

Human Respiration

Anatomy and Physiology, Mathematical Modeling, Numerical Simulation and Applications

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Modeling, Numerical Simulation and
Applications

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Published by

WIT Press

Ashurst Lodge, Ashurst, Southampton, SO40 7AA, UK

Tel: 44 (0) 238 029 3223; Fax: 44 (0) 238 029 2853

E-Mail: witpress@witpress.com

<http://www.witpress.com>

For USA, Canada and Mexico

WIT Press

25 Bridge Street, Billerica, MA 01821, USA

Tel: 978 667 5841; Fax: 978 667 7582

E-Mail: infousa@witpress.com

<http://www.witpress.com>

British Library Cataloguing-in-Publication Data

A Catalogue record for this book is available
from the British Library

ISBN: 1-85312-944-5

ISSN: 1464-9292

Library of Congress Catalog Card Number: 2004116359

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Printed in Great Britain by Athenaeum Press Ltd.

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Preface

Since ancient times breathing was believed to be the most important feature of life itself. The very Universe was viewed as a huge breathing organism, within which every part was related to everything else through a process of vibration – breath. Nowadays, our understanding of the laws governing the Universe and life has grown tremendously. Yet this has not changed our perception of breathing as one of the most important mechanisms of life support. In the human body, everything depends on the delivery of oxygen. Just think how long we can survive without eating and drinking in comparison to our ability to survive without breathing!

Therefore, the scientific study of the respiratory function becomes of paramount importance. Recent advances in applied mathematics, physics, engineering and other natural sciences make such a study quite feasible.

The book became possible as a result of a ten-year research collaboration of physicians, engineers, physicists and applied mathematicians. Hence, the material presented in this book covers a wide range of phenomena related to human respiration. Beginning with physiological and anatomical aspects of the respiratory system, the study goes into macro- and micro-scale modeling of the gas exchange processes that take place in the course of breathing. Such models allow *in vitro* simulations and even computer visualization of the processes involved. This is possible due to the recent advances in computational techniques and computer graphics, in particular.

It is worth mentioning here that the application of mathematical methods immediately yielded several very important results. To provide just one example: it became possible to explain the appearance of respiratory spaces on the walls of higher respiratory ways starting from the mass conservation principle applied to the system of respiratory ways. Another very important achievement from applying seemingly pure mathematical concepts was the possibility of modeling air flow through *all* the scales of the respiratory ways if these ways are viewed as a fractal structure.

A special chapter is devoted to the anatomically based computer modeling of the pulmonary structure. This modeling is essential if one wishes to obtain realistic results of computer simulations within the respiratory system. This modeling, therefore, may be of great help to those who concern themselves with numerical simulations within the lungs.

From these quite general models, the study evolves into more detailed investigations of such aspects as the impact that microscopic particles present in

the air have on the respiratory performance – both on their way downstream the respiratory duct and within the alveolar region. The breathing in an environment polluted by toxic substances has been as well considered: it becomes possible to *quantify* the physiological response of humans in such environments.

The lung ventilatory function is also investigated. As a result, some integral criteria (indices) for characterizing the lung performance have been proposed. In addition, the lung performance has been related to the cardiac function.

Consideration of therapeutic techniques employed for treatment of respiratory diseases was not left aside from the text either. Thus, mechanics of proportional assist ventilation is studied in detail. Some aspects of applied chest-wall vibration therapy are also considered.

It is our hope that the present book will help many researchers and students to keep abreast of the most recent developments in the area and will serve as a starting point to those who will carry out further investigations.

The editor is particularly grateful to all the contributing authors for their strong dedication to the project, continuous help and patience in the course of preparing this book.

The Editor
Singapore, March 2006

Nomenclature

A	area, m^2
B	amplitude of the net pressure wave form applied by the ventilator, m
C	compliance, $(cmH_2O)^{-1}$
c	concentration, kg/m^3
d	distance from RBC distribution center to center of domain, m
D_{eff}	effective diffusivity, m^2/s
D_L	lung-diffusing capacity, $m^3/(Pa \cdot s)$
G	control gain
E	elastance of respiratory system, cmH_2O/l
H	integration constant in the solution for the dynamic-equilibrium differential equation governing lung dynamics
K_1	proportionality between airway pressure and inspired volume, cmH_2O/l
K_2	proportionality between airway pressure and inspired flow rate, $cmH_2O/l/s$
k_a	averaged time constant of the respiratory cycle, s
K_c	control parameter
M	gas molecular mass, $kg/kg\text{-mol}$
N	total number of RBC
P	gas partial pressure, Pa
P_{al}	alveolar pressure, cmH_2O
P_{app}	total applied pressure to respiratory system, cmH_2O
P_{aw}	airway pressure, cmH_2O
P_k	peak pressure: maximum lung pressure, cmH_2O
P_{el}	pressure generated by elastic recoil of respiratory system, cmH_2O
P_L	lung airflow driving pressure, cmH_2O
P_m	mouth pressure, cmH_2O
P_{mus}	pressure produced by respiratory muscles, cmH_2O
P_N	net lung pressure, cmH_2O
P_p	pleural pressure, cmH_2O
P_{ref}	reference gas partial pressure, Pa
P_{res}	dissipated pressure due to resistance of respiratory system, cmH_2O

P_1	pause pressure: lung pressure at which the lung volume is maximal, cmH ₂ O
$P_{O_2}^{al}$	alveolar O ₂ partial pressure, mmH ₂ O
$P_{O_2}^{cap}$	capillary O ₂ partial pressure, mmH ₂ O
$P_{CO_2}^{al}$	alveolar CO ₂ partial pressure, mmH ₂ O
$P_{CO_2}^{cap}$	capillary CO ₂ partial pressure, mmH ₂ O
\dot{Q}^{AB}	arterial blood flow rate, l/min
\dot{Q}^{AE}	arterial blood flow rates at arterial end, l/min
\dot{Q}^{VB}	venous blood flow rate, l/min
\dot{Q}^{VE}	venous blood flow rate at venous end, l/min
R	resistance of respiratory system, cmH ₂ O/l/s
R	distribution radius or effective radius, m
S	diagonal half-length, m
T	temperature, K
t	time, s
V	volume, m ³
\dot{V}	volumetric flow rate, m ³ /s
x, y, z	Cartesian coordinates
X, Y, Z	coordinates

Greek symbols

γ	dimensionless gas partial pressure
θ	phase of oscillating pressure profile applied by the ventilator, rad
κ	coefficient corresponding to the rate of improvement or deterioration in lung status
ω	frequency of the oscillating pressure profile applied by the ventilator, Hz

Mixed and other symbols

Δt	time lag between the peak and pause pressures, s
∇	gradient
∇^2	the Laplace operator

Abbreviations

BMI	body-mass index
CF	cystic fibrosis
COH	coherence function
COPD	chronic obstructive pulmonary disease

CPT	chest physiotherapy
CRF	chest-resonance frequency
FRF	frequency-response function
HFCCT	high-frequency chest-compression therapy
HFWCO	high-frequency chest-wall oscillation
LII	lung-improvement index
LVI	lung-ventilatory index
PSV	pressure-support ventilation
RBC	red blood cell
RF	respiratory rate or frequency
RSBI	rapid shallow breathing index
SBT	spontaneous breathing trial
SIMV	synchronized intermittent mandatory ventilation
TV	tidal volume
WOB	work of breathing
CABG	coronary-artery-bypass-graft
SEPs	successfully extubated patients
UEPs	unsuccessfully extubated patients

