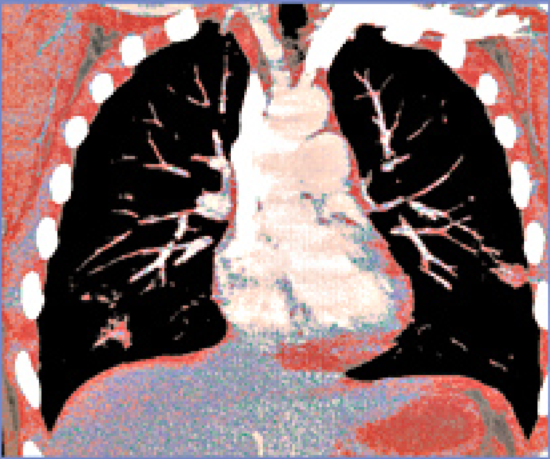
CORE TOPICS IN

MECHANICAL VENTILATION



Edited by Iain Mackenzie

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Core Topics in Mechanical Ventilation

Iain Mackenzie in zero-gravity training for Professor Hawking's flight, April 26, 2007.

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Foreword

Bjorn Ibsen, an anaesthetist and intensivist who practiced for most of his career in Copenhagen, Denmark, died on 7 August 2007. Ibsen is widely regarded as the father of Intensive Care Medicine, the nativity of which occurred in his home city in 1952 during a polio epidemic. Ibsen had trained in radiology, surgery, pathology and gynaecology before travelling to Massachusetts General Hospital in 1949 to gain specialist experience in anaesthesia. He returned to Copenhagen in 1950 and assumed a leading role in managing one of the world's worst polio epidemics that started only two years later. Some 2899 cases developed among the population of two million. Too weak to cough, many patients succumbed to secretion retention with associated carbon dioxide retention. Negative pressure ventilation was effectively the only form of support then available, but Ibsen found that tracheostomy, or endotracheal intubation combined with the careful application of intermittent positive pressure ventilation administered by relays of doctors, medical students and others, was an effective means of overcoming the devastating effects of the disease. In the end, over 1500 practitioners aspirated secretions and performed manual ventilation in shifts. Mortality fell markedly. As a result, the idea that critically ill patients should be supported in centralized facilities by individuals experienced in their care was adopted worldwide.

The new specialty emerged in varying phenotypes according to the history, individual preferences and expertise of those driving the change. In the United States, physicians trained in pulmonary medicine have traditionally also provided critical care. In the United Kingdom, the base specialty of anaesthesia has borne the brunt of intensive care provision over many decades. Only in recent years has the value of bringing varying expertise to intensive care management (ICM) from different clinical base specialties been recognized more formally. Thus in Australia a joint intercollegiate faculty of ICM has been developed, a model that was to an extent copied in the UK. Formal training programmes have been developed, culminating in the UK in ICM being recognized as a specialty in the year 2000. The emergence of diploma and other examinations designed to test competencies in intensive care has been rapid. The strength of national and international specialist societies has grown, with associated academic advancement publicized through congresses and increasingly in highly cited journals.

Against this background, it has given me great pleasure to write the foreword for this exciting volume, expertly conceived and edited by Dr Iain Mackenzie. The contributors to this book come from a wide range of clinical and national backgrounds, thereby reflecting the heterogeneity that is in many senses the strength of the specialty. Moreover, the content reflects the staggering advances that have been made during the past 50 years in the delivery of mechanical ventilatory support. Even those phenomena which would have been easily recognizable to Ibsen, such as the delivery of oxygen therapy, have been subjected to scientific evaluation and technological development. Tracheostomy, used widely in the 1950s polio epidemic, is now performed at the bedside, an innovation of which I suspect Ibsen would have approved. The content of chapters dealing with sedation, paralysis and analgesia might have been more familiar to him, but the agents now employed, the increased understanding of their properties and the clinical benefits attributable to their avoidance, where possible, are evidence of the advances made in this area of pharmacology. The outreach of expertise into the wards in pursuit of the 'intensive care without walls' has been greatly facilitated by the advent of non-invasive mechanical ventilatory support.

Finally, the scientific advances in our evaluation of the effects of mechanical ventilation, the recognition that it can do harm if applied inappropriately and the evidence base concerning its use in patients with a wide variety of primary and secondary lung pathologies is a truly outstanding achievement that intensive care medicine can be proud of. I suspect that Bjorn Ibsen, were he privileged to read this volume, would feel the same.

