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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	Volume-Time Graph and Pressure-Time Graph	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

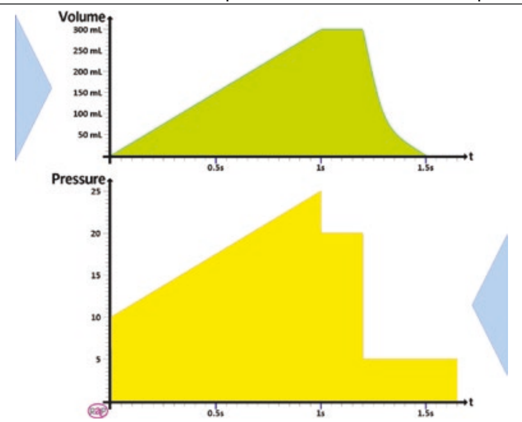


Fig. 1.1 Tables and graphs of volume time and pressure time

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)

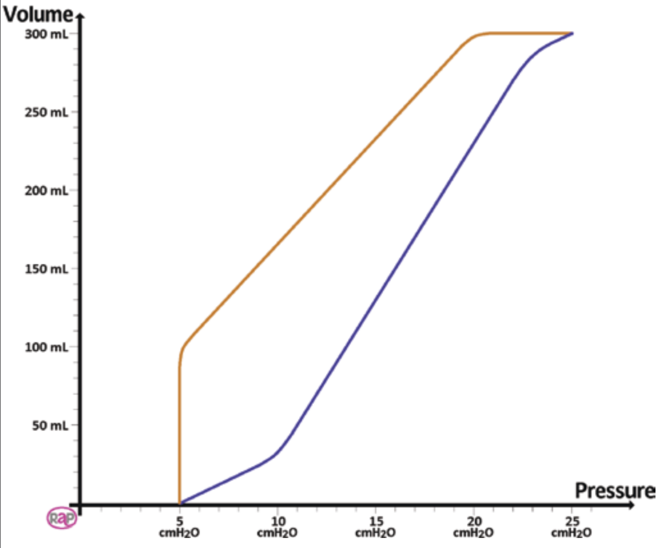


Fig. 1.2 Table and graph combination of volume and pressure

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.

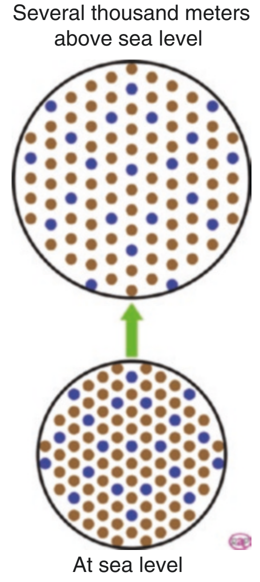


Fig. 1.3 Illustration of gas molecules at sea level and several thousand meters above sea levels

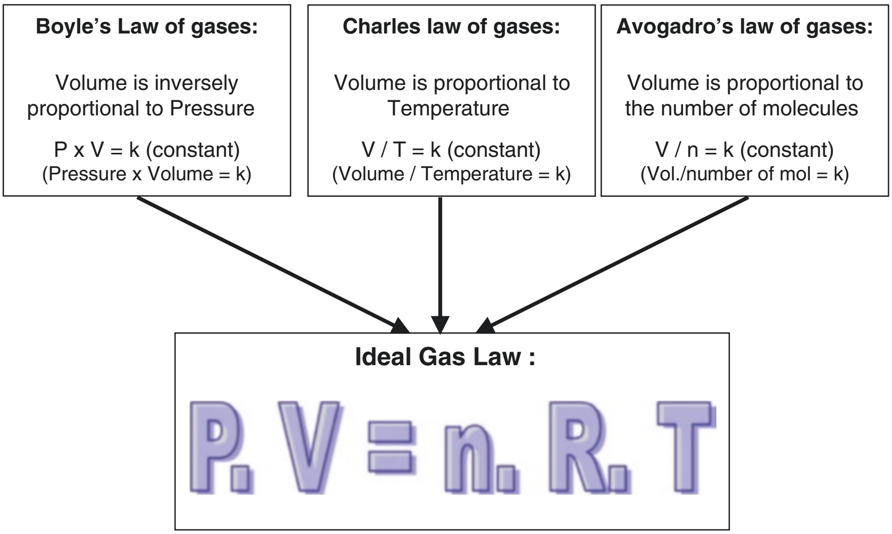


Fig. 1.4 Illustration and summary of all the gas laws

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.

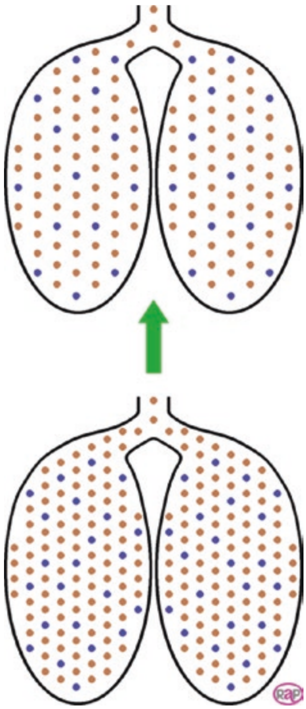


Fig. 1.5 Illustration of gas molecules inside the lungs at sea level and several thousand meters above sea level

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.

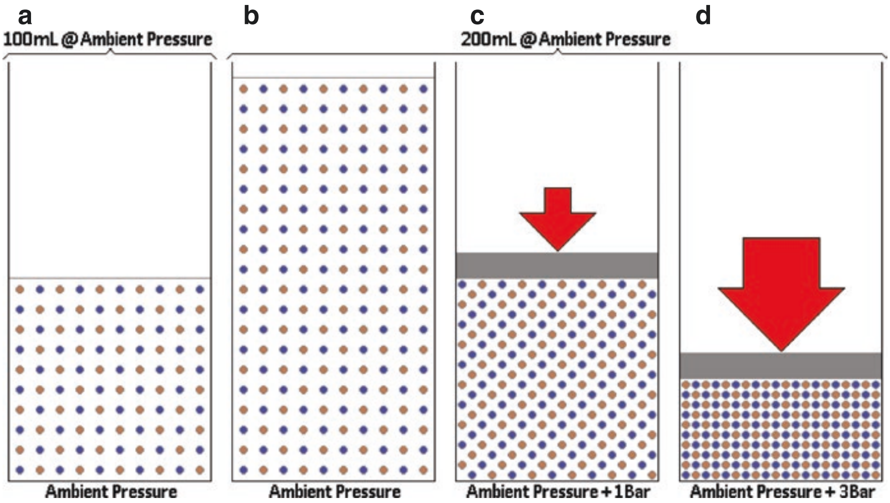


Fig. 1.6 Illustration of gas molecules with ambient pressure

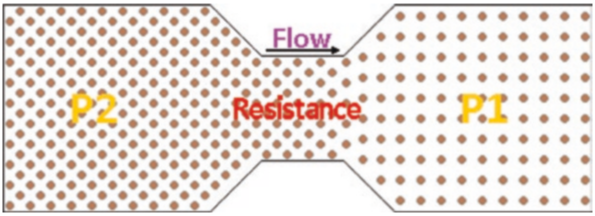


Fig. 1.7 Gas molecules flow under resistance

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:

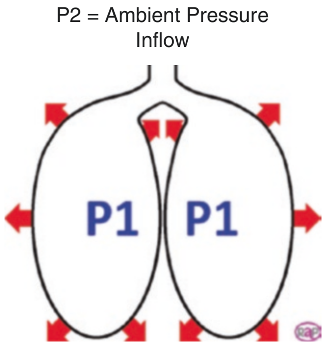
$$\text{Pressure difference}\left(\text{P2}-\text{P1}\right)=\text{Flow}\left(F\right)\times\text{Resistance}\left(R\right)$$

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.

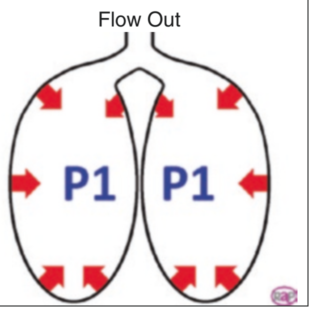


Fig. 1.8 Muscle and airflow movement during inspiratory and expiratory

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.

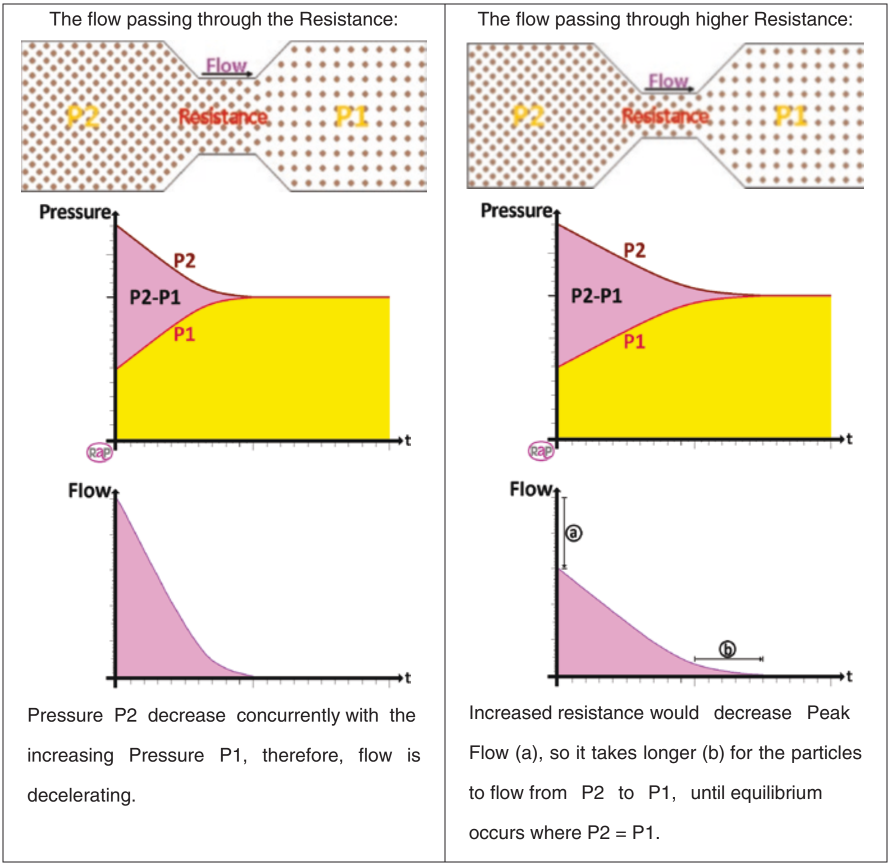


Fig. 1.9 Illustration of flow passing through resistance

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.

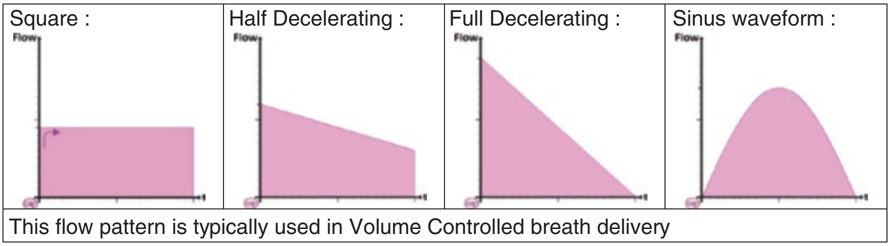


Fig. 1.10 Various flow patterns typically used in volume-controlled breath delivery

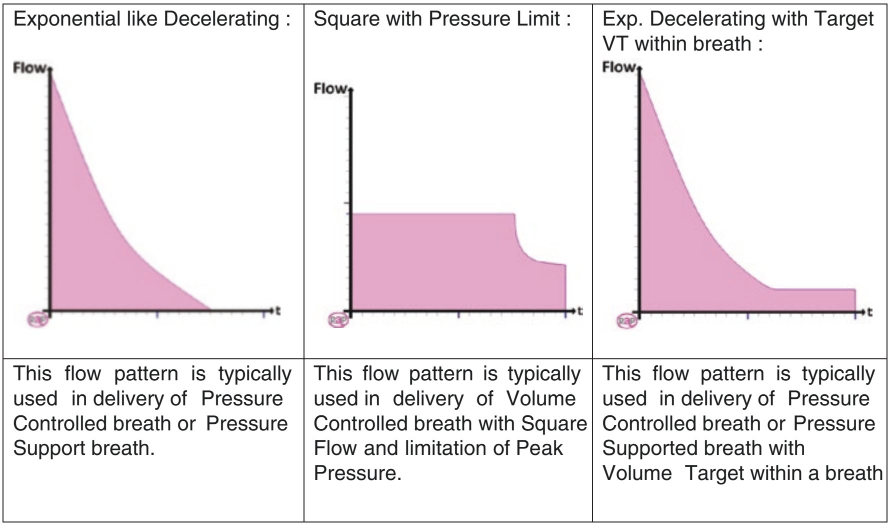


Fig. 1.11 Other flow patterns typically used in other modes of breath delivery

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.

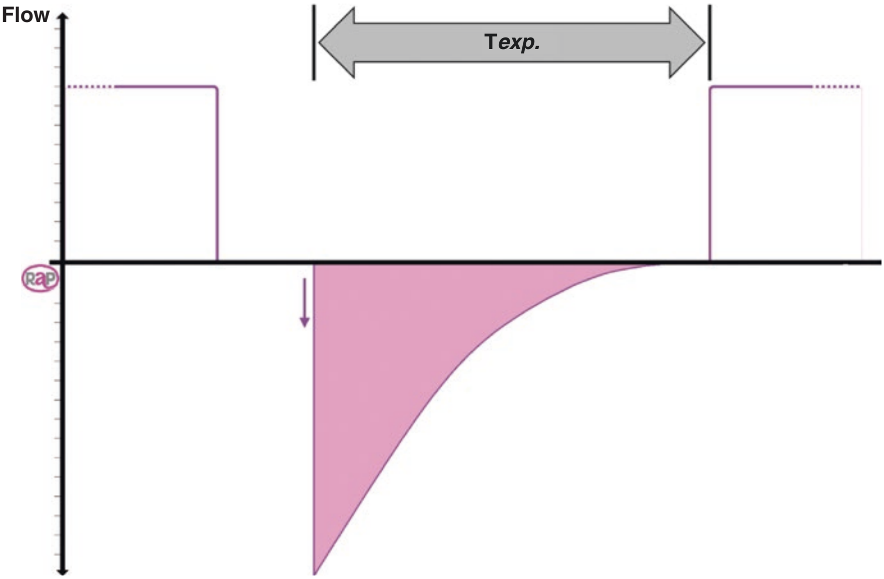


Fig. 1.12 Graph of expiratory flow

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.

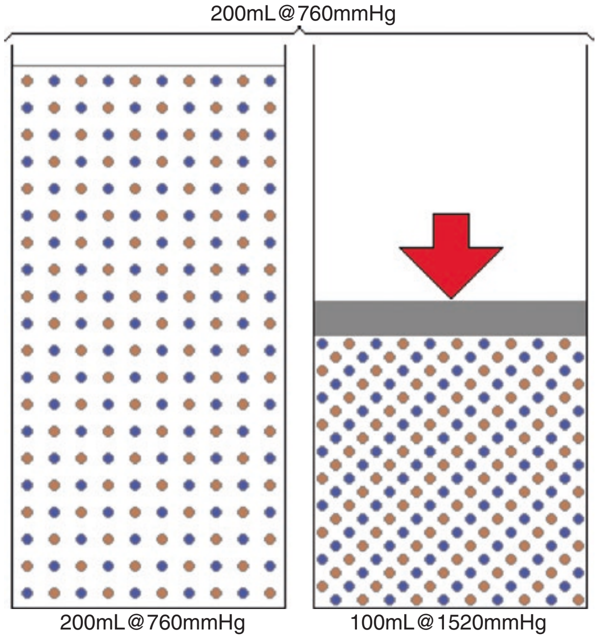


Fig. 1.13 Gas particles/molecules with different volumes because of pressure

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

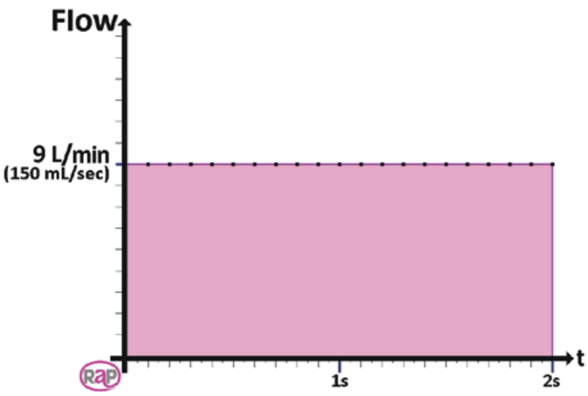
Look at Fig. 1.14. It shows square flow waveform, and the table shows sample of measurement with the showed waveform.

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.

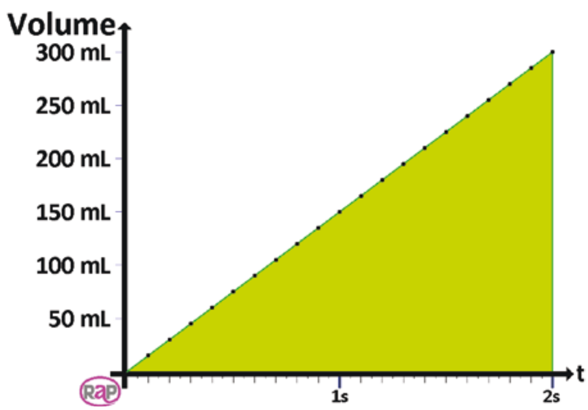
Look at Fig. 1.16. It shows quite similar flow waveform with Fig. 1.15, but it is half decelerating, and the table shows sample of measurement with the showed waveform.

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).

Calculation of Inspiratory Flow waveform area	Sampling Measurement		
Example with Peak Flow = 150 mL/second and t = 2 seconds Then, Volume = Peak Flow x t = 300 mL	Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)



Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)
0.1	150 mL/sec	15 mL
0.2	150 mL/sec	15 mL
0.3	150 mL/sec	15 mL
0.4	150 mL/sec	15 mL
0.5	150 mL/sec	15 mL
0.6	150 mL/sec	15 mL
0.7	150 mL/sec	15 mL
0.8	150 mL/sec	15 mL
0.9	150 mL/sec	15 mL
1.0	150 mL/sec	15 mL
1.1	150 mL/sec	15 mL
1.2	150 mL/sec	15 mL
1.3	150 mL/sec	15 mL
1.4	150 mL/sec	15 mL
1.5	150 mL/sec	15 mL
1.6	150 mL/sec	15 mL
1.7	150 mL/sec	15 mL
1.8	150 mL/sec	15 mL
1.9	150 mL/sec	15 mL
2.0	150 mL/sec	15 mL
	Total :	300 mL

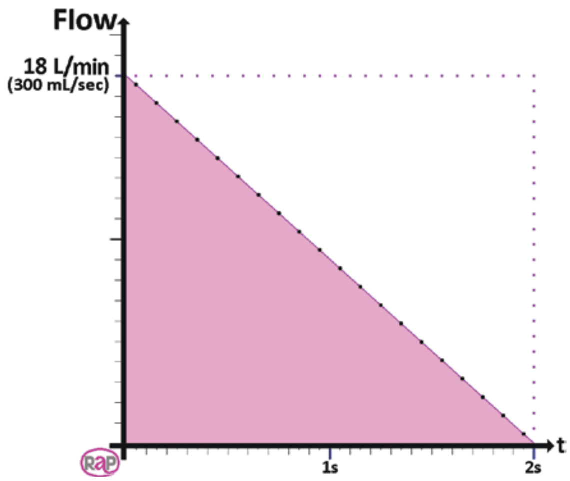


Time	Volume (Accumulated)
0.0	0 mL
0.1	15 mL
0.2	30 mL
0.3	45 mL
0.4	60 mL
0.5	75 mL
0.6	90 mL
0.7	105 mL
0.8	120 mL
0.9	135 mL
1.0	150 mL
1.1	165 mL
1.2	180 mL
1.3	195 mL
1.4	210 mL
1.5	225 mL
1.6	240 mL
1.7	255 mL
1.8	270 mL
1.9	285 mL
2.0	300 mL

Fig. 1.14 Inspiratory flow with square waveform

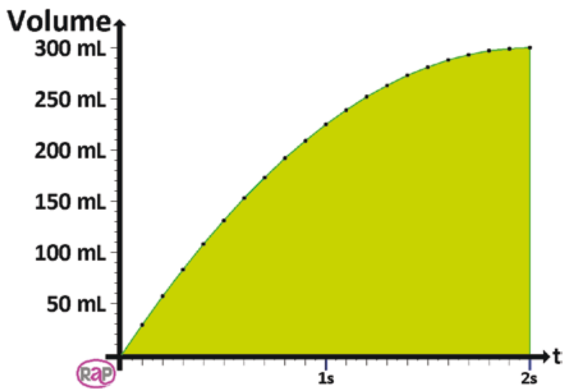
Calculation of Inspiratory Flow waveform area

Example with Peak Flow = 300 mL/second and t = 2 seconds
Then Volume = (Peak Flow x t) /2 = 300 mL



Sampling Measurement		
Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)
0.1	292.5 mL/sec	29.25 mL
0.2	277.5 mL/sec	27.75 mL
0.3	262.5 mL/sec	26.25 mL
0.4	247.5 mL/sec	24.75 mL
0.5	232.5 mL/sec	23.25 mL
0.6	217.5 mL/sec	21.75 mL
0.7	202.5 mL/sec	20.25 mL
0.8	187.5 mL/sec	18.75 mL
0.9	172.5 mL/sec	17.25 mL
1.0	157.5 mL/sec	15.75 mL
1.1	142.5 mL/sec	14.25 mL
1.2	127.5 mL/sec	12.75 mL
1.3	112.5 mL/sec	11.25 mL
1.4	97.5 mL/sec	9.75 mL
1.5	82.5 mL/sec	8.25 mL
1.6	67.5 mL/sec	6.75 mL
1.7	52.5 mL/sec	5.25 mL
1.8	37.5 mL/sec	3.75 mL
1.9	22.5 mL/sec	2.25 mL
2.0	7.5 mL/sec	0.75 mL
	Total :	300 mL

With Δt=0.1 then Flow (at each point) is the average flow of the previous 0.05 second and after 0.05 second

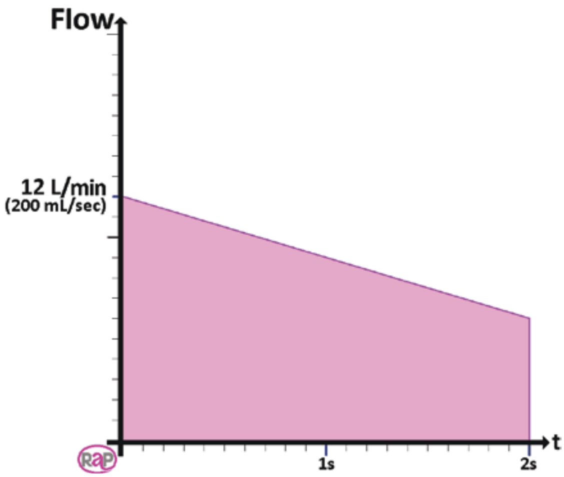


Time	Volume (Accumulated)
0.0	0.00 mL
0.1	29.25 mL
0.2	57.00 mL
0.3	83.25 mL
0.4	108.00 mL
0.5	131.25 mL
0.6	153.00 mL
0.7	173.25 mL
0.8	192.00 mL
0.9	209.25 mL
1.0	225.00 mL
1.1	239.25 mL
1.2	252.00 mL
1.3	263.25 mL
1.4	273.00 mL
1.5	281.25 mL
1.6	288.00 mL
1.7	293.25 mL
1.8	297.00 mL
1.9	299.25 mL
2.0	300.00 mL

Fig. 1.15 Inspiratory flow with full decelerating waveform

Calculation of Inspiratory Flow waveform area

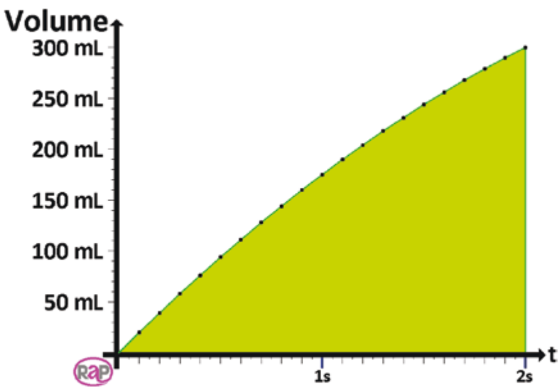
Example with Peak Flow = 200 mL/second and t = 2 seconds
Then Volume = (Peak Flow x t) * 3/4 = 300 mL



Sampling Measurement

Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)
0.1	197.5 mL/sec	19.75 mL
0.2	192.5 mL/sec	19.25 mL
0.3	187.5 mL/sec	18.75 mL
0.4	182.5 mL/sec	18.25 mL
0.5	177.5 mL/sec	17.75 mL
0.6	172.5 mL/sec	17.25 mL
0.7	167.5 mL/sec	16.75 mL
0.8	162.5 mL/sec	16.25 mL
0.9	157.5 mL/sec	15.75 mL
1.0	152.5 mL/sec	15.25 mL
1.1	147.5 mL/sec	14.75 mL
1.2	142.5 mL/sec	14.25 mL
1.3	137.5 mL/sec	13.75 mL
1.4	132.5 mL/sec	13.25 mL
1.5	127.5 mL/sec	12.75 mL
1.6	122.5 mL/sec	12.25 mL
1.7	117.5 mL/sec	11.75 mL
1.8	112.5 mL/sec	11.25 mL
1.9	107.5 mL/sec	10.75 mL
2.0	102.5 mL/sec	10.25 mL
	Total :	300 mL

With Δt=0.1 then Flow (at each point) is the average flow of the previous 0.05 second and after 0.05 second

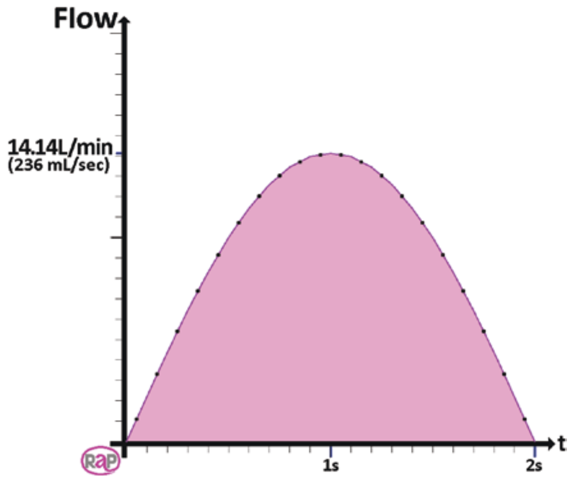


Time	Volume (Accumulated)
0.0	0.00 mL
0.1	19.75 mL
0.2	39.00 mL
0.3	57.75 mL
0.4	76.00 mL
0.5	93.75 mL
0.6	111.00 mL
0.7	127.75 mL
0.8	144.00 mL
0.9	159.75 mL
1.0	175.00 mL
1.1	189.75 mL
1.2	204.00 mL
1.3	217.75 mL
1.4	231.00 mL
1.5	243.75 mL
1.6	256.00 mL
1.7	267.75 mL
1.8	279.00 mL
1.9	289.75 mL
2.0	300.00 mL

Fig. 1.16 Inspiratory flow with half-decelerating waveform

Calculation of Inspiratory Flow waveform area

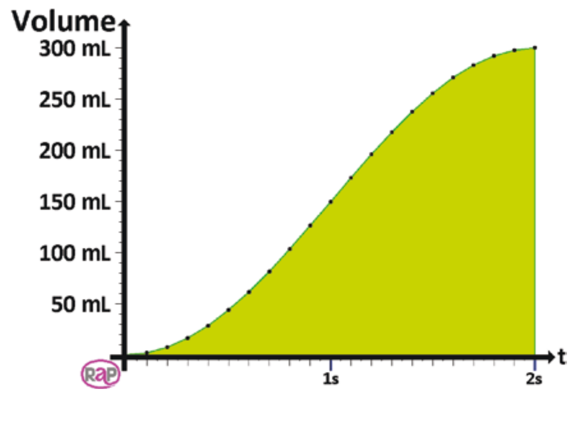
Example with Peak Flow = 235.62 mL/second and t = 2 seconds
Then Volume = (Peak Flow x t) * 0.6366 = 300 mL



