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MEDICAL VENTILATOR SYSTEM BASICS

A Clinical Guide

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Foreword by Peter Rimensberger

From the development of positive pressure ventilators in the 1940s—ventilators that offered only non-synchronized volume-controlled ventilation—technical development has continued, resulting in today's sophisticated ventilatory systems. These systems can provide patient-triggered mechanical ventilation and a wide array of ventilator modes.

At the same time, we observe a clear trend towards 'smart' or 'intelligent' ventilation concepts and algorithms that provide decision support and even automation of mechanical ventilation. This involves integrating physiological data which has been acquired directly from the ventilator's built-in monitoring or indirectly through other bedside technologies.

However, these sophisticated control systems, while exploiting many of the advantages of today's microprocessor technology, do not eliminate the responsibility of the critical care team to optimize mechanical ventilation for each patient. To be able to carry out this responsibility and to provide mechanical ventilation in the best possible way, the care provider not only has to have a good understanding of mechanical ventilation, physiology, and respiratory mechanics, but also of the device's operating principles, essential variables, and control parameters.

Unfortunately, in the clinical setting we observe that a basic understanding of how a ventilator works and how to apply the information it provides, is increasingly lost to the younger generation of health care providers. In parallel, the knowledge of what might be detrimental to a ventilated patient is increasing—although there is often a tendency to generalize and even oversimplify the best ventilator strategies and concepts to be applied in a patient. The increasing number of sophisticated algorithm-based ventilator modes on which we quickly come to rely further supports this trend.

So the question arises whether we, as care providers, still know how to 'drive' the ventilator and to 'troubleshoot' in an appropriate and rapid way without putting the patient at risk.

A good understanding of the technical equipment, including its operating principles and safety backup systems, seems to be crucial to maintain this knowledge.

This has been recognized by Yuan Lei, the author of this book, who, like me, can look back on about 45 years of progress in the development of ventilator technology for intensive care. Over these years we have seen, either from the standpoint of a product manager or of a clinician, many ICU ventilators of various brands. We have also read their user manuals. Although the manuals should provide all the necessary information on how to use the devices, they mainly explain the details of their ventilator modes and provide some information on the alarms that may occur, along with some troubleshooting advice. This information often does not really help one to understand how the ventilator interacts with the patient and how the data provided by the ventilator can be used to assure its proper functioning and settings.

In short, there is generally little education offered to help one understand first, the ventilator equipment, including its operating principle and technical limitations, and second, how the device's respiratory mechanics information can be used to set basic ventilator parameters appropriately.

Based on his extensive personal experience in this field and many lessons learned from direct contact with ventilator users, as well as the recognition that those who design and manufacture devices have to take some responsibility in the process of education and training of users, the author has, for many years, had a dream to help. His goal, that we, the clinical users, gain a greater understanding of a properly functioning ventilator system and its proper use—this will be a key determinant in the successful application of specific ventilator strategies.

With the realization of this book for clinical ventilator users, he not only fulfils his own dream, but also gives us a comprehensive educational tool to improve our understanding of the essential basic principles for the use of a mechanical ventilator—a highly dangerous medical device, when inappropriately used.

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Foreword by Giorgio A. Iotti

In his preface, the author recommends reading the chapters of his book in sequence. I also recommend the reader start the sequence from the preface, reading his story of the young physician faced with the challenge of introducing intensive care and modern mechanical ventilation in China in the 1980s.

Although at that time intensive care was well established in Europe, our problems in understanding and implementing modern mechanical ventilation were not so different from those experienced by the author in China. We were leaving the old established way, using simple and robust machines that provided just volume control ventilation, with PEEP generated by water-seal or spring valves, and monitoring based simply on a mechanical manometer and spirometer. We were starting to use the new electronic machines, which provided a number of ventilation modes (each one with a number of controls), without a clear knowledge of their indications and benefits.

Also, monitoring of mechanical ventilation was changing from the pure technical control of the ventilator to functional assessment of the patient with respiratory failure. Finally, the new technology included extensive alarming; the new ventilator alarms were sounding a lot, sometimes with bells and whistles upsetting both clinicians and patients, especially during the night! Considering all these issues, the sources of information available to guide our use of mechanical ventilators were limited.

Since then, education in the field of mechanical ventilation has become a complex matter indeed. The science of mechanical ventilation has greatly advanced and several important principles are now consolidated. However, driving a mechanical ventilator is not just a matter of understanding principles that can be found in the scientific literature; it also requires a deep knowledge of the actual machine that we are using. And here comes one major difficulty: unlike vehicles, that are necessarily designed to respond homogeneously to approved standards, mechanical ventilators are frequently designed to look different from each other, even more different than they actually are. The difficulty in 'driving' a mechanical ventilator could be overcome by reading and studying the user's manual, usually a great source of accurate and useful information. Unfortunately, this simple solution fails to consider a common professional disease of clinicians: a severe allergy to reading user's manuals! On the other hand, the language and approach of user's manuals, usually written by engineers, do not help.

