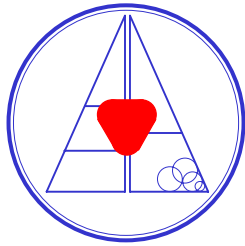


Fundamentals of

Mechanical Ventilation

*A short course on the
theory and application
of mechanical ventilators*

Robert L. Chatburn, BS, RRT-NPS, FAARC



Director
Respiratory Care Department
University Hospitals of Cleveland
Associate Professor
Department of Pediatrics
Case Western Reserve University
Cleveland, Ohio

Mandu Press Ltd.
Cleveland Heights, Ohio



Published by:

Mandu Press Ltd.

PO Box 18284

Cleveland Heights, OH 44118-0284

All rights reserved. This book, or any parts thereof, may not be used or reproduced by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without written permission from the publisher, except for the inclusion of brief quotations in a review.

First Edition

Copyright © 2003 by Robert L. Chatburn

Library of Congress Control Number: 2003103281

ISBN, printed edition: 0-9729438-2-X

ISBN, PDF edition: 0-9729438-3-8

First printing: 2003

Care has been taken to confirm the accuracy of the information presented and to describe generally accepted practices. However, the author and publisher are not responsible for errors or omissions or for any consequences from application of the information in this book and make no warranty, express or implied, with respect to the contents of the publication.

Table of Contents

1. INTRODUCTION TO VENTILATION.....	1
Self Assessment Questions.....	4
Definitions.....	4
True or False	4
Multiple Choice	5
Key Ideas	6
2. INTRODUCTION TO VENTILATORS	7
Types of Ventilators.....	7
Conventional Ventilators.....	8
High Frequency Ventilators.....	8
Patient-Ventilator Interface	9
Positive Pressure Ventilators.....	9
Negative Pressure Ventilators	9
Power Source.....	10
Positive Pressure Ventilators.....	10
Negative Pressure Ventilators	10
Control System.....	10
Patient Monitoring System.....	11
Alarms.....	11
Graphic Displays.....	12
Self Assessment Questions.....	14
Definitions.....	14
True or False	15
Multiple Choice	15
Key Ideas	16
3. HOW VENTILATORS WORK.....	17
Input Power	18

Power Transmission and Conversion	18
Control System.....	19
The Basic Model of Breathing (Equation of Motion).....	19
Control Circuit.....	25
Control Variables.....	26
Phase Variables.....	28
Modes of Ventilation	41
Breathing Pattern	42
Control Type.....	52
Control Strategy.....	57
The Complete Specification	58
Alarm Systems	61
Input Power Alarms	64
Control Circuit Alarms	64
Output Alarms	65
Self Assessment Questions	67
Definitions	67
True or False.....	69
Multiple Choice	71
Key Ideas.....	80
4. HOW TO USE MODES OF VENTILATION.....	82
Volume Control vs Pressure Control.....	82
The Time Constant	90
Continuous Mandatory Ventilation (CMV).....	94
Volume Control	95
Pressure Control	98
Dual Control	102
Intermittent Mandatory Ventilation (IMV).....	104
Volume Control	105
Pressure Control	106
Dual Control	107
Continuous Spontaneous Ventilation (CSV).....	108
Pressure Control	108
Dual Control	113
Self Assessment Questions	114

Definitions.....	114
True or False	114
Multiple Choice	116
Key Ideas	119
5. HOW TO READ GRAPHIC DISPLAYS.....	121
Rapid Interpretation of Graphic Displays	121
Waveform Display Basics	122
Volume Controlled Ventilation.....	123
Pressure Controlled Ventilation	128
Volume Controlled vs. Pressure Controlled Ventilation.....	134
Effects of the Patient Circuit.....	138
Idealized Waveform Displays.....	142
Pressure.....	144
Volume.....	145
Flow	146
Recognizing Modes.....	147
How to Detect problems	165
Loop Displays	175
Pressure-Volume Loop	175
Flow-Volume Loop.....	185
Calculated Parameters	190
Mean Airway Pressure	190
Leak	192
Calculating Respiratory System Mechanics: Static vs Dynamic	192
Compliance	194
Dynamic Characteristic	196
Resistance	197
Time Constant.....	199
Pressure-Time Product.....	200
Occlusion Pressure ($P_{0.1}$).....	201
Rapid Shallow Breathing Index	201
Inspiratory Force	202
AutoPEEP	202
Work of Breathing	203
Self Assessment Questions.....	211
Definitions.....	211
True or False	211

