GAS EXCHANGE

Respiration: An Introduction

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Glossary

Bohr effect Effect of the proton concentration (pH) on the oxygen affinity of hemoglobin.

Carbonic anhydrase A zinc metalloenzyme that reversibly catalyzes the reaction of CO_2 and H_2O to form H^+ and HCO_3^-.

Diffusion Net movement of a solute from an area of higher concentration to an area of lower concentration.

Equilibrium Pertaining to the situation when all forces acting are balanced by others resulting in a stable unchanging system.

Haldane effect Proton binding to hemoglobin (as a function of oxygenation).

Hypoxia Low partial pressures of oxygen in external or internal environments.

Interlamellar cell mass (ILCM) A mass made up of undifferentiated cells and ionocytes, and possibly other cell types, filling up a variable part of the space between the lamellae of fish gills.

Lamellae Also known as secondary lamellae, these are attached in rows to the gill filaments. They are the primary sites for gas exchange in fish gills. Each lamella is made up of two epithelial layers separated by pillar cells. Oxygen is taken up by erythrocytes flowing inside the lamellae from water flowing between the lamellae.

Mitochondria Organelles that produce most of the aerobic energy required by the cell.

P_{50} The oxygen partial pressure at half-maximal oxygen saturation of blood or hemoglobin.

Partial pressure The atmospheric pressure exerted by O_2 alone proportional to the total concentration of this gas. It is typically measured in either mmHg (torr) or kPa.

Respiratory cascade A model of gas exchange in which gas is viewed as flowing through a series of resistances from the environment to the tissues or vice versa. The model is based on the analogy of water flowing down a series of cascades with the difference being that gas flow is driven by differences in partial pressure rather than gravity.

Rete Structure consisting of blood vessels arranged to facilitate the exchange of heat or oxygen.

Root effect A property of fish hemoglobin in which protons decrease the maximal oxygen saturation of hemoglobin. For practical purposes, it is defined as a reduction of oxygen saturation at atmospheric oxygen tension.

Ventilation The movement of the respiratory medium (air or water) over the surface of the gas exchanger.

Introduction

Respiration and gas exchange is an essential process to maintain an aerobic existence in all vertebrates, including fishes. The uptake of oxygen (O_2), along with metabolism of organic substrates such as glucose and lipids, is needed to power the biochemical machinery (e.g., in the mitochondria) in cells for body maintenance, as well as for other aerobic functions such as growth, movement, reproduction, and disease resistance (**see also Energetic Models**: Bioenergetics in Aquaculture Settings and Bioenergetics in Ecosystems), all of which are important determinants of fitness.

The complex process of respiration in fish is discussed in detail in this section. It starts with the environment where O_2 and CO_2 move into and out of the animal, respectively, by simple diffusion. Gases diffuse across a gas-exchange organ which represents the interface between the organism and the environment and may consist of skin, gills, and in some cases an air-breathing organ. Ventilation of the respective media (water and in some cases air if an air-breathing organ is present) in conjunction with blood perfusion across the gas-exchange organ, both of which can be altered proportionally depending upon the animal's metabolic state, ensures sufficient gas exchange to meet the demands of the animal.

The circulatory system provides the conduit through which the blood is ultimately delivered to the tissues; hemoglobin (Hb), maintained within the red blood cell, plays a vital role in the transport of both O_2 and CO_2 in all fishes, except icefishes, which represent the only vertebrate that lacks Hb. Hemoglobin is a remarkable molecule and is one of the best-understood proteins in terms of how changes in the environment of the red blood cell alter the tertiary and quaternary structure of Hb to influence the nature in which Hb binds and releases ligands such as O_2, CO_2, and H^+'s in particular. These changes optimize conditions for gas exchange to tissues in general, as well as specifically to the eye and swimbladder allowing for acute vision and buoyancy control respectively in many teleosts.

Finally, blood reaches the tissues where waste products are removed and substrates supplied to cells and mitochondria providing the basics for cellular and mitochondrial respiration, and thus life. The following describes these various steps in respiration in more detail, providing background information and introducing each article that appears within the section.

The Environment: Water and Air as Respiratory Media

Characteristics of the environment can have a profound effect on respiration. Respiratory gas exchange in aquatic environments presents different problems when compared with respiration in air. Water is a dense, viscous medium, which also has a high heat capacity and 20–30-fold lower oxygen concentration (due to low gas solubility) relative to air. Increases in temperature or salinity further decrease oxygen solubility in water, and therefore oxygen content for a given gas pressure as indicated in Figure 1.