Medical Ventilator System Basics: A Clinical Guide stems from the recognition of all these difficulties. It is indeed a book conceived to answer a need for education, with simplicity and completeness being the evident bywords that inspired the author's work. The book deals with technology, but it is not written by an engineer: it is written by a physician for the needs of clinicians. It intends to provide practical information for the proper use of mechanical ventilators, but it is not focused on a specific machine; rather, the book aims to help the reader to obtain the best from his own ventilator.

Very interestingly, the book is based on an original concept: the 'ventilator system', which is not just the 'mechanical ventilator', but the unit composed of all the elements, both natural and artificial, that make up the functional respiratory system of a mechanically ventilated patient. Thus, the 'ventilator system' also includes the patient's airways, lungs, chest wall, and respiratory muscles, as essential components contributing to and affecting the physiological result of gas exchange. Similarly, the artificial components include not just the high technology ventilator, but also humble but essential parts such as the external circuit (that might be leaking, for instance) and the endotracheal tube (that might be clogged). The analytical view provided by the 'ventilator system' concept can be extremely useful for fast troubleshooting when mechanical ventilation becomes ineffective. This kind of concept may be profitably translated to other kinds of artificial support of organs, such as extracorporeal membrane oxygenation.

I am confident that *Medical Ventilator System Basics: A Clinical Guide* will become a classic of medical literature on mechanical ventilation, mostly appreciated by those clinicians aware of the importance of integrating a strong theoretical background with a deep understanding of the instruments used to provide mechanical ventilation.

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Preface

In the late 1980s, as a young surgical resident at a teaching hospital in Shanghai, I experienced first-hand the introduction of the intensive cáre unit (ICU) and mechanical ventilation to mainland China. Medical professionals then perceived an ICU and ventilator to be a cure-all, although few had the knowledge to back up their beliefs. 'We must have our own ICUs', the head of my hospital declared. So a new surgical ICU was set up in two large, air-conditioned rooms. It was equipped with three Siemens SERVO 900C ventilators, a few patient monitors, and other basic equipment. The first ICU crew included a group of young physicians and nurses. I was a crew member.

A big challenge we faced was that none of us knew about mechanical ventilation or the ventilator and its operation; something I was then assigned to learn. I delved into the operator's manual, which was, at the time, the only source of information available. I quickly discovered that the manual was written by technical people, for technical people, and that my medical education was of little use in this particular area. And so the nightmare began as I was called around the clock to resolve various problems with mechanical ventilation. In a typical scenario, I would find the ventilated patient clearly in trouble, the ventilator was alarming persistently, and I hadn't a clue what had gone wrong. I was forced to learn in a tough way, through trial and error.

Ironically, around a decade later I became product manager for a ventilator manufacturer. In this position, I had the opportunity for the comprehensive study of mechanical ventilation and equipment. I also became deeply involved in ventilator development, marketing, and customer training. From this experience I made several interesting discoveries:

a. The current mechanical ventilation education in medical or nursing schools is neither adequate nor structured. Meaningful learning often begins after a graduate starts clinical practice.
b. The equipment required for mechanical ventilation is a ventilator system with six essential components. A ventilator is just one of them.
c. All positive pressure ventilator systems have the same or highly similar operating principles and system composition, and all require the same conditions for operation. They may differ here and there in technical implementation. Interestingly, their differences are often exaggerated and the similarities unmentioned.
d. The clinical outcome of mechanical ventilation relies much more on the user's knowledge of this therapy than it does on the equipment in use.
e. The knowledge specific to mechanical ventilation has two dimensions: its clinical application and its equipment. The second dimension is often ignored in the related education.
f. Today, ample information about clinical application is widely available, but little exists about the equipment.
g. Clinicians often feel responsible for the clinical application of mechanical ventilation, but hold technicians responsible for the equipment.

Mechanical ventilation can be described as the clinical application of a ventilator system. Clinicians who conduct this therapy need to understand both the application and the equipment for three reasons. First, equipment knowledge is required to set up and maintain a properly functioning ventilator system. Second, equipment knowledge is required to understand the real meaning of a ventilator's functions and features. Third, equipment knowledge is required to determine the source of, and to resolve, problems that can stem from the equipment, the ventilated patient, or the operator's commands or settings.

Recognizing this need, I wrote this book, mainly for the clinician involved in mechanical ventilation therapy, to clearly and systematically explain the operating principles, composition, required operating conditions, and major functions of positive pressure ventilator systems, regardless of brand and model. The book is based on my own knowledge, experience, and the information I have collected.