Sampling Measurement

Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)
0.1	18.47 mL/sec	1.85 mL
0.2	54.95 mL/sec	5.50 mL
0.3	90.07 mL/sec	9.01 mL
0.4	122.98 mL/sec	12.30 mL
0.5	152.86 mL/sec	15.29 mL
0.6	178.98 mL/sec	17.90 mL
0.7	200.69 mL/sec	20.07 mL
0.8	217.46 mL/sec	21.75 mL
0.9	228.87 mL/sec	22.89 mL
1.0	234.65 mL/sec	23.46 mL
1.1	234.65 mL/sec	23.46 mL
1.2	228.87 mL/sec	22.89 mL
1.3	217.46 mL/sec	21.75 mL
1.4	200.69 mL/sec	20.07 mL
1.5	178.98 mL/sec	17.90 mL
1.6	152.86 mL/sec	15.29 mL
1.7	122.98 mL/sec	12.30 mL
1.8	90.07 mL/sec	9.01 mL
1.9	54.95 mL/sec	5.50 mL
2.0	18.47 mL/sec	1.85 mL
	Total :	300 mL

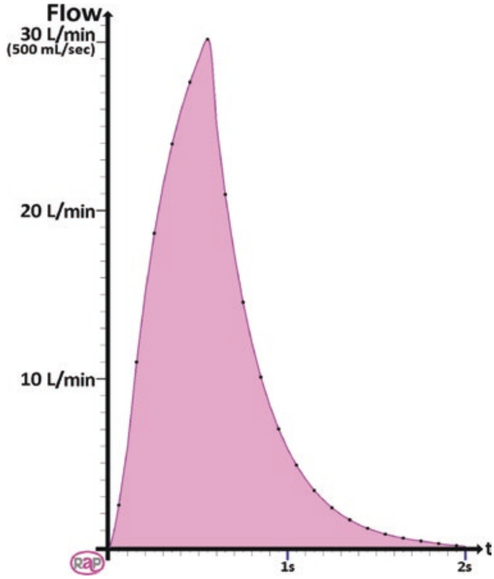
With Δt=0.1 then Flow (at each point) is the average flow of the previous 0.05 second and after 0.05 second



Time	Volume (Accumulated)
0.0	0.00 mL
0.1	1.85 mL
0.2	7.34 mL
0.3	16.35 mL
0.4	28.65 mL
0.5	43.93 mL
0.6	61.83 mL
0.7	81.90 mL
0.8	103.65 mL
0.9	126.53 mL
1.0	150.00 mL
1.1	173.46 mL
1.2	196.35 mL
1.3	218.09 mL
1.4	238.16 mL
1.5	256.06 mL
1.6	271.35 mL
1.7	283.64 mL
1.8	292.65 mL
1.9	298.15 mL
2.0	300.00 mL

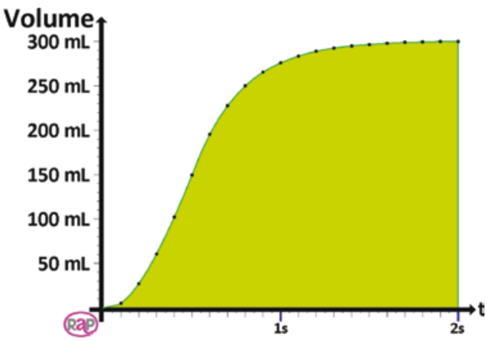
Fig. 1.17 Inspiratory flow with sine waveform

Flow is regulated according to the pressure pattern
(Slope and Inspiratory Pressure/Pressure Support)



Sampling Measurement		
Time (Δt=0.1)	Flow (at the point)	Volume (Flow x Δt)
0.1	35.0 mL/sec	3.50 mL
0.2	182.0 mL/sec	18.20 mL
0.3	L309.0 mL/sec	30.90 mL
0.4	398.0 mL/sec	39.80 mL
0.5	459.0 mL/sec	45.90 mL
0.6	503.0 mL/sec	50.30 mL
0.7	348.0 mL/sec	34.80 mL
0.8	241.0 mL/sec	24.10 mL
0.9	167.0 mL/det	16.70 mL
1.0	116.0 mL/sec	11.60 mL
1.1	80.0 mL/sec	8.00 mL
1.2	55.0 mL/sec	5.50 mL
1.3	38.0 mL/sec	3.80 mL
1.4	26.0 mL/sec	2.60 mL
1.5	17.0 mL/sec	1.70 mL
1.6	12.0 mL/sec	1.20 mL
1.7	8.0 mL/sec	0.80 mL
1.8	4.0 mL/sec	0.40 mL
1.9	1.5 mL/sec	0.15 mL
2.0	0.5 mL/sec	0.05 mL
	Total :	300 mL

With Δt=0.1 then Flow (at each point) is the average flow of the previous 0.05 second and after 0.05 second



Time	Volume (Accumulated)
0.0	0.00 mL
0.1	3.50 mL
0.2	21.70 mL
0.3	52.60 mL
0.4	92.40 mL
0.5	138.30 mL
0.6	188.60 mL
0.7	223.40 mL
0.8	247.50 mL
0.9	264.20 mL
1.0	275.80 mL
1.1	283.80 mL
1.2	289.30 mL
1.3	293.10 mL
1.4	295.70 mL
1.5	297.40 mL
1.6	298.60 mL
1.7	299.40 mL
1.8	299.80 mL
1.9	299.95 mL
2.0	300.00 mL

Fig. 1.18 Inspiratory flow with “exponential-like” decelerating waveform

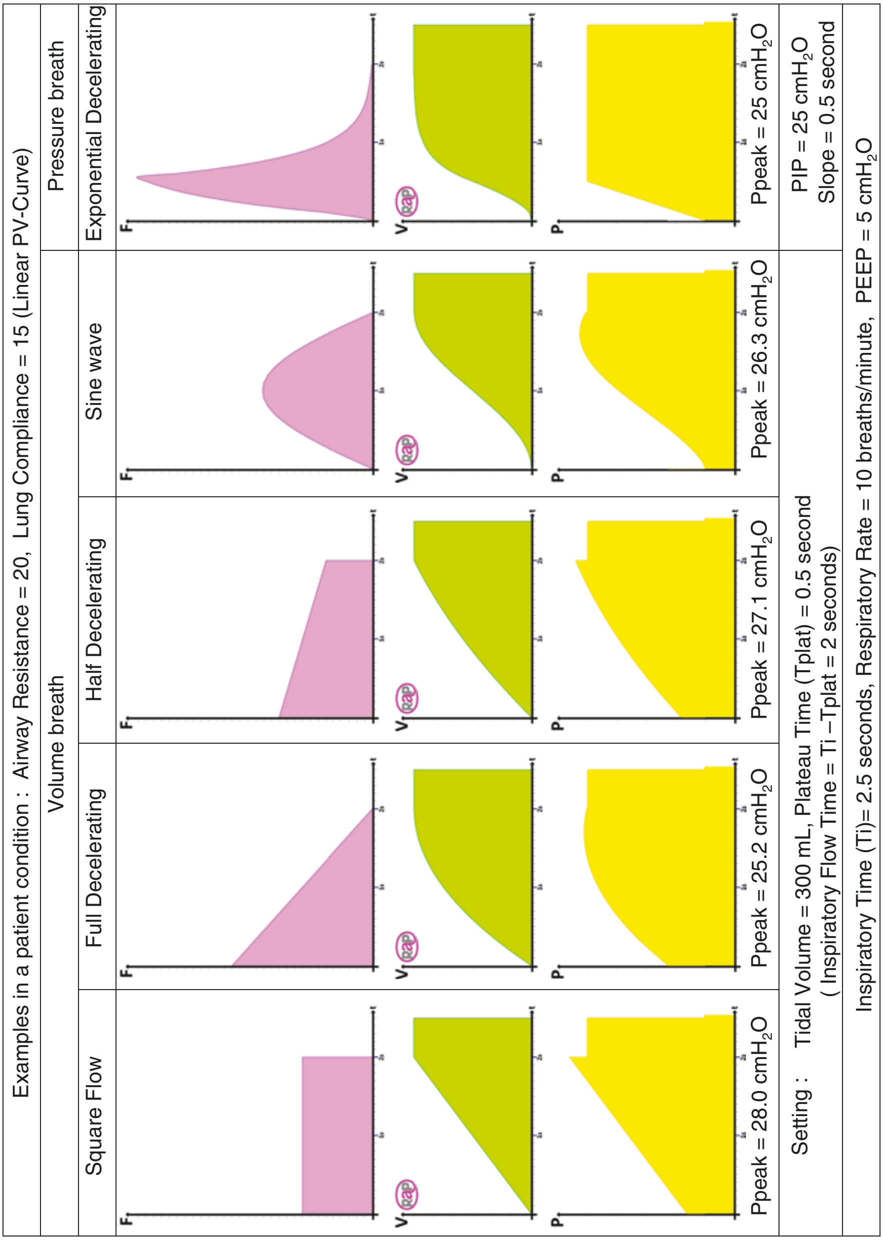


Fig. 1.19 Flow, volume, and pressure waveform on some shape of inspiratory flow

2 Respiratory Anatomy

2.1 Introduction

Ventilatory support should be initiated when a patient's spontaneous breathing is not enough to maintain gas exchange, which causes gas exchange to fail, putting the patient in a life-threatening situation if support is not provided. Gas exchange failure or inadequate gas exchange means that either oxygen or carbon dioxide or even both in the arterial blood are not at normal levels. This is called respiratory failure. Respiratory failure is classified as hypoxemic and hypercapnic. The principal benefits of mechanical ventilation on patients with respiratory failure are improved gas exchange in the lungs and decreased work of breathing.

During spontaneous breathing, it is simply the air which is moving into and out of the lungs. The contraction of respiratory muscles causes the thorax to expand; therefore, the air in the atmosphere goes into the lungs. This is how spontaneous breathing occurs.

During ventilation with mechanical ventilator, the user has to consider the lung condition or the diagnosis of the patient in order to fulfill the best ventilation for the patient. The things to be considered are dead space of the airway of the patient, lung compliance, etc. In this chapter, the variables to be considered will be explained to understand more what these variables are and how they are related in mechanical ventilation. Control system of the respiratory and the anatomy of the respiratory, including the intrathoracic pressure or pressure gradient which causes ventilation to occur, will also be described.

2.2 Dead Space

The air that enters the alveoli is required for an exchange with the blood cell. The air passing through the carrier media, e.g., bronchus, bronchiole, lower/upper airway, or endotracheal tube or tracheostomy tube, and even external media such as breathing circuit and filters should be taken into account as dead space (see Fig. 2.1).

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DOI 10.1007/978-981-10-5340-5_2

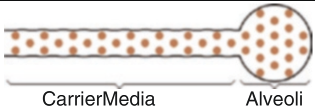
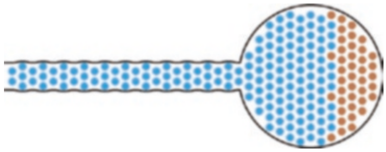
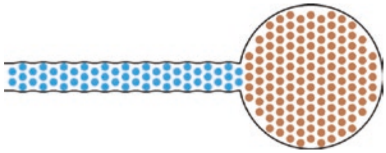
At the end of expiration : At the end of expiration, the air (Brown) that last goes out of the alveoli, fills the carrier media. Those used air is rich in CO_2 and contains less O_2. Thus, used air does not totally go out but there is still remaining air in the carrier media.	
At the beginning of inspiration : At the beginning of inspiration, the air which first enters into alveoli, is the air (Brown) that previously remained in carrier media. That used air is rich in CO_2 and contains less O_2. Thus, used air which previously remained in carrier media go back to the alveoli.	
At the end of inspiration: At the end of inspiration, the air (Blue) that last goes out of the alveoli, fills the carrier media and does not enter the alveoli. That fresh air is rich in O_2 and contains less CO_2. Thus, not all fresh air goes into the alveoli but rather there is still remaining air in the carrier media.	
Right before the expiration: The first air that comes out, it is from the carrier media and not from the alveoli. The fresh air is rich in O_2 and contains less CO_2.	
Conclusion : The Deadspace Volume (V_D) determine show much fresh air (O_2) that comes out when the expiration starts from the tip of the carrier media which then goes to the atmosphere. It also determines how much air isused (CO_2) that goes back into the alveoli when the inspiration starts from the tip of the carrier media which then goes into the alveoli. Thus, that fresh air that is inside the carrier media then goes back out of the carrier media and that used air that remains inside the carrier media then goes back inside the alveoli, is categorized as Deadspace Ventilation. The Deadspace Ventilation also happens if fresh air goes into the alveoli but gas exchange does not occur with the pulmonary capillaries, for example, due to problems of the pulmonary capillaries with a result of blood does not undergo gas exchange.	

Fig. 2.1 Movement of gas particles in deadspace ventilation

2.3 Lung Compliance

A space can be called flexible if there is an increase in physical volume in every unit of pressure that is given. So, the relationship between volume and compliance toward pressure is

$$\text{Compliance} = \frac{V_2 - V_1}{P_2 - P_1} = \frac{\Delta V}{\Delta P}$$

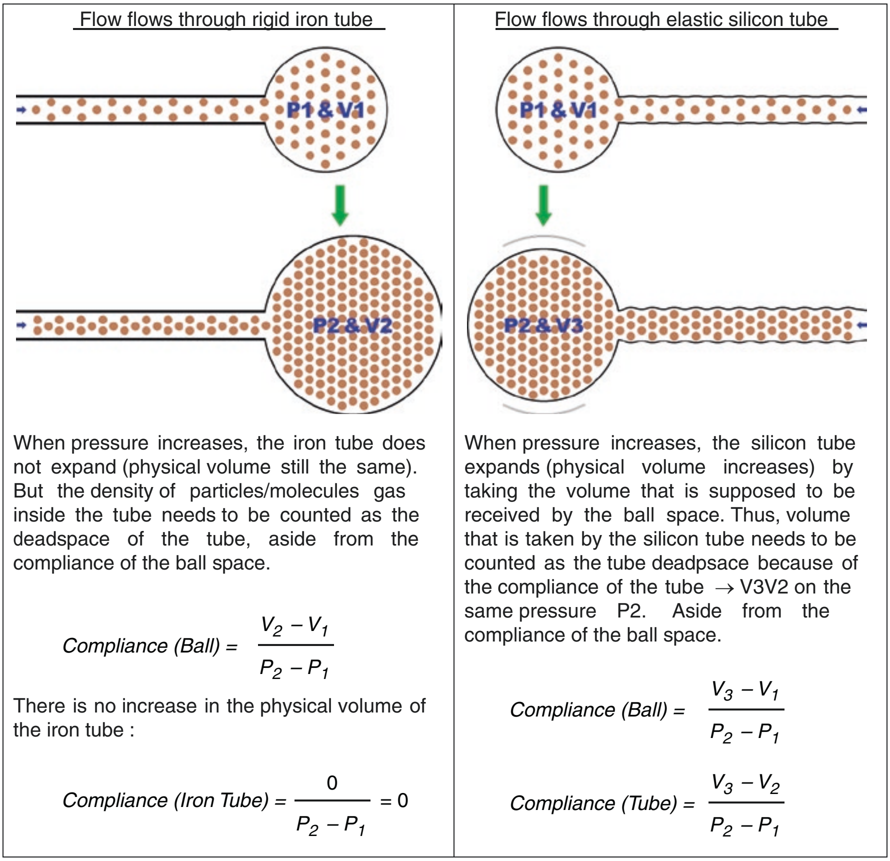


Fig. 2.2 Difference of flow in lungs with compliance and lack of compliance

(see Fig. 2.2). An elastic/flexible space with initial pressure (P_1) and physical volume (V_1) is blown until the density of particles/molecules in gas increases or the pressure increases to P_2 and produces physical volume (V_2), and so the difference of the volumes (ΔV) is divided by the difference of the pressure (ΔP), which is called compliance of that space.

2.4 Control System and Respiratory Anatomy

The anatomy of mechanism control system and distribution system/perfusion is shown in Fig. 2.3. It will be explained further in the following explanation about the control system of respiration, distribution system/perfusion, and friction and external pressure.

Control System of Respiration

1. Brain sensors, which are near the medulla, will sense the level of CO_2 by knowing the pH of the blood that flows through the brain. Sensors in the aortic arch and carotid artery will sense the level of O_2 and CO_2 in the blood.

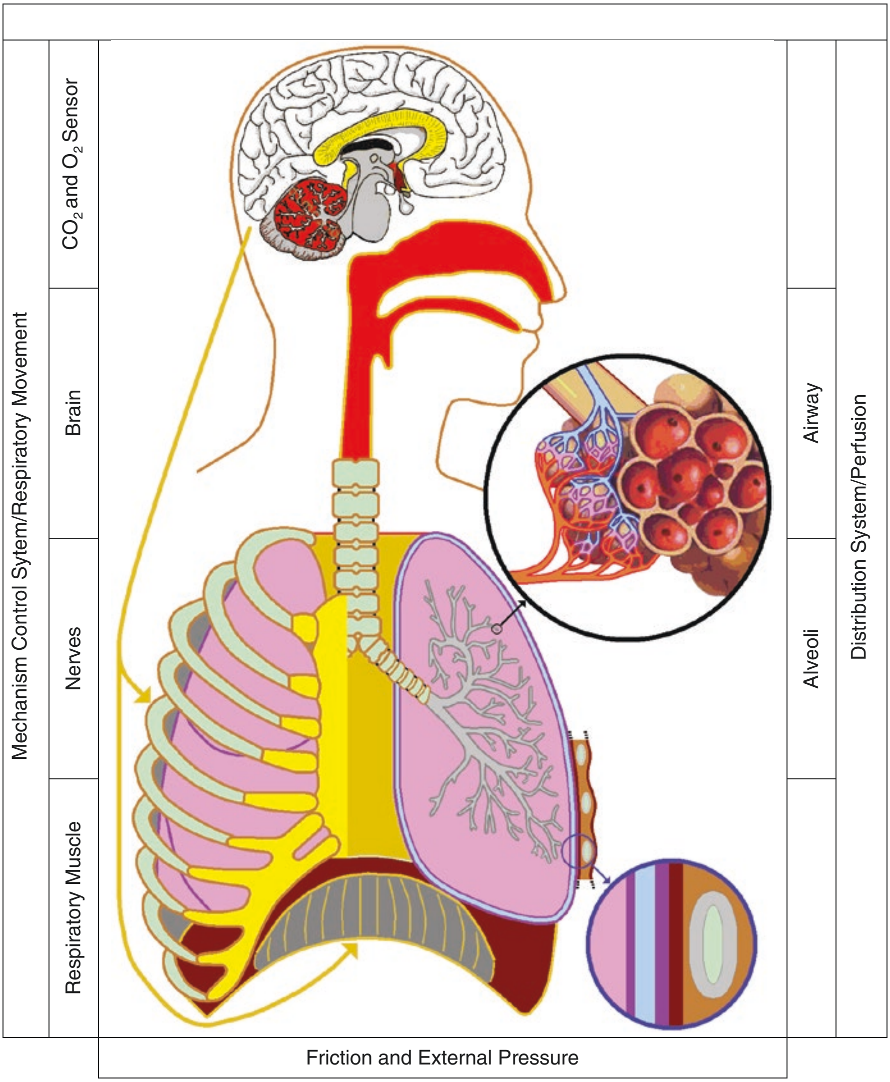


Fig. 2.3 Control system and respiratory anatomy

2. The brain decides to either increase or decrease the inspiratory rate or the depth of breathing.
3. The brain stimulates the respiratory center through the nerves for the respiratory muscles (diaphragm and intercostal muscles) to move.
4. The diaphragm and the intercostal muscles move to expand the lungs and the alveoli inside the lungs.

Distribution System/Perfusion

1. On inspiration, fresh air goes into the upper airway then into the lower airway.
2. Fresh air goes into the alveoli, so gas exchange with the blood occurs.
3. Gas exchange occurs when O_2 goes into the blood cell and CO_2 from the blood goes into the alveoli.
4. On expiration, used air goes out of the alveoli.
5. Used air goes out through the lower airway and the upper airway.

Friction

Friction between the lungs and the chest wall is minimized by the existence of pleural space.

External Pressure

The ribs, intercostal muscles, and diaphragm have a relaxed position that gives pressure to the alveoli. This condition is good when expiration occurs because this lessens the occurrence of air trapping. But because of the external pressure, lung compliance decreases, resulting to the lungs needing more pressure to expand the alveoli.

Pleural Space

The increase of fluid in the pleural space will cause pressure changes in the lungs and its surrounding. Figure 2.4 shows increased pleural space during expiration and inspiration.

For better understanding, Fig. 2.5 shows the difference between fluid filled and air filled inside the pleural space by the illustration of a syringe filled with fluid.

Notes:

Fluid has the same mass and has higher density of particles than air; then with the same force, the air will expand more than fluid.

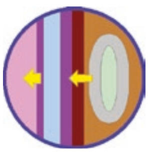
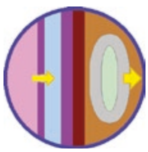
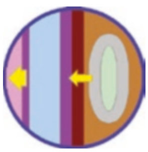
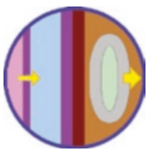
	Expiration	Inspiration	Description
Normal Pleural Space			Pleural space (light blue) is filled with fluid that works as a lubricant which prevents friction and shake. Particularly, it functions as an attachment of respiratory muscles that pull the lungs to expand on inspiration. Because of this, pleural space works as a conductor media to pull the respiratory muscles so the lungs and the alveoli could expand.
Increased Pleural Space			If pleural space (light blue) increases due to increasing of fluid inside or due to presence of air inside, then the lungs and the alveoli inside will be compressed that may cause the alveoli collapse and also compresses the venous return. On inspiration, expanding of the lungs and the alveoli inside will be lesser.

Fig. 2.4 Comparison of normal and increased pleural space during expiration and inspiration

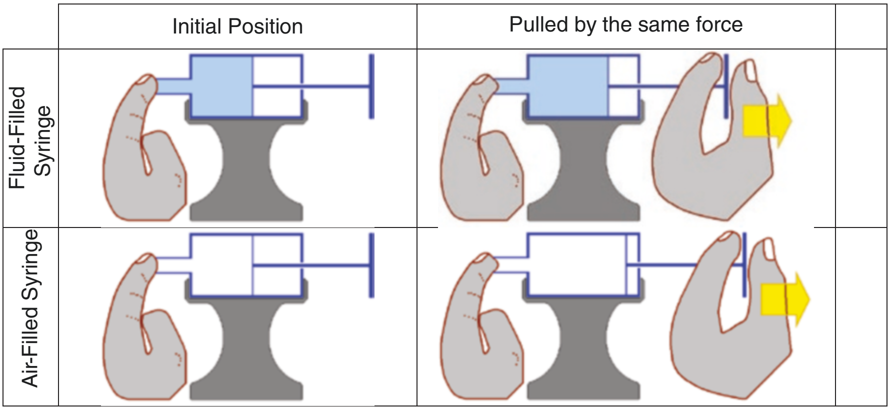


Fig. 2.5 Illustration of the difference between fluid filled and air filled inside the pleural space

Having more air inside the pleural space, with the same work of breathing, will result to shorter lung movement or will result to alveoli expanding lesser due to the increase of air inside the pleural space.

So, alveoli will most likely collapse and may need more work of breathing.

Intrathoracic Pressure

The different pressures involved during breathing (Fig. 2.6) are as follows:

(a)	Lungs	Intrapulmonary pressure (alveolar pressure)
(b)	Visceral pleura	Transpulmonary pressure
		Pressure between
		–intrapulmonary pressure
		–intrapleural pressure
(c)	Pleura space	Intrapleural pressure
(d)	Parietal pleura	Transthoracic pressure
		Pressure between
		–intrapleural pressure
		–body surface pressure
(e)	Outer skin	Body surface pressure
(f)		Transrespiratory pressure (or transthoracic pressure)
		Pressure between
		–intrapulmonary pressure
		–body surface pressure

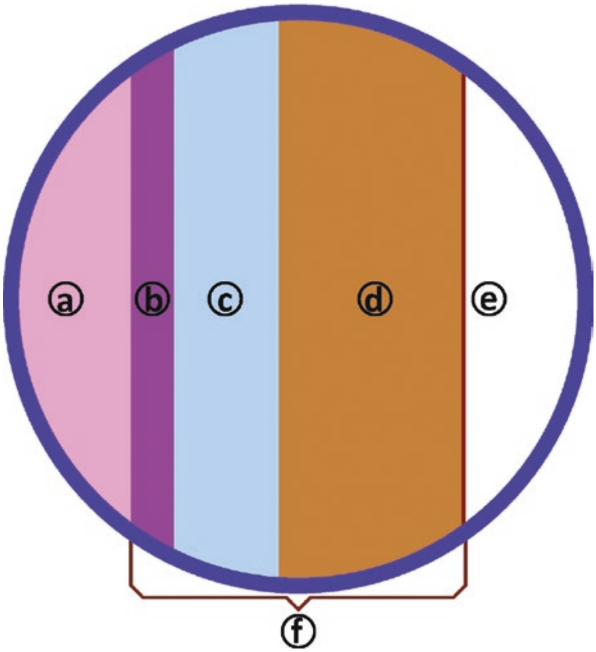


Fig. 2.6 Illustration of intrathoracic pressure

2.5 Spontaneous Inspiration and Expiration in Healthy Human

Inspiration is an active movement of the intercostal muscles and the diaphragm (Fig. 2.7a). The movement of the respiratory muscles will cause the surface of the alveoli to expand, resulting to the decrease of the alveolar pressure, which is lower than the atmospheric pressure, and will cause air in the atmosphere to enter the lungs.

Expiration is a spontaneous movement (Fig. 2.7b). In general, it is passive because the patients do the expiration themselves by relaxing the respiratory muscles. Expiration means flow of breath out to the atmosphere; so there is no barrier/resistance.

Intrathoracic pressure during spontaneous breathing is shown in Fig. 2.7c.

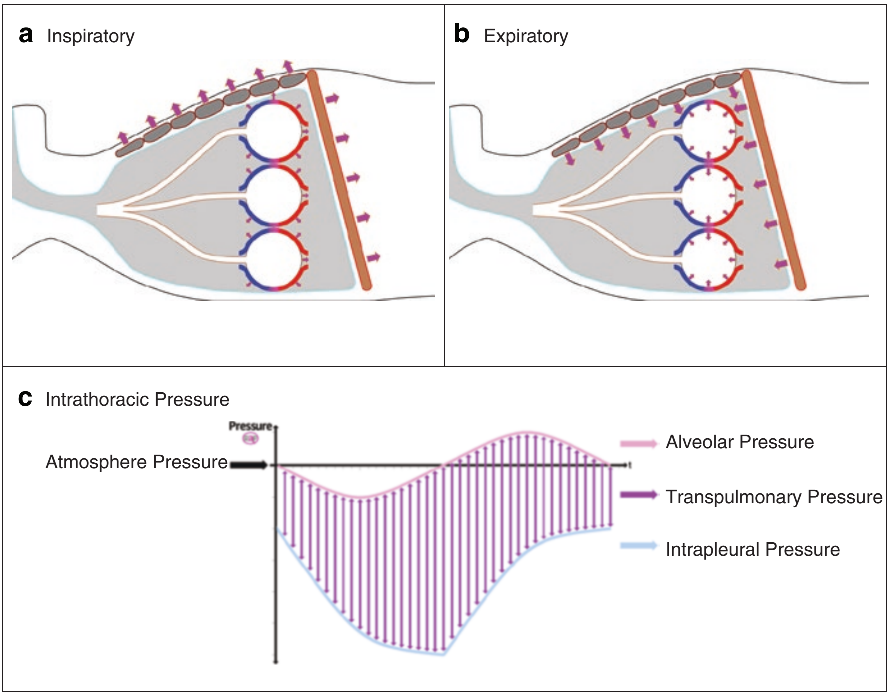


Fig. 2.7 Spontaneous breathing in healthy human during inspiration (**a**), expiration (**b**), and intrathoracic pressure (**c**)

2.6 Inspiration and Expiration of Patient with Mechanical Ventilatory Support

Inspiration is an active movement by blowing air into the alveoli until it produces positive pressure inside the alveoli and pushes the alveolar wall outward (Fig. 2.8a). Upper alveoli (ventral) expand bigger because they have lesser gravitational load. Lower alveoli (dorsal) expand lesser because they have the biggest gravitational load which is the support of all alveoli above. Positive pressure plus gravitation will also compress the blood vessels and cause decrease in venous return.

