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Control of air-breathing in fishes: Central and peripheral receptors

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ABSTRACT

This review considers the environmental and systemic factors that can stimulate air-breathing responses in fishes with bimodal respiration, and how these may be controlled by peripheral and central chemoreceptors. The systemic factors that stimulate air-breathing in fishes are usually related to conditions that increase the O_2 demand of these animals (e.g. physical exercise, digestion and increased temperature), while the environmental factors are usually related to conditions that impair their capacity to meet this demand (e.g. aquatic/aerial hypoxia, aquatic/aerial hypercarbia, reduced aquatic hidrogenionic potential and environmental pollution). It is now well-established that peripheral chemoreceptors, innervated by cranial nerves, drive increased air-breathing in response to environmental hypoxia and/or hypercarbia. These receptors are, in general, sensitive to O_2 and/or CO_2/H^+ levels in the blood and/or the environment. Increased air-breathing in response to elevated O_2 demand may also be driven by the peripheral chemoreceptors that monitor O_2 levels in the blood. Very little is known about central chemoreception in air-breathing fishes, the data suggest that central chemosensitivity to CO_2/H^+ is more prominent in sarcopterygians than in actinopterygians. A great deal remains to be understood about control of air-breathing in fishes, in particular to what extent control systems may show commonalities (or not) among species or groups that have evolved air-breathing independently, and how information from the multiple peripheral (and possibly central) chemoreceptors is integrated to control the balance of aerial and aquatic respiration in these animals.

1. Introduction

An adequate supply of O_2 to meet metabolic demands is essential for life of aerobic organisms; any impairment can compromise performance and even be fatal, depending upon the physiological adaptations of the species concerned. Water has a low capacitance for O_2, containing only a few milligrams per litre, and has low diffusion constants for dissolved gases, such that hypoxia can be a common condition in aquatic environments (Richards et al., 2009). Therefore, organisms that breathe water can often be challenged to meet their demands for O_2 (Carter, 1931; Rahn, 1966; Driedzic and Hochachka, 1978; Kramer and Mehegan, 1981; Kramer and McClure, 1982; Randall, 1982; Kramer, 1987; Diaz and Breitburg, 2009).

Air is much richer in oxygen and fishes were the first vertebrates to evolve adaptations to breathe air, the fossil record dates to the late Silurian, ~420 million years ago. This predates the conquest of land by the ancestors of tetrapods, which evolved from lobe-finned fishes (Sarcopterygii) that resembled the extant Dipnoi (Panchen, 1980; Little, 1983, 1990; Gordon and Olson, 1994; Long, 1995; Schultze and Trueb, 1991; Amemiya et al., 2013). Aquatic hypoxia or periodic emersion (caused by tidal oscillations or by unfavorable environmental conditions), are considered the two main circumstances that exerted evolutionary pressure for selection of aerial respiration in fishes (Inger, 1957; Johansen, 1970; Graham et al., 1978; Randall et al., 1981; Horn and Gibson, 1988; Sayer and Davenport, 1991; Graham, 1997). However, it is important to emphasize that these were probably not the only selective pressures involved in the evolution of air-breathing, because it is a very diverse adaptation found in over 40 families, such that it seems to have evolved independently on numerous occasions (Randall et al., 1981; Graham, 1997; Hsia et al., 2013). All air-breathing fishes are

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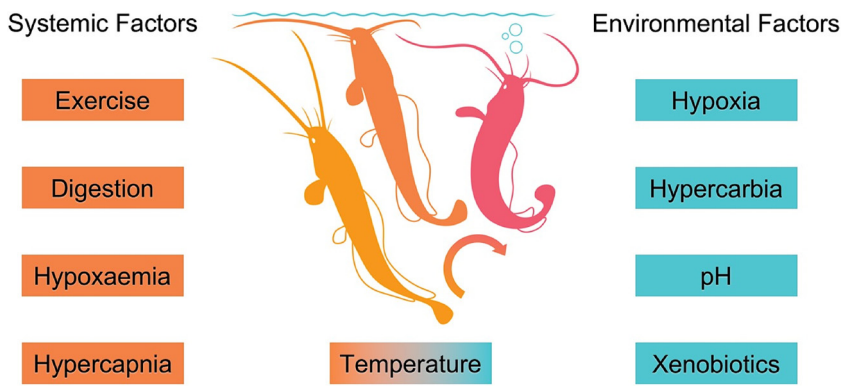

Fig. 1. Systemic and environmental factors with effects on air-breathing behavior in fishes. Note that temperature can be both a systemic factor and an environmental factor. The arrow indicate the chronological order of an air-breathing event.

'bimodal breathers', they possess gills that play a role in gas exchange and they vary in the extent to which they rely on air-breathing to meet their routine O_2 demands, from entirely 'obligate' to entirely 'facultative' (Johansen, 1970; Graham, 1997; Lefevre et al., 2014).