The information in this book is organized into 13 chapters. Chapters 1 through 3 lay the groundwork for understanding the ventilator system; Chapters 4 through 6 deal primarily with the 'anatomy' of a ventilator system; Chapters 7 through 10 detail how the ventilator system performs mechanical ventilation; Chapters 11 and 12 describe ventilator monitoring and alarms; and Chapter 13 tells you how to troubleshoot common ventilator problems, and how to report adverse events to authorities.

I tried to make the content easy to understand, with plain English text and plentiful graphics. Reading the chapters in sequence is recommended. It is helpful, but not required, that the reader has experience in mechanical ventilation and/or a technical background.

After reading through the entire book, you should have a clear and thorough understanding of positive pressure ventilator systems, independent of brand and model. This knowledge can help pave the way for further study of advanced features and functions.

This project was a great challenge because I did it solely in my spare time. The writing occupied over half of my weekends and holidays over the last five years, and proved difficult, because, in many cases, there was little or no reference material to be found. Some concepts I set forth are original, for instance, the concept of a ventilator system.

I would like to thank Sandy Miller for her valuable encouragement, constructive discussions, and excellent editing. I would also like to thank my wife, Zhiping, and children, Mathias and Andrea, for their understanding and patience. This book would not have seen the light of day without their support.

Yuan Lei, MD

Abbreviations

A/C	assist/control
AARC	American Association of Respiratory Care
AC	alternating current
AH	absolute humidity
ALI	acute lung injury
APRV	airway pressure release ventilation
ARDS	acute respiratory distress syndrome
ASV	adaptive support ventilation
ATC	automatic tube compensation
ATP	adenosine triphosphate
BCT	breath cycle time
BiPAP	bilevel positive airway pressure
CMV	continuous mandatory ventilation
COPD	chronic obstructive pulmonary disease
CPAP	continuous positive airways pressure
DISS	diameter indexed safety system
EPAP	expiratory positive airway pressure
ETS	expiratory trigger sensitivity
ETT	endotracheal tube
EVA	ethylene-vinyl acetate
F_iO_2	fraction of inspired oxygen
FRC	functional residual capacity
GUI	geographical user interface
Hb	haemoglobin
HFOV	high-frequency oscillatory ventilation
HFPV	high-frequency percussive ventilation
HFV	high-frequency ventilation
HIS	hospital information system
HME	heat and moisture exchanger
I:E	inspiratory:expiratory ratio
ICU	intensive care unit
IMV	intermittent mandatory ventilation
INPV	intermittent negative pressure ventilation
IPAP	inspiratory positive airway pressure
IPPV	intermittent positive pressure ventilation
IRV	inverse ratio ventilation
LCD	liquid crystal display
LED	light-emitting diode
MAP	mean airway pressure
MVexp	expiratory minute volume
NAVA	neurally adjusted ventilatory assist
NIST	non-interchangeable screw thread
NIV	non-invasive ventilation
$PaCO_2$	partial pressure of CO_2 in arterial blood
P_{alv}	alveolar pressure
P_{ao}	airway opening pressure
PaO_2	partial pressure of oxygen in arterial blood
PAO_2	partial pressure of O_2 in alveoli
PAV	proportional assist ventilation
P_{AW}	airway pressure
$P_{control}$	pressure control
PDMS	patient data management system
PEEP	positive end-expiratory pressure
$P_{et}CO_2$	partial pressure of CO_2 (end-tidal)
P_{insp}	inspiratory pressure
PIP	peak inspiratory pressure
PLV	pressure-limited ventilation
Pmean	mean airway pressure
PO_2	partial pressure of oxygen
Ppeak	peak airway pressure
P_{ramp}	pressure ramp

$P_{support}$	pressure support
PSV	pressure support ventilation
PVC	polyvinyl chloride
PvO_2	partial pressure of O_2 in venous blood
RC	time constant
RDS	respiratory distress syndrome
RH	relative humidity
SAAS	severe acute respiratory syndrome
SIMV	synchronized intermittent mandatory ventilation
SpO_2	oxygen saturation
SSRD	sudden and severe respiratory distress
T_e	expiratory time
TF	technical fault/failure
T_i	inspiratory time
TRC	tube resistance compensation
TT	tracheostomy tube
VAPS	volume-assured pressure support
V_T	tidal volume
VTE	expiratory tidal volume
VTI	inspiratory tidal volume
WOB	work of breathing
ZEEP	zero PEEP

Contents

Chapter 1

Introduction

1.1 What is mechanical ventilation?

Mechanical ventilation can be realized with one of three operating principles: *intermittent positive pressure ventilation (IPPV), intermittent negative pressure ventilation (INPV)*, and *high-frequency ventilation (HFV)*. Of these, IPPV is currently the most popular and is the basis for most commercially available ventilators. Unless otherwise noted, 'mechanical ventilation' in this book means mechanical ventilation using the IPPV principle.