The P_{O_2} and P_{CO_2} of water can vary dramatically compared to those of atmospheric air. This is because the gases contained in air do not necessarily exchange readily with water. The P_{O_2} of aquatic environments can be zero (anoxia), low (hypoxic), normoxic, or high (hyperoxic), depending on the photosynthetic and respiratory rates of the biotic community and on water circulation characteristics. Some shallow, freshwater habitats may vary between 20 and 40 mmHg P_{O_2} just before dawn to 200–400 mmHg at mid-day. Thus, water can be less saturated and more saturated with oxygen, even on a diel basis. Many fishes, especially those that spend at least part of their lives in shallow habitats, have evolved structural and functional abilities to deal with variable water P_{O_2} values.

Fish in boreal, subpolar, or polar lakes may experience a seasonal challenge of oxygen availability – a

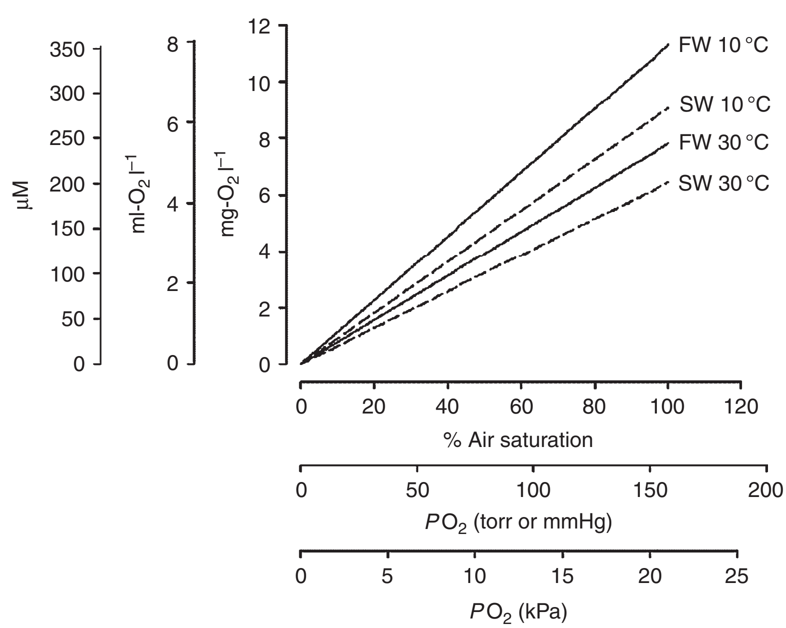

Figure 1 The relationship between partial pressure of oxygen (*x*-axis) and total oxygen content (*y*-axis) at 10 and 30 °C in either freshwater (FW) or seawater (SW). The three legends for each of the axes represent the different units that are used to describe both partial pressure and content in water. Reproduced from Diaz RJ and Breitburg DL (2009) The hypoxic environment. In: Richards JG, Farrell AP, and Brauner CJ (eds.) *Fish Physiology, Volume 27 Hypoxia*, pp. 1–23. Academic Press, with permission from Elsevier.

gradually deepening hypoxia (lowered P_{O_2}, s) during the winter as ice cover seals off gas exchange with the atmosphere and snow cover, along with shortened photoperiods, attenuate incoming light decreasing photosynthetic production of O_2. Extreme winters may prolong these conditions leading to a total consumption of the remaining dissolved O_2 (anoxia) by the lake's biota, leading to a winter fish kill (**see also Hypoxia**: The Expanding Hypoxic Environment).

Fishes living in high-altitude environments must also cope with low-P_{O_2} water. In this case, it is due to the lower total barometric pressure (and the correspondingly lowered partial pressures of the atmospheric gases). Finally, certain types of pollution, including those that introduce excessive nutrients into waterways (eutrophication), typically lead to wider, diel dissolved-O_2 ranges, often including quite hypoxic P_{O_2},s. Thus, fish living and respiring aquatic media are subjected to large and routine changes in O_2 availability relative to air-breathing animals and many are adapted to these potentially extreme conditions.

Ventilation and Gas-Exchange Organs

The physical and chemical characteristics of aquatic environments, specifically low oxygen solubility of water, probably contributed to the evolutionary development of gill structure and function, and to the many mechanisms some fishes use to extract oxygen directly from the air. Article **Ventilation and Animal Respiration**: Efficiency of Gas Exchange Organs discusses in greater detail the implications of water and air as respiratory media on gas exchange and how various gas-exchange organs differ in terms of efficiency of, and capacity for, gas exchange. The control of gill ventilation is crucial for survival to ensure adequate water flow over the gills. While control of ventilation and ventilatory responses to hypoxia are discussed in other sections, article **Control of Respiration**: The Ventilatory Response to CO_2/H^+ discusses the effect of CO_2 on ventilation and the role of CO_2 in controlling ventilation in fish.

