**Respiratory Physiology of Vertebrates**

How do vertebrates get the oxygen they need, or even manage without it for shorter or longer periods of time? How do they sense oxygen, how do they take it up from water or air, and how do they transport it to their tissues? Respiratory system adaptations allow numerous vertebrates to thrive in extreme environments in which oxygen availability is limited, or where there is no oxygen at all.

Written for students and researchers in comparative physiology, this authoritative summary of vertebrate respiratory physiology begins by exploring the fundamentals of oxygen sensing, uptake and transport in a textbook style. Subsequently, the reader is shown important examples of extreme respiratory performance, such as diving and high-altitude survival in mammals and birds, air breathing in fish, and those few vertebrates that can survive without any oxygen at all for several months, showing how evolution has solved the problem of life without oxygen.

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Respiratory Physiology of Vertebrates

Life with and without Oxygen

Göran E. Nilsson
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To Peter L. Lutz
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Preface

For good reasons, many people have a fascination with the key role that oxygen plays in the life (and death) of animals and humans. That is the theme of this book: how vertebrates get the oxygen they need, and how some even manage without it for shorter or longer periods. We therefore hope it will find a relatively wide audience. Thus, the book aims to provide a thorough introduction to the respiratory physiology of vertebrates for anyone with some basic physiological knowledge, including biologists, biomedical researchers, veterinarians, and physicians. We also hope that the book will function as a textbook for courses at the MSc and PhD student level, and we have made an effort to start treating the subject at a level intelligible for bachelor students who have had their first introductory year in biology (including some physiology). By being extensively referenced, each chapter should also function as an up-to-date review for researchers who have decided to venture into a particular area of respiratory physiology.

The first four chapters cover basic aspects of vertebrate respiration, whereas the last five chapters describe particular physiological challenges met by many vertebrates and include many examples of more-or-less extreme respiratory adaptations.

The idea for this book was born in April 2006, when I was approached by Jacqueline Garget from Cambridge University Press in connection with the Society of Experimental Biology meeting in Canterbury. At that meeting, I was organizing a session on ‘Life with and without oxygen’ to honor the memory of my friend Peter L. Lutz, who left us much too early, in February 2005. After some discussion, Jacqueline and I agreed that I should try to put together a comprehensive book on the subject of vertebrate respiratory physiology, rather than producing a volume of talks given by Peter’s friends at this session. I knew that two journals (The Journal of Experimental Biology and Comparative Biochemistry and Physiology) were engaged in producing special issues in Peter’s honor, and a book
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Based on the session in Canterbury would inevitably be a somewhat arbitrary collection of quite specialized papers. While fearing being naııve, I aimed high and approached a number of outstanding researchers who collectively should be able to cover virtually all important aspects of vertebrate respiratory physiology. To my surprise, they all accepted the task. Indeed, they did so with enthusiasm. I am very grateful to all of them. The result is this book.
Abbreviations

ABO  air-breathing organ
ACR  air convection requirement
ADH  alcohol dehydrogenase
ADP  adenosine diphosphate
AhR  aryl hydrocarbon receptor
ALDH aldehyde dehydrogenase
AMP  adenosine monophosphate
AMPK AMP-activated protein kinase
AMS  acute mountain sickness
ARNT aryl hydrocarbon receptor nuclear translocator
ASR  aquatic surface respiration
ATP  adenosine triphosphate
βblood blood capacitance coefficient
βgas air capacitance coefficient
BGB  blood–gas barrier
βO2  O2 capacitance coefficient
BOD  biological oxygen demand
\(|\text{Ca}^{2+}\)_i intracellular Ca^{2+} concentration
CAT  catalase
CO  carbon monoxide
CO₂  carbon dioxide
D₁O₂ lung diffusion capacity for oxygen
DPG  2,3-diphosphoglycerate
D/QO₂ equilibration coefficient
D₅ skin diffusion capacity
DₒO₂ tissue diffusion capacity for oxygen
fH heart rate
### List of abbreviations

