fertilized eggs (Kulkarni, 1940). Internal fertilization and embryo retention is facultative in some ricefishes. Facultative embryo retention was reported in the medaka, Oryzias latipes, by Amemiya and Murayama (1931). One specimen of Adrianichthys kruyti, a large, pelagic ricefish from Lake Poso, Sulawesi, was reported to be hermaphroditic, having both testis and ovary, by Klie (1988, in Kottelat, 1990a:57). Much information available on the reproduction of the large
ricefishes is anecdotal (see Weber and de Beaufort, 1922; Kottelat, 1990a; Rosen, 1964). More detailed study of the reproductive morphology of the large Sulawesi ricefishes is needed to determine the extent of internal fertilization, embryo retention, and hermaphroditism in the Adrianichthyidae.

**Atheriniformes**

Since 1981, there have been several, solely morphological, phylogenetic analyses of atheriniform fishes (White et al., 1984; Stiassny, 1990; Saeed et al., 1994; and Dyer and Chernoff, 1996; Fig. 11). Monophyly of atheriniforms was not supported by Rosen and Parenti (1981) or Parenti (1984b), but it has been argued for strongly in these other studies.

Atheriniform monophyly was supported by two developmental characters by White et al. (1984:357): short preanal length of flexion larvae and a single row of melanophores on the dorsal margin of larvae. Eight adult characters were added to the diagnosis by Dyer and Chernoff (1996:1): vomerine ventral face concave, long A1 muscle tendon to lacrimal, two anterior infraorbital bones, pelvic-rib ligament, pelvic medial plate not extended to anterior end, and second dorsal-fin spine flexible.

This atheriniform diagnosis requires homoplasy within several characters. For example, newly hatched adrianichthyids also have a single row of dorsal melanophores (White et al., 1984:359). Number of anterior infraorbital bones ranges from one to three in atheriniforms (Dyer and Chernoff, 1996). The three anterior infraorbital bones of the rainbowfishes *Melanotaenia* and *Chilatherina* were considered evidence of their sister-group relationship by Dyer and Chernoff (1996:67), whereas Rosen and Parenti (1981) considered the character to be primitive for atherinomorphs. Outgroups of atheriniforms in Dyer and Chernoff’s (1996: Table 2) data matrix include representative cyprinodontiform and beloniform taxa and the mullet, *Mugil*. Given the strong support for atherinomorph monophyly and the tentative support for a mullet-atherinomorph sister group relationship, as argued above, additional acanthomorph outgroups may yield alternate interpretations of phylogeny when included in a parsimony analysis of either morphological or molecular data.

Despite the ambiguity in distribution of characters discussed above, I use the formal term order Atheriniformes for the included taxa because it is more popular than the vernacular “atherinoids.”

Phylogenetic analyses of atheriniform subgroups include an analysis of the internally fertilizing freshwater and coastal family Phallostethidae, proposed as sister taxon of the marine Dentatherina (Parenti, 1984b, 1989b). This sister group relationship was corroborated by Dyer and Chernoff (1996) who classified Dentatherina in an expanded Phallostethidae. Atheriniformes are oviparous, although report of facultative embryo retention would not be surprising. Phallostethids (*sensu* Parenti, 1989b) are internally fertilizing and lay fertilized eggs. Internal fertilization was reported in the brook silverside, *Labidesthes sicculus*, by Grier et al. (1990).

Other morphological phylogenies of subgroups of Atheriniformes include Chernoff (1986, menidiines), Saeed et al. (1989, Pseudomugilidae), and Dyer (1998, Atherinopsidae).

**Conclusions**

The series Atherinomorpha is a well-corroborated, monophyletic taxon. As for other such well-corroborated taxa, the list of characters diagnostic of the Atherinomorpha continues to grow (Rosen and Parenti, 1981; Parenti, 1993;
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...herein). Each of its included orders, the Cyprinodontiformes, Beloniformes, and Atheriniformes is monophyletic, although the quality and quantity of support for each is variable.

Molecular tests of morphological hypotheses of atherinomorph relationships agree, in large part. Where they differ, molecules present novel hypotheses of relationship, most notably in beloniforms (Lovejoy, 2000), and invite reinterpretations of our traditional understanding of morphological characters. Not all molecular analyses agree, however. Two phylogenetic hypotheses based on partial sequences of the oncogene, X-src, yielded different interpretations of relationships of the poeciliid Tomeurus. Notably, Parker’s (1997: Fig. 2) hypothesis of the sister group relationship of Tomeurus and Cnesterodon was corroborated in a reinterpretation of morphological data by Ghedotti (2000). Molecular and morphological hypotheses may each offer other and point to weak areas in the other analysis. The Cyprinodontiformes has been studied most intensively during the past twenty years; morphological and molecular analyses share repeated statements of relationship to such a degree that a stable classification of the order is within reach.

Monophyly of the order Atheriniformes has been supported by numerous morphological studies, most recently that of Dyer and Chernoff (1996). Interpretation of polarity of the characters used by Dyer and Chernoff (1996) to diagnose atheriniforms hinges on the choice of an atherinomorph outgroup, however. Their choice of mullets may be appropriate, but a broader range of outgroup taxa may yield other interpretations of atheriniform relationships. A molecular test of the Dyer and Chernoff (1996) hypothesis may reveal novel relationships as well. As for cyprinodontiforms and beloniforms, however, a molecular hypothesis of atheriniforms will not substitute for that based on morphology.

Atherinomorph fishes likely will continue to be studied broadly, especially as they include numerous model organisms, such as the poeciliids Xiphophorus, Poecilia, and Gambusia, the ricefishes Oryzias, as well as a wide range of live-bearing teleost fish taxa in the families Goodeidae and Anablepidae and other poeciliids. Phylogenetic hypotheses of atherinomorphs and their subgroups are among the most examined and re-examined within bony fishes, which makes their continued use as model organisms and their unique role in understanding evolution of fish reproduction even more justifiable.

Acknowledgments and abbreviations

I am indebted to the organizers, Mari Carmen Uribe, Raúl Pineda, Topiltzin Contreras and Harry J. Grier for inviting me to participate in the II International Symposium on Livebearing Fishes. Research on ricefish systematics was supported, in part, by NSF grant BSR 87-00351. Heok Hui Tan, National University of Singapore, photographed the ricefish in figure 8. Maurice Kottelat, Switzerland, lent specimens in his care and discussed ricefish systematics. Darrell Siebert allowed access to specimens at the BMNH. My colleagues, Ralf Britz, Bruce Collette, Carlos Figueiredo, Dave Johnson, Amy Meisner, Joe Nelson, and Melanie Stiassny read and provided helpful comments on earlier versions of the manuscript.


