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ISBN 978-981-10-5339-9 ISBN 978-981-10-5340-5 (eBook)
DOI 10.1007/978-981-10-5340-5

Library of Congress Control Number: 2017958356

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Dedicated with love
to both my parents and my family
for their support in my studies: they deserve this
for everything

Preface

Mechanical ventilation is one important part of care for many critically ill patients, especially for patients with respiratory failure. It is mostly provided inside the hospital, especially inside the ICU, but it is also provided at sites outside the ICU and even outside the hospital. A deep and thorough understanding of mechanical ventilation is a requirement for respiratory therapists and also critical care physicians. Basic knowledge of the principles of mechanical ventilation is also required by critical care nurses and other physicians (aside from critical care physicians) whose patients occasionally need ventilatory support.

This book is focused on this subject, which is explained also with graphs and tables concerning the mechanical ventilator. The contents are applicable to any adult mechanical ventilator. This book does not cover issues related to pediatric and neonatal mechanical ventilation; its topics are limited to the focus of this book, adult mechanical ventilation.

Acknowledgments

I owe a great debt and wish to offer my sincere gratitude to the people who have made this book possible. First, I would like to thank the professors who taught me during my college days and my training to be a respiratory therapist; especially, my two professors—Tito C. Capaycapay and Jeffrey S. Lim—for teaching me and reaching out to me with the knowledge they have, and also for reviewing this book for the finalization of the contents and topics. This is the first book that I have written, specifically about understanding mechanical ventilation in patients with respiratory failure, which has taken a lot of time and a significant amount of editorial work and also support.

Second, I would like to offer special thanks for the guidance provided by the staff of Springer throughout this project, particularly Dr. Naren Aggarwal, Executive Editor Clinical Medicine and Abha Krishnan, Project Coordinator. Their dedication to this project has been immensely helpful, and I feel fortunate to have had the opportunity to work with such a professional group.

I owe so much also to my family for their patience, encouragement, and perseverance through the creation of this book. I give my grateful thanks to my Dad and Mom, who keep on supporting and encouraging me no matter what I'm working on. Special thanks to my Dad, who has helped me by giving me ideas and also in the making of figures, graphs, and illustrations, because I am not really an expert in this discipline. When I started developing this book, I was still in my fourth and last year of college, and was doing my internship while also working on this.

I am grateful to all the people I have mentioned above, because without them this book would not have been possible.

Contents

About the Author

Rosalia Ameliana Pupella recently graduated from Emilio Aguinaldo College Manila, Philippines, with a Bachelor of Science in Respiratory Therapy (BSRT). She was a member and became the President of the Respiratory Therapy Student Association from 2014 to 2015. She has received the College Leadership Award, and was also selected as the Most Outstanding Student during her last year of college.

Introduction

This book can be your reference for reviewing a mechanical ventilation graph to differentiate the changes of condition in a patient with respiratory failure and getting breathing support from a ventilator. To make for easier understanding, almost every page of this book has an illustration such as a picture or waveform, covering such topics as:

– Gas particles, gas particle density, and gas (oxygen) concentration
– Relationship between resistance, pressure, flow, and volume
– Illustration of respiratory anatomy from control system to alveoli
– Comparison of alveolar pressure, transpulmonary pressure, intrapleural pressure and airway pressure in control breath and spontaneous breath
– Effect of increased liquid or accumulated air in pleural space
– Effect of airway resistance change and compliance change in inspiratory and expiratory conditions, including intrinsic-PEEP, air-trapping and dynamic hyperinflation
– Pressure, flow, and volume waveform in volume breath, pressure control breath and pressure-supported breath
– Basic ventilation modes in volume and pressure → control, SIMV, and spontaneous
– Advance ventilation modes → dual control, BiPAP, APRV and guaranteed minute volume
– Graphical loops in controlled breath, triggered controlled breath and spontaneous breath, in airway resistance and lung compliance change and also leakage indication

This is the only book which explains with so many illustrations, pictures, and graphs.