Expiration is a spontaneous movement (Fig. 2.8b). In general, it is passive because the patients do the expiration themselves by relaxing the respiratory muscles. The ventilator does not "pull" for the expiration, except when using HFO (high-frequency oscillatory) ventilation. This would cause asynchrony by

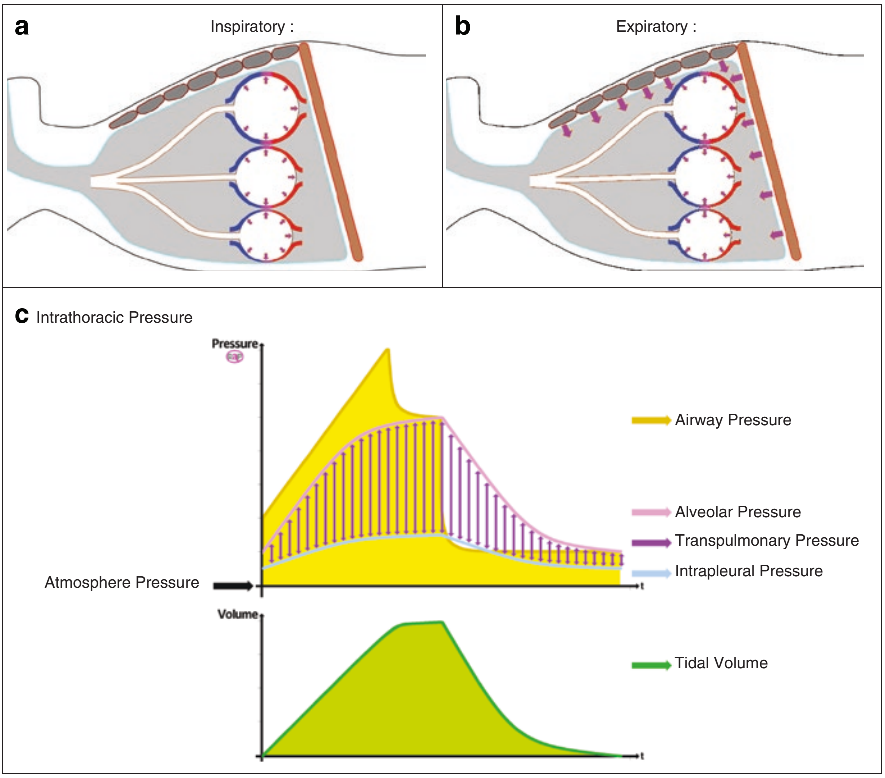


Fig. 2.8 Breathing of patient with mechanical ventilatory support

increasing the pressure due to collision with the inspiratory flow from the ventilator. Figure 2.8c shows the intrathoracic pressure changes with ventilatory support.

2.7 Complete Expiration

During expiration, it is important for the expiratory flow ($\mathbf{E}_{frz}$) and even pressure to return to zero (except when there is PEEP (positive end-expiratory pressure)) or baseline of the waveform. Figure 2.9 shows that flow returns to zero which is the baseline of the flow waveform. This means that expiration is completed. Complete expiration does not only mean that expiratory flow returns to zero but also complete exhalation of the patient without the occurrence of air trapping or even auto-PEEP.5

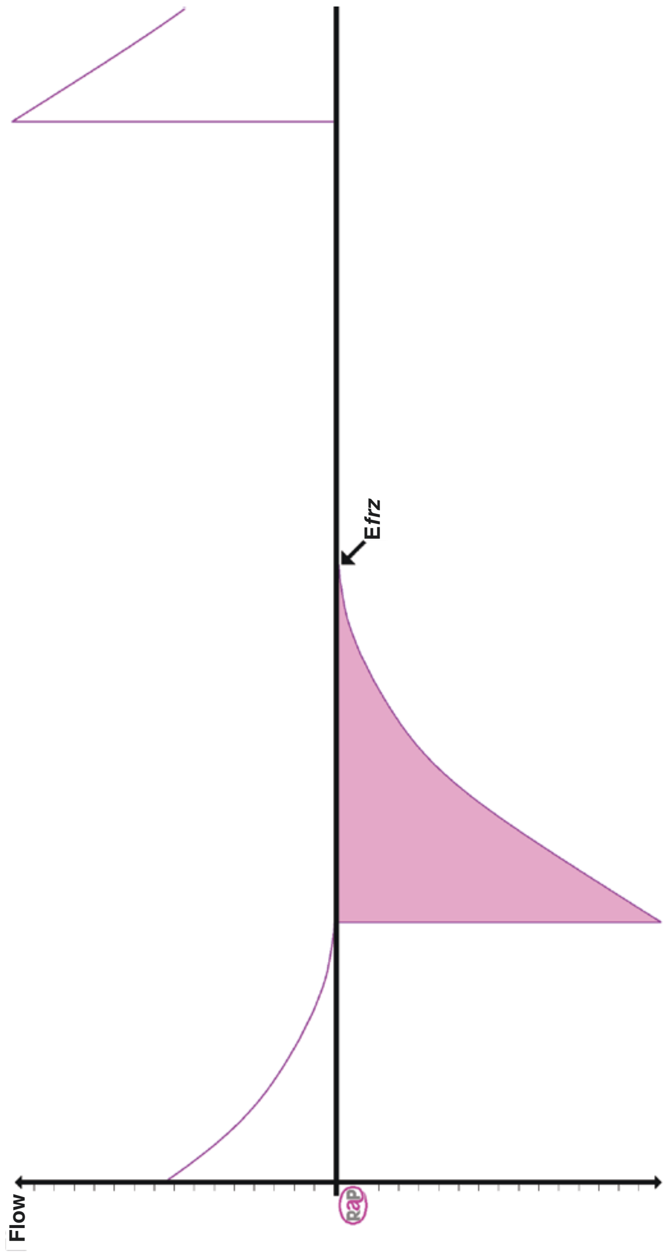


Fig. 2.9 Flow waveform with complete expiration

2.8 Expiration in Mechanical Ventilation: PEEP and Base Flow

2.8.1 PEEP (Positive End-Expiratory Pressure: Pressure at the End of Expiration)

The ventilator will have to keep the pressure at the end of expiration. This has already been set, as shown in Fig. 2.10, by regulating the expiratory valve which is generally membrane-like, how big is the opening or the closing proportionally based by the pressure in one time and the expected positive end-expiratory pressure (PEEP).

During expiration:

(a) The expiratory valve will open to attain the highest point for the peak expiratory flow; by proportionally controlling it, the pressure is continuously regulated.
(b) The expiratory valve is still regulated during expiratory flow and the pressure is monitored, which almost reaches the set PEEP.
(c) The expiratory flow has finished and the pressure has reached PEEP. The ventilator will still be monitored and PEEP is maintained despite changes in either pressure or flow.

2.8.2 Base Flow

Some ventilators have base flow feature to compensate for leak and to simplify or to make work of breathing of patient in triggering ventilator easy.

Base flow is continuous (e.g., in Fig. 2.11, 5 L/min from inspiration directly to expiration). On the view of ventilator simulates flow to or from patients and so inspiratory base flow is reduced with expiratory flow.

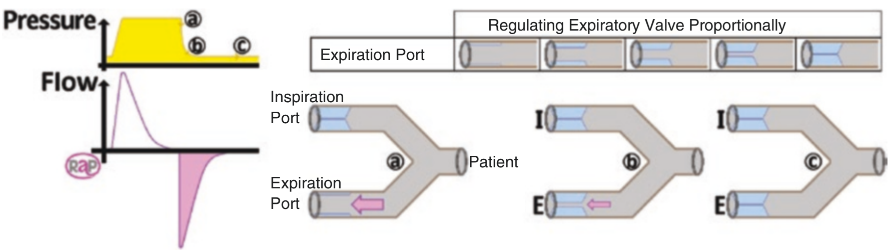


Fig. 2.10 Regulation of base flow

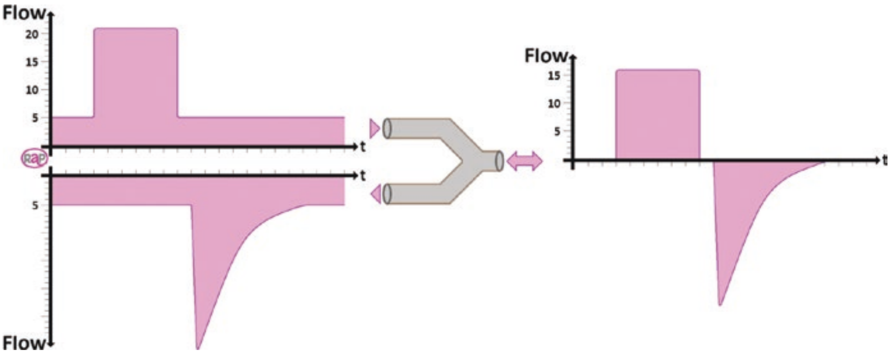


Fig. 2.11 Example of how base flow works and looks on ventilator

2.9 Incomplete Expiration: Air Trapping and Intrinsic PEEP

The previous topic about how important complete expiration is has been discussed. In another way, incomplete expiration (Fig. 2.12) could be defined by flow waveform that does not go back to zero ($\mathbf{E}_{frz}$). This could happen because of the lesser expiratory time than the inspiratory time. For example, the patient is still in the phase of expiration, but then the time for expiration is finished; so ventilator starts inspiration immediately without even finishing expiration totally. Incomplete expiration can cause critical effects to patients on ventilation, such as air trapping which can lead to auto-PEEP or intrinsic PEEP.

2.10 Needs of Patient on Mechanical Ventilatory Support

Failure of Respiratory Control System:

1. Gas sensor – CO_2 sensor failure in the brain
2. Brain
   (a) Dysfunction/brain trauma
   (b) Post-operation of the brain
   (c) Effects of sedation
3. Nerves
   (a) Failure to send information from the CO_2 and O_2 gas sensor in the brain, near the medulla, the aortic arch, and the carotid artery to the respiratory center
   (b) Failure to send instruction or stimuli from the respiratory center to the respiratory muscles
   (c) Effects of sedation
4. Respiratory muscles
   (a) Failure or trauma of respiratory muscles
   (b) Effects of muscle relaxant drugs
   (c) Increase of work of breathing
   (d) Respiratory muscles need more O_2

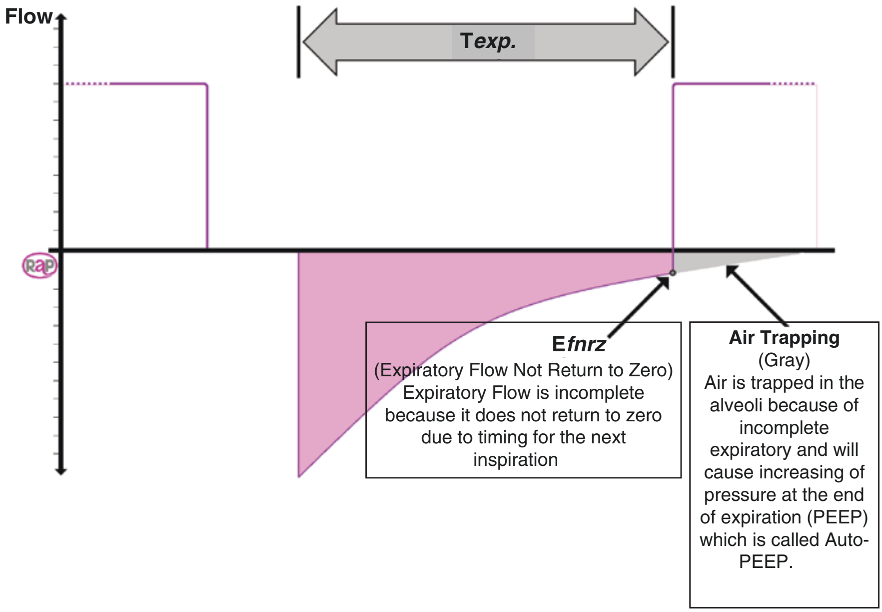


Fig. 2.12 Flow waveform with incomplete expiration which results to air trapping

Failure/Dysfunction of Distribution/Perfusion:

1. Airway
   (a) Constriction of airway
   - Constriction because of airway compliance
   - Constriction because of tumor, asthma, or excessive mucus

   (b) Inability to clear the airway, inability to secrete phlegm
2. Alveoli
   (a) Collapsed alveoli
   - Surface of alveoli becomes more stiff
   - Alveoli are compressed from outside, for example, from the intercostal muscle, the ribs; increasing amount of fluid in the pleural space or even the presence of air in the pleural space

   (b) Alveoli have less elasticity
   - The surface of the alveoli becomes more sensitive like a plastic that is difficult to deflate to remove used air

   (c) Dirt or fluid inside the alveoli
   - Filling the alveoli and preventing the alveoli to be filled with air
   - Blocking the airway to the alveoli
   - Blocking the pores which causes blocking of perfusion

   (d) Airways
3. Blood vessels (pulmonary capillaries)
   (a) If the blood vessels or the pulmonary capillaries are blocked, the gas exchange inside the alveoli with the blood will be useless because blood does not flow

3 Mechanical Breath

3.1 Introduction

Mechanical ventilation is one important part of care of many critically ill patients especially in patients with respiratory failure. It is mostly provided inside the hospital, especially inside the ICU, but it is also provided at the side outside the ICU and outside the hospital (Hess and Kacmarek 2014).

Ventilatory support should be initiated when a patient's spontaneous breathing is not enough to maintain gas exchange, which causes gas exchange to fail to the level that death is threatening the patient's life if support is not provided. Every patient has different cases or diagnoses when it comes to respiratory failure. For example, clinician should consider the patient's condition and patient needs to decide the best settings and mode of delivery of mechanical ventilator to fulfill also patient needs. It is important to know and understand different mechanical ventilation modes in order to match breath delivery to specific clinical application and patient needs.

Mechanical ventilator can be set to deliver various types of breath delivery based on flow control target. In every type of breath delivery, it has its own breath sequence, for example, its initiation, target of breath, and cycling. Each breath has its own type of breath based also on the initiation source of breath. Clinician should base on these variables to set the suitable breath delivery based on specific patient's condition and patient needs. This chapter will describe those various breath deliveries, a breath sequence, and type of breath based on breath initiation source. Graphs and waveform will also be shown for a better understanding.

R.A. Pupella, *Mechanical Ventilation in Patient with Respiratory Failure*,
DOI 10.1007/978-981-10-5340-5_3

3.2 Various Types of Breath Delivery Based on Flow Control Target

3.2.1 Volume-Controlled Breath Delivery

One of the various types of breath delivery based on flow control target is volume-controlled breath delivery. It shows how the ventilator works during this type of breath delivery (see Fig. 3.1). Inspiration is done through cycle (Fig. 3.1) which is by regulating inspiratory flow and then comparing the given flow with flow pattern that has been set.

There are definitely advantages and disadvantages of this volume-controlled ventilation (Table 3.1).

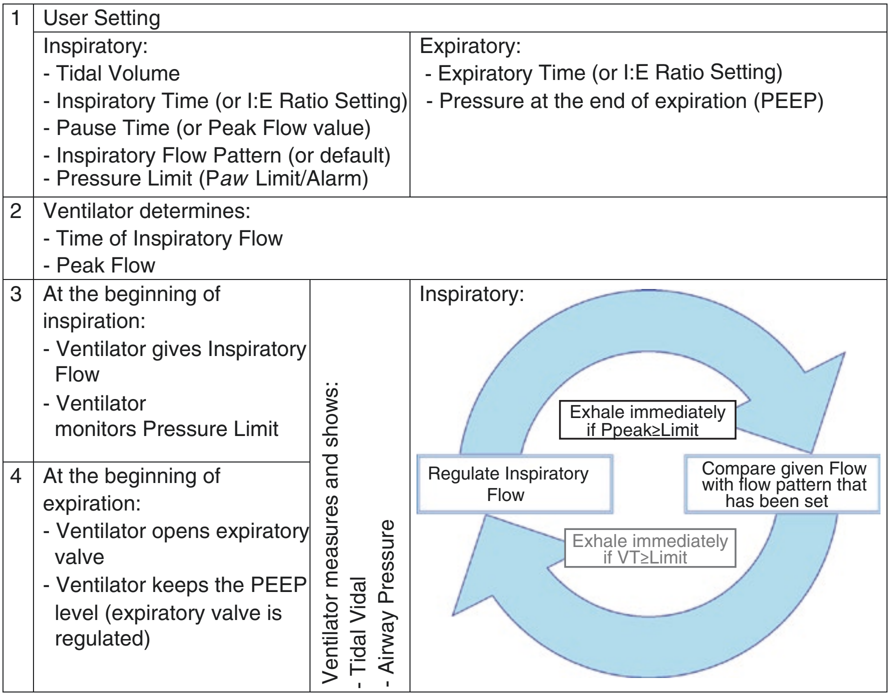


Fig. 3.1 Breath delivery of volume controlled

Table 3.1 Advantages and disadvantages of volume-controlled ventilation

Advantages	Disadvantages
– Tidal volume of the lungs is more constant and safer from the risk of volutrauma – Minute volume (MV) is constant with the same respiratory rate to stabilize the removal of CO_2	– Peak pressure is not always stable, which depends on the changes of airway resistance and needs to be stabilized by the pressure alarm – Peak pressure is not always stable, which depends also on the lung compliance and that has the possibility of having risk of barotrauma. Because of this, this needs to be stabilized by the pressure alarm – Inspiratory flow demand has already been set with the tidal volume setting and inspiratory time (and plateau time)

3.2.1.1 Inspiration and Expiration in Volume-Controlled Ventilation

Inspiration:

As shown in Fig. 3.2, ventilator gives flow with the set pattern, and the peak is **I*pf*** until the set tidal volume ($\mathbf{V_T}$) has been reached at the end of time of the flow **T*if***. With the said flow, there will be solidity of particles going to airway resistance. Because of this, airway pressure increases to pressure on resistance **P*res***. Alveoli compliance will produce compliance pressure **P*compl*** with the presence of tidal volume **VT** inside the alveoli. Then the peak pressure **P*peak*** is the sum of **P*EEP***, **P*compl***, and **P*res***.

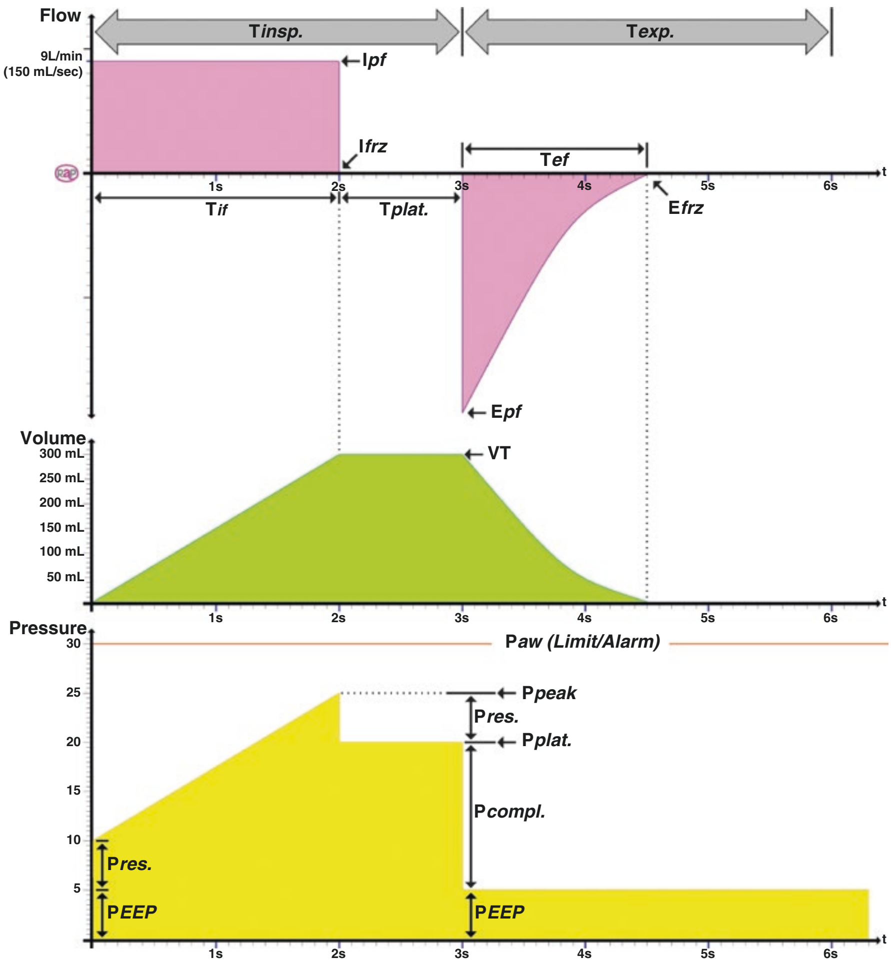


Fig. 3.2 Example waveform of volume-controlled ventilation

Note:
While inspiratory flow is ongoing and peak pressure **P*peak*** has been reached or exceed the set **P*aw (Limit/Alarm)***, then inspiratory flow will be stopped and inspiratory phase ends where the ventilator starts expiratory phase by opening the expiratory valve.

When the airway pressure reaches **P*peak***, it means concentration of gas particles that passes by the airway resistance is really high. Because of the difference of **P*peak*** compared to actual pressure in the alveoli, then flow will go faster passing through the airway resistance to alveoli until equilibrium happens. This equilibrium is the solidity or concentration of the gas or pressure which is the same between airway pressure and pressure inside the alveoli, which then measured pressure in the airway can present the alveolar pressure **P*compl***.

The difference between inspiratory time **T*insp*** and inspiratory flow time **T*if*** is plateau time **T*plat*** where tidal volume $\mathbf{V_T}$ is still inside the alveoli until inspiratory time **T*insp*** ends.

Expiration:
As shown in Fig. 3.2 again, ventilator opens expiratory valve, and expiratory flow starts with a peak of **E*pf*** while also maintains the pressure limit and prevents it to drop below **P*EEP***. The drop of pressure below PEEP can be prevented by regulating the expiratory valve that is also indirectly regulating the expiratory flow.

The time needed for the expiratory flow is **T*ef*** that will end if point 0 (**E*frz***) has been reached. Expiratory time **T*exp*** needs to be regulated until expiratory flow ends and until point 0 (**E*frz***) has been reached and just before expiratory time **T*exp*** ends and the beginning of next inspiration.

Abbreviations in Fig. 3.2 are explained in Table 3.2 for better understanding.

Additional explanation of symbols on Fig. 3.2:

Plateau/Pause Pressure

It is the pressure measured at the end of inspiratory time, just before expiration.

To get good plateau pressure value, then measurement is better done:

- When inspiratory flow from the ventilator has ended:
  If inspiratory flow from the ventilator has ended which is marked by returning of inspiratory flow to point 0 (**I*frz***), then there is no addition of gas particles that come in and pass by airway resistance to the alveoli.
  If inspiratory flow from the ventilator is still ongoing which is marked by point 0 and has not been reached yet, then addition of gas particles or the density will increase the airway pressure that passes by the airway resistance until the difference will get bigger with pressure inside the alveoli.
- When airway pressure is below **P*peak*:**
  If airway pressure is below **P*peak***, it means density of gas particles has moved to the alveoli and passes by the airway resistance.
- When airway pressure stabilizes and does not change again (increase/decrease):
  If gas particle passes by airway resistance to alveoli, the density is the same with the density of gas inside the alveoli, and then there are no flows of gas particle

Table 3.2 Explanation of symbols

Abbreviation	Definition and explanation
T*insp.*	Inspiratory time that has been set
T*exp.*	Expiratory time that has been set (or by I:E ratio setting)
T*if*	Inspiratory time calculated by the ventilator Note: The set tidal volume is the same as area of inspiratory flow Thus, in square flow, VT = **I*pf*** (inspiratory peak flow) × **T*if***
T*plat*	Plateau/pause time that has been set where air is already inside and stays in the alveoli Note: **T*plat*** = **T*insp*** − **T*if*** *(inspiratory flow time)*
T*ef*	Time needed by expiratory flow will be longer if airway resistance increases
I*pf*	Peak of inspiratory flow that has been set or calculated by ventilator
E*pf*	Peak of expiratory flow that will be lower if airway resistance increases
I*frz*	Inspiratory flow back to point 0 which means inspiration has ended
E*frz*	Expiratory flow back to point 0 which means expiration has ended
VT	Tidal volume on inspiration that has been set and will be reached by ventilator by giving calculated inspiratory flow
PEEP	Positive end expiratory pressure
P*compl*	Pressure measured inside the airway because of alveolar compliance by giving tidal volume **VT** to the alveoli Note: Alveolar compliance = $\frac{\text{Tidal volume }(\mathbf{VT})}{\text{Pressure due to compliance }(\mathbf{P}\boldsymbol{compl})}$ Measured compliance can also be affected by spontaneous movement of the respiratory muscles, for example: – Respiratory muscles move to take a breath and cause **P*compl*** to decrease (compliance increases) – Respiratory muscles relax like exhaling out air and cause **P*compl*** to increase (compliance decreases)
P*plat*	Plateau/pause pressure is measured in the airway when pressure decreases to PEEP because of timing for expiration. Measuring is done when pressure has reached equilibrium or stabilize and does not increase or decrease before going to PEEP. Equilibrium with stabilized pressure means airway pressure, and pressure inside the alveoli is the same because all gas particles have passed through airway resistance and inside the alveoli Note: **P*plat*** = ***PEEP*** + **P*compl***
P*res*	Pressure measured in the airway due to airway resistance Note: **P*res*** = **I*pf*** (inspiratory peak flow) × airway resistance
P*peak*	Peak of inspiratory pressure which is also called PIP (peak inspiratory pressure) Note: **P*peak*** = ***PEEP*** + **P*compl*** + **P*res***
P*aw (Limit/ Alarm)*	Airway pressure limit that will stop inspiratory flow and starts expiration (expiratory valve is open)

between the two sides until the pressure stabilizes and does not change. In this condition, density of gas particle or pressure measured in the airway can present the pressure inside the alveoli.

Summation of Pressure

Pressure in volume controlled is the summation of PEEP. Pressure due to lung compliance and pressure due to airway resistance can be seen in Fig. 3.3.