Multiple Choice	213
Key Ideas	218
APPENDIX I: ANSWERS TO QUESTIONS	220
Chapter 1: Introduction to Ventilation.....	220
Definitions	220
True or False.....	220
Multiple Choice	220
Key ideas	221
Chapter 2: Introduction to Ventilators.....	221
Definitions	221
True or False.....	222
Multiple Choice	223
Key Ideas	223
Chapter 3: How Ventilators Work.....	223
Definitions	223
True or False.....	229
Multiple Choice	230
Key Ideas	232
Review and Consider.....	232
Chapter 4: How to Use Modes of Ventilation.....	241
Definitions	241
True or False.....	242
Multiple Choice	244
Key ideas	244
Review and Consider.....	245
Chapter 5: How to Read Graphic Displays	253
Definitions	253
True or False.....	255
Multiple Choice	256
Key ideas	257
Review and Consider.....	258
APPENDIX II: GLOSSARY.....	273
APPENDIX III: MODE CONCORDANCE	283

Table of Figures

Figure 2-1. A display of pressure, volume, and flow waveforms during mechanical ventilation.....	13
Figure 2-2. Two types of loops commonly used to assess patient-ventilator interactions.....	13
Figure 3-1. Models of the ventilatory system. P = pressure. Note that compliance = 1/elastance. Note that inertance is ignored in this model, as it is usually insignificant.....	20
Figure 3-2. Multi-compartment model of the respiratory system connected to a ventilator using electronic analogs. Note that the right and left lungs are modeled as separate series connections of a resistance and compliance. However, the two lungs are connected in parallel. The patient circuit resistance is in series with the endotracheal tube. The patient circuit compliance is in parallel with the respiratory system. The chest wall compliance is in series with that of the lungs. The function of the exhalation manifold can be shown by adding a switch that alternately connects the patient and patient circuit to the positive pole of the ventilator (inspiration) or to ground (the negative pole, for expiration). Note that inertance, modeled as an electrical inductor, is ignored in this model as it is usually negligible.	23
Figure 3-3. Series and parallel connections using electronic analogs.	24
Figure 3-4. The criteria for determining the control variable during mechanical ventilation.....	26
Figure 3-5. Time intervals of interest during expiration.....	29
Figure 3-6. The importance of distinguishing between the terms <i>limit</i> and <i>cycle</i> . A. Inspiration is pressure limited and time cycled. B. Flow is limited but volume is not, and inspiration is volume cycled. C. Both volume and flow are limited and inspiration is time cycled.	32
Figure 3-7. Time intervals of interest during inspiration.....	34
Figure 3-8. Airway pressure effects with different expiratory pressure devices. A. The water-seal device does not maintain constant pressure and does not allow the patient to inhale, acting like a one-way valve; B. A flow restrictor does not maintain constant pressure but allows limited flow in both directions; C. An electronic demand valve maintains nearly	

constant pressure and allows unrestricted inspiratory and expiratory flow.....39

Figure 3-9. Operational logic for dual control between breaths. The cycle variable can be time as shown or flow depending on the specific mode and ventilator.44

Figure 3-10. Operational logic for dual control within breaths as implemented in the Pressure Augment mode on the Bear 1000 ventilator.....45

Figure 3-11. Operational logic for dual control within breaths as implemented using P_{max} on the Dräger Evita 4 ventilator.....47

Figure 3-12. Schematic diagram of a closed loop or feedback control system. The + and – signs indicate that the input setting is compared to the feedback signal and if there is a difference, an error signal is sent to the controller to adjust the output until the difference is zero.....53

Figure 4-1. Influence diagram showing the relation among the key variables during volume controlled mechanical ventilation....83

Figure 4-2. Influence diagram showing the relation among the key variables during pressure controlled mechanical ventilation. The shaded circles show variables that are not set on the ventilator.....84

Figure 4-3. Radford nomogram for determining appropriate settings for volume controlled ventilation of patients with normal lungs. Patients with parenchymal lung disease should be ventilated with tidal volumes no larger than 6 mL/kg.....85

Figure 4-4. Comparison of volume control using a constant inspiratory flow (left) with pressure control using a constant inspiratory pressure (right). Shaded areas show pressure due to resistance. Unshaded areas show pressure due to compliance. The dashed line shows mean airway pressure. Note that lung volume and lung pressure have the same waveform shape....88

