Fundamentals of

Mechanical Ventilation

A short course on the theory and application of mechanical ventilators

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Preface

Find a better way to educate students than the current books offer. If you can't improve on what's available, what's the point?

Earl Babbbie
Chapman University

This book is about how ventilators work. It shows you how to think about ventilators, when to use various modes, and how to know if they are doing what you expect. This book does not say much about how to use ventilators in various clinical situations or how to liberate patients from the machine. Mechanical ventilation is still more of an art than a science. This book leads you to expertise with the theory and tools of that art. You will then be able to make the best use of other books and actual clinical experience.

There are 18 books devoted to mechanical ventilation on my bookshelf. They are all well written by noted experts in the field. Some are commonly used in colleges while others have fallen into obscurity. Yet, in my opinion, they all have the same limitation; they devote only a small fraction of their pages to how ventilators actually work. Most of their emphasis is on how ventilators are used to support various disease states, the physiological effects of mechanical ventilation, weaning, and adjuncts like artificial airways and humidifiers. This book is different.

The reason I made this book different may be clarified by analogy. Suppose you wanted to learn how to play the guitar. You go to the library, but all you can find are books that give you a few pages describing what different guitars look like and all the fancy names and features their manufacturers have made up. There may be a little information about how many strings they have and even what notes and chords can be played. Unfortunately, many of the books use words with apparently conflicting or obscure meanings. There is no consistency and no music theory. They all devote most of their content to a wide variety of song scores, assuming the few pages of introduction to the instrument will allow you to play them. How well do you think you would learn to play the guitar from these books? If you have ever actually tried it, you would see the difficulty. That approach works for a simple instrument like a harmonica, but it does not work well for a complex device like a mechanical ventilator. In a similar fashion, we don't let our teenagers drive cars after simply pointing out the controls on the dashboard; they have to sit through weeks of theory before ever getting behind the wheel.

You can kill or injure somebody with a ventilator just as fast as you can with a car.

Certainly there is a great need for understanding the physiological effect of mechanical ventilation. But most authors seem to put the cart before the horse. In this book, I have tried to present the underlying concepts of mechanical ventilation from the perspective of the ventilator. All terminology has been clearly defined in a way that develops a consistent theoretical framework for understanding how ventilators are designed to operate. There is one chapter devoted to how to use ventilators, but it is written from the perspective of what the ventilator can do and how you should think about the options rather than from what physiological problem the patient may have. There is also a chapter devoted to monitoring the ventilator-patient interface through waveform analysis, a key feature on modern ventilators. In short, this book will teach you how to think about ventilators themselves. It teaches you how to master the instrument. That way you are better prepared to orchestrate patient care. Only after thoroughly understanding what ventilators do will you be in a position to appreciate your own clinical experience and that of other expert authors.

The unique approach of this book makes it valuable not only to health care workers but to those individuals who must communicate with clinicians. This includes everyone from the design engineer to the marketing executive to the sales force and clinical specialists. Indeed, since manufacturers provide most of the education on mechanical ventilation, the most benefit may come from advancing their employees' level of understanding.

How to Use This Book

This book may be read on a variety of levels depending on your educational needs and your professional background. Look at the different approaches to reading and see what is most appropriate for you.

Basic Familiarity: This level is appropriate for people not directly responsible for managing ventilators in an intensive care environment. This may include healthcare personnel such as nurses, patients on home care ventilators, or those not directly involved at the bedside such as administrators or ventilator sales personnel. Study the first two chapters and the section on alarms in Chapter 3. Skim the others for areas of interest, paying attention to the figures in Chapter 5.

Comprehensive Understanding: Respiratory care students should achieve this level along with physicians and nurses who are responsible for ventilator management. Some sales personnel may wish to understand ventilators at this level in order to converse easily with those who buy and use them. Study all the chapters, but skip the "Extra for Experts" sections. Pay attention to the "Key Idea" paragraphs and the definitions in the Glossary. Make sure you understand Chapter 5.

Subject Mastery: This level is desirable for anyone who is in a position to teach mechanical ventilation and particularly for those who are involved with research on the subject. All material in the book should be understood, including the "Extra for Experts" sections. A person at this level should be able to answer all the questions and derive all the equations used throughout.