Basic Mathematics and Physics

1

1.1 Introduction

An important point to appreciate how ventilation occurs is the concept of gas flow itself. Gas has its own characteristics, like when it is on sea level, it is different compared when it is under sea level or even above sea level. This means even the gas or air inside our lungs, e.g., oxygen and carbon dioxide, changes its characteristics on sea level, under sea level, or above sea level. In this chapter, basic mathematics and physics will be explained. They are related to gas characteristics in the lungs and also related to the tables and graphs shown on ventilator. Mechanical ventilator also shows graphs of flow, pressure, and volume. In the following chapter, all those variables which are often encountered on mechanical ventilator will be discussed; the relationship of flow and resistance to pressure, which is related to pressure from mechanical ventilator against resistance in the lungs and even the ventilator tubings, will also be in this chapter.

In mechanical ventilator, there are various flow patterns, square, decelerating, and sinus waveform, which will be explained and shown further in this chapter.

1.1.1 Multiplication and Division

Based on the equations in Table 1.1, it is concluded that:

A is inversely proportional to *B*:
For the same *C* value, when *A*, for example, increases three times, then *B* needs to be decreased 1/3 time.
A is proportional to *C*:

Table 1.1 Simple equation of multiplication and division

$A \times B = C$	$\frac{A}{C} = B$	$\frac{B}{C} = A$

R.A. Pupella, *Mechanical Ventilation in Patient with Respiratory Failure*,
DOI 10.1007/978-981-10-5340-5_1

For the same B value, when A, for example, increases three times, then C needs to be increased three times as well.

B is proportional to C:

For the same A value, when B, for example, increases three times, then C needs to be increased three times as well.

1.1.2 Electrical Equation

$$\text{Electric Voltage}(V) = \text{Electric Current}(I) \times \text{Resistance}(R)$$

The voltage difference between two electric poles

$$= \text{V2} - \text{V1} = V = \text{Electric Current}(I) \times \text{Resistance}(R)$$

Electric voltage represents ion density which is more positive.

Electric current will flow through a resistance of poles with higher voltage to a lower voltage. So when the electric voltage of both two poles is the same, then electric current will not flow.

When electric current is injected through a resistance, there will be differences in the density of ions which produces electric voltage.

1.2 Data Tables and Graphs

To understand the waveforms of volume and pressure, Fig. 1.1 shows those waveforms, and the table shows the number of volume and pressure according to time.

The waveforms (graphs) from Fig. 1.1 of volume and pressure are combined into a loop in Fig. 1.2, which shows amount of pressure and volume at the same time as they increase in table.

Time	Volume	Time	Pressure
0.0	0 mL	0.0	5.0 cmH_2O
0.1	30 mL	0.1	11.5 cmH_2O
0.2	60 mL	0.2	13.0 cmH_2O
0.3	90 mL	0.3	14.5 cmH_2O
0.4	120 mL	0.4	16.0 cmH_2O
0.5	150 mL	0.5	17.5 cmH_2O
0.6	180 mL	0.6	19.0 cmH_2O
0.7	210 mL	0.7	20.5 cmH_2O
0.8	240 mL	0.8	22.0 cmH_2O
0.9	270 mL	0.9	23.5 cmH_2O
1.0	300 mL	1.0	25.0 cmH_2O
1.1	300 mL	1.1	20.0 cmH_2O
1.2	300 mL	1.2	20.0 cmH_2O
1.3	98 mL	1.3	5.0 cmH_2O
1.4	32 mL	1.4	5.0 cmH_2O
1.5	0 mL	1.5	5.0 cmH_2O