The gill represents the predominant surface for gas exchange, which occurs predominantly across the gill lamellae in adult fish, and a great deal of variability in gill design has evolved among fishes. However, there is also a great deal of plasticity in gill morphology where large changes are observed in some fishes during exposure to hypoxia in particular. In hypoxia, there can be expansion of the total lamellar surface area in some fish species, such as carp, by as much as sevenfold due to the disappearance of an interlamellar cell mass that exists under normoxic conditions. These relatively large and often rapid changes in gill morphology may be more common among fish than previously thought. This exciting, relatively novel finding is discussed in **Ventilation and Animal Respiration**: Plasticity in Gill Morphology.

While the gills are usually the predominant site for gas exchange in adult fish, this is not the case early in development when the total body surface area:volume ratio in larval and juvenile fish is high and gill secondary lamellae in particular have yet to be fully developed. At this point, all gas exchange is across the skin. The fundamental principles associated with gas exchange in aquatic media and their implications for larval fishes are discussed in **Ventilation and Animal Respiration**: Respiratory Gas Exchange During Development: Models and Mechanisms. This article lays the foundations for a discussion of when the gills become important for gas exchange during development which is discussed in **Ventilation and Animal Respiration**: Respiratory Gas Exchange During Development: Respiratory Transitions. Interestingly, the gills may take on a more significant role for ionoregulation than for gas exchange early in development, based upon the time that 50% of whole body unidirectional Na^+ uptake and O_2 uptake transitions to the gills. This ontogeny has interesting implications for the evolution of gill function.

Gas Transport and Exchange

Once O_2 has diffused across the gill lamellae, about 98% is reversibly bound to Hb (oxyhemoglobin) contained within the red blood cell. The relatively high affinity of Hb for oxygen helps to maintain the partial pressure gradient for diffusion, maintaining high rates of oxygen uptake at the gills. The importance of Hb-O_2 affinity (usually characterized by the partial pressure at which 50% of the Hb molecules are oxygenated; P_{50}), and the shape of the oxygen equilibrium curve to O_2 uptake and transport are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: O_2 Uptake and Transport: The Optimal P50. Once within the red blood cell, O_2 is bound to Hb which consists of two α and two β globin chains. The structure of Hb, models that describe Hb-O_2 binding, and factors that influence O_2 binding in different fish groups are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Hemoglobin.

At the gills, any physically dissolved CO_2 diffuses down its partial pressure gradient to be excreted across the gill lamellae into the water. About 95% of the CO_2 transported in the blood exists as HCO_3^-, mostly in the plasma. The dissolved CO_2, which moves easily across gill epithelia, diffuses across the lamellar epithelium into the aquatic environment, which usually has a high absorbing capacity (i.e., acts as an infinite sink) for CO_2. The corresponding decrease in plasma CO_2 creates conditions for HCO_3^- dehydration ($H^+ + HCO_3^- \rightarrow H_2CO_3 \rightarrow CO_2 + H_2O$), which occurs relatively slowly in the plasma but very rapidly in the red blood cell due to high levels of the catalyst carbonic anhydrase. Carbonic anhydrase accelerates the reaction by up to 25 000 times and fish have many different isoforms, which are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Carbonic Anhydrase in Gas Transport and Exchange. With continued HCO_3^- dehydration, plasma HCO_3^- is transported into the red blood cell by Cl^-/HCO_3^- exchange and H^+'s are supplied within the red blood cell by Hb, which can act as a buffer, or release H^+'s upon Hb oxygenation known as the Haldane effect. This process continues until the blood leaves the gills which is discussed in greater detail in **Transport and Exchange of Respiratory Gases in the Blood**: Carbon Dioxide Transport and Excretion. The microenvironment of the red blood cell is regulated independently of that in the blood plasma, which is crucial for both O_2 and CO_2 transport. The processes responsible for the regulation of red blood cell pH and volume are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Red Blood Cell Function.