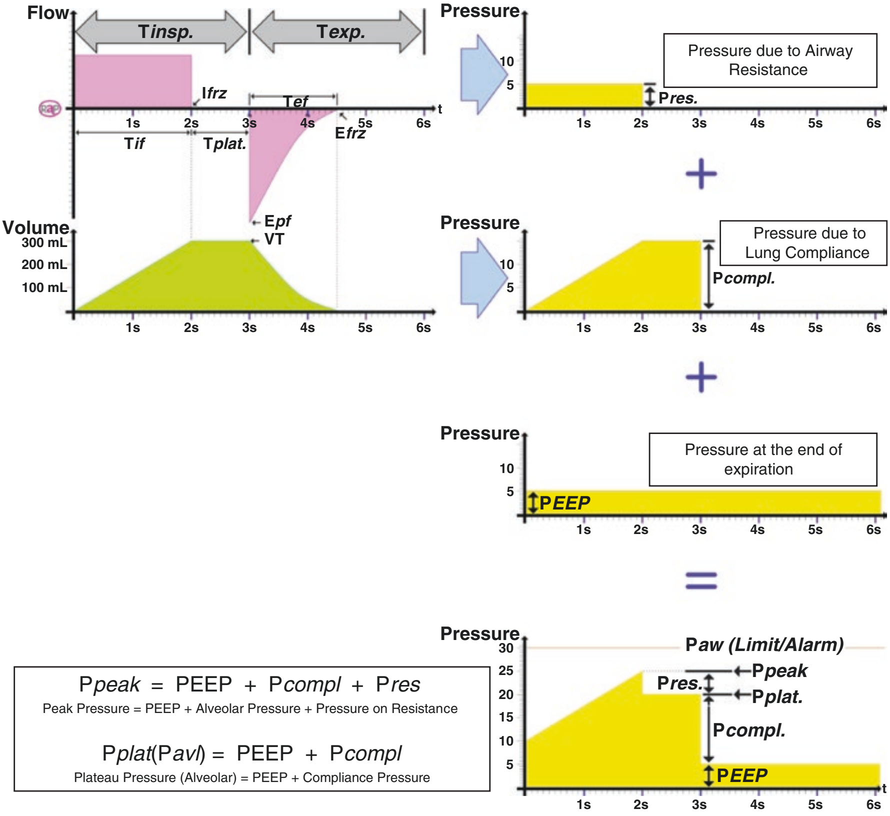


Fig. 3.3 Summation of pressure on compliance and airway resistance

Note:
Paw (Alarm/Limit) limits the peak pressure ***Ppeak*** and includes compliance pressure ***Pcompl*** and pressure on resistance ***Pres***.

3.2.1.2 An example of "High Airway Pressure" Alarm

If airway pressure ***Ppeak*** is the same or greater than ***Paw (Limit/Alarm)***, then flow is stopped until the set **VT** has not been reached and then ventilator moves to expiratory phase (beginning of ***Texp***). Ventilator also gives alarm sign "high airway pressure" (see Fig. 3.4).

Several causes of increased airway pressure ***Ppeak***:

- Airway resistance increases, and then ***Pres*** increases on the same peak inspiratory flow ***Ipf***.
- Compliance decreases, which is due to stiff lungs, and then ***Pcompl*** increases on the same tidal volume **VT**.
- Patient has asynchrony with ventilator and enables "fighting" that is spontaneous movement of the respiratory muscles while exhaling on inspiratory time ***Tinsp***

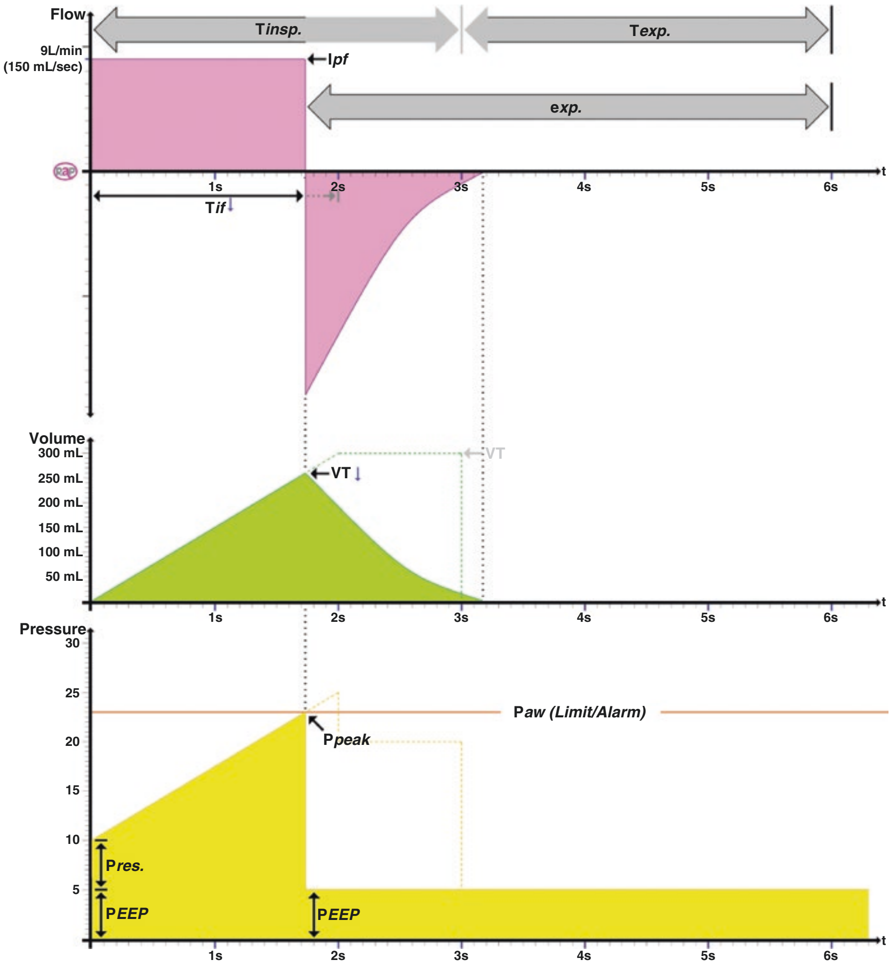


Fig. 3.4 Example of "high airway pressure" alarm

period, which is when air goes inside (**T*if***) or when holding breath/plateau time (**T*plat***).

Some changes in setting parameter that increases the airway pressure **P*peak***:

– Prolong the plateau/pause time **T*plat*** or shorten inspiratory time **T*insp*** that will also shorten inspiratory flow time **T*if*** until it reaches the same tidal volume **VT** that has been set. Then ventilator will increase peak flow **I*pf*** that surely will also increase pressure on airway resistance **P*res***.
– Increase the tidal volume **VT** that will increase inspiratory peak flow **I*pf***, which then increases pressure on airway resistance **P*res***. And increase of tidal volume **VT** inside the alveoli also increases the compliance pressure **P*compl***.

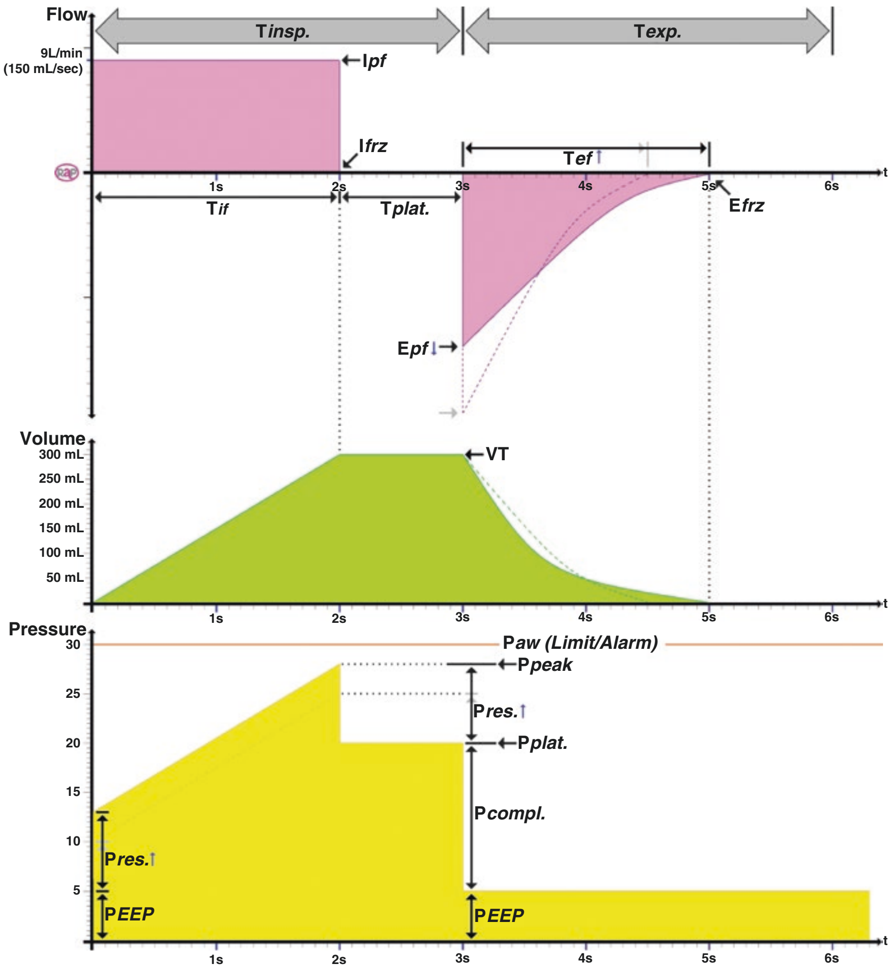


Fig. 3.5 Example of increased airway resistance

3.2.1.3 An Example of Increased Airway Resistance

Changes of condition of lungs of the patient on the same ventilator setting parameter:

Inspiration:

As shown in Fig. 3.5, if airway resistance increases, then ***Pres*** will also increase and that will also increase peak pressure ***Ppeak*** with the same inspiratory peak flow ***Ipf***.

Expiration:

Because exhalation is passive, which means patients do the expiration themselves without being triggered or started by the ventilator, then inspiratory peak flow ***Epf*** will decrease (Fig. 3.5). Therefore, to produce the same tidal volume **VT** from the

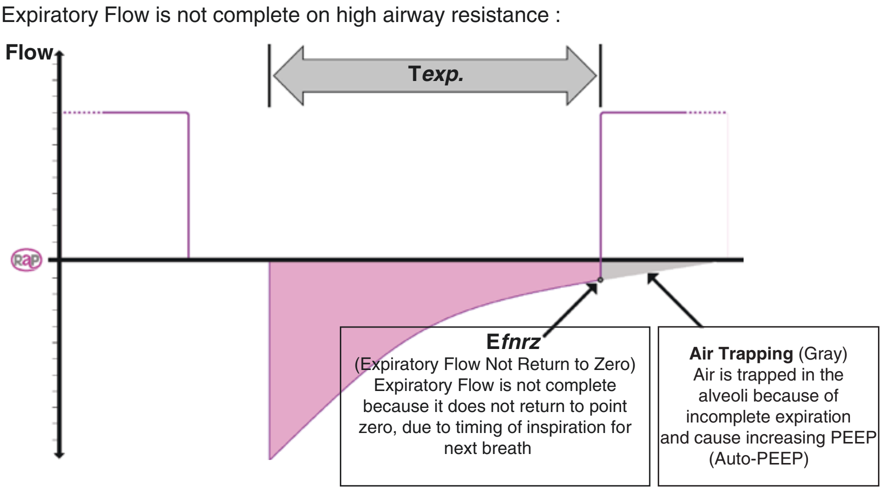


Fig. 3.6 Incomplete expiratory flow because of high airway resistance

alveoli, it needs longer expiratory flow time **T*ef*** until the expiratory flow ends and returns to point 0 (**E*frz***).

Maybe expiratory time **T*exp*** needs to be regulated to make sure expiratory flow ends; thus, there is no expiratory volume left in the alveoli, which will cause air trapping that also will cause increased ***PEEP*** (intrinsic PEEP).

Note:

Air trapping can also be caused by spontaneous muscle movement that holds expiration or by trying to inhale during expiratory time **T*exp*** (Fig. 3.6).

Several causes of increased airway resistance:

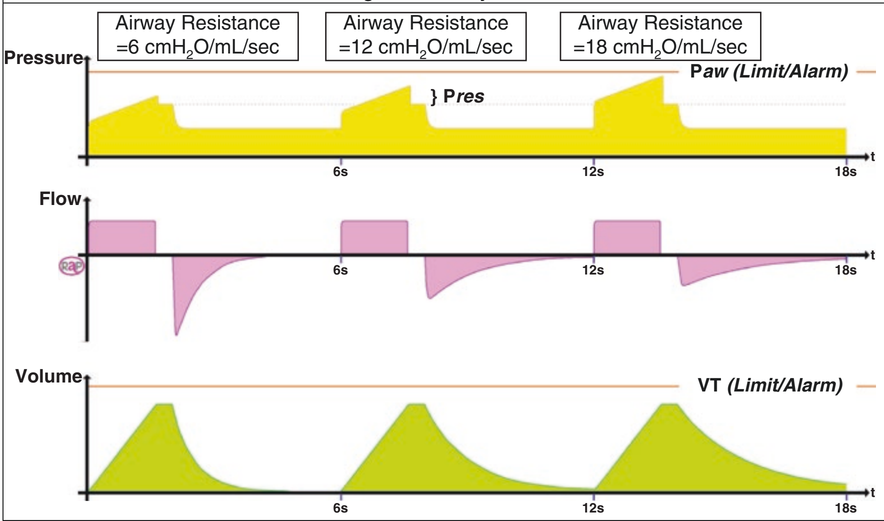
- Presence of phlegm or foreign object inside the airway or tube (ETT/tracheostomy).
- Size of tube (ETT/tracheostomy) is smaller or kinked.

Figure 3.7 shows an example of airway pressure and flow waveform in volume controlled with increased airway resistance. The difference between lesser and greater airway resistance is explained in table.

Another example of volume controlled is shown in Fig. 3.8 which shows decreasing peak airway pressure by decreasing peak inspiratory flow and prolonged inspiratory flow time (shorten plateau time) to maintain the same tidal volume.

This example is explained further in table given in Fig. 3.8.

Changes of Airway Resistance



Lesser Airway Resistance:	Greater Airway Resistance:
Pressure on Airway Resistance (P*res*) is lesser which causes lower Peak Airway Pressure on the same Inspiratory Peak Flow.	Pressure on Airway Resistance (P*res*) is greater which causes increasing Peak Airway Pressure on the same PeakInspiratory Flow.
Peak Inspiratory Flow is the same as what the ventilator has measured based on Tidal Volume and Time Setting.	Peak Inspiratory Flow is the same as what the ventilator has measured based on Tidal Volume and Time Setting.
Peak Expiratory Flow is higher and completed to zero in shorter time because of lesser airway resistance.	Peak Expiratory Flow is lower and needs longer time to be completed to zero and even cannot be completed because of timing for the next inspiration.

Note: Make sure exhalation is completed which is returning of expiratory flow to zero

Fig. 3.7 Example of airway pressure and flow in volume controlled with increased airway resistance

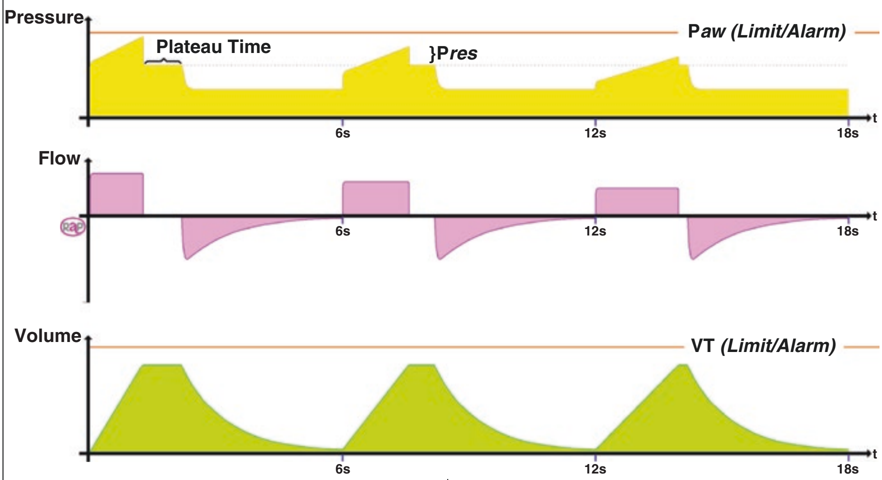
3.2.1.4 An Example of Increased Airway Pressure Caused by Decreased Lung Compliance

If lung compliance decreases or the patient exhales spontaneously during inspiratory time **T***insp*, then **P***compl* increases and will also increase peak pressure (**P***peak*) (see Fig. 3.9).

Several causes of decreased lung compliance:

- Surface of alveoli becomes too stiff.
- Decreased total alveoli capacity:

Adjusting Inspiratory Flow to decrease Peak Pressure



Greater/higher Peak Inspiratory Flow:	Smaller/lower Peak Inspiratory Flow:
Pressure on Airway Resistance (**P*res***) is greater which causes increasing Peak Inspiratory Pressure on the same airway resistance.	Pressure on Airway Resistance (**P*res***) is lesser which causes decreasing Peak Inspiratory Pressure on the same airway resistance.
Inspiratory Flow Time needs to be shorten or prolong Plateau Time for the same Tidal Volume setting.	Inspiratory Flow Time needs to be longer or shorter Plateau Time for the same Tidal Volume setting.
On the same airway resistance and the same Tidal Volume without accumulating volume from the previous expiration then expiratory flow pattern will be mostly the same.	On the same airway resistance and the same Tidal Volume without accumulating volume from the previous expiration then expiratory flow pattern will be mostly the same.
Example of Setting: VT = 400 mL, Inspiratory Time (Ti) = 2 sec, PeakFlow = 24 L/min (400 mL/sec) →Inspiratory Flow Time = 1 sec, Plateau Time = 1 sec	Example of Setting: VT = 400 mL, Inspiratory Time (Ti) = 2 sec, Peak Flow = 15 L/min (250 mL/sec) →Inspiratory Flow Time = 1.6 sec Plateau Time = 0.4 sec

Note: Make sure exhalation is completed which is returning of expiratory flow to zero

Fig. 3.8 Example of decreasing peak airway pressure by decreasing peak inspiratory flow

For example, alveoli collapsed – for example, due to atelectasis – then on the same volume will cause increased alveolar pressure.

– Increased transthoracic pressure that pushes lungs inside:

For example, the presence of air inside the pleural cavity or increased fluid inside the pleural cavity

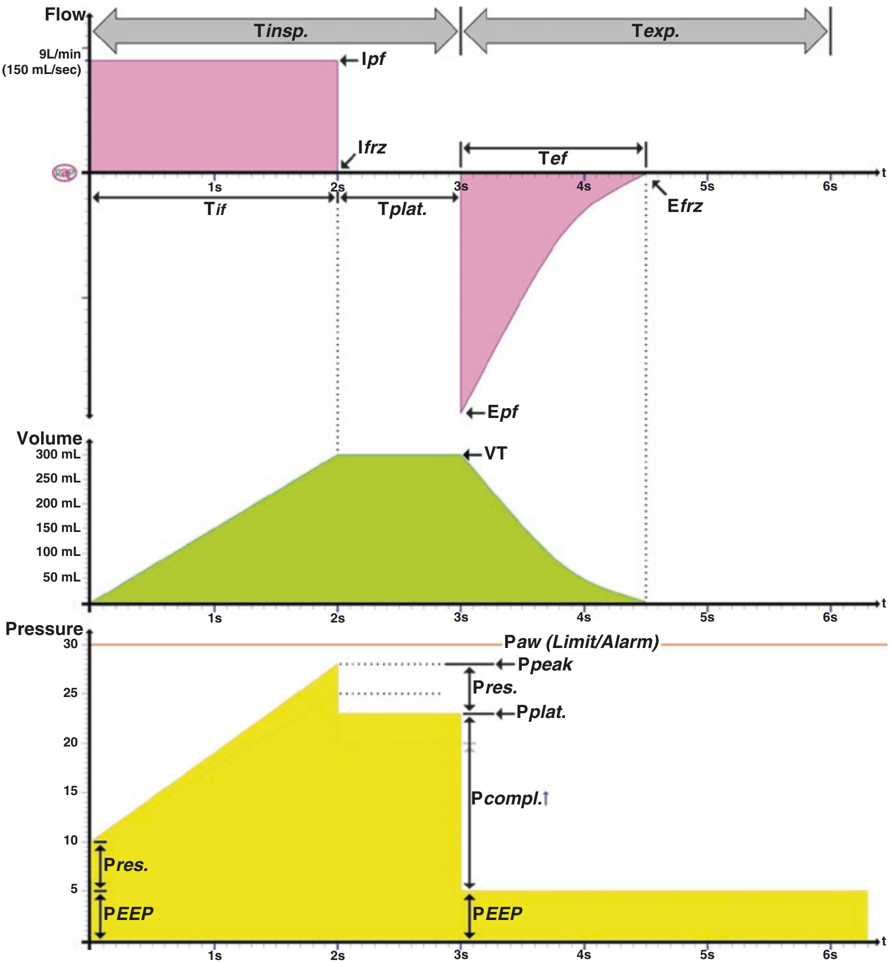


Fig. 3.9 Example of increased airway pressure due to decreased lung compliance

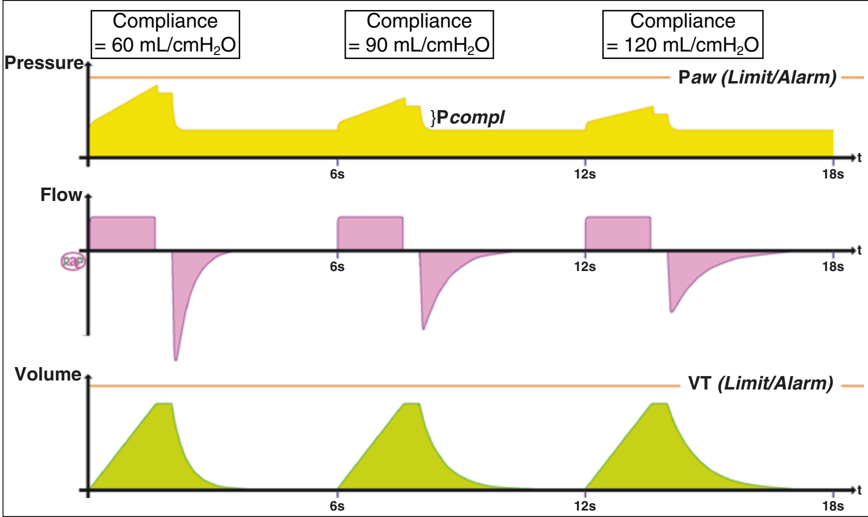
Example of increased airway pressure caused by decreased or increased lung compliance is further explained in table, and it also shows the waveform in this condition (Fig. 3.10).

Example of volume-controlled setting:

An adult patient with predicted body weight of 50 kg needs support of mechanical ventilator with the following target:

– Concept of lung protective ventilation with low tidal volume of 6–8 mL/kg body weight.
– Removal of CO_2 is expected to reach at minute volume of 0.1 L/min/kgBW.

Changes of Compliance of the Alveoli/Lungs



Lesser Lung Compliance:	Greater Lung Compliance:
In more stiff lungs, Compliance Pressure (**P*compl***) is greater which causes increased Peak Airway Pressure on the same Peak Inspiratory Flow.	In more elastic lungs, Compliance Pressure (**P*compl***) is lower which causes decreased Peak Airway Pressure on the same Peak Inspiratory Flow.
Peak Inspiratory Flow is the same as measured by the ventilator as Tidal Volume and Time that have been set.	Peak Inspiratory Flow is the same as measured by the ventilator as Tidal Volume and Time that have been set.
Peak Expiratory Flow is higher and complete until has reached point zero in shorter time and because of stiffness of the lungs, then it pushes expiratory flow bigger and faster.	Peak Expiratory Flow is lower and needs more time to be completed until point zero.

Note: Decreased compliance will increase airway pressure because of increased Compliance Pressure (**P*compl***)

Fig. 3.10 Example of airway pressure and flow in different lung compliance

Then calculation for volume-controlled setting as the following and further setting is shown in Table 3.3:

– Tidal volume (VT) = 300–400 mL
– Minute volume (MV) = 5 L/min (approximately more or less)
– Respiratory rate (RR) = MV/VT = 17–13 breaths/min

Table 3.3 Example of range setting of volume controlled

Range setting	
Setting: – Ventilation mode = volume controlled – Tidal volume = 300 mL – Respiratory rate = 17 BPM (breath period = 60 s/17 = 3.5 s) – I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 3.5 × 1/3 = 1.2 s, Te = 2.3 s) – Flow pattern = square – Inspiratory flow = 18 L/min (300 mL/s) (flow time = VT/300 = 1 s) (plateau time = Ti – 1 s = 0.2 s) Set smaller initial flow to prevent higher resistance pressure, and flow can be increased by keeping on maintaining resistance pressure and if needed can also prolong the plateau pressure – PEEP = 5 cmH_2O Measured parameter: – Peak pressure = ?? cmH_2O – Plateau pressure = ?? cmH_2O	Setting: – Ventilation mode = volume controlled – Tidal volume = 400 mL – Respiratory rate = 13 BPM (breath period = 60 s/13 = 4.6 s) – I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 4.6 × 1/3 = 1.5 s, Te = 3.1 s) – Flow pattern = square – Inspiratory flow = 18 L/min (300 mL/s) (flow time = VT/300 = 1.3 s) (plateau time = Ti − 1.3 s = 0.2 s) Set smaller initial flow to prevent higher resistance pressure and flow can be increased by keeping on maintaining resistance pressure and if needed can also prolong the plateau pressure – PEEP = 5 cmH_2O Measured parameter: – Peak pressure = ?? cmH_2O – Plateau pressure = ?? cmH_2O

3.2.1.5 Volume-Controlled Ventilation and Pressure-Controlled Ventilation Transition

P*compl* is the pressure measured in the airway because of lung compliance by giving tidal volume **VT** to the alveoli:

$$\text{Compliance Pressure}\left(\mathbf{P}\boldsymbol{compl}\right) = \text{Tidal Volume}\left(\mathbf{VT}\right)\text{Lung Compliance}$$

If spontaneous movement from the respiratory muscles of the patient in one breath is absence, then the **P*compl*** will totally represent lung compliance. The value of **P*compl*** can be used as reference for inspiratory pressure setting in pressure-controlled breath to get the desired tidal volume **VT** for the patient. The mentioned pressure is also called as driving pressure because it produces **VT**. That pressure is also called as delta pressure (ΔP) because it is the difference between PEEP and **P*peak***:

$$\text{Driving Pressure}\left(\text{Delta Pressure, }\Delta P\right) = \text{Tidal Volume}\left(\mathbf{VT}\right)\text{Lung Compliance}$$

$$\text{Peak of }\mathbf{P}\boldsymbol{plat} = \mathbf{P}\boldsymbol{EEP} + \mathbf{P}\boldsymbol{compl}\left(\text{Driving Pressure}\right)$$

And the **P*plat*** can also be used as reference for peak inspiratory pressure setting in pressure-controlled breath. The formula for **P*insp*** would be the following:

$$\mathbf{P}\boldsymbol{insp} = \mathbf{P}\boldsymbol{EEP} + \text{Driving Pressure}\left(\Delta P\right)$$

Setting:
- Ventilation Mode = Volume-Controlled
- Tidal Volume = 400 mL
- Respiratory Rate = 12 BPM
  (Breath Period = 60 sec/12 = 5 sec)
- I:E Ratio = 1:1
  (Ti:Te = 1:1 -->Ti=Te=2.5 sec)
- Flow Pattern = Square
- Inspiratory Flow = 12 L/min (200mL/sec)
  (Flow Time = VT/200 = 2 sec)
  (Plateau Time = Ti -2 sec = 0.5 sec)
- PEEP = 5 cmH_2O

Measured:
- Peak Pressure = 30 cmH_2O
  (No 'fighting' from the patient)
- Plateau Pressure = 25 cmH_2O
  (Pcompl = 25-PEEP = **20 cmH_2O**)

Setting:
- Ventilation Mode = Pressure-Controlled
- Pc (ΔP) = **20 cmH_2O** above PEEP
  (Initial Setting, needs to be rearranged to reach and maintain VT with changes in Lung Compliance)
- Slope = 0.25 sec (Initial Setting)
- Respiratory Rate = 12 BPM
- I:E Ratio = 1:1
- PEEP = 5 cmH_2O

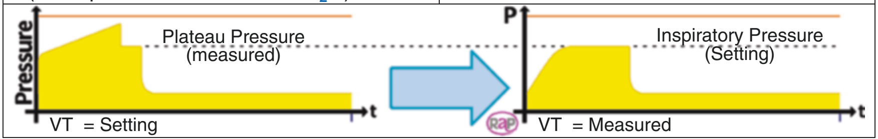
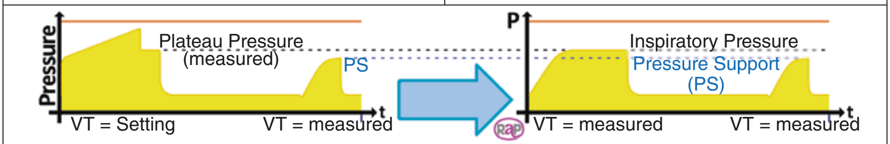


Fig. 3.11 Example of transition ventilation mode volume controlled to pressure controlled

Setting :
- Ventilation Mode = Volume SIMV
- Tidal Volume = 300 mL
- Respiratory Rate = 6 BPM
  (SIMV Period = 60 sec/6 = 10 sec)
- Inspiratory Time (Ti) = 2 sec
- Flow Pattern = Square
- Plateau Time = 1 sec
  (Flow Time = Ti -1 = 1 sec)
  (Inspiratory Flow = VT/1 = 300 mL/sec)
- PEEP = 5 cmH_2O
- Pressure Support = 12 cmH_2O(Initial Setting)

Measured :
- Peak Pressure = 30 cmH_2O
  (No 'fighting' of patient)
- Plateau Pressure = 20 cmH_2O
  (Pcompl = 20-PEEP =**15cmH_2O**)

Setting :
- Ventilation Mode = Pressure SIMV
- Pc (ΔP) = **15cmH_2O** above PEEP
  (Initial Setting, needs to be rearranged to reach and maintain VT with changes in Lung Compliance)
- Slope = 0.25 sec (Initial Setting)
- Pressure Support = 12 cmH_2O above PEEP
  (Initial Setting, look at note below)
- Respiratory Rate = 6 BPM
- Inspiratory Time(Ti) = 2 sec
- PEEP = 5 cmH_2O



Note :
Initial setting of Pressure Support is given lower than the Compliance Pressure or Inspiratory Pressure Pc (ΔP) to trigger patient to inhale more deeply, but need to be rearranged based on changes of the strength of the respiratory muscles and Lung Compliance

Fig. 3.12 Example of transition ventilation mode volume SIMV to pressure SIMV

Table 3.4 Example of transition ventilation mode assist volume controlled to assist pressure controlled

Setting: – Ventilation mode = assist volume controlled – Tidal volume = 300 mL – Respiratory rate = 10 BPM (breath period = 60 s/10 = 6 s) – I:E ratio = 1:2 (Ti:Te = 1:2 → Ti = 2 s and Te = 4 s) – Flow pattern = square – Plateau time = 0.5 s (flow time = Ti − 0.5 = 1.5 s) (inspiratory flow = VT/1.5 = 200 mL/s) – PEEP = 5 cmH_2O Measured: – Peak pressure = 25 cmH_2O (no "fighting" of patient) – Plateau pressure = 20 cmH_2O (Pcompl = 20-PEEP=**15 cmH_2O**)	Setting: – Ventilation mode = assist pressure controlled – Pc (ΔP) = **15 cmH_2O** above PEEP (initial setting needs to be rearranged to reach and maintain VT with changes in lung compliance) – Slope = 0.25 s (initial setting) – Respiratory rate = 10 BPM – I:E ratio = 1:2 – PEEP = 5 cmH_2O

Example of volume-controlled ventilation and pressure-controlled ventilation transition is shown in table and waveform of transition is shown in Fig. 3.11.