Volume-Time Graph and Pressure-Time Graph

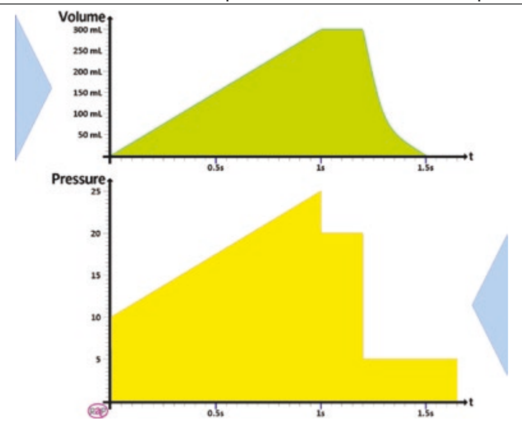


Fig. 1.1 Tables and graphs of volume time and pressure time

Pressure	Volume
5.0 cmH_2O	0 mL
11.5 cmH_2O	30 mL
13.0 cmH_2O	60 mL
14.5 cmH_2O	90 mL
16.0 cmH_2O	120 mL
17.5 cmH_2O	150 mL
19.0 cmH_2O	180 mL
20.5 cmH_2O	210 mL
22.0 cmH_2O	240 mL
23.5 cmH_2O	270 mL
25.0 cmH_2O	300 mL
20.0 cmH_2O	300 mL
20.0 cmH_2O	300 mL
5.0 cmH_2O	98 mL
5.0 cmH_2O	32 mL
5.0 cmH_2O	0 mL

Volume-Pressure Graph (Loop)

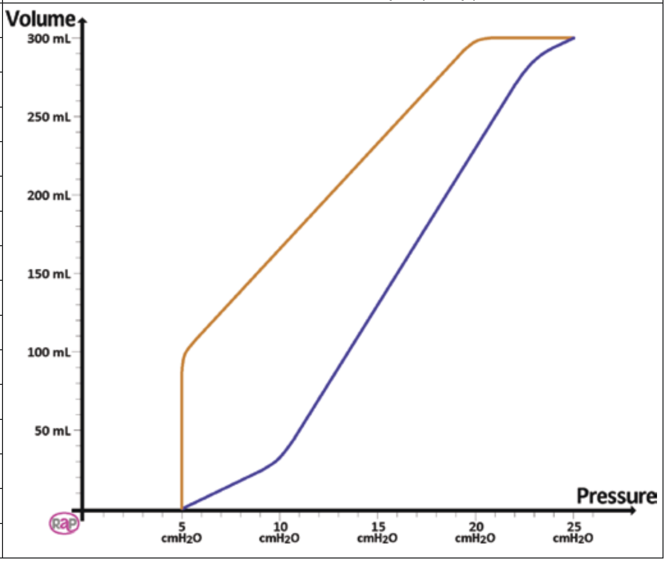


Fig. 1.2 Table and graph combination of volume and pressure

1.3 Gas Law

1.3.1 Boyle's Law of Gases

Look at Fig. 1.3 which explains a condition when a temperature which is considered does not change; then:

$$P1 \cdot V1 = P2 \cdot V2$$

P1 = Pressure on the condition 1	V1 = Volume on the condition 1
P2 = Pressure on the condition 2	V2 = Volume on the condition 2

1.3.2 The Ideal Gas Law

Ideal gas law is a combination of Boyle's law of gases, Charles' law of gases, and Avogadro's law of gases which is shown in Fig. 1.4.

The pressure (P) and volume (V) of a gas in a confined space are determined by the amount of gas particles (n) and temperature (T) of a gas and multiplied to the constant ideal gas 0.08205 L atm/mol K.

P = Pressure on condition 1	V = Volume on condition 1	
n = Number of gas particles	R = Constant Ideal gas	T = Gas temperature

Condition 1: At sea level

With ambient pressure of 760 mmHg (P1) at sea level, a sealed bag containing a number of gas molecules, would form a Physical Volume (V1).

Condition 2: Several thousand meters above sea level

Ambient pressure will go down, for example, would be 660 mmHg (P2), then the distance between the molecules of gas will increase even with the same number of molecules, so that the Physical Volume (V2) will be increased by a multiplication factor of 760/660.

Conclusion / Notes :

1. Gas pressure represents the density of the particles / molecules of the gas according to the distance between the particles / molecules of the gas in the confined space.
2. The concentration of particles in gases, including oxygen, were unchanged despite change in pressure.