Aquatic surface respiration (ASR) is a common adaptation of unimodal water-breathing fishes, that apparently helps to maintain O_2 uptake and aerobic metabolism during aquatic hypoxia. It consists of rising to the surface to ventilate the gills with the uppermost layer of water in contact with air, where there is constant diffusion of gases from the atmosphere (Kramer and Mehegan, 1981; Kramer and McClure, 1982). This adaptation is a reflex triggered by low O_2 availability and is believed to have led towards the evolution of true air-breathing in fishes (Shingles et al., 2005; Florindo et al., 2006; Chapman and McKenzie, 2009; Richards, 2011). It is postulated that the ASR reflex may have favored the selection of air-breathing based on the following hypotheses: (1) ASR allowed individuals to survive in waters under severe hypoxia; (2) some individuals inadvertently came into contact with the air during ASR (e.g. by inhaling it), which provided conditions for O_2 uptake from the air across vascularized epithelia, making it possible to select them as air-breathing organs (ABO) (Burggren, 1982; Gee and Gee, 1995); and (3) ASR exposes the animals to predation, so individuals with the capacity to gulp and hold air could protect themselves from predators by temporarily returning to the depths, hence further favoring the evolution of adaptations for true aerial respiration (Kramer et al., 1983; Smith and Kramer, 1986; Gee and Gee, 1995; Shingles et al., 2005; Chapman and McKenzie, 2009).

Despite being a phylogenetically ancient specialization, aerial respiration retains great importance in the natural history of many extant fish species, especially in tropical freshwaters that can become hypoxic due to reduced O_2 capacitance at high temperatures (Rahn, 1966; Kramer et al., 1978; Graham, 1997; Diaz and Breitburg, 2009; Pörtner and Lannig, 2009), a condition that may be intensified by climate global change (Lehtonen, 1996; Diaz, 2001; Diaz and Breitburg, 2009). In addition to its importance in O_2-poor environments, air-breathing behavior in fishes can also supply O_2 to support aerobic activities such as exercise or digestion, although this has received less research attention than responses to hypoxia (Johansen, 1970; Gee and Graham, 1978; Stevens and Holeton, 1978; Dejours, 1994; Brauner et al., 1995; Graham, 1997; Seymour et al., 2004, 2007; McKenzie et al., 2012; Lefevre et al., 2014; Blasco et al., 2017).

Fishes possess specialized chemosensitive cells, located in the central and/or peripheral nervous system, capable of monitoring the partial pressure of O_2 (P_{O2}) or CO_2 (P_{CO2}), as well as the hydrogenionic potential (pH), in the blood and/or the environment (internally and/or externally oriented chemoreceptors) (see Hara, 1992; Milsom, 2012 for reviews). These chemoreceptors modulate a wide range of behavioral and physiological adjustments that favor the survival of fishes during situations of hypoxia/hypoxaemia (i.e. reduced levels of O_2 in the environment or in the body, respectively) and hypercarbia/hypercapnia (i.e. increased levels of CO_2 in the environment or in the body, respectively), and air-breathing behavior is a prime example (Smatresk et al., 1986; McKenzie et al., 1991a; Milsom et al., 2002; Florindo et al., 2004, 2006; Boijink et al., 2010; Lopes et al., 2010; Milsom, 2012; Zeraik et al., 2013; Belöo et al., 2015). There are differences in the location, distribution and orientation of these chemoreceptors among species, and their functions may vary depending on the specificity of these cells – such characteristics of fish chemoreceptors and their respective physiological influences have been previously reviewed by Gilmour (2001), Perry and Gilmour (2002), Gilmour and Perry (2006), Milsom (2012), Perry and Abdallah (2012), Porteus et al. (2012) and Zachar and Jonz (2012).

The number of studies on the role of chemoreceptors in controlling air-breathing in fishes is still modest, especially regarding central chemoreceptors. However, peripheral chemoreceptors appear to be more involved in air-breathing modulation than central chemoreceptors, as in many species studied to date the disruption of afferent nervous pathways attenuates or abolishes this behavior in response to aquatic hypoxia or hypercarbia (Hedrick et al., 1991; McKenzie et al., 1991a; Boijink et al., 2010; Lopes et al., 2010; Belão et al., 2015). Thus, given this overall context, this review evaluates current knowledge about systemic and environmental factors that stimulate air-breathing in fishes, and the role of chemoreceptors in the reflex control of this behavior.

2. Stimulators of reflex air-breathing responses

Several factors stimulate air-breathing behaviors in fishes, which can be classified as either "systemic" or "environmental" (Fig. 1). Systemic factors are states of the organism that increase O_2 demand for aerobic metabolism, in particular warming, exercise and digestion, which then stimulate overall ventilatory activity. Environmental factors, on the other hand, are external conditions that increase the animals' O_2 demand; challenge respiratory gas exchange, and/or damage the fragile epithelium of the gill lamellae. This includes warming, hypoxia, hypercarbia, pH and pollutants. In species that are obligate air-breathers such factors will alter the intensity of aerial respiration whereas, in facultative air-breathers, such factors can trigger the air-breathing behavior as well as modulate its intensity.

2.1. Systemic factors

The O_2 demands of fishes increase considerably during physical exercise, and this leads to an increase in air-breathing frequency in all species studied to date (Smatresk, 1988; Lefevre et al., 2014). Although this response would be expected in obligate air-breathers, it also occurs in all facultative species that have been studied, namely *Amia calva*,