Mechanical ventilation is a respiratory care therapy to treat serious respiratory failure or respiratory deficiency resulting from a wide variety of clinical causes. If performed appropriately, this therapy can temporarily and artificially support or replace seriously damaged pulmonary functions, maintaining normal or nearly normal ventilation and oxygenation. This gives the clinician time to treat primary diseases and to improve the patient's general clinical condition. If performed appropriately, mechanical ventilation is a powerful and effective life-saving tool. If performed inappropriately, however, mechanical ventilation may be equally powerful and effective in harming the ventilated patient.

A set of specialized medical equipment is essential to perform this therapy (see Box 1.1). This equipment is a *ventilator system*, which typically has six essential components: (1) compressed gas (oxygen and air) supplies, (2) an electrical power supply, (3) a ventilator, (4) a breathing circuit, (5) an artificial airway, and (6) the patient's pulmonary system. A ventilator, therefore, is just one part of a ventilator system. We will discuss the concept of the ventilator system in greater depth in Chapter 4.

Mechanical ventilation is highly risky, not only because respiration is vital for survival, but also because, with IPPV a ventilated patient breathes exclusively through a gas-tight ventilator system. If the therapy goes awry clinically or technically, the patient's safety may be immediately endangered.

Mechanical ventilation is highly complicated, because it requires a clinician to have two types of specialized expertise in addition to their knowledge and skills in general clinical medicine. The clinical outcome of this therapy depends heavily on this specialized knowledge. Thus, a clinician who is good at clinical medicine is not automatically qualified to perform mechanical ventilation.

Mechanical ventilation is labour intensive. In addition to the clinician's typical routines, mechanical ventilation requires therapy-specific work. This includes defining and modifying the therapeutic strategy, assembling and maintaining the ventilator system, checking and adjusting ventilator settings, responding to alarms and troubleshooting, managing the airway, and managing nebulization and humidification, not to mention taking care of documentation.

Mechanical ventilation is error prone. Because it is complex and labour intensive, mechanical ventilation invites human error. Errors occur far more frequently than we would like to believe; some, with very serious consequences.

Box 1.1 Primary characteristics of mechanical ventilation

1. It is a life-supporting respiratory therapy;
2. It requires a ventilator system;
3. It is powerful and effective;
4. It is highly risky;
5. It is highly complicated;
6. It is labour intensive;
7. It is error prone;
8. It is typically applied by a group of clinicians on different shifts;
9. It is extraordinarily costly;
10. It is widely applied the world over.

Typically, a patient is ventilated for a period ranging from several hours to several days, although this period can be much longer. So, several clinicians on different shifts—experts and novices alike—perform the therapy jointly. The quality of the therapy on a single patient may vary, depending on the expertise of the clinicians on duty and how well they communicate with one another.

Mechanical ventilation therapy is very expensive. To a great extent it defines the length of stay in the intensive care unit (ICU). A large-scale investigation discovered that in the US, the mean incremental cost of mechanical ventilation was $1522 per patient per day (Dasta et al., 2005). In theory, if the therapy could be shortened by even one hour for every ventilated patient, enormous savings would result.

The application of mechanical ventilation has accelerated the world over. This is particularly the case in developing countries.

1.2 What knowledge is required for mechanical ventilation?

Many hospitals are eager to perform mechanical ventilation, knowing that it is an effective life-supporting and sustaining therapy. Their directors may believe that a mere investment in first-class ventilators along with a strong medical and nursing staff and infrastructure will guarantee the therapy's success. In truth, the results may be very disappointing, if not catastrophic.

What can go wrong? Unwanted consequences can occur for a number of reasons. The primary one is that clinicians do not have adequate knowledge to perform this therapy.

What types of knowledge are required for mechanical ventilation therapy, then?

Well, to achieve the best possible outcome from mechanical ventilation, clinicians must have two types of expertise: clinical knowledge and therapy-specific knowledge (Fig. 1.1).

Obviously, any clinician involved in mechanical ventilation must be sufficiently qualified in the related branches of clinical medicine, e.g. intensive care medicine, anaesthesiology, pulmonology, intensive care nursing, and emergency medicine. Less obvious is the need for therapy-specific knowledge. Mechanical ventilation can become a nightmare for a clinician—even an excellent one—with little therapy-specific knowledge. Without this knowledge, they cannot understand what the problem is, why it occurred, and how to correct it. Even the most determined clinician cannot help the patient in trouble. Blind trials often make the situation even worse. This happened to the author, as described in the preface.