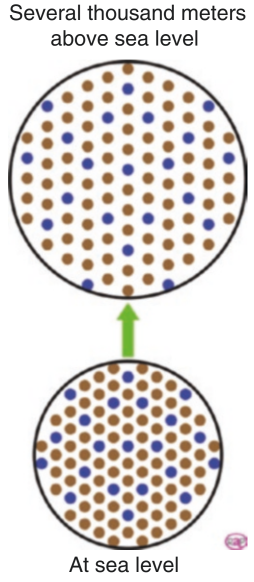


Fig. 1.3 Illustration of gas molecules at sea level and several thousand meters above sea levels

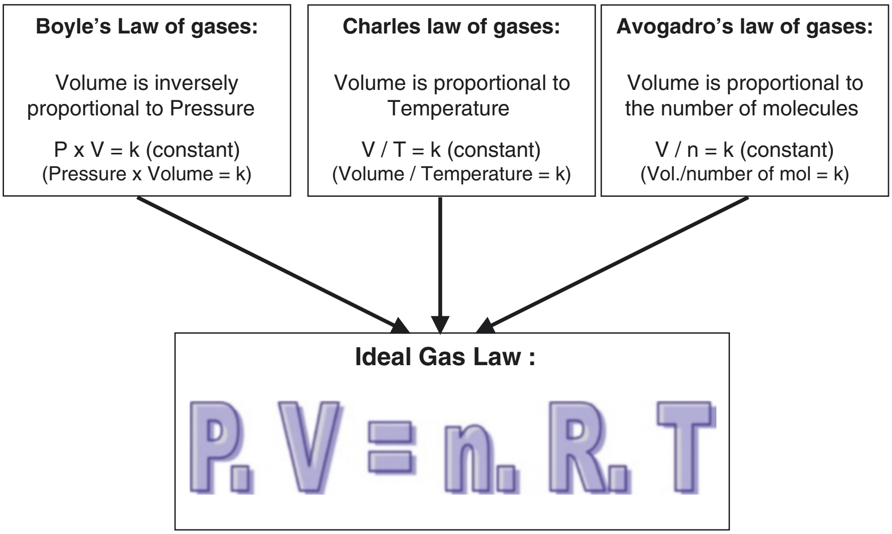


Fig. 1.4 Illustration and summary of all the gas laws

Condition 1: At sea level

With ambient pressure of 760 mmHg (P1) at sea level, humans inhale an amount of gas molecules (n1) thus forming a Physical Volume (V1).

Condition 2: Several thousand meters above sea level

Ambient pressure will go down, for example, would be 660 mmHg (P2), then the distance between the molecules of gas will increase. Humans inhale a same physical volume as the sea level(V2 = V1), resulting in fewer amount of the molecules, which is a decrease of multiplication factor of 660/760.

Conclusion / Notes :

1. Rising higher than sea level, if human does not inhale deeper then the number oxygen particles/molecules will be reduced due to the percentage is fixed but the total number of gas particles is reduced → Risk of Hypoxia.
2. Inside the cabin of the aircraft, pressure is given which almost equal to pressure at sea level. When the cabin pressure dropped, then an oxygen mask will come out for immediate use.

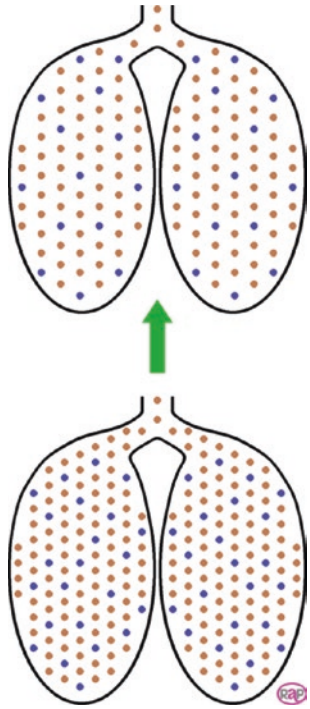


Fig. 1.5 Illustration of gas molecules inside the lungs at sea level and several thousand meters above sea level

Look at Fig. 1.5 which explains when a temperature (T) which is considered does not change and same constant (R); therefore:

$$\frac{P1 \bullet V1}{n1} = \frac{P2 \bullet V2}{n2}$$

When humans inhale the air on the same physical volume (V2 = V1), therefore:

$$\frac{P1}{n1} = \frac{P2}{n2}$$

1.4 Pressure

Gas pressure (Fig. 1.6) represents the density of the particles/molecules of the gas according to the distance between the particles/molecules of the gas in a confined space.