Figure 4-5. Graph illustrating inspiratory and expiratory time constants.....92

Figure 5-1. Pressure, volume and flow waveforms for different physical models during volume controlled ventilation. A Waveforms for a model with resistance only showing sudden initial rise in pressure at the start of inspiration and then a constant pressure to the end. B Waveforms for a model with elastance only showing a constant rise in pressure from baseline to peak inspiratory pressure. C Waveforms for a model with resistance and elastance, representing the respiratory system. Pressure rises suddenly at the start of

inspiration due to resistance and then increases steadily to peak inspiratory pressure due to elastance. 124

Figure 5-2. Effects of changing respiratory system mechanics on airway pressure during volume controlled ventilation. Dashed line shows original waveform before the change A Increased resistance causes an increase in the initial pressure at the start of inspiration and a higher peak inspiratory pressure and higher mean pressure. B An increase in elastance (decrease in compliance) causes no change in initial pressure but a higher peak inspiratory pressure and higher mean pressure. C A decrease in elastance (increase in compliance) causes no change in initial pressure but a lower peak inspiratory pressure and lower mean pressure. 127

Figure 5- 3. Pressure, volume and flow waveforms for different physical models during pressure controlled ventilation. A Waveforms for a model with resistance only. B Waveforms for a model with elastance only. C Waveforms for a model with resistance and elastance, representing the respiratory system. Note that like Figure 5-1, the height of the pressure waveform at each moment is determined by the height of the flow waveform added to the height of the volume waveform. 129

Figure 5-4. Effects of changing respiratory system mechanics on airway pressure during pressure controlled ventilation. A Waveforms before any changes. B Increased resistance causes a decrease in peak inspiratory flow, a lower tidal volume, and a longer time constant. Note that inspiration is time cycled before flow decays to zero. C An increase in elastance (decrease in compliance) causes no change in peak inspiratory flow but decreases tidal volume and decreases the time constant..... 133

Figure 5-5. Volume control compared to pressure control at the same tidal volume. On the pressure waveforms the dotted lines show that peak inspiratory pressure is higher for volume control. On the volume/lung pressure waveforms, the dotted lines show (a) peak lung pressure is the same for both modes and (b) that pressure control results in a larger volume at mid inspiration. 135

Figure 5-6. Waveforms associated with an inspiratory hold during volume controlled ventilation. Notice that inspiratory flow time is less than inspiratory time and flow goes to zero during the inspiratory pause time while pressure drops from peak to plateau. 137

Figure 5-7. Theoretical pressure, volume, and flow waveforms for the same tidal volume and inspiratory time. (A) pressure control with a rectangular pressure waveform; (B) flow control with a rectangular flow waveform; (C) flow control with an ascending ramp flow waveform; (D) flow control with a descending ramp flow waveform; (E) flow control with a sinusoidal flow waveform. Short dashed lines represent mean inspiratory pressure. Long dashed lines show mean airway pressure.....	143
Figure 5-8. Two methods of calculating mean airway pressure..	192
Figure 5-9. Static compliance measurement	194
Figure 5-10. The least squares regression method for calculating compliance. The linear regression line is fit to the data by a mathematical procedure that minimizes the sum of the squared vertical distances between the data points and the line.....	195
Figure 5-11. Calculation of the dynamic characteristic.....	197
Figure 5-12. Static method of calculating resistance.....	198
Figure 5-13. Calculation of $P_{0.1}$ on the Drager Evita 4 ventilator. PTP = pressure-time product.....	201
Figure 5-14. AutoPEEP and the volume of trapped gas measured during an expiratory hold maneuver. The airway is occluded at the point where the next breath would normally be triggered. During the brief occlusion period, the lung pressure equilibrates with the patient circuit to give a total PEEP reading. When the occlusion is released, the volume exhaled is the trapped gas.....	203
Figure 5-15. Work of breathing during mechanical ventilation. The patient does work on the ventilator as he inspires a small volume from the patient circuit and drops the airway pressure enough to trigger inspiration. The ventilator does work on the patient as airway pressure rises above baseline.	204

Table of Tables

Table 3-1. Mode classification scheme.....	42
Table 3-2. Breathing patterns.....	51
Table 3-3. Control types, descriptions, and examples.....	56
Table 3-4. Examples of how to describe simple, moderately complex and complex modes using the classification scheme shown in Table 3-1.....	60
Table 3-5. Classification of Desirable Ventilator Alarms.....	63
Table 4-1. Equations relating the variables in shown in Figures 4-1 and 4-3.....	86

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 Babbie
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".



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.

Mechanical Ventilation



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

1. Introduction to Ventilation

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

Mechanical Ventilation

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.

Mechanical Ventilation

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