Another example is transition of assist volume controlled to assist pressure controlled with settings shown in Table 3.4.

Last example is the transition of volume SIMV to pressure SIMV setting shown in table, and the transition waveform is shown in Fig. 3.12.

3.2.2 Pressure-Controlled Breath Delivery

Another type of breath delivery based on flow control target is pressure-controlled breath delivery. Figure 3.13 shows how the ventilator works during this type of breath delivery. Inspiration is done through cycle (Fig. 3.13) which is by regulating inspiratory flow and then comparing measured pressure with pattern that has been set.

There are definitely advantages and disadvantages of this pressure-controlled ventilation (Table 3.5).

3.2.2.1 Inspiration and Expiration in Pressure-Controlled Ventilation

Inspiration:

As shown in Fig. 3.14, ventilator regulates inspiratory flow while continuously comparing peak inspiratory pressure that has been measured with target of inspiratory pressure pattern which is pressure rise/gradient setting and peak inspiratory pressure setting.

Regulation of inspiratory flow is done to reach and maintain the target pattern of inspiratory pressure toward these changes:

– If airway resistance increases or decreases, then ventilator will regulate inspiratory flow, and so pressure still follows the pattern and does not increase or decrease significantly because of changes of resistance.

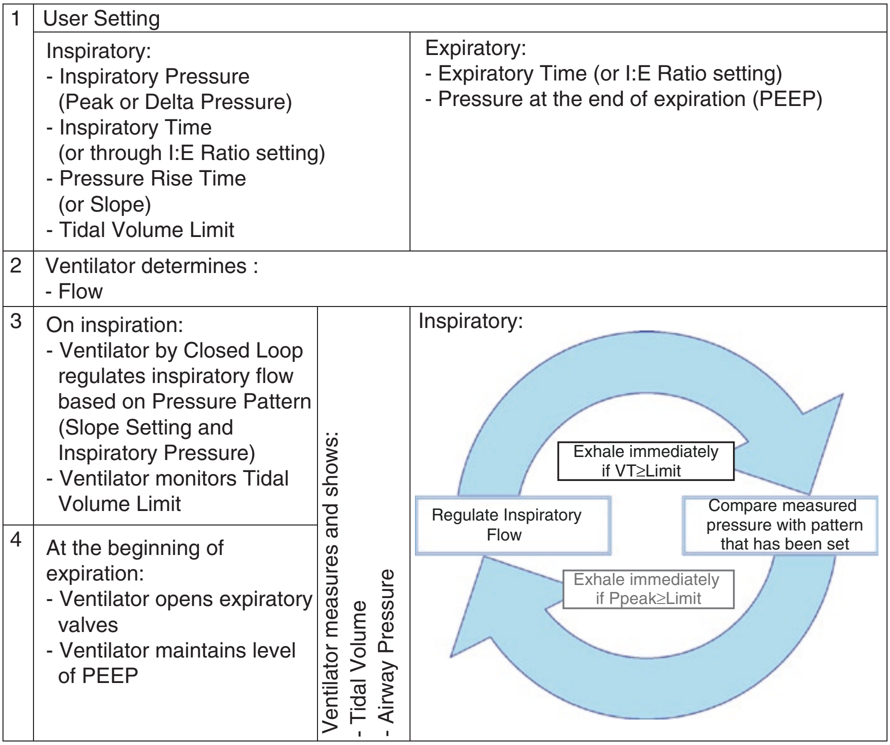


Fig. 3.13 Breath delivery of pressure controlled

Table 3.5 Advantages and disadvantages of pressure-controlled ventilation

Advantages	Disadvantages
– Peak pressure is more constant even lung compliance is changing and so is safer from the risk of barotrauma – Inspiratory flow demand is fulfilled because of regulated inspiratory flow → improve gas distribution → inflate collapsed alveoli	– Tidal volume change depends on changes of lung compliance which gives a possible risk of volutrauma that needed to be limited by volume alarm – Minute volume (MV) change depends on changes of tidal volume with the same respiratory rate, which causes unstable removal of CO_2

– If compliance increases or decreases because alveoli is getting more elastic or stiff, then ventilator will also regulate inspiratory flow, and so pressure still follows the pattern and does not increase or decrease significantly because of changes of compliance.

In pressure-controlled ventilation, inspiratory pressure pattern that has been set (slope parameter and inspiratory pressure) will affect the peak, the gradient (steep or ramp), and the length of inspiratory flow until it will affect measured tidal volume. Note:

When inspiratory flow is flowing, if measured **VT** reaches or exceeds **VT *Limit/ Alarm*** that has been set, or measured **P*peak*** reaches or exceeds **P*aw (Limit/Alarm)*** that has been set, then inspiratory flow will be terminated and inspiratory phase will be ended where ventilator starts expiration by opening expiratory valves.

In inspiratory time **T*insp***, if inspiratory flow has ended and reached point 0 (**I*frz***) and no more flow is flowing to or from the patient, then airway pressure at that time and tidal volume that has been measured can be used as reference of calculation for alveoli compliance.

For safety and prevention of trauma in the lungs, initial setting of inspiratory pressure can be started from the lowest level and then goes up step-by-step (e.g.,

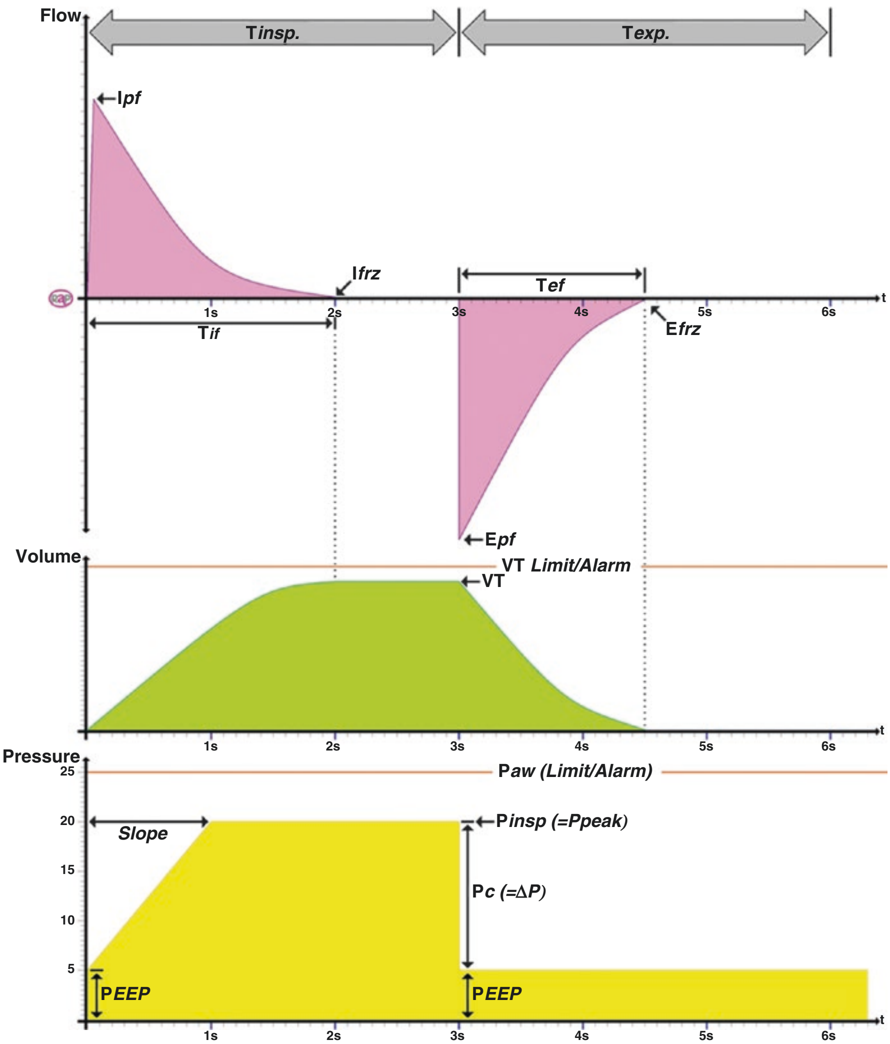


Fig. 3.14 Example waveform of pressure-controlled ventilation

breath-by-breath, steps 1–2 cmH_2O) until **VT** that has been measured reaches value that can be tolerated by the patient's lungs with maximum limit **VT *Alarm/Limit***. The inspiratory pressure should also be monitored regularly to maintain the **VT** and maximum limit **VT *Alarm/Limit***.

Expiration:

As shown in Fig. 3.14, ventilator opens expiratory valves to let expiratory flow flows with a peak of **E*pf*** while keeping the level of pressure, to prevent it to fall below **P*EEP*** by regulating the expiratory valves while also indirectly regulating the expiratory flow.

Time needed for the expiratory flow is **T*ef*** which is complete if reaches point 0 (**E*frz***).

Table 3.6 Explanation of symbols

Abbreviation	Definition and explanation
T*insp*	Inspiratory time that has been set
T*exp*	Expiratory time that has been set (or by I:E ratio setting)
T*if*	Inspiratory flow time that is measured
T*ef*	Time needed by expiratory flow that will be longer if airway resistance increases
I*pf*	Peak inspiratory flow regulated by ventilator
E*pf*	Peak expiratory flow that will be smaller if airway resistance increases
I*frz*	Inspiratory flow returns to point 0 which means inspiration is completed
E*frz*	Expiratory flow returns to point 0 which means expiration is completed
VT	Inspiratory tidal volume which is measured because inspiratory flow is given
VT *Limit/Alarm*	Limit alarm of tidal volume measured which will eliminate inspiratory flow and start expiratory (expiratory valve is open)
Slope	Time that has been set decides the length of increasing pressure from PEEP to peak inspiratory (PEEP + Pc) where ventilator regulates inspiratory flow Note: Pressure acceleration = $\frac{\mathbf{Pc}(\Delta P)}{\mathbf{Slope}} = \frac{\mathbf{P}peak - \mathbf{PEEP}}{\mathbf{Slope}}$ Because pressure acceleration is due to the effect of flow which is regulated by closed loop, then it can also be called as flow acceleration
P*EEP*	Positive pressure at the end of expiration
P*c (ΔP)*	Pressure that has been set as driving pressure above PEEP to reach and maintain tidal volume Note: Driving pressure (**Δ*P***) = Tidal Volume (**VT**)Lung Compliance For safety, pressure can be started from the lowest level and then goes up step-by-step (e.g., breath-by-breath, steps 1–2 cmH_2O) until **VT** that has been measured reaches value that can be tolerated by the patient's lungs Driving pressure needs also to be monitored regularly to maintain the **VT** Measured compliance can also be affected by spontaneous movement from the patient's respiratory muscles
P*peak*	Peak of inspiratory pressure that is also called PIP (peak inspiratory pressure) If there is no spontaneous movement of the respiratory muscles from the patient just like exhaling in inspiratory flow, then **P*peak* = P*EEP* + Pc(Δ*P*) + P*res(when flow is ongoing)***
P*aw (Limit/ Alarm)*	Limit alarm of airway pressure that will eliminate inspiratory flow and immediately start exhalation (expiratory valve is open)

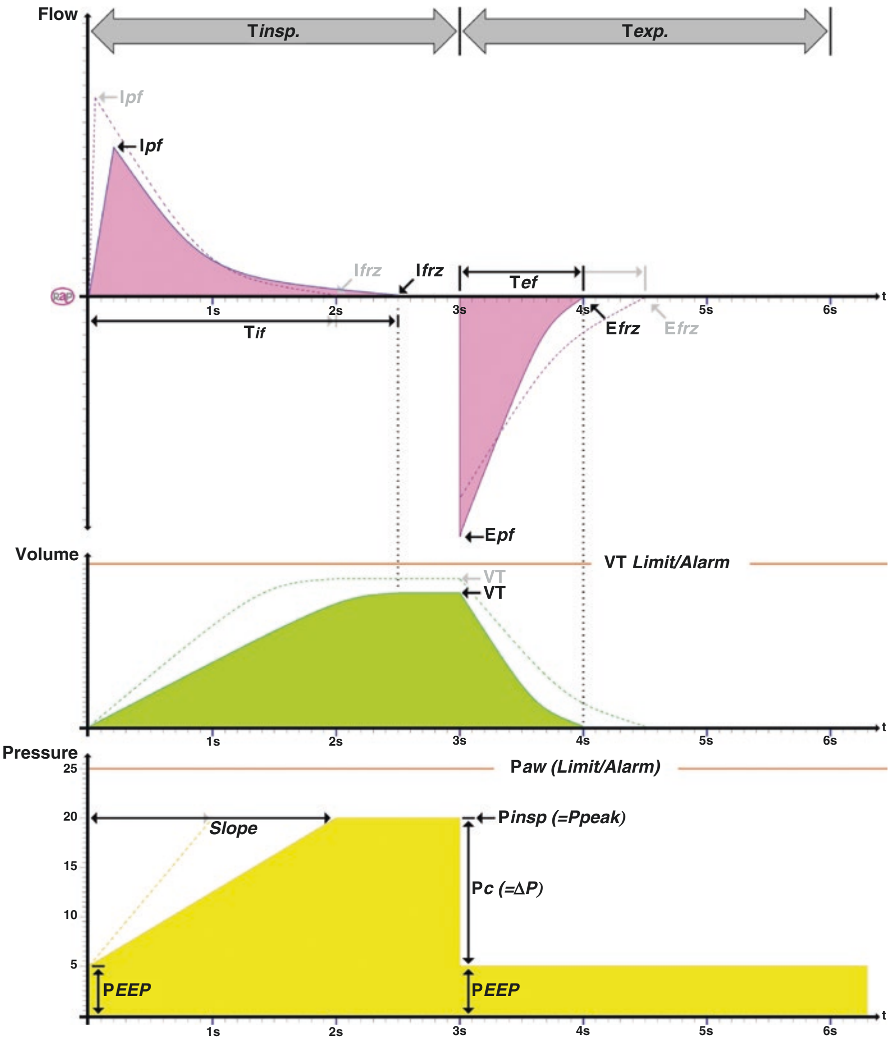


Fig. 3.15 Example of increased pressure rise time setting

Expiratory time **T*exp*** needs to be arranged until expiratory flow is complete and returns to point 0 before expiratory time **T*exp*** ends and the next inspiration begins.

Abbreviations in Fig. 3.14 are explained in Table 3.6 for better understanding.

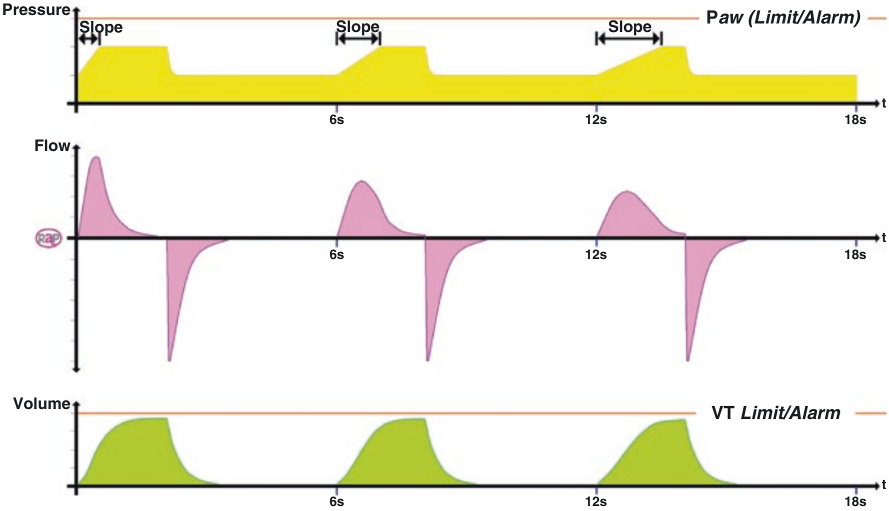


Fig. 3.16 Prolong slope time or pressure rise time

3.2.2.2 An Example of Extended Slope (Pressure Rise Time) Setting

If ***slope*** time (pressure rise time) is longer, then ventilator will regulate inspiratory flow to be lower and longer to make the pressure rise not too fast. But changing of inspiratory flow pattern will definitely affect tidal volume (see Fig. 3.15).

If airway resistance is too big and inspiratory flow is higher, then measured airway pressure is more represented by pressure because of resistance (**P*res***):

$$\mathbf{P}\boldsymbol{peak} = \mathbf{P}\boldsymbol{EEP} + \mathbf{P}\boldsymbol{res} + \mathbf{P}\boldsymbol{compl}$$

To decrease or lower the inspiratory flow, the slope time (pressure rise time) should be prolonged just like in Fig. 3.16.

Note:

In patient with higher and/or faster need of flow, for example, air hunger, then probably it needs shorter slope.

3.2.2.3 Airway Resistance and Compliance in Pressure-Controlled Breath

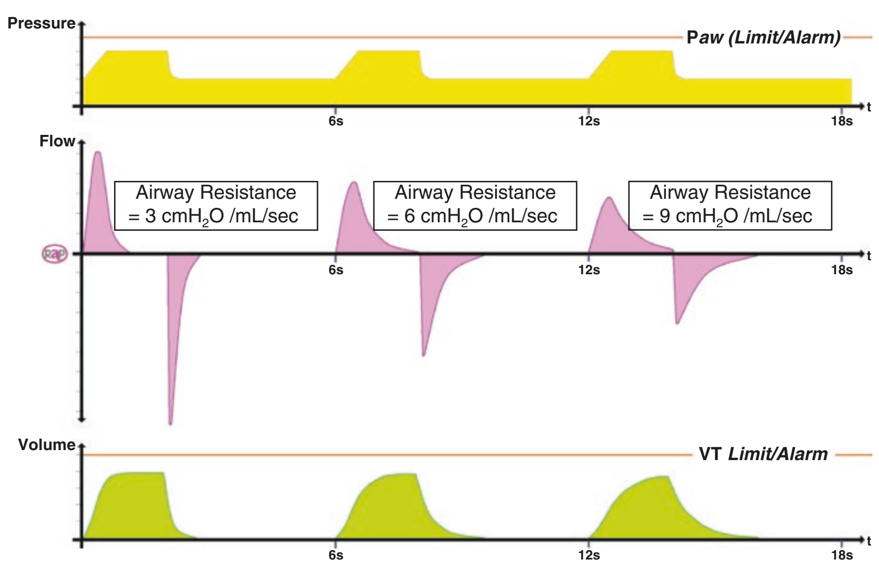
As airway resistance and compliance during pressure-controlled ventilation change, breath delivery will also change. See Fig. 3.17, for example, of flow in pressure-controlled ventilation with change in airway resistance. Table 3.7 explains what happen when lesser or greater airway resistance.

Another example in Fig. 3.18 shows flow and volume with change in lung compliance and is further explained in table.

Example of pressure-controlled setting:

Adult patient with predicted body weight of 50 kg needs support of mechanical ventilator with the following target:

Changes of Airway Resistance



Lesser Airway Resistance:	Greater Airway Resistance:
Higher Peak Flow With lesser resistance, then peakflow is higher because of smooth flow Shorter Flow Time With lesser solidity of particles because of lesser resistance, then time needed by the flow is shorter to pass by those resistance	Lower Peak Flow Solidity of gas inside the airway with resistance will increase which then, with low peak flow and increased pressure, ventilator will decrease flow so pressure pattern will not increase. Longer Flow Time Increasing of solidity of gas that passes by the airway resistance, will need longer time

Note: Make sure that exhalation is completed which is by expiratory flow returns to zero

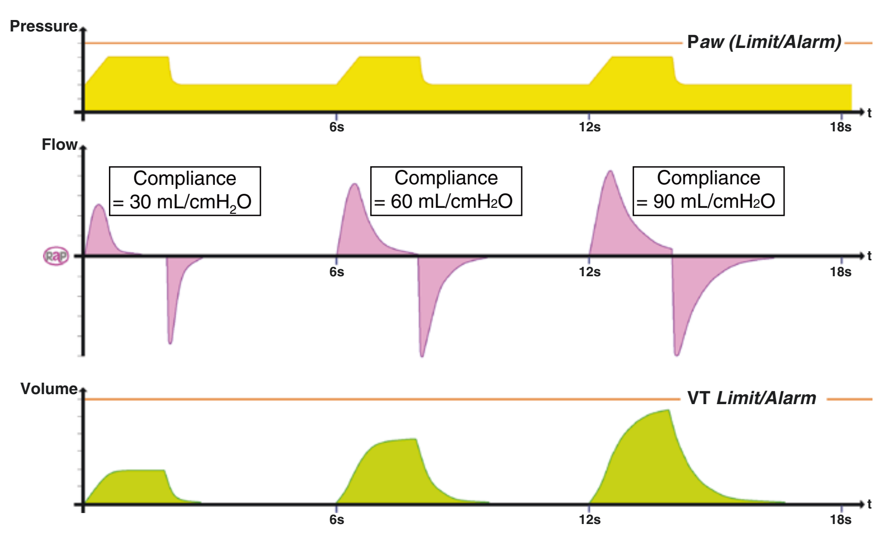
Fig. 3.17 Example of flow in pressure-controlled breath with different airway resistance

– Concept of lung protective ventilation with low tidal volume of 6–8 mL/kg body weight.
– Removal of CO_2 is expected to reach at minute volume of 0.1 L/min/kgBW.

Then calculation for pressure-controlled setting as the following and further setting is shown in Table 3.7:

– Inspiratory pressure begins with lowest level (e.g., 10 cmH2O above PEEP) and
– then increase in stages until it reaches VT = 300–400 mL.

Changes of Compliance of the Alveoli/Lungs



Lesser Lung Compliance:	Greater Lung Compliance:
Lower Peak Flow With more stiff lungs, then pressure has reached lower volume even flow.	Higher Peak Flow With more elastic lungs, then it needs greater flow to reach pressure pattern that has been set (Slope and Peak Inspiratory Pressure)
Shorter Flow Time With more stiff lungs, then pressure inside the alveoli will increase alveolar pressure until flow ends early.	Longer Flow Time With more elastic lungs, then it needs more volume (longer flow time) to reach pressure pattern that has been set

Note: Increasing Compliance will also increase Tidal Volume (**VT**)

Fig. 3.18 Example of flow and volume with different lung compliance

– Minute volume MV = 5 L/min (or greater).
– Respiratory rate RR = MV/VT = 17–13 breath/min.

3.2.2.4 Pressure-Controlled Ventilation and Volume-Controlled Ventilation Transition

Driving pressure (delta pressure, ΔP) has been adjusted to reach an expected tidal volume **VT** with changes of lung compliance. Then

$$\text{Driving Pressure}\ (\text{Delta Pressure}, \Delta P) = \frac{\text{Tidal Volume}\ (\mathbf{VT})}{\text{Lung Compliance}}$$

Table 3.7 Range setting of pressure controlled

Range setting	
Setting: – Ventilation mode = pressure controlled – Pc (ΔP) = 10 cmH_2O above PEEP Initial setting that needs to be adjusted, for example, breath-per-breath, to reach tidal volume of 300 mL – Respiratory rate = 17 BPM (breath period= 60 s/17 = 3.5 s) – I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 3.5 × 1/3 = 1.2 s, Te = 2.3 s) – Slope = 0.2–0.3 s Initial setting that needs to be arranged depends on the flow demand of the patient In patient with a need of greater flow (air hunger), shorter slope is needed in order for inspiratory flow to go higher – PEEP = 5 cmH_2O Measured parameter: – Tidal volume = ?? mL – Minute volume = ?? L/min	Setting: – Ventilation mode = pressure controlled – Pc (ΔP) = 10 cmH_2O above PEEP Initial setting that needs to be adjusted, for example, breath-per-breath, to reach tidal volume of 400 mL – Respiratory rate = 13 BPM (breath period = 60 s/13 = 4.6 s) – I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 4.6 × 1/3 = 1.5 s, Te = 3.1 s) – Slope = 0.2–0.3 s Initial setting that needs to be arranged depends on the flow demand of the patient In patient with a need of greater flow (air hunger), shorter slope is needed in order for inspiratory flow to go higher – PEEP = 5 cmH_2O Measured parameter: – Tidal volume = ?? mL – Minute volume (MV) = ?? L/min

If inspiration has ended (and completed until it reaches point 0 (**I*frz***), and there is absence of patient's spontaneous movement of respiratory muscles, then driving pressure that has been adjusted will be measured as pressure due to compliance **P*compl*** with the same tidal volume **VT** in volume-controlled ventilation:

$$\text{Pressure on Compliance}\left(\mathbf{P}\boldsymbol{compl}\right) = \frac{\text{Tidal Volume}\left(\mathbf{VT}\right)}{\text{Lung Compliance}}$$

Peak pressure **P*peak*** that happens will also be affected by pressure on resistance **P*res***:

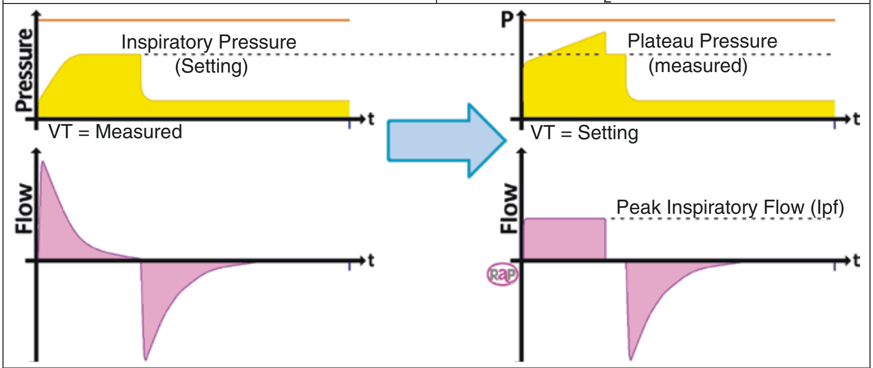
$$\mathbf{P}\boldsymbol{peak} = \mathbf{PEEP} + \mathbf{P}\boldsymbol{compl} + \mathbf{P}\boldsymbol{res}$$

Pressure on resistance **Pres** is affected by how big is the airway resistance and the inspiratory flow. Then the formula for **P*res*** will be the following:

$$\text{Pressure on Resistance}\left(\mathbf{P}\boldsymbol{res}\right) = \text{Inspiratory Peak Flow}\left(\mathbf{I}\boldsymbol{pf}\right) \times \text{Airway Resistance}$$

Thus, inspiratory peak flow **I*pf*** needs to be adjusted so that the peak pressure does not exceed the limit. To reach **VT** that has been set, then inspiratory flow time **T*if*** also needs to be adjusted by adjusting plateau time **T*plat*** or even inspiratory time **T*if***:

Setting: - Ventilation Mode = Pressure-Controlled - Pc(ΔP) = 20 cmH_2O above PEEP (Last Setting after reaches VT, for example, 400 mL by managing Inspiratory Flow returns to point zero) - Respiratory Rate = 12 BPM - I:E Ratio = 1:1 - PEEP = 5 cmH_2O Measured : - Tidal Volume = **400 mL**	Setting: - Ventilation Mode = Volume-Controlled - Tidal Volume = **400 mL** - Respiratory Rate = 12 BPM (Breath Period = 60 sec/12 = 5 sec) - I:E Ratio = 1:1 (Ti:Te = 1:1 --> Ti=Te = 2.5 sec) - Pattern Flow = Square - Inspiratory Flow = 9.6 L/min (160 mL/sec) (Flow Time = VT/160 = 2.5sec) (Set Initial Plateau Time = Ti –2.5 sec = 0, Plateau Timecan be prolong by rising Inspiratory Flow while maintaining the Peak Pressure) - PEEP = 5 cmH_2O



Note :

To prevent overshoot of Peak Pressure (**P*peak***) because Pressure on Resistance (**P*res***), then Peak Inspiratory Flow (**I*pf***) needs to be set from the lowest level and to reach **VT,** then prolong Inspiratory Flow Time (**T*if***) by decreasing Plateau Time (**T*plat***) or prolong Inspiratory Time (**T*insp***).