Looking at Fig. 1.6:

(a) Gas volume/content of 100 mL at ambient pressure
(b) Gas volume/content of 200 mL at ambient pressure
(c) Gas volume/content of 200 mL compressed into half of its original physical volume = gas volume/content of 100 mL added 100 mL without changing the physical volume
(d) Gas volume/content of 200 mL compressed into a quarter of its original physical volume = gas volume/content of 50 mL added 100 mL without changing the physical volume

Note:

Ambient pressure at sea level is about 760 mmHg.

The pressure is called negative if less than the ambient pressure, such as inhaling.

The pressure is called positive if greater than the ambient pressure, such as exhaling.

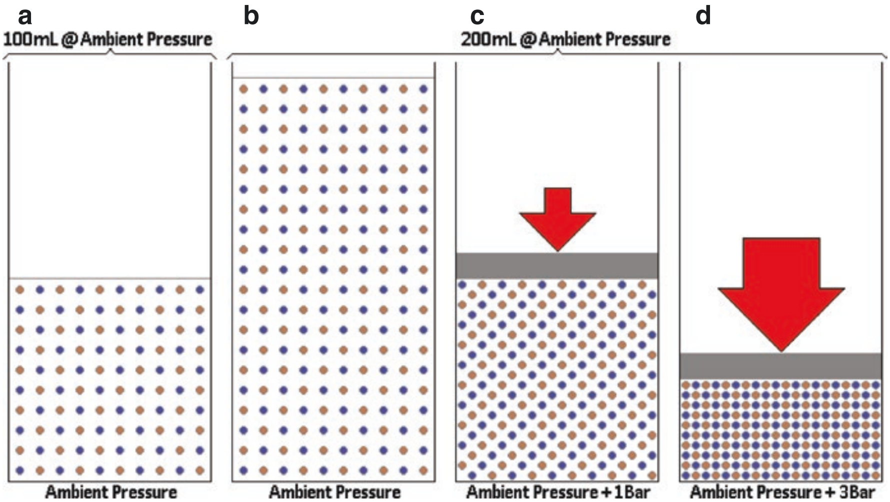


Fig. 1.6 Illustration of gas molecules with ambient pressure

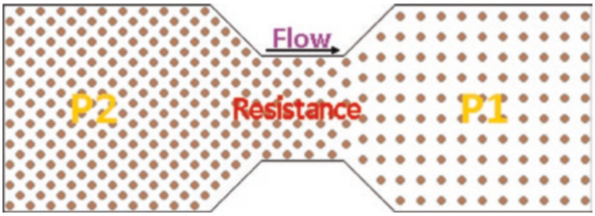


Fig. 1.7 Gas molecules flow under resistance

1.4.1 Pressure Due to Flow Resistance

Such as electricity equation:

$$\text{Electrical Voltage}\left(\text{V2}-\text{V1}\right)=\text{Electric Current}\left(i\right)\times\text{Resistance}\left(R\right)$$

Therefore the relationship between flow and resistance to pressure would be:

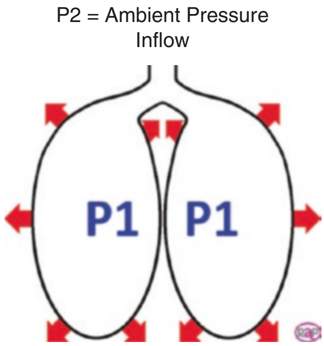
$$\text{Pressure difference}\left(\text{P2}-\text{P1}\right)=\text{Flow}\left(F\right)\times\text{Resistance}\left(R\right)$$

Looking at Fig. 1.7, gas particles/molecule densities on the left side (P2) are greater than the right side (P1). And because the pressure P2 > P1, then the gas particles/molecules will move from P2 side to P1 side which will generate flow through resistance. Those gas particle displacements will reduce the density of particles in P2, while the density of particles in P1 will be increased. The density difference between P2 and P1 will keep getting lower; therefore, the flow will continue to decrease.