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Preface

Respiratory support is recognized to be a key component in the resuscitation of acutely ill patients and, as such, the basics are taught to all those who seek to acquire life support skills. Following stabilization, the continued provision of respiratory support, be it in the emergency department, respiratory ward or intensive care unit, is largely taken for granted. However, as the ARDSnet study has recently reminded us, the way we manage mechanical ventilation in the medium and long term actually has a significant impact on patient outcome. Although the literature is full of the evidence necessary to provide optimal respiratory support, synthesizing this evidence into a cohesive and logical approach would be an enormous task for one individual. On the other hand, excellent sections on respiratory support can be found in the major textbooks on critical care and indeed the 'principles and practice of mechanical ventilation' is the sole subject of Martin Tobin's authoritative tome of that name. However, these large reference books are expensive and less than suitable for those who need a more concise and practical overview of the subject. This book therefore seeks to fill the gap between the journals and the major textbooks by bringing together clear, concise and evidence-based accounts of important topics in respiratory support, together with, where necessary, explanations of its physiology and pathology. It is hoped, therefore, that this book will appeal to a very wide audience, and will make a substantial contribution to the interest in, and teaching of, the art and science of mechanical ventilation. In addition, since many of those who work with patients who require respiratory support do not have an anaesthetic background, knowledge particular to this specialty has not been assumed.

I would welcome any feedback so that future editions of this book can better meet the needs of its readers.

My colleagues in Cambridge, both nursing and medical, must be credited with persuading me of the need for a book such as this, and for that I am grateful. I am also indebted to the contributors from around the world who responded so favourably to my request that they contribute, and then followed through with their chapters. Frank McGinn (GE Healthcare Technologies), Dan Gleeson (Cape Engineering) and John Wines (Cape Engineering) kindly supplied me with information about the histories of their respective companies. I have received assistance in sourcing some of the images from Mr Pyush Jani and Dr Helen Smith. I am very grateful to David Miller for checking the correctness of the English, but must accept any blame for any errors that have crept through. Finally, I would like to thank Diane, my wife, and Katherine, Rebecca, Charlotte and Amy, my daughters, for their unfailing support over the last two years while this book was in production.

Iain Mackenzie

Introductory notes

Physiological notation

Those with a dislike of mathematics will be pleased to know that none of the equations in this book need to be memorized. Having said that, though, understanding the concepts that are encapsulated by the equations presented will help the reader enormously in achieving a significantly deeper level of understanding. As many of the terms in the equations refer to physiological quantities, physiological notation is used, and therefore being able to decipher physiological notation will be helpful

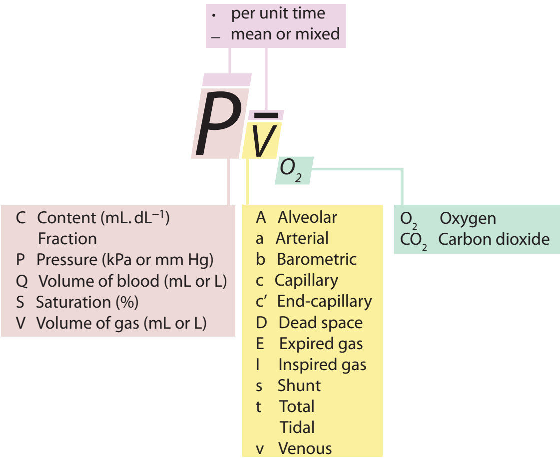

Figure 1 Key to physiological notation.

In the example illustrated, the physiological quantity being referred to is the mixed venous partial pressure of oxygen. Note also that when blood or gas volume, *V* and *Q* respectively, are expressed 'per minute' by placing a dot above the letter, they then refer to volume/time, or flow. Thus *Q*, blood volume, can be converted to $\dot{Q}$, blood flow.

Table 1 In-text notation for commonly used physiological quantities

Quantity	Correct notation	In-text notation
Fractional inspired oxygen concentration	$F\mathrm{I}_{O_2}$	$\mathrm{FIO_2}$
Partial pressure of carbon dioxide in alveolar gas	$P\mathrm{A}_{CO_2}$	$\mathrm{PACO_2}$
Partial pressure of carbon dioxide in arterial blood	Pa_{CO_2}	$\mathrm{PaCO_2}$
Partial pressure of oxygen in alveolar gas	$P\mathrm{A}_{O_2}$	$\mathrm{PAO_2}$
Partial pressure of oxygen in arterial blood	Pa_{O_2}	$\mathrm{PaO_2}$
Partial pressure of carbon dioxide	P_{CO_2}	$\mathrm{PCO_2}$
Partial pressure of oxygen	P_{O_2}	$\mathrm{PO_2}$
Haemoglobin oxygen saturation in arterial blood	Sa_{O_2}	$\mathrm{SaO_2}$

(Figure 1). The reader may be relieved to hear that formal physiological notation has been completely avoided in the text because it can sometimes extend significantly below the text baseline, as in, for example, the notation representing the partial pressure of oxygen in arterial blood:

$$Pa_{O_2}.$$

However, some quantities are mentioned so often in the text that to refer to these in words would hinder, rather than help, the flow of the text. Therefore, for the most common of these quantities, non-physiological notation has been used for

Table 2 Pressure conversion

	multiply → / divide ←	
mm Hg	1.3595	**cm H_2O**
kPa	10.197	**cm H_2O**
kPa	7.5	**mm Hg**
Atm	101.325	**kPa**
Bar	100	**kPa**

in-text references, as it is in many other publications (Table 1).