Of course, these levels are only suggestions and you will undoubtedly modify them for your own use.

Acknowledgement

The central ideas of this text came from two seminal papers I published in Respiratory Care, the official scientific journal of the American Association for Respiratory Care. The first was published in 1991, and introduced a new classification system for mechanical ventilators (Respir Care 1991:36(10):1123-1155). It was republished the next year as a part of the Journal's Consensus Conference on the Essentials of Mechanical Ventilators (Respir Care 1992:37(9):1009-1025). Eventually, those papers became the basis for book chapters on ventilator design in every major respiratory care textbook:

- Tobin MJ. *Principles and Practice of Mechanical Ventilation*, 1994. McGraw-Hill.
- Branson RD, Hess DR, Chatburn RL. *Respiratory Care Equipment*, 1st and 2nd editions, 1995 & 1999. Lippincott.
- White GC. Equipment for Respiratory Care 2nd edition, 1996, Delmar.
- Hess DR, Kacmarek RM. *Essentials of Mechanical Ventilation*, 1996. McGraw-Hill.
- Pilbeam SP. Mechanical Ventilation. Physiological and Clinical Applications, 3rd edition, 1998. Mosby.
- Scanlan CL, Wilkins RL, Stoller JK. *Egan's Fundamentals of Respiratory Care* 7th edition, 1999. Mosby.
- Branson RD. MacIntyre NR. *Mechanical Ventilation*, 2001. WB Saunders.
- Wyka KA, Mathews PJ, Clark WF. *Foundations of Respiratory Care*, 2002. Delmar.
- Hess DR, MacIntyre NR, Mishoe SC, Galvin WF, Adams WB, Saposnick AB. *Respiratory Care. Principles and Practice*, 2002. Saunders.

In 2001, my coauthor, Dr. Frank Primiano Jr., and I introduced a new system for classifying modes of ventilation (Respir Care 2001; 46(6):604-621), tying in with the principles established in the earlier publications. That paper received the Dr. Allen DeVilbiss Technology Paper Award for best paper of the year at the 2001 International Respiratory Care Congress. Only the last book listed above has that information.

In this book you are getting the latest information, undiluted, uninterpreted, from the original author.

Dedication

It's an endless, glamorless, thankless job.
But somebody's got to do it.

Sergeant Joe Friday
LAPD

This book is dedicated to everyone who has ever tried to teach the subject of mechanical ventilation. It has always been a daunting task, given the lack of a unified lexicon, complex technological advances, and an endless stream of clinical studies and conflicting opinions. Yet, here and there, lone educators stay up endless nights writing textbooks and lectures; intrepid clinical specialists fly red-eye specials around the globe to eager but clueless audiences; sales personnel valiantly argue their cause; and frustrated engineers try to communicate with inventive clinical researchers. Much of this effort is expended simply for the love of the subject. Keep up the good work; you benefit countless lives.

1. INTRODUCTION TO VENTILATION

During breathing, a volume of air is inhaled through the airways (mouth and/or nose, pharynx, larynx, trachea, and bronchial tree) into millions of tiny gas exchange sacs (the alveoli) deep within the lungs. There it mixes with the carbon dioxide-rich gas coming from the blood. It is then exhaled back through the same airways to the atmosphere. Normally this cyclic pattern repeats at a breathing rate, or frequency, of about 12 breaths a minute (breaths/min) when we are at rest (a higher resting rate for infants and children). The breathing rate increases when we exercise or become excited.[1]

Gas exchange is the function of the lungs that is required to supply oxygen to the blood for distribution to the cells of the body, and to remove carbon dioxide from the blood that the blood has collected from the cells of the body. Gas exchange in the lungs occurs only in the smallest airways and the alveoli. It does not take place in the airways (conducting airways) that carry the gas from the atmosphere to these terminal regions. The size (volume) of these conducting airways is called the **anatomical dead space** because it does not participate directly in gas exchange between the gas space in the lungs and the blood. Gas is carried through the conducting airways by a process called "convection". Gas is exchanged between the pulmonary gas space and the blood by a process called "diffusion".