If the density of the particles in P2 side is already equal to the density of the particles in P1, which means P2 = P1, then there is no flow that will be flowing between P2 and P1 in any direction. Figure 1.8 will explain further how airflow moves inside the lungs with the movement of the lungs.

Inspiratory:

In Inspiratory, respiratory muscles (red) will pull the Lung to inflate, therefore, the distance between the Particles/ Molecules of Gas in the alveoli will increase or pressure in the Alveoli (P1 = Pavl) will be less than Ambient Pressure (P2). With the ambient pressure of 760 mmHg (P2) and for example the pressure in the Alveoli (P1 = Pavl) of 560 mmHg then the difference of both, which is 200 mmHg will result in the inflow to the Alveoli pass through Resistance in the Airway.



Expiratory:

In Expiratory, respiratory muscle (Red) will become relax and return to its original state, therefore, the pressure in the Alveoli (P1=Pavl) will be greater than the Ambient Pressure (P2). With the ambient pressure of 760 mmHg (P2) and for example the pressure in the Alveoli (P1=Pavl) of 960 mmHg mmHg then the difference of both, which is 200 mmHg will flow out of the Alveoli pass through Resistance in the Airway.

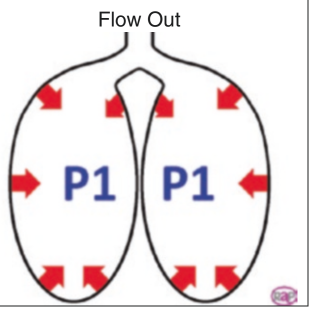


Fig. 1.8 Muscle and airflow movement during inspiratory and expiratory

1.5 Flow

The relationship between flow and resistance to pressure is:

$$\text{Pressure difference}(\text{P2} - \text{P1}) = \text{Flow}(F) \times \text{Resistance}(R)$$

Flow occurs from the side with the higher pressure/density (P2) to the side with the lower pressure/density (Fig. 1.9). With the flowing out of the particle, the pressure/density of particles on the P2 will decrease gradually, and simultaneously pressure/density of particles on the P1 will increase gradually. Until equilibrium occurs, where pressure P2 = P1, thus, there is no longer flow going to any direction.