Units

The European convention on units has been maintained throughout, using kilopascals (kPa) for gas pressures rather than millimetres of mercury (mm Hg), but the conversion factors can be found in Table 2. However, for clarity the symbol for the litre, which is usually abbreviated to the lower case letter 'l', has been substituted by the North American convention of using the capital letter 'L'; thus 'ml' becomes 'mL' and 'dl' becomes 'dL'.

Compound units in clinical practice commonly use the forward slash '/' as the delimiter to denote a denominator unit. For example, 'millilitres per kilogram' would be written 'mL/kg'. In compound units with only two components, this usage is not subject to misunderstanding, but in those with more than two components, the use of the forward slash is potentially confusing and should be avoided. The convention in this book, therefore, is to use the more correct scientific notation. In this form, the relationship between units is indicated by the superscript power notation, as shown in Table 3.

Table 3 Convention for the use of compound units

Quantity	Common clinical notation	Correct scientific notation
Millilitres **per** kilogram	mL/kg	$mL.kg^{-1}$
Microgram **per** kilogram **per** hour	µg/kg/hr	$\mu g.kg^{-1}.hr^{-1}$
Millilitres **per** minute	mL/min	$mL.min^{-1}$
Litres **per** minute	L/min	$L.min^{-1}$
Milliequivalents **per** litre	mEq/L	$mEq.L^{-1}$
Millimoles **per** litre	mmol/L	$mmol.L^{-1}$
Kilocalorie **per** milliliter	kcal/mL	$kcal.mL^{-1}$
Millilitres **per** hour	mL/hr	$mL.hr^{-1}$
Milligrams **per** kilogram	mg/kg	$mg.kg^{-1}$
Kilocalories **per** kilogram	kcal/kg	$kcal.kg^{-1}$
Grams **per** kilogram	g/kg	$g.kg^{-1}$
Grams **per** deciliter	g/dL	$g.dL^{-1}$
Micrograms **per** minute	µg/min	$\mu g.min^{-1}$
Millilitres **per** kilogram	mL/kg	$mL.kg^{-1}$
Millilitres **per** day	mL/d	$mL.d^{-1}$

Chapter **1**

Physiology of ventilation and gas exchange

HUGH MONTGOMERY

Among its many functions, the lung has two major ones: it must harvest oxygen to fuel aerobic respiration and it must vent acid-forming carbon dioxide. This chapter will offer a brief overview of how the lung fulfills these functions. It will also discuss some of the mechanisms through which adequate oxygenation can fail. A secure understanding of these principles allows an insight into the way in which mechanical ventilation strategies can be altered in order to enhance oxygenation and carbon dioxide clearance.

Functional anatomy of the lung

The airways

During inspiration, air is drawn into the oropharynx through either the mouth or the nasal airway. Nasal breathing is preferred, as it is associated with enhanced particle removal (by nasal hairs and mucus-laden turbinates) and humidification. However, this route is associated with a fall in pharyngeal pressure. Just as Ohm's law dictates that voltage is the product of current and resistance, so pharyngeal pressure is the product of gas flow and pharyngeal resistance. A 'fat apron' around the pharynx because of obesity may lead to increased pharyngeal compliance, and thus increase the risk of dynamic pharyngeal collapse in such patients. In adults, when pharyngeal flows exceed 30 to 40 litres per minute, the work of breathing becomes high and the fall in pharyngeal pressure too great for the adequate intake of air: the mouth then becomes the preferred route for breathing.

The larynx remains a protector of the airway, with aryepiglottic and arytenoid muscles able to draw the laryngeal entrance closed like a purse-string and the epiglottis pulled down from above like a trap door. In addition, the arytenoid cartilages can swing inwards to appose the vocal cords themselves, thus offering an effective seal to the entry of particles or gases to the airway beneath. Meanwhile, tight occlusion can be achieved during swallowing or to 'fix' the thorax during heavy lifting, allowing the larynx to resist internal pressures of some 120 cm H_2O. Laryngeal sensitivity to irritation, causing a cough, makes the larynx effective at limiting entry of noxious gases or larger particles, while more intense chemoreceptor stimulation can cause severe laryngeal spasm, preventing any meaningful gas flow. In the anaesthetic room, this can be life-threatening.

