Cardio-Respiratory Control in Vertebrates
Cardio-Respiratory Control in Vertebrates

Comparative and Evolutionary Aspects
Hopefully, this book will be taken off of the shelf frequently to be studied carefully over many years. More than 40 researchers were involved in this project, which examines respiration, circulation, and metabolism from fish to the land vertebrates, including human beings. A breathable and stable atmosphere first appeared about 500 million years ago. Oxygen levels are not stable in aquatic environments and exclusively water-breathing fish must still cope with the ever-changing levels of $O_2$ and with large temperature changes. This is reflected in their sophisticated countercurrent systems, with high $O_2$ extraction and internal and external $O_2$ receptors.

The conquest for the terrestrial environment took place in the late Devonian period (355–359 million years ago), and recent discoveries portray the gradual transitional evolution of land vertebrates. The oxygen-rich and relatively stable atmospheric conditions implied that oxygen-sensing mechanisms were relatively simple and low-gain compared with acid–base regulation. Recently, physiology has expanded into related fields such as biochemistry, molecular biology, morphology and anatomy. In the light of the work in these fields, the introduction of DNA-based cladograms, which can be used to evaluate the likelihood of land vertebrates and lungfish as a sister group, could explain why their cardio-respiratory control systems are similar. The diffusing capacity of a duck lung is 40 times higher than that of a toad or lungfish. Certainly, some animals have evolved to rich high-performance levels.

June 2009

M.L. Glass

S.C. Wood
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Overview of the Respiratory System

S.C. Wood

This monograph comprises a diverse collection of chapters dealing with gas exchange, circulation, and metabolism in species ranging from fish to man. As you read the chapters, the unifying theme that emerges is one that was proposed 18 years ago by Weibel et al. (1991), i.e., the hypothesis of symorphism.

The concept that animals, and humans as well, should be designed economically (i.e., that structural design should be matched to functional demand) follows from common sense, but it is also supported by many observations.

The respiratory system is often depicted as four processes; ventilation, diffusion to blood, circulation, and diffusion to cells that are arranged in series. This series arrangement means that the total resistance to gas transport is the sum of the four resistances and that any of the steps can be rate-limiting. Many authors liken this system to an “oxygen cascade”, referring to the progressive drop in PO$_2$ that occurs at each step of transport. Kuper and Soni (2003) have likened oxygen transport to a whirlpool instead of a cascade. They pointed out that mitochondria “suck” oxygen out of cells, generating an oxygen flux to meet the demand. The drop in PO$_2$ between arterial blood and venous blood leaving tissues depends on the O$_2$ content removed from the blood. The venous PO$_2$ is then a dependent variable of venous O$_2$ content and, due to the shape of the PO$_2$ = f(venous [O$_2$]) curve, is held at fairly constant value over a wide range of venous O$_2$ contents.

For a given species, each of the four steps in the oxygen cascade (or whirlpool) is adaptable to changes in demand for oxygen uptake and carbon dioxide output. The passive steps of diffusion to blood and diffusion to cells can increase acutely with increased surface areas due to recruitment and distension of capillaries, and can increase chronically with increased capillary density, increased mitochondrial density and increased oxidative enzyme activity (Andersen 1975; Holloszy and Booth 1976). Likewise, the active step of circulation can increase acutely by increasing heart rate and stroke volume, and chronically by increasing maximum stroke volume. This step also includes O$_2$ transport properties of hemoglobin, which show adaptive changes both acutely and chronically. The other active step, ventilation, shows the same capacity to increase frequency and tidal volume acutely, but does not normally show responses to chronic increases in O$_2$ demand (Ekblom 1969). When different species or animal groups are compared, the same pattern of adaptation

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emerges as structure is matched quite closely with differences in oxygen demand. An additional variable is now important, i.e., genetic differences.

An alternate approach to examining plasticity of the oxygen transport system is to focus on diminished oxygen supply, i.e., hypoxia. For healthy individuals, this normally becomes a problem only at high altitude. The adaptations of animals to acute and chronic exposure to hypoxia differ somewhat from the adaptations to exercise. For example, a key aspect of adaptation to hypoxia is increased ventilation. Unlike exercise, where the ventilation increases to match increased CO$_2$ production, the hypoxia-induced increase in ventilation is not related to increased CO$_2$ production and is, in fact, hyperventilation. Without this hyperventilation, the tolerance to hypoxia would be greatly diminished. Perhaps the clearest example of this is man on the summit of Mt. Everest. Alveolar PCO$_2$, normally kept at about 40 mmHg at sea level, is reduced by hyperventilation to about 7 mmHg (West et al. 1983). With this hyperventilation, alveolar PO$_2$ on the summit was about 35 mmHg. Without this hyperventilation, alveolar PO$_2$ would have been only about 2 mmHg. The downside of this acute response to hypoxia is a pronounced respiratory alkalosis, a condition with medical risks of cerebral and coronary vasoconstriction and cardiac arrhythmias. A chronic response to hypoxia is stimulation of red blood cell production, leading to increased O$_2$-carrying capacity. The downside of this chronic response is increased blood viscosity and in some natives to altitude, chronic mountain sickness or Monge’s disease (Monge-Medrano et al. 1928).

For many species, coping with hypoxia elicits the interesting and effective strategy of hypothermia, which reduces oxygen demand by roughly 11% per degree centigrade (Wood 1991). The mechanism in mammals and birds is disruption of the normal thermogenesis responses to lower body temperature. In ectothermic species, the mechanism is behavioral, i.e., seeking out cooler ambient temperatures. The downside of this response is loss of normal fight or flight speed or, more dramatically, becoming a popsicle by seeking a freezing temperature.

References

Part I

Control of Respiration in Aquatic Vertebrates
Abstract This review focuses on four areas of fish gill function: oxygen transport and transfer, carbon dioxide transport and transfer, oxygen and carbon dioxide sensing, and ammonia excretion. Each section presents a synthesis of previous work while also highlighting recent and ongoing studies that are shaping the growth of these research fields. Where possible, we will comment on the utility of using emerging technologies, including gene knockdown in zebrafish, to evaluate the function of the fish gill.

1 Introduction

Is another review chapter on gas transport across fish gills really necessary? We asked ourselves the same question before taking on this task, and decided to try and determine what impact previous scholarly reviews of fish respiration were having in educating the public at large. A quick Google search using the key words ‘fish AND gill’ produced 319,000 hits (about half the number of hits obtained by Googling ‘rat AND lung’). The very first hit (arguably the most popular) directed us to a site about respiration in fish where we learned that ‘fish breathe by drinking’… Clearly, there is still work to be done! Here, we try to address this need while avoiding competition with other recent reviews, notably the ambitious and comprehensive tome on fish gills by Evans et al. (2005), which has soared to Google hit number 12 of 319,000 in only 3 years. For a wealth of detail on the structure and function of the fish gill, we urge the reader to consult Evans et al. (2005). In this review, we have focused on four areas of gill function: oxygen transport and transfer, carbon dioxide transport and transfer, oxygen and carbon dioxide sensing, and ammonia excretion.

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