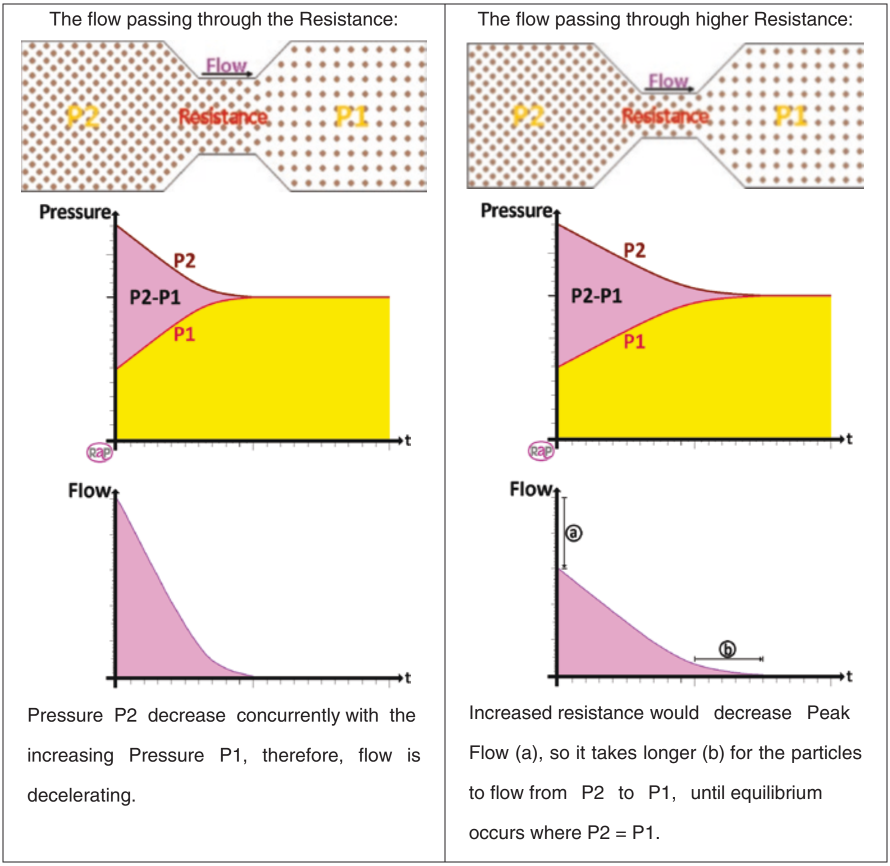


Fig. 1.9 Illustration of flow passing through resistance

1.6 Various Inspiratory Flow Pattern

There are various flow patterns used in mechanical ventilator, and they are used based on the mode that is being used. Flow patterns that are typically used in volume-controlled breath delivery are shown in Fig. 1.10, and other flow patterns typically used in other modes of breath delivery are shown in Fig. 1.11.

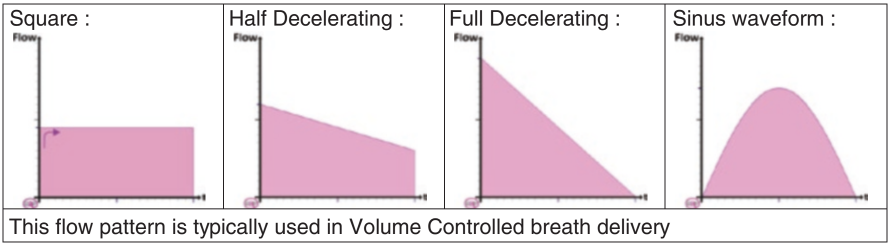


Fig. 1.10 Various flow patterns typically used in volume-controlled breath delivery

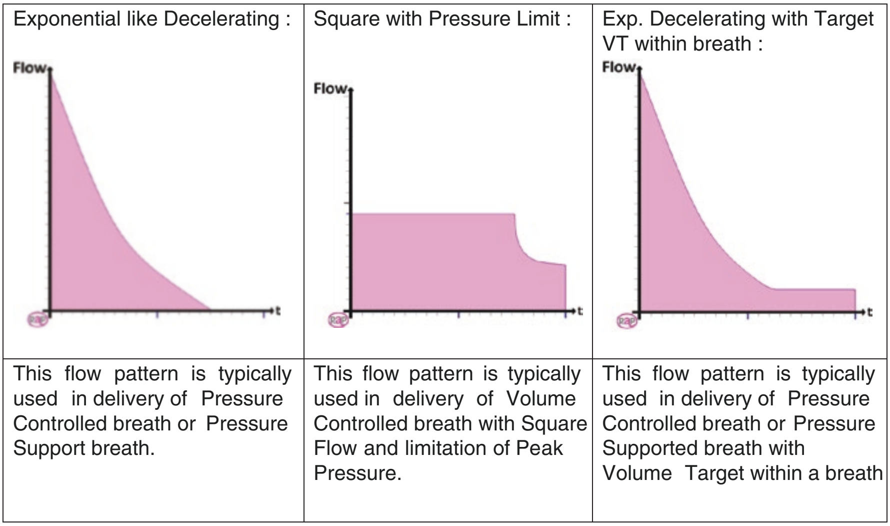


Fig. 1.11 Other flow patterns typically used in other modes of breath delivery

1.7 Expiratory Flow

Expiratory flow direction is from the patient to the expiratory valve on ventilator and then to the ambient air.

And on the graphical flow waveform, the direction is downward from the horizontal line as shown in Fig. 1.12.