If Plateau Time (**T*plat***) needs to be prolong or Inspiratory Time (**T*insp***) needs to be shorten, it can be done by increasing Peak Inspiratory Flow (**I*pf***) while watching Peak Pressure (**P*peak***) that is mostly increasing.

Fig. 3.19 Example of transition of ventilation mode pressure controlled to volume controlled

$$\text{Inspiratory Flow Time}\left(\mathbf{T}\boldsymbol{if}\right) = \text{Inspiratory Time}\left(\mathbf{T}\boldsymbol{insp},\text{setting}\right) - \text{Plateau Time}\left(\mathbf{T}\boldsymbol{plat}\right)$$

Example of pressure-controlled ventilation and volume-controlled ventilation transition is shown in the table, and waveform of transition is shown in Fig. 3.19.

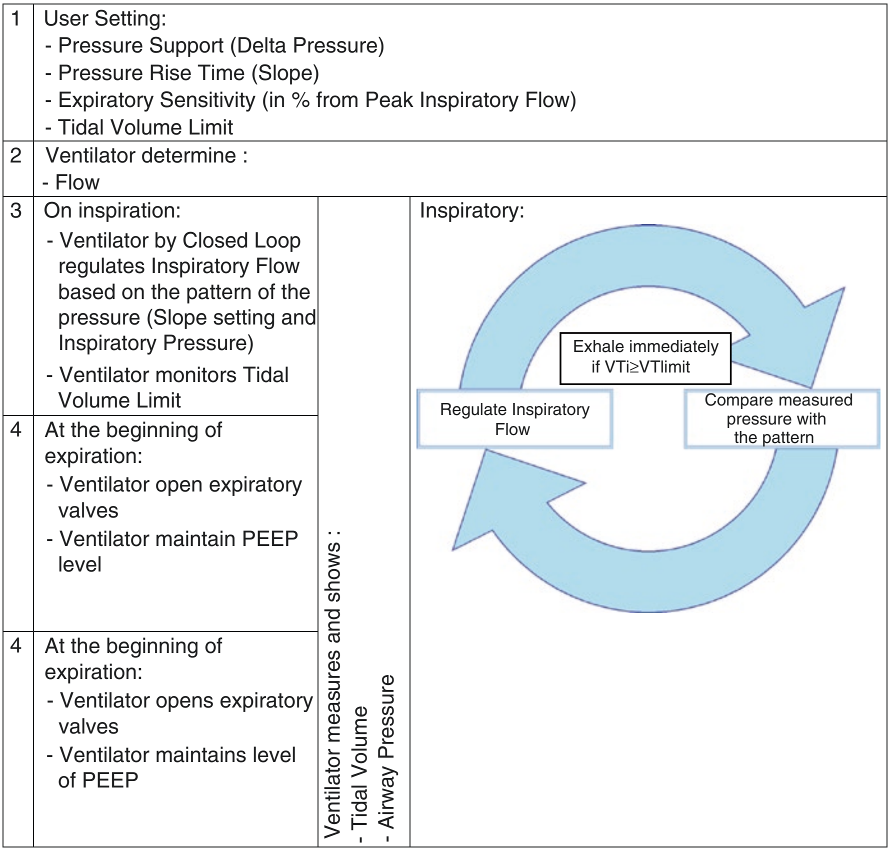


Fig. 3.20 Breath delivery of pressure support

Table 3.8 Advantages and disadvantages of pressure support breath delivery

Advantages	Disadvantages
– Peak pressure support is more constant even respiratory drive/muscles and lung compliance changes and so safe from the risk of barotrauma – Inspiratory flow demand is fulfilled because of adjusted/regulated inspiratory flow → improve gas distribution → inflate collapsed alveoli	– Tidal volume changes depend on changes of lung complianceand respiratory drive which cause possibility of having risk of volutrauma that needs to be restricted by volume alarm – Minute volume (MV) changes depend on changes of tidal volume at the same respiratory rate which cause unstable removal of CO_2 – Inspiratory time (cycling) is determined by peak inspiratory flow and so with lower flow (respiratory muscles are weak), and then inspiratory time is shorter (volume decreases)

3.2.3 Pressure Support Breath Delivery

Another type of breath delivery based on flow control target is pressure support breath delivery. Figure 3.20 shows how the ventilator works during this type of breath delivery. Inspiration is done through cycle (Fig. 3.20) which is by regulating inspiratory flow and then comparing measured pressure with pattern that has been set.

There are definitely advantages and disadvantages of this pressure support ventilation (Table 3.8).

3.2.3.1 Inspiration and Expiration on Pressure Support Breath

Inspiration:

As shown in Fig. 3.21, ventilator regulates inspiratory flow while continuously comparing measured peak inspiratory pressure with the target pattern of inspiratory pressure which is pressure rise/gradient setting and pressure support setting.

Regulation of inspiratory flow is done to reach and maintain the target pattern of inspiratory pressure toward these changes:

– If airway resistance increases or decreases, then ventilator will regulate inspiratory flow so that pressure still follows the pattern and does not increase/decrease significantly due to changes of the resistance.
– If the respiratory muscles move spontaneously to take a deep or shallow breath by the chest moving fast or slow, which is also affected by the lung compliance that increases or decreases because of more elastic or more stiff alveoli, then ventilator will also regulate inspiratory flow so that pressure still follows the pattern and does not increase/decrease significantly due to spontaneous breathing or changes of the compliance.

In pressure support, pattern of inspiratory pressure that has been set (slope parameter and pressure support) and also how fast and deep patient's spontaneous breathing will affect the peak; how big is the gradient (steep or ramp) and the length of inspiratory flow will affect measured tidal volume.

Note:

When inspiratory flow is flowing, if measured **VT** reaches or exceeds **VT *Limit/Alarm*** that has been set, or measured **P*peak*** reaches or exceeds **P*aw (Limit/Alarm)*** that has been set, then inspiratory flow is immediately terminated and inspiratory phase is ended where ventilator begins expiratory phase by opening expiratory valve.

Expiration:

As shown in Fig. 3.21, ventilator opens expiratory valve which allows beginning of expiratory flow with peak of **E*pf*** while maintaining the level of pressure, so that it

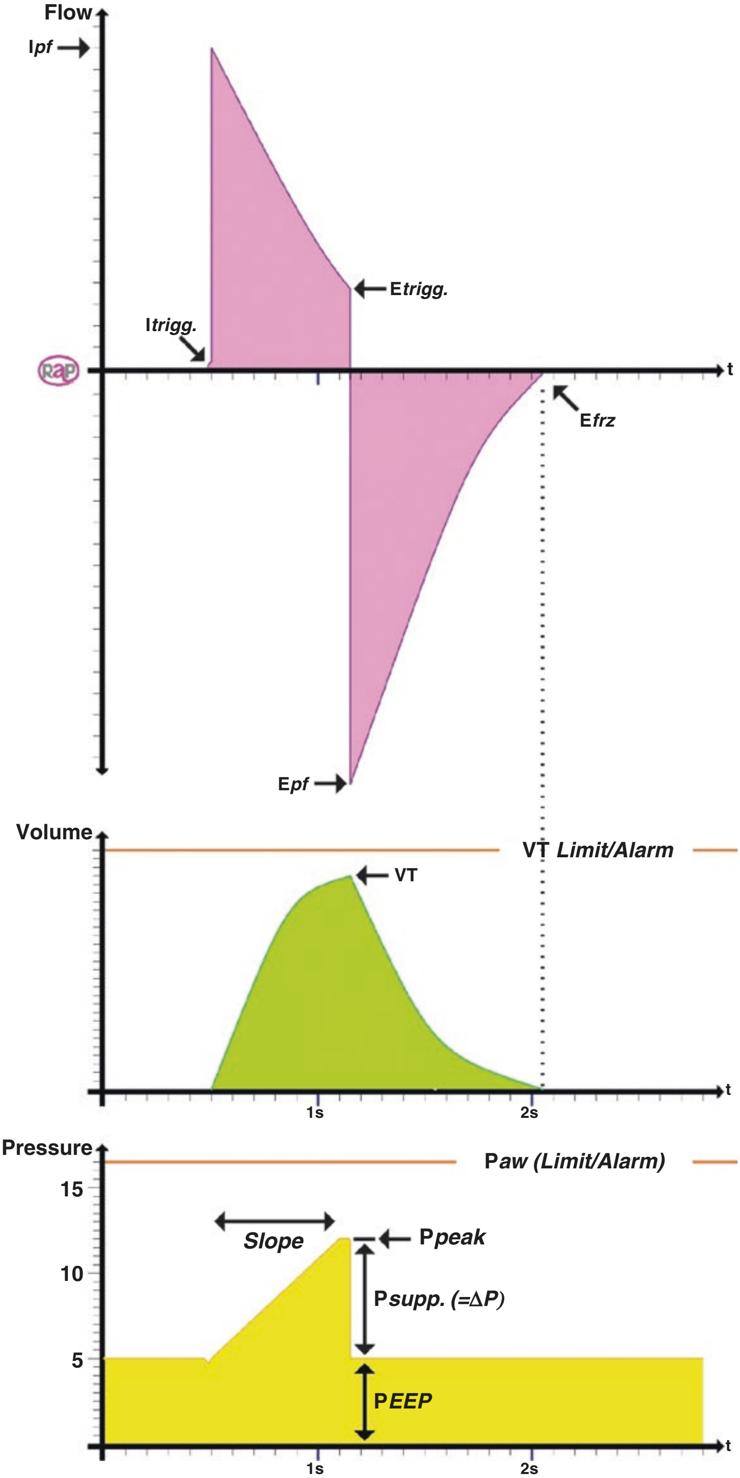


Fig. 3.21 Example waveform of pressure support ventilation

Table 3.9 Explanation of symbols

Abbreviation	Definition and explanation
I*pf*	Peak inspiratory flow which is regulated by ventilator
E*pf*	Peak expiratory flow which is lower if airway resistance increases
I*trigg*	Trigger which signs beginning of giving inspiratory flow
E*trigg*	Trigger which signs beginning of expiration where ventilator opens expiratory valve
I*frz*	Inspiratory flow returns to point 0 which means inspiration has ended
E*frz*	Expiratory flow returns to point 0 which means expiration has ended
VT	Tidal volume which is measured because of inspiratory flow has been given
VT *Limit/Alarm*	Limit of tidal volume which is measured that will end inspiratory flow and immediately begins expiration (expiratory valve opens)
Slope	Time that has been set determines the length of time of pressure increases from PEEP to inspiratory peak (PEEP + Psupp.) where ventilator regulates inspiratory flow Note: Pressure acceleration = $\frac{\textbf{Psupp.}(\Delta P)}{\textbf{S}\textit{lope}} = \frac{\textbf{P}\textit{peak} - \textbf{PEEP}}{\textbf{Slope}}$ Because pressure acceleration is the cause of regulated flow by closed loop, then it can also be called as flow acceleration
P*EEP*	Positive pressure at the end of expiration
Psupp. *(ΔP)*	Pressure that has been set to be given to the alveoli as pressure support for patient that cannot breathe deeply because of weak respiratory muscles so that expected tidal volume can be reached
P*peak*	Peak of inspiratory pressure that is also called PIP (peak inspiratory pressure) If there is no spontaneous breathing from the patient just like exhaling when it is time for inspiratory flow, then **P*peak* = P*EEP* + Psupp. *(ΔP)***
P*aw (Limit/ Alarm)*	Limit of airway pressure that will eliminate inspiratory flow and immediately begin expiration (expiratory valve is open)

does not fall below **P*EEP*** by regulating opening of expiratory valve which indirectly regulates expiratory flow.

When expiratory flow has ended and return to point 0 (**E*frz***), then the time needed is **T*ef***. Expiratory time **T*exp*** needs to be adjusted until expiratory flow ends and returns to point 0 before expiratory time **T*exp*** ends and the next inspiration begins.

Abbreviations in Fig. 3.21 are explained in Table 3.9 for better understanding.

3.2.3.2 Inspiratory Time in Pressure Support Breath

In pressure support, inspiratory time does not apply because the length of the breath depends on the patient himself. So, for example, the patient inhales slowly but the breath is deep, then as long as the flow is taken by the patient, ventilator will still continue giving support. Inspiratory flow, which is taken by the patient, will be smaller because of lung capacity that is being filled, and if inspiratory flow decreases until expiratory trigger **E*trigg*** level (Fig. 3.22) that has been set which is percentage of the peak inspiratory flow, then ventilator will begin expiratory phase by opening expiratory valve.

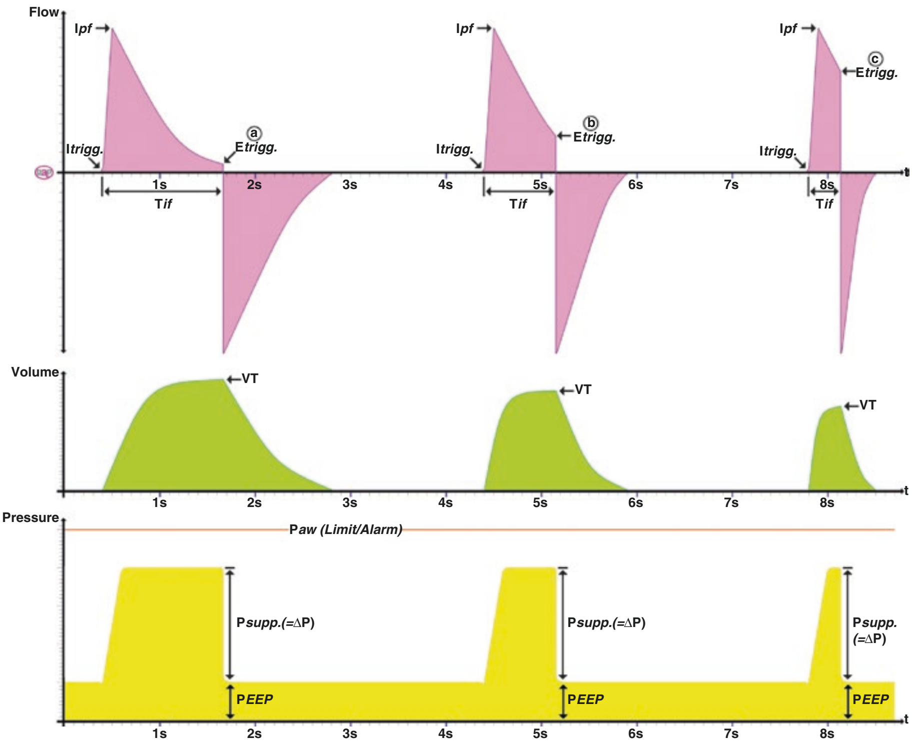


Fig. 3.22 Example of pressure support breath

(a) If expiratory trigger ***Etrigg*** is being set 5% from the inspiratory peak flow, then ventilator will begin expiratory phase when inspiratory flow decreases to 5%, and so inspiratory flow time will be longer that might be needed by patient with acute respiratory distress syndrome (ARDS).
(b) Generally ***Etrigg*** is being set 25% from the inspiratory peak flow in normal lungs.
(c) If ***Etrigg*** is being set 70% from the inspiratory peak flow, then inspiratory flow needs shorter time, and so the volume is lesser that might be needed by patient with chronic obstructive pulmonary disease (COPD).

3.2.3.3 Deep Breath Effort of Patient in Pressure Support Breath

Patient's spontaneous breathing by fast/slow movement of respiratory muscles and shallow/deep breath will affect the pattern of inspiratory flow which is peak inspiratory flow ***Ipf*** and the length of inspiratory flow time ***Tif***.

In the same expiratory trigger ***Etrigg*** setting, for example, 25% from peak flow inspiratory, if:

(a) Patient inhales deeply and fast, then peak inspiratory flow ***Ipf*** reaches the highest but inspiratory flow time ***Ipf*** is shorter.
(b) Patient inhales slowly but deeply, then peak inspiratory flow ***Ipf*** is lower but inspiratory flow time ***Ipf*** is longer.

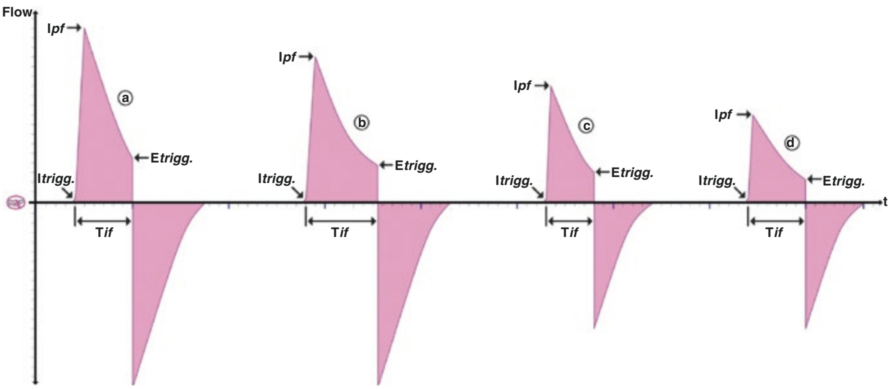


Fig. 3.23 Example of pressure support breath with patient deep breath effort

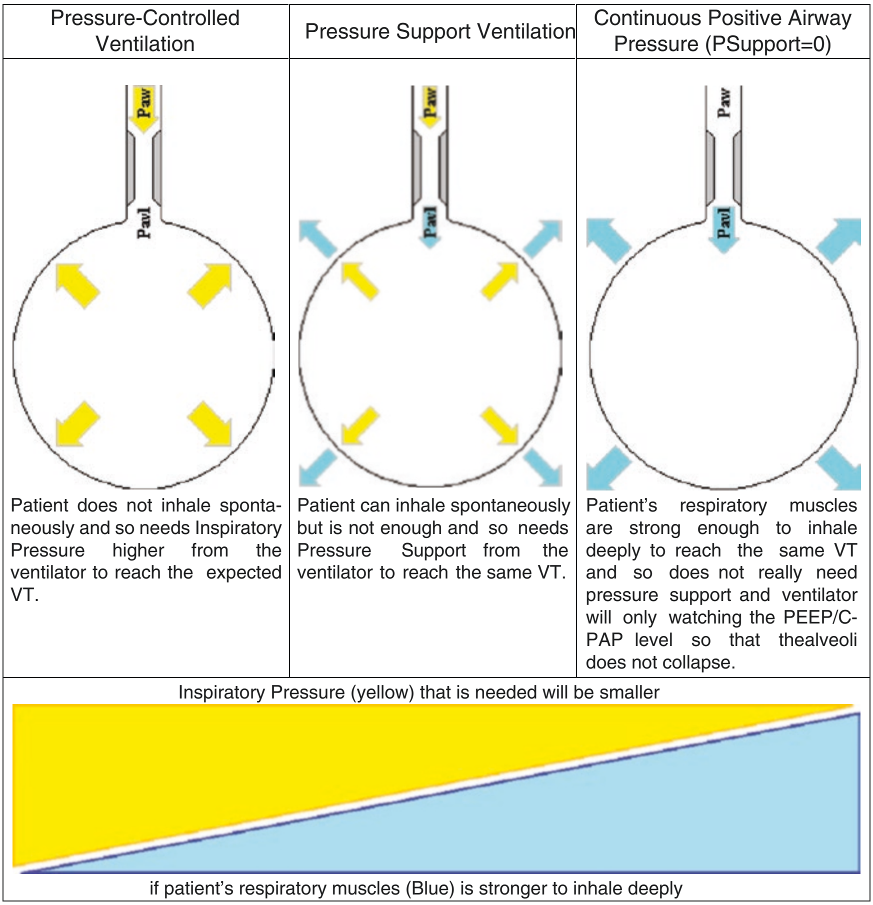


Fig. 3.24 Difference of inspiratory pressure delivered by ventilator with patient effort

(c) Patient inhales fast but shallow, then peak inspiratory flow **Ipf** is lower because breathing is shallow and inspiratory flow time **Tif** is shorter (see Fig. 3.23).
(d) Patient inhales slowly but shallow, then peak inspiratory flow **Ipf** is lower because breathing is shallow but inspiratory flow time **Tif** is longer.

To fulfill in case of patient respiratory demand:

– Peak flow can be increased by shortening the slope or pressure rise time.
– Inspiratory flow time can be prolonged by decreasing expiratory trigger sensitivity, for example, from 25% of peak inspiratory flow to 15%.

Follow these steps by also considering and maintaining the tidal volume inhaled by patient.

3.2.3.4 Inspiratory Pressure Delivered and Deep Breath Effort of Patient

Figure. 3.24 shows different inspiratory pressures delivered by ventilator which when patient's effort is smaller or even none, then more inspiratory pressure by ventilator is needed. But if patient's effort is strong or enough to do spontaneous breathing, then inspiratory pressure by ventilator will be smaller.

3.3 A Breath Sequence (Initiation, Target, Cycling, and Expiratory Baseline)

3.3.1 Breath Initiation (Trigger Variable)

There are several ways of breath initiation from the ventilator to the patient:

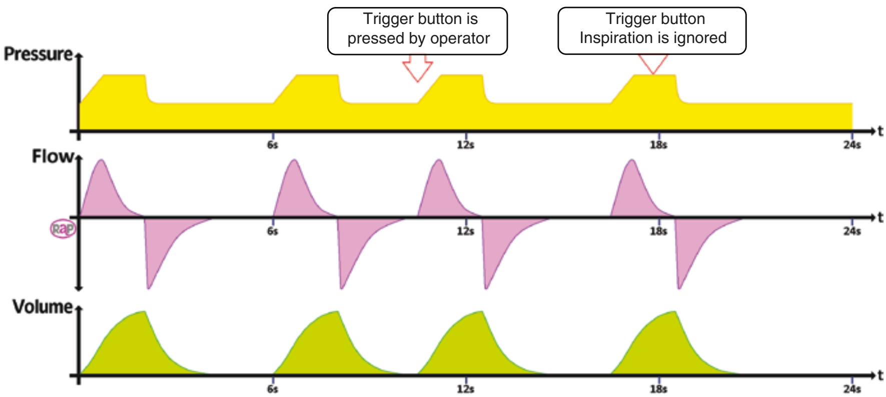


Fig. 3.25 "Manual Trigger" button pressed by the user which only allowed when pressure is at PEEP level

1. Breath initiation from the operator:
   By pressing the "Manual Trigger" button (Fig. 3.25) particularly when pressure is at PEEP level, then ventilator will be giving breath that has been set, for example, volume-controlled breath in volume-controlled ventilation or giving pressure-controlled breath in pressure-controlled ventilation. On inspiration, generally "Manual Trigger" button will be ignored until breath given by the ventilator has ended or pressure returns to PEEP level.