Key Idea

One of the major factors determining whether breathing is producing enough gas exchange to keep a person alive is the ventilation the breathing is producing. Ventilation (usually referred to as **minute ventilation**) is expressed as the volume of gas entering, or leaving, the lungs in a given amount of time. It can be calculated by multiplying the volume of gas, either inhaled or exhaled during a breath (called the **tidal volume**), times the breathing rate (for example: 0.5 Liters *x* 12 breaths/min = 6 L/min).

[1] This section is adapted from: Primiano FP Jr, Chatburn RL. What is a ventilator? Part I. www.VentWorld.com; 2001.

Key Idea

> The level of ventilation can be monitored by measuring the amount of carbon dioxide in the blood. For a given level of carbon dioxide produced by the body, the amount in the blood is inversely proportional to the level of ventilation.

Therefore, if we were to develop a machine to help a person breathe, or to take over his or her breathing altogether, it would have to be able to produce a tidal volume and a breathing rate which, when multiplied together, produce enough ventilation, but not too much ventilation, to supply the gas exchange needs of the body. During normal breathing the body selects a combination of a tidal volume that is large enough to clear the dead space and add fresh gas to the alveoli, and a breathing rate that assures the correct amount of ventilation is produced. However, as it turns out, it is possible, using specialized equipment, to keep a person alive with breathing rates that range from zero (steady flow into and out of the lungs) up to frequencies in the 100's of breaths per minute. Over this frequency range, convection and diffusion take part to a greater or lesser extent in distributing the inhaled gas within the lungs. As the frequency is increased, the tidal volume that produces the required ventilation gets smaller and smaller.

There are two sets of forces that can cause the lungs and chest wall to expand: the forces produced when the muscles of respiration (diaphragm, inspiratory intercostal, and accessory muscles) contract, and the force produced by the difference between the pressure at the airway opening (mouth and nose) and the pressure on the outer surface of the chest wall. Normally, the respiratory muscles do the work needed to expand the chest wall, decreasing the pressure on the outside of the lungs so that they expand, which in turn enlarges the air space within the lungs, and draws air into the lungs. The difference between the pressure at the airway opening and the pressure on the chest wall surface does not play a role in this activity under normal circumstances. This is because both of these locations are exposed to the same pressure (atmospheric), so this difference is zero. However, when the respiratory muscles are unable to do the work required for ventilation, either or both of these two pressures can be manipulated to produce breathing movements, using a mechanical ventilator.

It is not difficult to visualize that, if the pressure at the airway opening (the mouth and nose or artificial airway opening) of an individual were increased while the pressure surrounding the rest of the person's body remained at atmospheric, the person's chest would expand as air is literally forced into the lungs. Likewise, if the pressure on the person's body surface were lowered as the pressure at the person's open mouth and nose remained at atmospheric, then again the pressure at the mouth would be greater than that on the body surface and air would be forced into the lungs.

Key Idea

> Thus, we have two approaches that can be used to mechanically ventilate the lungs: apply positive pressure (relative to atmospheric) to the airway opening - devices that do this are called **positive pressure ventilators**; or, apply negative pressure (relative to atmospheric) to the body surface (at least the rib cage and abdomen) - such devices are called **negative pressure ventilators**.

Sometimes positive airway pressure is applied to a patient's airway opening without the intent to ventilate but merely to maintain a normal lung volume. Originally, devices were designed to present resistance to expiratory flow, and hence provide positive pressure throughout expiration. The pressure at end expiration was called positive end expiratory pressure or **PEEP**. The problem with these early devices was that the patient had to inhale with enough force to drop the airway pressure through the PEEP level to below atmospheric pressure before inspiratory flow would begin. This often increased the work of breathing to intolerable levels. Newer devices were designed to avoid this problem. The key was to design the device so that the patient could inspire by dropping the pressure just below the PEEP level, rather than all the way to atmospheric pressure. As a result, the pressure in the patient's lungs remained positive (above atmospheric) throughout the breathing cycle. Thus, the new procedure was called continuous positive airway pressure or **CPAP**. Almost all current ventilators provide CPAP rather than PEEP. There are also devices that just produce CPAP for patients that are breathing without a ventilator.