- $F_{O_2}$: fraction of oxygen in inspired air
- $f_R$: frequency of ventilation
- $G$: conductance
- GABA: γ-amino butyric acid
- $G_{diffO_2}$: transfer factor (or diffusion conductance) for $O_2$
- GPX: glutathione peroxidase
- GST: glutathione-S-transferase
- HACE: high-altitude cerebral edema
- HAPE: high-altitude pulmonary edema
- Hb: hemoglobin
- $HCO_3^-$: bicarbonate (hydrogencarbonate) ion
- HIF: hypoxia-inducible factor
- HPV: hypoxic pulmonary vasoconstriction
- HRE: hypoxia response element
- $H_2O_2$: hydrogen peroxide
- $H_2S$: hydrogen sulfide
- KO$_2$: Krogh’s diffusion coefficient
- LDH: lactate dehydrogenase
- MIGET: multiple inert gas elimination technique
- MSO: methionine sulfoximine
- NMDA: N-methyl-D-aspartate
- NMDAR: NMDA receptor
- NO: nitric oxide
- $O_2$: oxygen
- $O_2^{-}$: superoxide anion
- $[O_2]_{a}$: arterial oxygen concentration (often $CaO_2$)
- $[O_2]_{c}$: end capillary oxygen concentration (often $CcO_2$)
- $[O_2]_{crit}$: critical oxygen concentration
- ODC: oxygen dissociation curve
- OH•: hydroxyl radical
- $[O_2]_{pv}$: oxygen concentration of pulmonary venous blood (often $C_{pv}O_2$)
- $[O_2]_{sv}$: oxygen concentration of systemic venous blood (often $C_{sv}O_2$)
- $[O_2]_{v}$: venous oxygen concentration (often $C_vO_2$)
- $P_{50}$: the $P_O_2$ at which hemoglobin is 50% saturated with $O_2$
- $P_{a}CO_2$: partial pressure of carbon dioxide in the arteries
- $P_{a}O_2$: partial pressure of oxygen in the alveoli
- $P_{a}O_2$: partial pressure of oxygen in the arteries
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- \( P_A - P_a \): alveolar-to-arterial \( PO_2 \) difference
- PASMC: pulmonary arterial smooth muscle cell
- \( P_B \): barometric pressure
- \( PCO_2 \): partial pressure of carbon dioxide
- PCR: phosphocreatine
- PDH: pyruvate dehydrogenase
- \( P_O_2 \): partial pressure of oxygen in exhaled air
- Perf. CR: convection requirement from blood
- \( PH_2O \): partial pressure for water vapor
- \( P_I O_2 \): partial pressure of oxygen in inspired air
- \( P_O_2 \): partial pressure of oxygen in the lung
- \( P_L - P_a \): \( PO_2 \) difference between lung and arteries
- \( P_L - P_{LA} \): \( PO_2 \) difference between mixed lung gas and gas in the left atrium
- \( P_{mit}O_2 \): mitochondrial \( PO_2 \)
- \( PO_2 \): partial pressure of oxygen
- \( \Delta PO_2 \): partial pressure difference for oxygen
- \( PO_2\text{crit} \): critical oxygen tension
- \( P_{pv} \): partial pressure in mixed pulmonary venous blood
- \( P_v O_2 \): partial pressure of oxygen in the veins
- \( Q_{pul} \): pulmonary blood flow
- QR–L: R–L shunt flow
- \( Q \): blood flow (cardiac output)
- \( Q_{10} \): metabolic rate increases for every 10°C rise in factor by which temperature
- ROS: reactive oxygen species
- \( S_a O_2 \): \( O_2 \) saturation in the arteries
- SOD: superoxide dismutase systemic \( O_2 \) delivery
- TUNEL: terminal transferase mediated dUTP nick-end labeling
- UCP: uncoupling protein
- \( V_A \): alveolar ventilation
- \( V_b \): blood flow (often written as Q)
- \( V_{CO_2} \): rate of \( CO_2 \) ventilation
- \( V_D \): anatomical respiratory dead space
- \( V_E \): minute ventilation
- \( V_{eff} \): effective ventilation of the gas-exchange structures
- Vent. CR: convection requirement from water
- \( V_1 \): total ventilation
- \( VO_2 \): rate of oxygen uptake
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\[ \dot{V}O_2 \text{max} \quad \text{maximal rate of oxygen uptake} \]
\[ V/Q \text{ ratio} \quad \text{ventilation/perfusion ratio} \]
\[ V_S \quad \text{stroke volume} \]
\[ V_t \quad \text{tidal volume} \]
\[ V_t_b \quad \text{cardiac output (often written as Q)} \]
\[ V_T CO_2 \quad \text{volume of carbon dioxide per breath} \]
\[ V_{tw} \quad \text{ventilation volume} \]
\[ V_{tw}/\dot{V}O_2 \quad \text{volume of water flow required per unit of O}_2 \text{ uptake} \]
\[ V_w \quad \text{water flow} \]