   Pressing the trigger button repeatedly and continuously will cause hyperventilation, but every press of the trigger button at PEEP level should make sure expiratory flow has ended which returns to 0 (**E*frz***) to prevent air traps inside the alveoli (e.g., air trapping) (see Fig. 3.26).
2. Breath initiation from the ventilator:

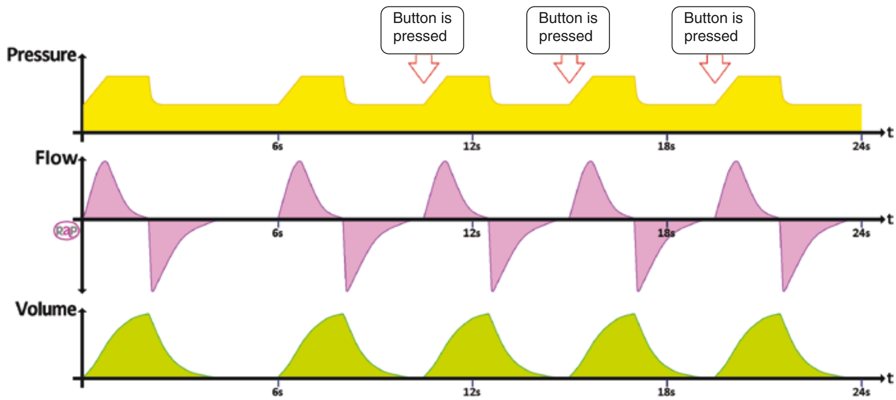


Fig. 3.26 Repeated "Manual Trigger" continuously will cause hyperventilation

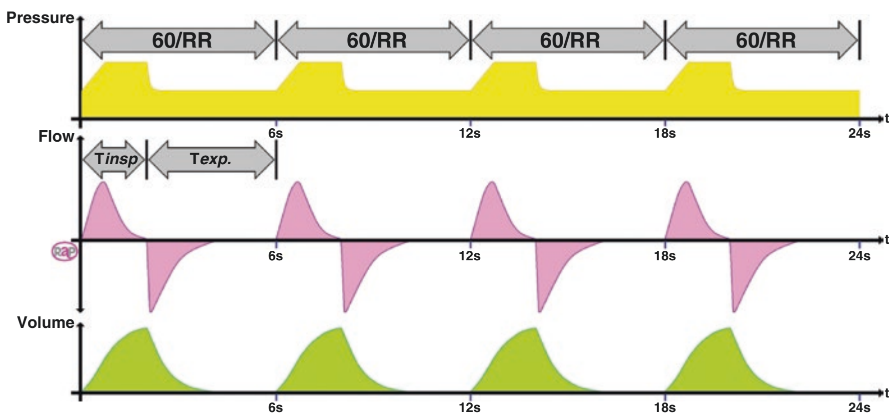


Fig. 3.27 Breath initiation from ventilator by **RR** or **f** setting

Table 3.10 Example of respiratory rate **RR** setting, inspiratory time, and I:E ratio

	Example 1	Example 2	Note
Ti (inspiratory time, **T*insp***)	2 s	2.5 s	
Te (expiratory time, **T*exp***)	4 s	2.5 s	
Breath period (**Ti + Te**)	6 s	5 s	$(\text{Ti}+\text{Te})=\frac{60}{\text{RR}}$
Respiratory rate (**RR**) or breath frequency (**f**)	10 breaths/min	12 breaths/min	$\text{RR}=\frac{60}{(\text{Ti}+\text{Te})}$
I:E ratio	1:2		2:4 = 1:2
		1:1	2.5 : 2.5 = 1:1

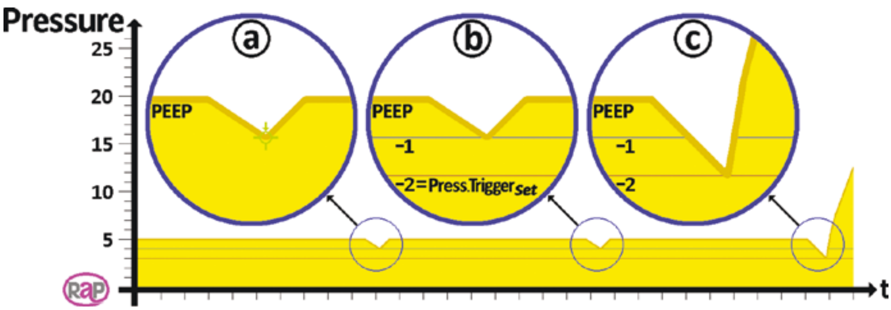


Fig. 3.28 Pressure trigger sensitivity

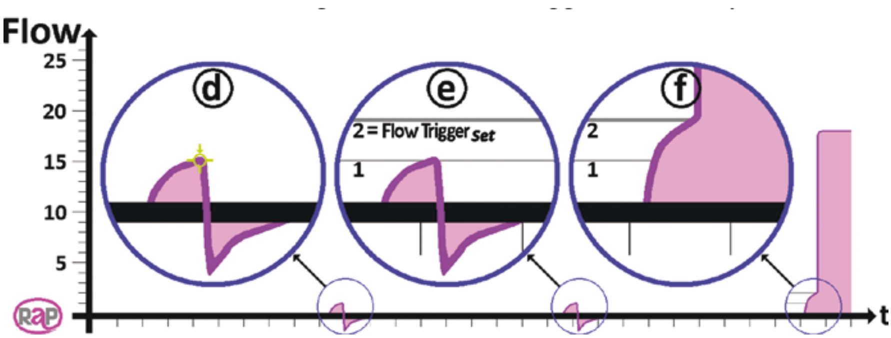


Fig. 3.29 Flow trigger sensitivity

In Fig. 3.27, by respiratory rate (**RR**) or breath frequency (**f**) setting, then ventilator will automatically give breath every 60/**RR** sec or 60/**f** sec.

Breath period for 60/**RR** is divided into two parts which are inspiratory time **T*insp*** and expiratory time **T*exp***:

$$\text{Breath Period}\left(60 / \mathbf{RR}\right) = \text{Inspiratory Time}\left(\mathbf{T}\boldsymbol{insp}\right) + \text{Expiratory Time}\left(\mathbf{T}\boldsymbol{exp}\right)$$

Comparison of inspiratory time and expiratory time is called I:E ratio. Look at Table 3.10 for example of given RR setting, inspiratory time, expiratory time, and I:E ratio (Table 3.10):

$$\text{Inspiratory Time}\left(\mathbf{T}\boldsymbol{insp}\right) : \text{Expiratory Time}\left(\mathbf{T}\boldsymbol{exp}\right) = \text{Ti} : \text{Te} = \text{I} : \text{E Ratio}$$

3. Breath initiation from the patient:
   When patient is conscious and is allowed to have spontaneous breathing by triggering the ventilator, in order for the ventilator to give breath, then the trigger sensitivity of the ventilator needs to be set which is how sensitive is the ventilator to sense trigger from the patient.
   There are two kinds of trigger sensitivity which generally the ventilator has in these days. They are pressure trigger sensitivity (Fig. 3.28) and flow trigger sensitivity (Fig. 3.29).

When patient is conscious and starts triggering, then his respiratory muscles can be measured how strong he can trigger. Some ventilators have special feature that can measure the strength of the respiratory muscles. The measurement can also be done by freezing the graphic screen and then using the cursor on the screen to measure the negative pressure, (a) or flow triggering (d) depends the strength of the muscles. Then pressure trigger sensitivity (b) or flow trigger sensitivity (e) can be adjusted.

Pressure trigger sensitivity is always negative because it sets below PEEP, while flow trigger sensitivity is positive because of flow that goes to the patient.

Trigger sensitivity setting will be more sensitive if the value is near zero:

- Pressure trigger sensitivity −1 is more sensitive than −2.
- Flow trigger sensitivity 1 is more sensitive than 2.

If the patient's respiratory muscles are weak compared to sensitivity that has been set (b and e), then patient trigger does not fulfill the criteria and will be ignored.

But if patient trigger reaches the set sensitivity (c and f), then ventilator will give breath as ventilation mode that has been set.

If trigger sensitivity is too sensitive, for example, it has been set that was supposed to be for neonates but is used for adult patient, then ventilator will sense as trigger and give breath although it was not patient's effort but rather the following reasons:

- Body movement of the patient particularly patient's jolt on exhalation
- Fluid movement inside the patient's airway, for example, sputum or vapor
- Fluid movement inside the breathing circuit/hose especially vapor in the inspiration
- Breathing circuit movement

Table 3.11 Respond from ventilator in patient trigger based on ventilation modes

	Breath variety	Ventilation mode	Respond to patient trigger
PEEP	Volume-controlled breath	(Full) volume controlled	Patient trigger is ignored
		(Assist) volume controlled	Volume-controlled breath is given
		Volume SIMV	Volume-controlled breath is given in assist period
	Pressure support breath		Pressure support is given in spontaneous period
		Pressure support ventilation	Pressure support breath is given
		Pressure SIMV	Pressure support is given in spontaneous period
	Pressure-controlled breath		Pressure-controlled breath is given in assist period
		(Assist) pressure controlled	Pressure-controlled breath is given
		(Full) pressure controlled	Patient trigger is ignored

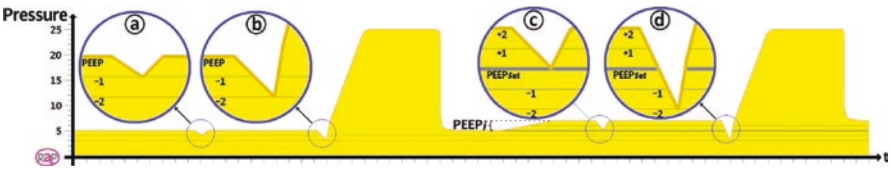


Fig. 3.30 Example of pressure triggering

Trigger due to those external influences is also called as **AutoTrigger**.

If trigger sensitivity is being set to less sensitive, for example, trigger sensitivity was supposed to be for adult patient but is used for neonates. Then ventilator will not sense the trigger due to high trigger sensitivity or less sensitive compared to neonate's effort to trigger the ventilator.

Risks that might occur are:

– Patient will be considered apnea although there is trigger but is not enough.
– Patient will continuously try to trigger the machine that will also increase work of breathing and might increase the need of oxygen in the respiratory muscles' tissue.

Trigger sensitivity initially can be set sensitive to decrease patient's work of breathing and then gradually making it less sensitive if AutoTrigger occurs.

See Table 3.11 for reference of respond from ventilator to patient trigger based on ventilation modes.

(A) Pressure Trigger Sensitivity

Pressure trigger setting is always negative because it should be set below PEEP level. For example, in Fig. 3.30, PEEP that has been set is 5 cmH_2O, and trigger sensitivity setting is −2 cmH_2O which means that for ventilator to give a breath to patient, he must inhale so that the pressure of PEEP is from 5 cmH_2O to 3 cmH_2O. With the same trigger sensitivity, for example, −2 cmH_2O, then:

(a) If patient trigger is not strong enough and only can only take a breath until −1 cmH_2O to 4 cmH_2O, then ventilator will ignore the patient trigger because he/she does not fulfill the criteria. If the goal is to minimize patient's work of breathing, then trigger sensitivity setting needs to be more sensitive by watching the total respiratory rate of the patient to prevent overlapping due to AutoTrigger.

(b) If patient's effort is enough and fulfill the criteria of trigger sensitivity setting, then ventilator will sense the patient trigger to give breath based on the ventilation mode that has been set.

Intrinsic PEEP (PEEPi) or auto-PEEP is the difference between measured PEEP with the set PEEP. Intrinsic PEEP can be caused by few factors, for example, trapped air/left at the end of expiration or the patient alone holds the exhalation.

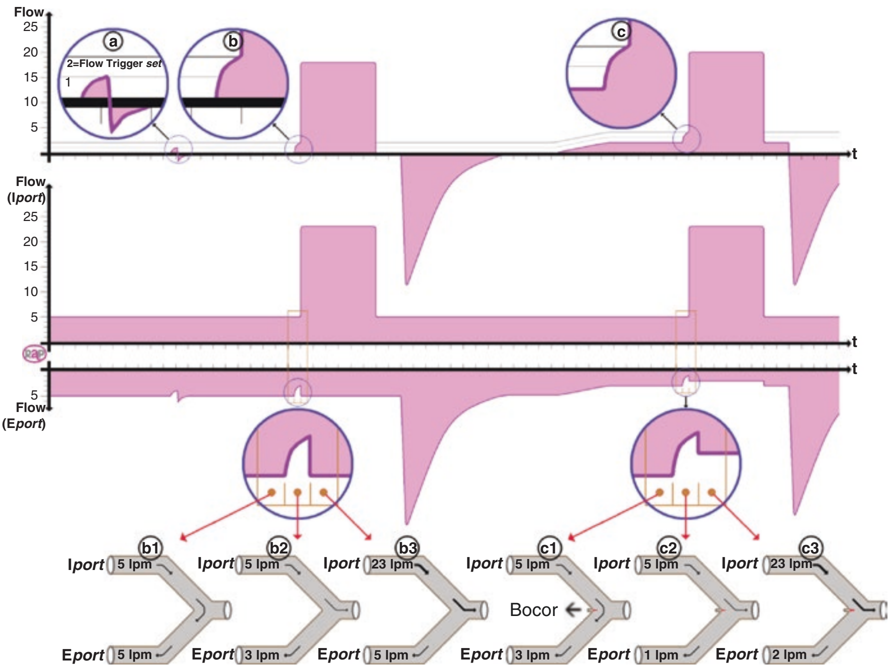


Fig. 3.31 Example of flow triggering

For example, in Fig. 3.30, the set PEEP is 5 cmH_2O and trigger sensitivity of −2 cmH_2O, and so pressure needs to decrease to 3 cmH_2O to be considered trigger, but intrinsic PEEP of 2 cmH_2O occurs until actual/measured PEEP is 7 cmH_2O; then:

(c) By the same patient's effort just like before, (b) pressure decreases from 7 cmH_2O to 5 cmH_2O causing the ventilator to ignore patient's effort because it does not fulfill the criteria which is 3 cmH_2O.

(d) To fulfill the trigger criteria, patient needs to inhale by greater effort to decrease pressure from 7 cmH_2O to 3 cmH_2O or the same as trigger sensitivity setting of −4 cmH_2O.

So, intrinsic PEEP will increase work of breathing of the patient although just to trigger ventilator to give a breath.

Base flow in pressure triggering:

If patient takes a breath to decrease pressure and to make patient trigger but if there is base flow, then decreased pressure will be ramp.

So, base flow can also be known as noise that delays respond of the trigger even increases work of breathing of the patient to trigger the ventilator.

(B) Flow Trigger Sensitivity

Flow triggering setting is always positive because it is an inspiration that flows toward the patient. Even the set value is greater, e.g., 6 L/min, measurement of the ventilator is in smallest unit, e.g., 1 mL/10 ms → 6 L/min = 100 m L/s = 1 mL/10 ms = 0.1 mL/ms. As shown in Fig. 3.31, there are possibilities of error in triggering. For example:

(a) If trigger sensitivity setting is 2 L/min and patient's effort can only inhale 1 L/min, then ventilator will ignore it because it does not fulfill the criteria. It should be considered to change the setting to be more sensitive to minimize work of breathing while monitoring it to prevent AutoTrigger to happen.

(b) If patient's effort can inhale flow just as big as the trigger sensitivity that has been set, then ventilator will categorize it as patient trigger to be given a breath based on the ventilation mode that has been set.

(c) If there is presence of leakage, then ventilator should be able to differentiate air that comes out from the inspiratory port of the ventilator, if the cause is due to leak or because it is inhaled by the patient. If ventilator cannot differentiate it, then leak can be mistaken as patient trigger and can cause AutoTrigger.

Base Flow and Leak in Flow Triggering

The presence of base flow then will help the patient to do the triggering because base flow is continuous from the inspiratory port from the ventilator and goes out to the expiratory port partly or completely.

Respond of ventilator toward patient trigger of 2 L/min with base flow of 5 L/min (Fig. 3.31):

b1. In position PEEP before patient trigger, base flow continuously flows from the inspiratory port of 5 L/min, and because patient does not inhale and is assumed, there is no leak, and then the base flow goes out to the expiratory port with the same amount of 5 L/min.

b2. When patients take a breath, then ventilator measures base flow that goes out to the expiration and decreases to 3 L/min. And so, with patient trigger of 2 L/min that fulfills the criteria of trigger sensitivity setting, then breath from the ventilator will be given.

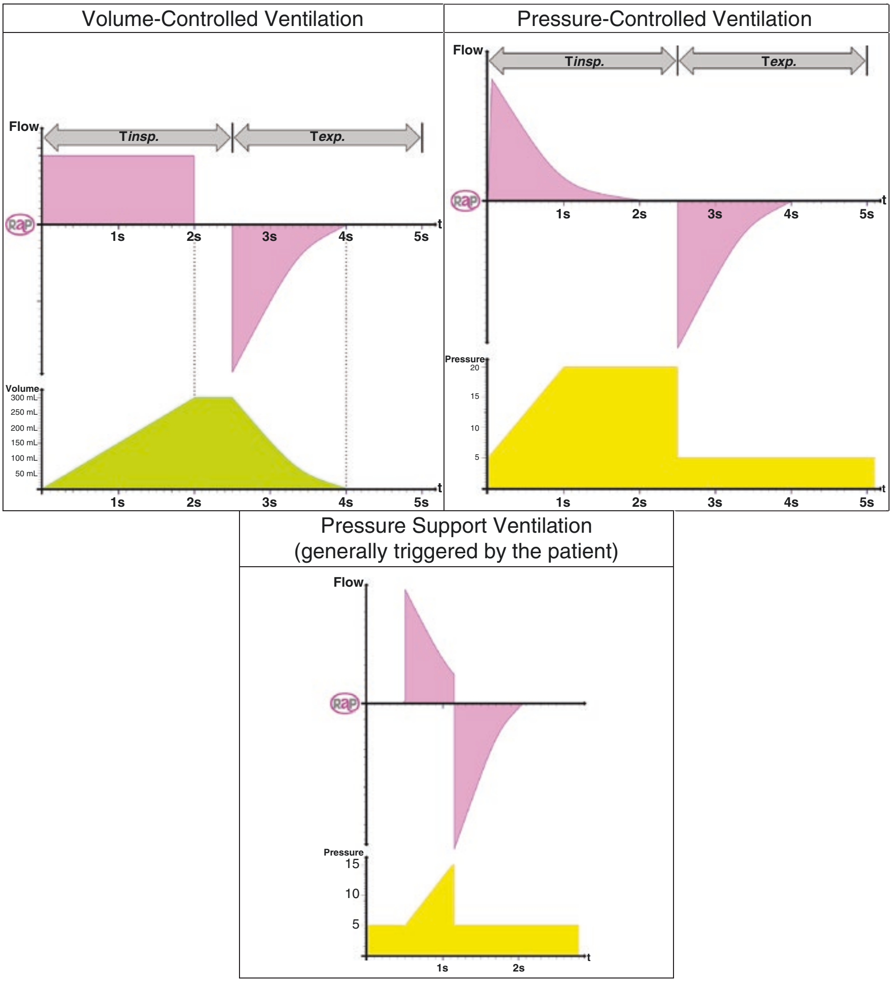


Fig. 3.32 Basic types of breath delivery

b3. Ventilator gives breath with peak inspiratory flow of 18 L/min and with addition of base flow, and then peak inspiratory flow from inspiratory port will be 23 L/mined and goes out to expiration of 5 L/min.

1. Time Cycled

Ventilator allows exhalation to begin when a preset inspiratory time has ended and a preset tidal volume or a preset inspiratory pressure has been reached. See Figs. 3.33 and 3.34, for example, of time cycles.

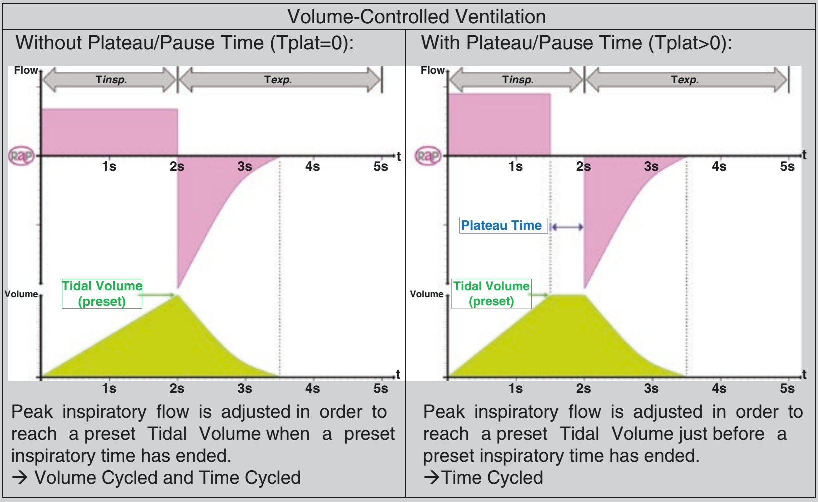


Fig. 3.33 Example of time cycled in volume controlled

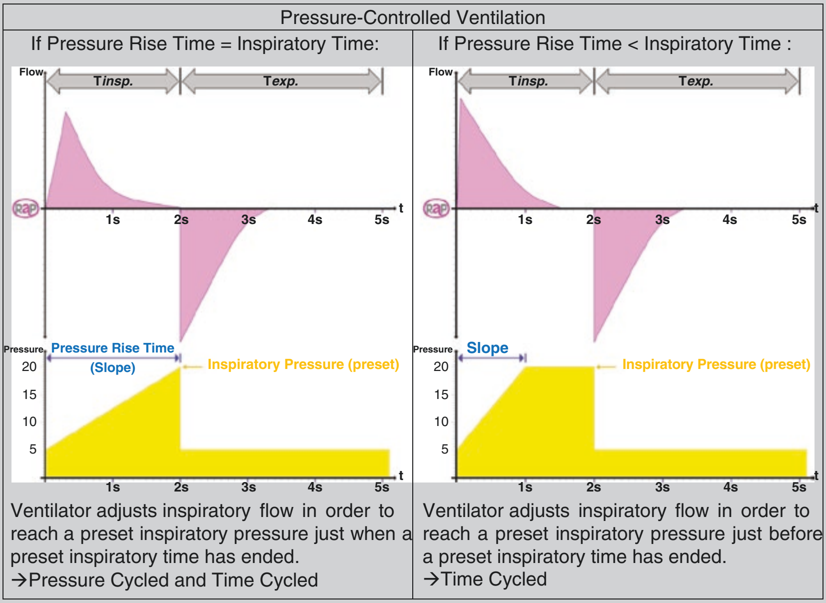


Fig. 3.34 Example of time cycled in pressure controlled

2. Flow Cycled

Ventilator allows exhalation to begin when inspiratory flow decreases to a preset expiratory trigger. See Fig. 3.35, for example, of flow cycled

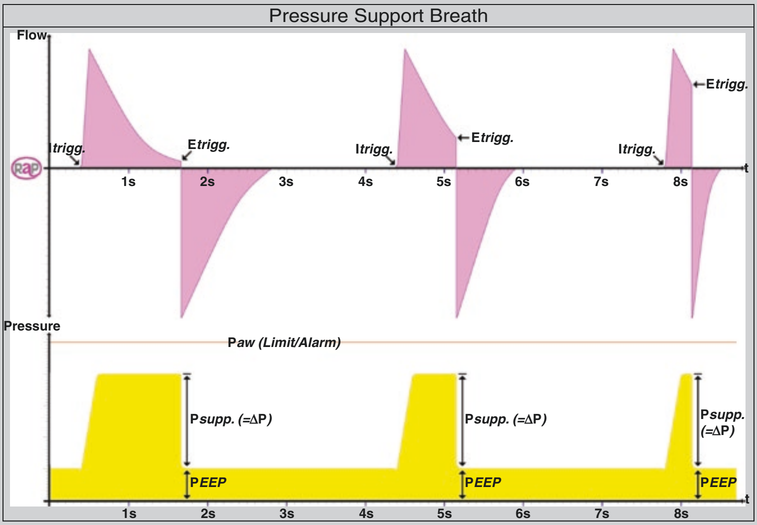


Fig. 3.35 Example of flow cycled in pressure support

The responds of ventilator toward patient trigger of 2 L/min when leak of 2 L/min occurs with base flow of 5 L/min (Fig. 3.31) are as follows:

c1. In position PEEP before patient trigger, base flow continuously flows from the inspiratory port of 5 L/min even patient does not inhale, but leak occurs in the breathing circuit or endotracheal tube of 2 L/min and then goes out to the expiratory port of 3 L/min only.

c2. When patient inhales, then ventilator measures base flow that goes out to the expiration and decreases to 1 L/min. And so, with patient trigger of 2 L/min that fulfills the criteria of trigger sensitivity setting, then breath from the ventilator will be given.

c3. Ventilator gives breath with peak inspiratory flow of 18 L/min and with addition base flow, and then peak inspiratory flow from the inspiratory port

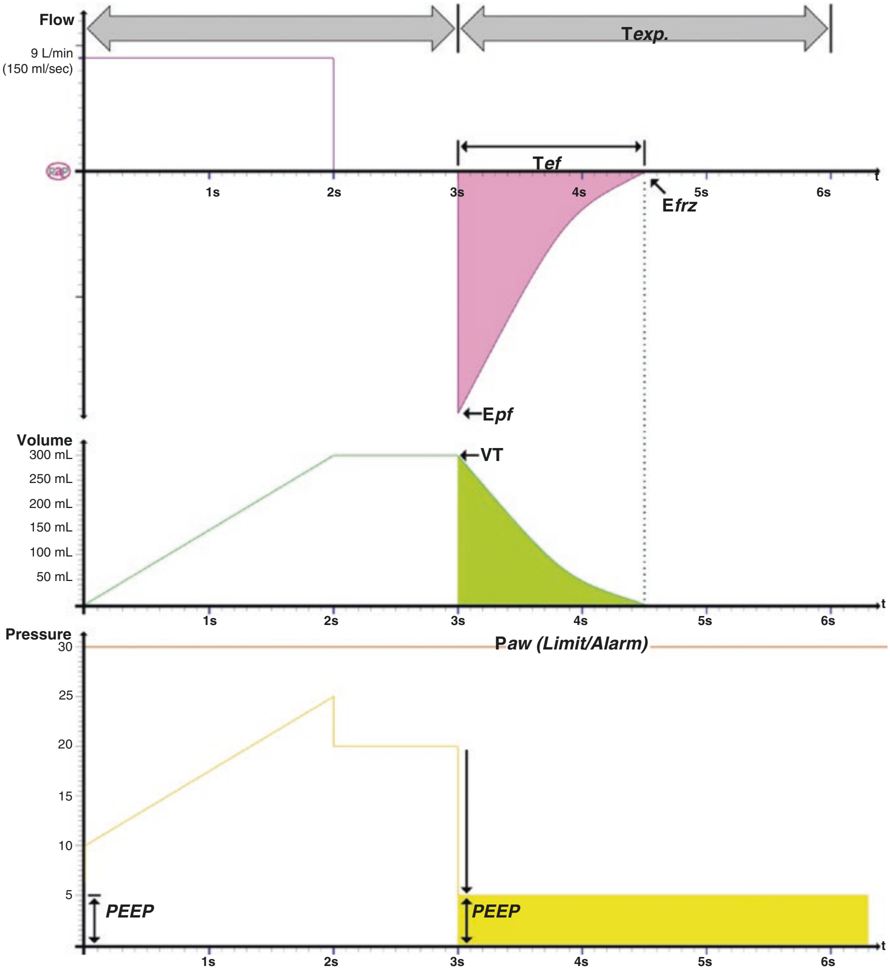


Fig. 3.36 Baseline variable in waveform

will be 23 L/min and goes out to the expiratory port of 2 L/min with predicted leak increases to 3 L/min because of increased inspiratory pressure.

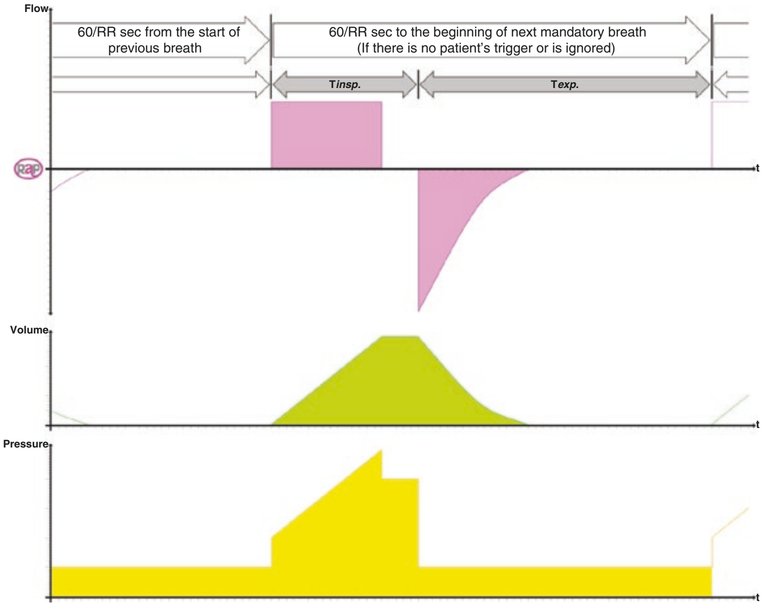


Fig. 3.37 Example waveform of mandatory breath in volume-controlled ventilation

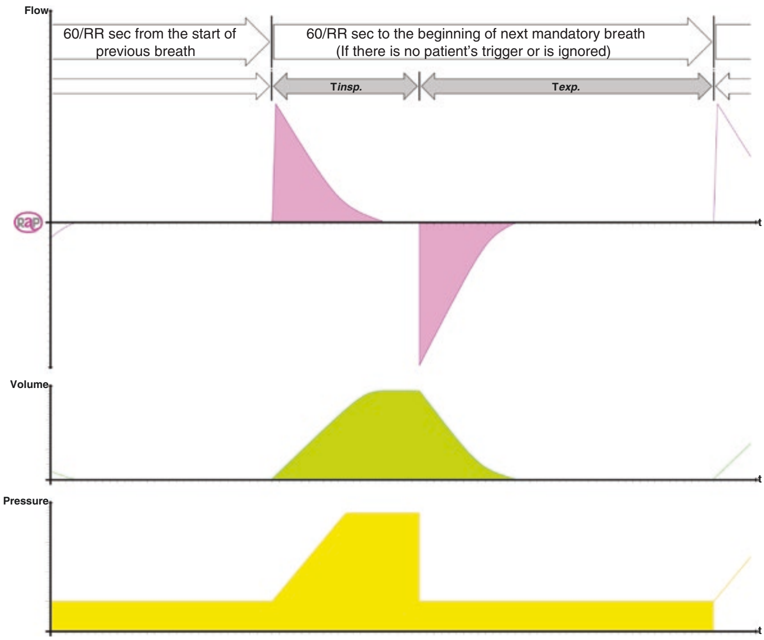


Fig. 3.38 Example waveform of mandatory breath in pressure-controlled ventilation

3.3.2 Breath Delivery Target

After triggering has been received, then ventilator will give inspiratory flow.