As time passed, people forgot the historic reasons for the distinction between PEEP and CPAP. The original PEEP therapy is now called "positive airway pressure", PAP, and is used to help patients (who are not connected to mechanical ventilators) to mobilize airway secretions and reverse atelectasis. Currently, the term PEEP is applied to the continuous positive airway pressure provided during assisted ventilation by a mechanical ventilator. Assisted ventilation means simply that the ventilator helps the patient with the timing and/or work of inspiration. The term CPAP is usually applied to continuous positive airway pressure provided while the patient breathes unassisted, such as for infants with respiratory distress syndrome after extubation or adults with sleep apnea.

It is important to remember that CPAP and PEEP themselves are not forms of assisted ventilation, in the sense that they do not supply any of the work of breathing. They may, however, make it easier for the patient to breathe by lowering airway resistance or increasing lung compliance.

Self Assessment Questions

Definitions

Explain the meaning of the following terms:

- Anatomical dead space
- Minute ventilation
- Tidal volume
- PEEP
- CPAP

True or False

1. Gas exchange is the function of the lungs that is required to supply oxygen to the blood for distribution to the cells of the body, and to remove carbon dioxide from the blood that the blood has collected from the cells of the body.
2. Gas exchange occurs in all the conducting airways and the alveoli.
3. Minute ventilation is calculated as the product of tidal volume and breathing rate.
4. The unit of measurement for minute ventilation is liters.
5. It is possible to keep a person alive with breathing rates that range from zero (steady flow into and out of the lungs) up to frequencies in the 100's of breaths per minute.

Multiple Choice

1. The forces that expand the lungs and chest wall during inspiration are:

    a. The forces produced when the muscles of respiration (diaphragm, inspiratory intercostal, and accessory muscles) contract.

    b. Positive end expiratory pressure (PEEP).

    c. The force produced by the difference between the pressure at the airway opening (mouth and nose) and the pressure on the outer surface of the chest wall.

    d. Both a and c.

2. In order to generate an inspiration, the following condition must be present:

    a. Lung pressure must be higher than pressure at the airway opening.

    b. Airway pressure must be higher than body surface pressure.

    c. Body surface pressure must be higher than airway pressure.

    d. Pleural pressure must be lower than body surface pressure.

3. In order to generate an expiration, the following condition must be present:

    a. Lung pressure must be higher than pressure at the airway opening.

    b. Pressure at the airway opening must be higher than body surface pressure.

    c. Body surface pressure must be higher than pressure at the airway opening.

    d. Body surface pressure must be lower than lung pressure.

Key Ideas

1. What two variables determine whether breathing is producing enough gas exchange to keep a person alive?
2. Explain how the level of ventilation can be monitored by measuring carbon dioxide in the blood. Why not just measure tidal volume and frequency?
3. Describe the difference between positive pressure ventilators and negative pressure ventilators.

2. INTRODUCTION TO VENTILATORS

A **mechanical ventilator** is an automatic machine designed to provide all or part of the work the body must produce to move gas into and out of the lungs. The act of moving air into and out of the lungs is called breathing, or, more formally, ventilation.

The simplest mechanical device we could devise to assist a person's breathing would be a hand-driven, syringe-type pump that is fitted to the person's mouth and nose using a mask. A variation of this is the self-inflating, elastic resuscitation bag. Both of these require one-way valve arrangements to cause air to flow from the device into the lungs when the device is compressed, and out from the lungs to the atmosphere as the device is expanded. These arrangements are not automatic, requiring an operator to supply the energy to push the gas into the lungs through the mouth and nose. Thus, such devices are not considered mechanical ventilators.

Automating the ventilator so that continual operator intervention is not needed for safe, desired operation requires:

- a stable attachment (interface) of the device to the patient,
- a source of energy to drive the device,
- a control system to regulate the timing and size of breaths, and
- a means of monitoring the performance of the device and the condition of the patient.

Types of Ventilators

We will consider two classes of ventilators here. First are those that produce breathing patterns that mimic the way we normally breathe. They operate at breathing rates our bodies normally produce during our usual living activities: 12 - 25 breaths/min for children and adults; 30 - 40 breaths/min for infants. These are called **conventional ventilators** and their maximum rate is 150