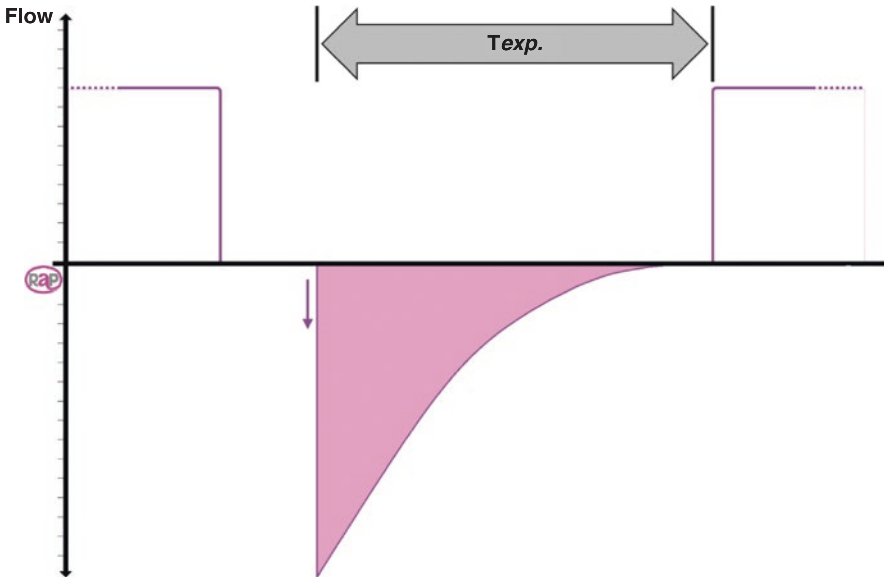


Fig. 1.12 Graph of expiratory flow

1.8 Volume

The volume indicates the number of particles/molecules of gas at a certain pressure unit.

The greater the volume at the same pressure indicates the increased number of particles/molecules of gas.

In Fig. 1.13, physical volume of 100 mL in 1520 mmHg pressure = physical volume of 200 mL at 760 mmHg pressure.

In order to facilitate the volume reading especially with pressure higher than ambient pressure, volume measurement on ventilator is converted to ambient pressure as standard BTPS (body temperature pressure saturated).

Volume is the result of flow delivered during a certain time:

$$\text{Volume} = \text{Flow} \times \text{time}$$

For example, the flow of 150 mL/s flowing into the space for 2 s and then the volume received in a space are 300 mL.

In other words, volume is the wide area of flow waveform.

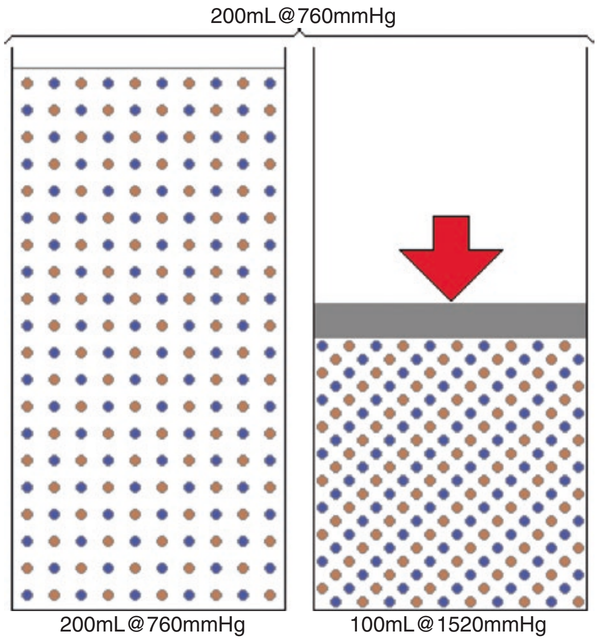


Fig. 1.13 Gas particles/molecules with different volumes because of pressure

There are different flow waveforms which result in also different inspiratory volumes based on the area of these flow waveforms (Fig. 1.19).

Look at Fig. 1.14. It shows square flow waveform, and the table shows sample of measurement with the showed waveform.

While Fig. 1.14 shows square flow waveform, Fig. 1.15 shows full decelerating waveform, and the table shows sample of measurement with the showed waveform.

Look at Fig. 1.16. It shows quite similar flow waveform with Fig. 1.15, but it is half decelerating, and the table shows sample of measurement with the showed waveform.

Look at Fig. 1.17. It shows quite different flow waveforms from the previous waveforms. It shows sine waveform, and the table shows sample of measurement with the showed waveform. Look at Fig. 1.18. It shows exponential-like flow waveform which is usually in pressure breath, and the table shows sample of measurement with the showed waveform (Fig. 1.19).