At the tissues, the processes discussed above occur in reverse. CO_2 produced by the tissues diffuses into the blood, where it is hydrated to HCO_3^- and H^+. The H^+'s may be bound by Hb reducing Hb-O_2 affinity by the Bohr effect and reducing Hb-O_2 affinity facilitating O_2 delivery to the tissues. The Bohr effect is thought to have evolved 3 times independently, and in teleosts was accompanied by a reduction in Hb buffer value so that small blood-acid loads exert relatively large effects relative to those in other vertebrates. This is discussed in greater detail in **Transport and Exchange of Respiratory Gases in the Blood**: Evolution of the Bohr Effect. The relatively large Bohr effect and low buffer value in teleosts have large implications for the interaction between O_2 and CO_2 exchange, where CO_2 production in the tissues facilitates O_2 delivery via the Bohr effect, and O_2 delivery promotes CO_2 removal via the Haldane effect, the reverse processes occurring at the gills. The implications of this are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Gas Transport and Exchange: Interaction Between O_2 and CO_2 Exchange, and taking into account large disequilibrium states that may exist in fish, the benefit to oxygen delivery may be much larger than previously thought.

While the Bohr effect refers to a decrease in Hb-O_2 affinity with a reduction in pH, the Root effect found in the blood of most teleosts refers to a decrease in the O_2-carrying capacity of Hb at low pH so that even at atmospheric O_2 tensions and higher, Hb cannot be fully oxygenated. The Root effect, together with a vascular countercurrent system called a rete and the generation of a localized acidosis, dramatically increases P_{O_2} and facilitates O_2 delivery to the poorly vascularized retinas and to the swimbladder in most teleosts. The molecular basis and evolution of the Root effect are discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Root Effect: Molecular Basis, Evolution of the Root Effect and Rete Systems, and the processes through which the Root effect facilitates O_2 delivery to these structures is discussed in **Transport and Exchange of Respiratory Gases in the Blood**: Root Effect: Root Effect Definition, Functional Role in Oxygen Delivery to the Eye and Swimbladder.

Tissue Respiration

As blood enters the tissues, O_2 diffuses down its partial pressure gradient into every cell in the body. Adenosine triphosphate (ATP) production by oxidative phosphorylation requires adequate delivery of both oxygen and metabolic fuels to cells and is regulated to meet metabolic demand. The biochemical pathways and fuels used in cellular respiration, along with the influence of the environment and limits to cellular respiration are discussed in **Tissue Respiration**: Cellular Respiration. The ultimate destination for O_2 within the body is the mitochondrion, an organelle found in most cells of all eukaryotic organisms. The mitochondrion is the site of ATP production and is responsible for most of the O_2 consumed by fish. Many of the characteristics of mitochondria are similar among eukaryotes as they arose through endosymbiosis prior to the divergence of plants, fungi, and animals. The basic features of mitochondria are discussed in **Tissue Respiration**: Mitochondrial Respiration, which provides the background for a discussion of some of the unique specializations that are seen in fish which is presented in **Tissue Respiration**: Specializations in Mitochondrial Respiration of Fish.

Whole Animal and Techniques in Respiratory Physiology

The whole is greater than the sum of its parts, and this certainly applies to respiration and the respiratory system in fishes. At each level of biological organization discussed above, respiration in fish is complex. However, adding to this complexity is that all these processes and reactions must be integrated within the whole animal, the level at which natural selection operates. Exercise increases the rate at which all these steps in the respiratory system must operate and is often used as a tool to shed light on which if any steps in the respiratory cascade from environment to tissues may be rate limiting. Changes in respiration during exercise are discussed in **Ventilation and Animal Respiration**: The Effect of Exercise on Respiration and some of the techniques used in the field are described in the section Techniques in Whole Animal Respiratory Physiology.

See also: **Control of Respiration**: The Ventilatory Response to CO_2/H^+. **Energetic Models**: Bioenergetics in Aquaculture Settings; Bioenergetics in Ecosystems. **Hypoxia**: The Expanding Hypoxic Environment. **Tissue Respiration**: Cellular Respiration; Mitochondrial Respiration; Specializations in Mitochondrial Respiration of Fish. **Transport and Exchange of Respiratory Gases in the Blood**: Carbon Dioxide Transport and Excretion; Carbonic Anhydrase in Gas Transport and Exchange; Evolution of the Bohr Effect; Gas Transport and Exchange: Interaction Between O_2 and CO_2 Exchange; Hemoglobin; O_2 Uptake and Transport: The Optimal P50; Red Blood Cell Function; Root Effect: Molecular Basis, Evolution of the Root Effect and Rete Systems; Root Effect: Root Effect Definition, Functional Role in Oxygen Delivery to the Eye and Swimbladder. **Ventilation and Animal Respiration**: Efficiency of Gas Exchange Organs; Plasticity in Gill Morphology; Respiratory Gas Exchange During Development: Models and Mechanisms; Respiratory Gas Exchange During Development: Respiratory Transitions; Techniques in Whole Animal Respiratory Physiology; The Effect of Exercise on Respiration.

Further Reading

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