When air enters the trachea, it is supported by anterior horse-shoes of cartilage (Figure 1.1). However, these are compliant, and tracheal collapse occurs with extrinsic pressures of only 40 cm H_2O. Ciliated columnar epithelium yields an upward-moving mucus 'escalator'. The trachea then divides into the right and left main bronchi (generation 1 airways), and then into lobar and

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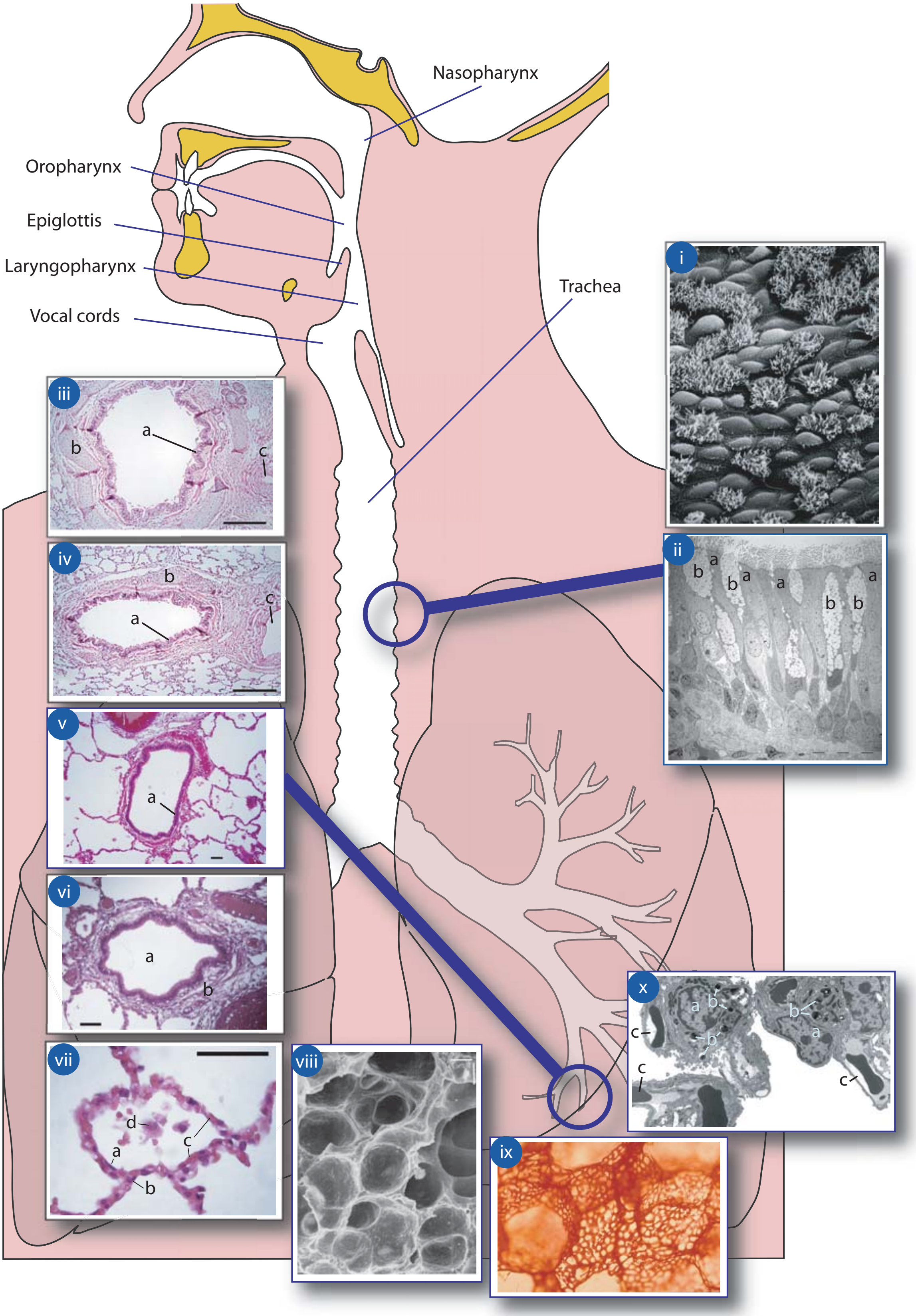
Nasopharynx
Oropharynx
Epiglottis
Laryngopharynx
Vocal cords
Trachea
i
ii
a
b
iii
a
b
c
iv
a
b
c
v
a
vi
a
b
vii
a
b
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