Just as what have been discussed previously, there are three basic types of breath delivery (see Fig. 3.32).

3.3.3 Cycling to Expiration (Cycle Variable)

Shifting from inspiratory phase to expiratory phase is called cycling.

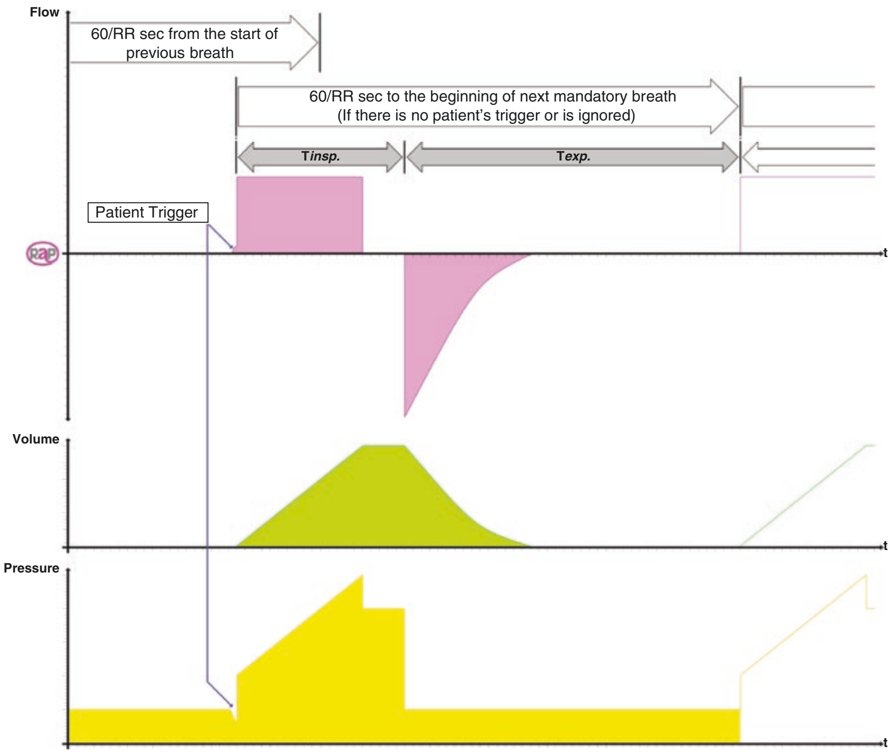


Fig. 3.39 Assist volume-controlled ventilation

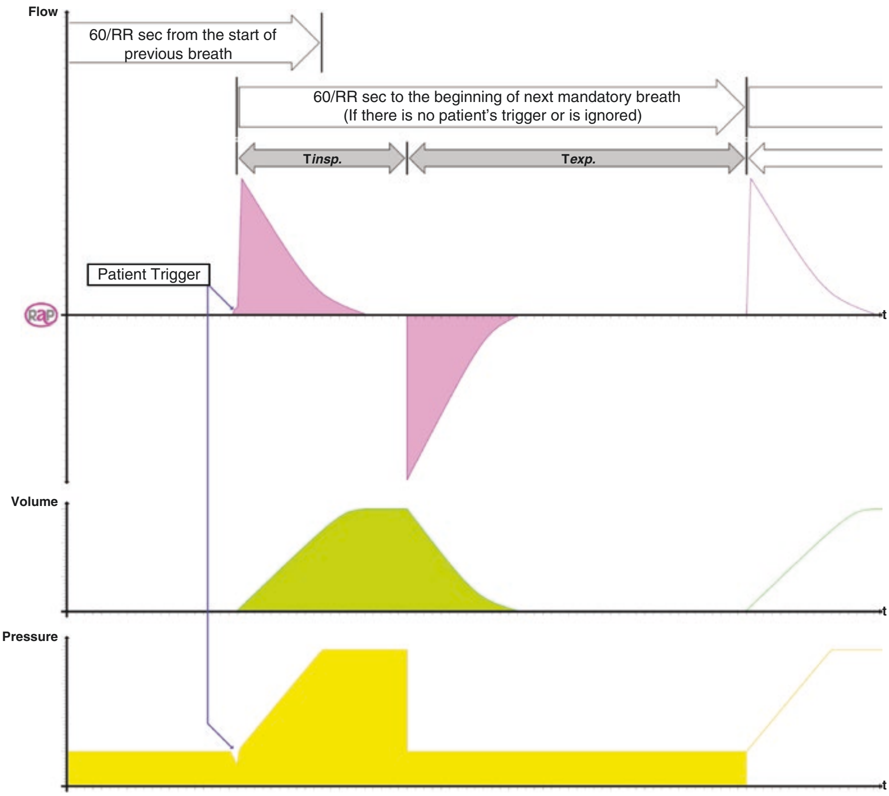


Fig. 3.40 Assist pressure-controlled ventilation

Most newer ventilators have two main references of cycling, they are:

3.3.4 Expiration (Baseline Variable)

The expiration starts after the inspiratory phase or inspiratory time has ended. During expiratory phase, the pressure should be controlled to prevent alveoli to collapse. This is called the baseline variable (Fig. 3.36). Baseline that is commonly used is positive end expiratory pressure (PEEP).

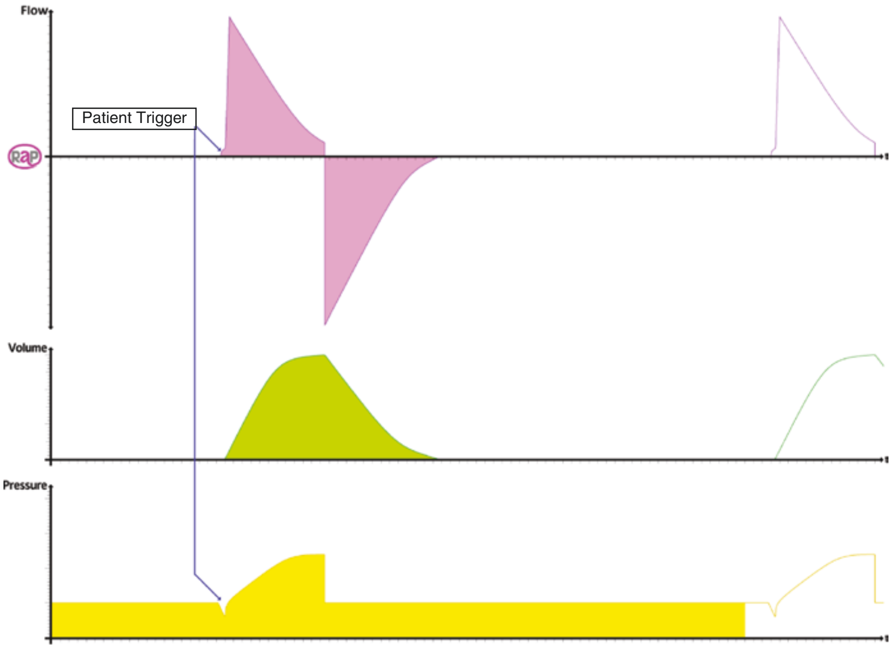
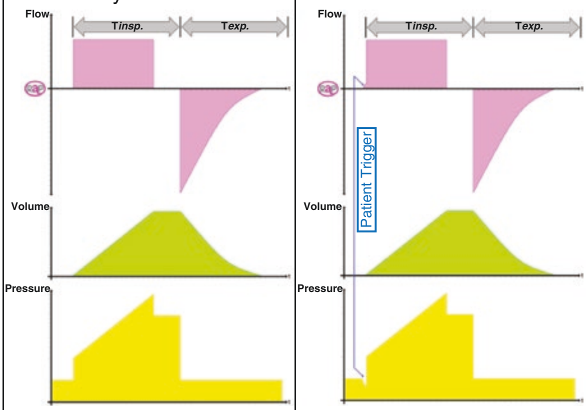


Fig. 3.41 Example waveform of pressure support

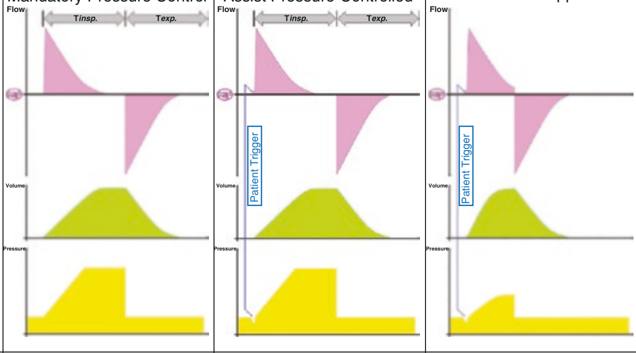
	Mandatory breath	Assisted breath
Volume-controlled:	Mandatory Volume Control	Assist Volume-Controlled



Breath initiation (Triggering)	Ventilator	Patient or Time
Breath delivery target	Volume-Controlled	Volume-Controlled
Cycle of breathing (Cycling)	Time Cycled (and Volume Cycled)	Time Cycle (and Volume Cycled)
Expiratory (Baseline)	PEEP	PEEP

Fig. 3.42 Mandatory and assisted breath in Volume-Controlled

Pressure-controlled:	Mandatory breath	Assisted breath	Pressure Support
	Mandatory Pressure Control	Assist Pressure-Controlled	Pressure Support



Breath initiation (Triggering)	Ventilator	Patient or Time	Patient
Breath delivery target	Pressure-Controlled	Pressure-Controlled	Pressure Support
Cycle of breathing (Cycling)	Time Cycled (and Pressure Cycled)	Time Cycled (and Pressure Cycled)	Flow Cycled
Expiratory (Baseline)	PEEP	PEEP	PEEP

Fig. 3.43 Mandatory, assisted, and spontaneous breath (in pressure support) in Pressure-Controlled

3.4 Type of Breath Based on Breath Initiation Source

3.4.1 Mandatory Breath

Mandatory breath is totally controlled by the ventilator which is ventilator triggering by a preset respiratory rate.

Breath delivery target is volume controlled or pressure controlled.

Cycle of breathing is determined by inspiratory time. See Figs. 3.37 and 3.38, for example, of waveform of mandatory breath in volume-controlled and pressure-controlled ventilation.

3.4.2 Assisted Breath

Assisted breath consists of both mandatory breath and spontaneous breathing. In assisted breath, trigger sensitivity is activated. When patient triggers the ventilator (spontaneous breathing), it will deliver breath as mandatory breath because it delivers the preset values (e.g., VT and flow) by the user.

Breath delivery target is volume controlled or pressure controlled. And cycle of breathing is determined by inspiratory time. See Figs. 3.39 and 3.40, for example, of waveform of assisted breath in volume-controlled and pressure-controlled ventilation.

3.4.3 Spontaneous Breathing

Spontaneous breathing is a breath from the patient himself. The patient himself starts the breath by trigger sensitivity that initiates the ventilator to deliver breath. Even if the patient has spontaneous breathing, he is still supported by ventilator.

Examples of ventilation modes with spontaneous breathing are pressure support ventilation (PSV) and SIMV (synchronized intermittent mandatory ventilation).

Figure 3.41 is an example of spontaneous breathing in PSV. Breath delivery target is pressure support just as the preset pressure support. Cycle of breathing is determined by inspiratory flow that has been reached and then decrease to expiratory trigger setting which is percentage of peak inspiratory flow.

Figures 3.42 and 3.43 show the summary of mandatory breath, assisted breath, and spontaneous breathing (in pressure support).

Reference

Hess DR, Kacmarek RM (2014) Essentials of mechanical ventilation, 3rd edn. McGraw-Hill, New York, NY

4 Basic Ventilation Modes

4.1 Introduction

Mechanical ventilation is basically beneficial to a critically ill patient, specifically with respiratory failure, to improve gas exchange for adequate oxygenation and to decrease work of breathing. The general objectives of mechanical ventilation are ensuring adequate gas exchange, avoiding lung injuries caused by the mechanical ventilator, preventing patient asynchrony but rather optimizing patient-ventilator synchrony, and minimizing the length of time of ventilation with the mechanical ventilator. These objectives are achieved by the mode of ventilation.

The mode of ventilation is a preset pattern of ventilation of patient-ventilator interaction. During mechanical ventilation, the mode of ventilation is one of the important parts of ventilator settings. There are many modes of ventilation available. The choice of mode suitable for a patient is based on the clinician's or the user's preference, which depends on the patient's case and needs.

The most common basic mechanical ventilators available in every ventilator are fully controlled and assist-controlled ventilation, SIMV, Pressure Support, and CPAP. Clinicians should know and understand these basic modes. This chapter will explain those modes further, which will be followed by waveforms or graphs of those modes for a better understanding.

Figure 4.1 shows waveforms of basic ventilation modes and their categorization

R.A. Pupella, *Mechanical Ventilation in Patient with Respiratory Failure*,
DOI 10.1007/978-981-10-5340-5_4

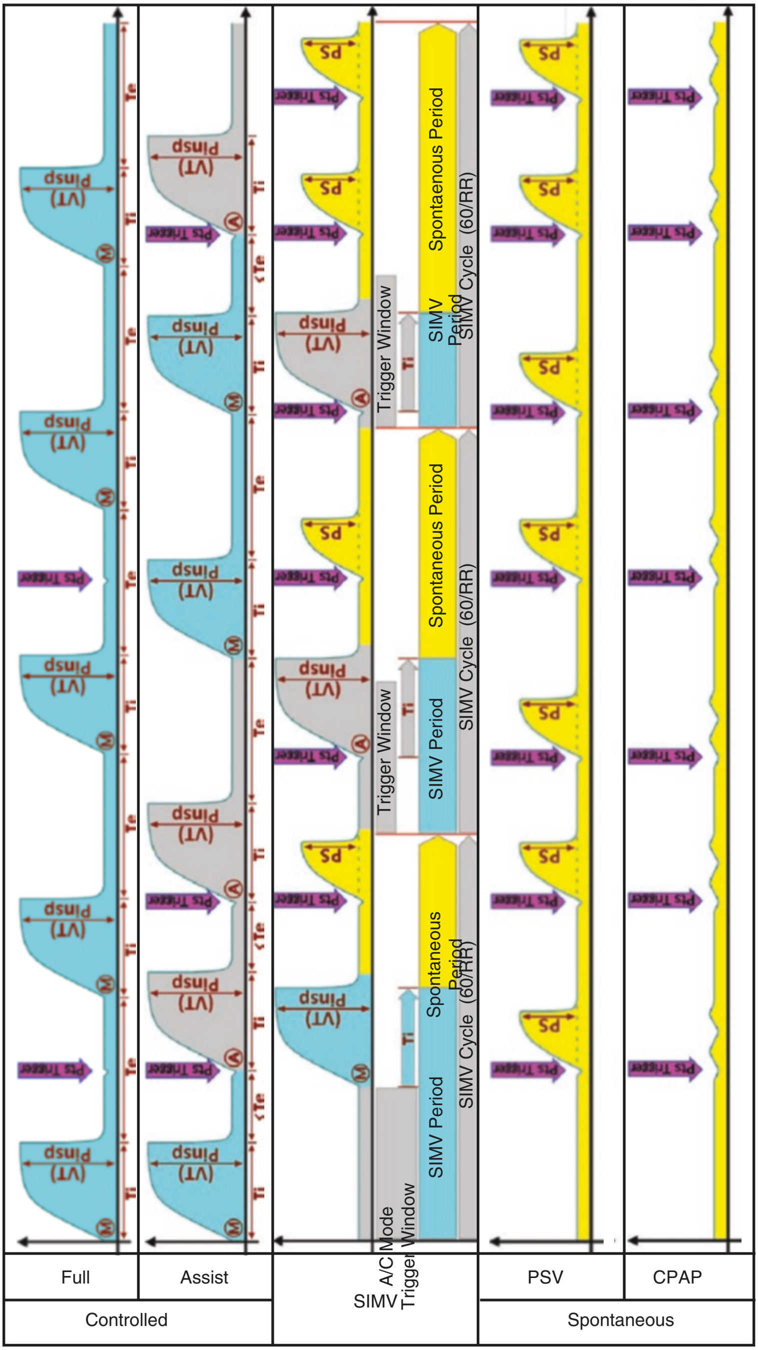


Fig. 4.1 Basic ventilation modes

4.2 Fully Controlled and Assist-Controlled Ventilation Modes

4.2.1 Fully Controlled Ventilation Mode

In fully controlled mode (Fig. 4.2), trigger sensitivity is deactivated, which leads to the failure of the ventilator to sense the presence of the patient's effort or initiation. For example, in the ventilator the respiratory rate has been set to 12 breath/min, then the patient has spontaneous breath and so the respiratory rate becomes between 15 and 18 breath/min. Because of increased CO_2, the patient's trigger will be ignored, and so the total RR will still be the same as the preset value which is 10 breath/min. Breath delivery is control breath which is volume controlled or pressure controlled (see Figs. 4.3 and 4.4).

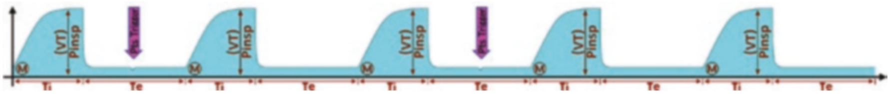


Fig. 4.2 Waveform of fully controlled mode with patient's trigger is ignored

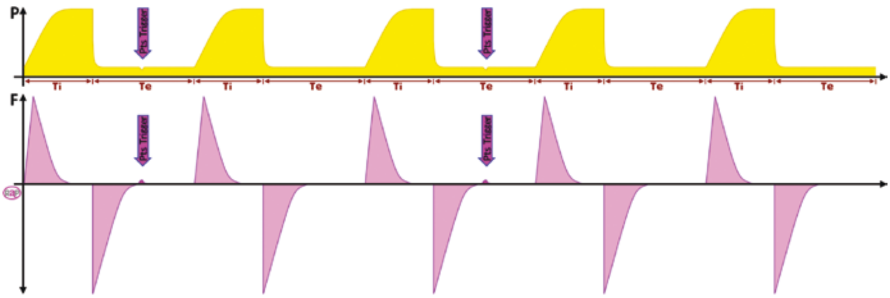


Fig. 4.3 Waveform of full pressure-controlled mode (breath delivery is pressure controlled)

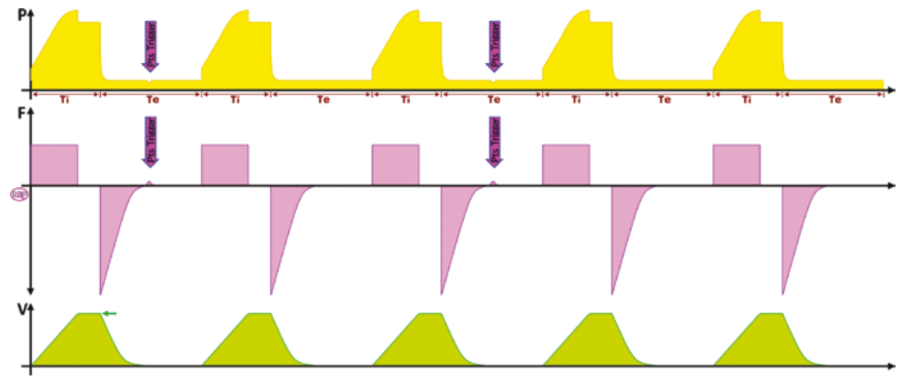


Fig. 4.4 Waveform of full volume-controlled mode (breath delivery is volume controlled)

4.2.2 Assist-Controlled Ventilation Mode

Trigger sensitivity is activated, and so the patient's effort can be added to the preset total respiratory rate (RR). For example, the preset RR is 10 breath/min, and the patient's CO_2 increases; the patient then will initiate breaths of 2–5 breath/min, which then results to a total RR of 12–15 breath/min (see Fig. 4.5). Mandatory breath will be delivered 60/RR sec from the previous breath (mandatory or assisted); if there is spontaneous breath before it reaches 60/RR sec, then assist-controlled breath will be delivered (see Figs. 4.6 and 4.7 for the waveform in pressure- and volume-controlled mode).

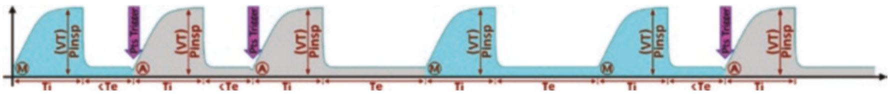


Fig. 4.5 Waveform of assist-controlled ventilation mode with mandatory breath and assist-controlled breath

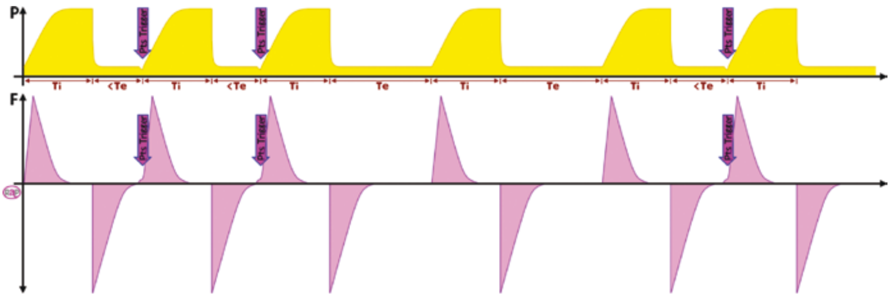


Fig. 4.6 Waveform of assist pressure-controlled mode

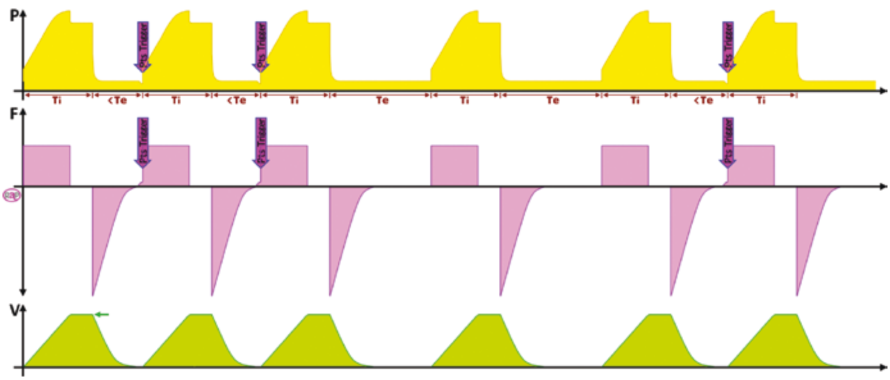


Fig. 4.7 Waveform of assist volume-controlled mode

4.3 Synchronized Intermittent Mandatory Ventilation (SIMV) Mode

This ventilation mode is a transition from assist-controlled (A/C) ventilation mode to pressure support ventilation (PSV) mode. So, the type of breath that is delivered is a combination of mandatory breath, assisted breath, and pressure support.

In this mode, the patient is allowed to trigger the ventilator and has spontaneous breath but still supported by the ventilator through assisted breath or pressure support. Because of this the trigger sensitivity is activated.

Cycle of SIMV is divided into two parts:

- SIMV period
  - Patient trigger in assist control trigger window will deliver assisted breath while in inspiratory time ***Ti.***
  - If there is no patient trigger until assist control trigger window has elapsed, the mandatory breath will be delivered while in inspiratory time ***Ti.***

    SIMV period ends when assisted or mandatory breath also ends, which is at the end of inspiratory time (***Ti***) or at the end of expiratory time (***Te***) in assisted or mandatory breath.
- Spontaneous period
  - Every patient trigger of spontaneous breath while in spontaneous period will be given and supported by pressure support. Spontaneous period ends when the SIMV cycle ends.

Examples of SIMV cycle:

In Fig. 4.8, there is no spontaneous breath or patient trigger until assist control trigger window ends; so in SIMV period, mandatory breath is delivered. After mandatory breath is delivered, spontaneous period begins where every spontaneous breath will be supported by pressure support until cycle of SIMV has elapsed.

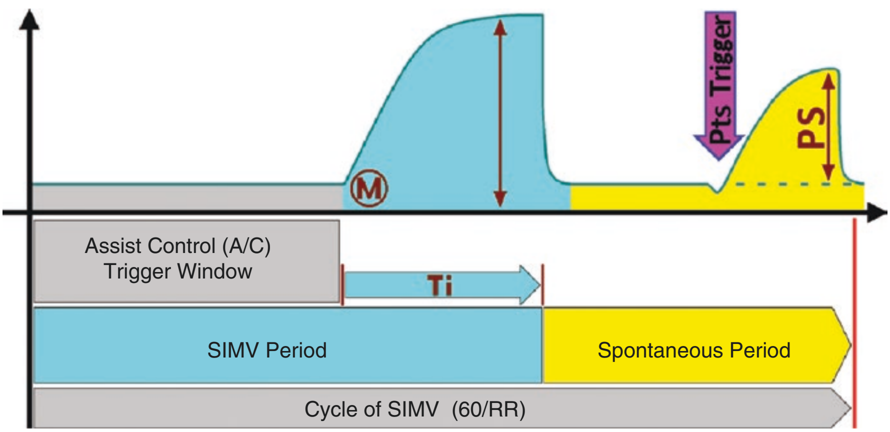


Fig. 4.8 Cycle of SIMV without spontaneous breath during Assist Control trigger window

In Fig. 4.9, there is patient trigger in assist control trigger window; so in SIMV period, assisted breath will be delivered. After assisted breath is delivered, spontaneous period begins where every spontaneous breath will be supported by pressure support until cycle of SIMV has elapsed.

In Fig. 4.10, there is patient trigger in the beginning of assist control trigger window until assisted breath will be delivered in the SIMV period. Because patient trigger is early in the SIMV period, the SIMV period ends earlier after assisted breath. If the SIMV period ends early, spontaneous period is longer where every patient trigger or spontaneous breath will be supported by pressure support until the SIMV cycle has elapsed.

If preset RR is decreased, then the SIMV cycle (60/RR) will be longer, which will give opportunity for spontaneous breath to be also longer (see Figs. 4.11, 4.12, and 4.13).

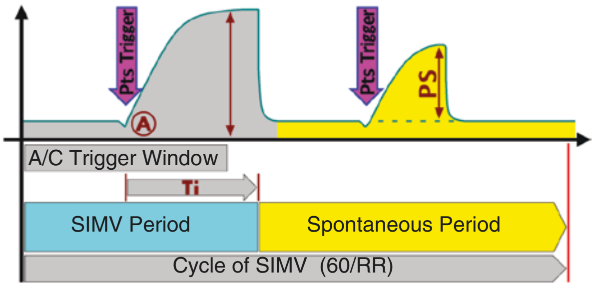


Fig. 4.9 Cycle of SIMV with spontaneous breath during Assist Control trigger window

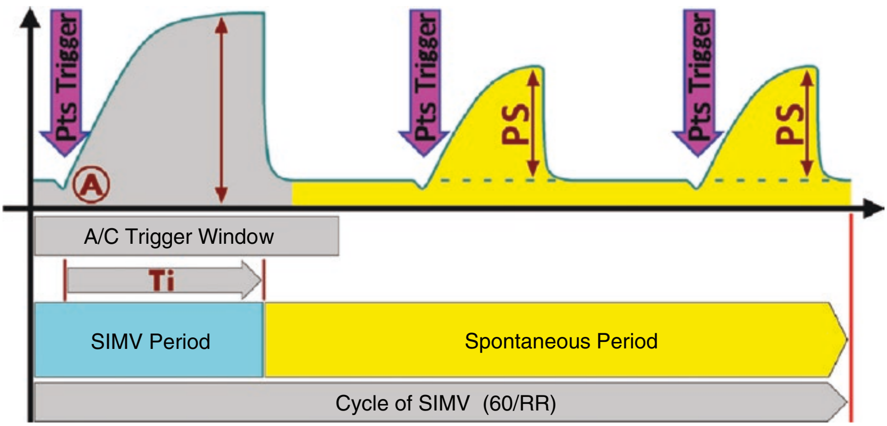


Fig. 4.10 Cycle of SIMV with spontaneous breath during Assist Control trigger window and shorter Assist Control trigger window

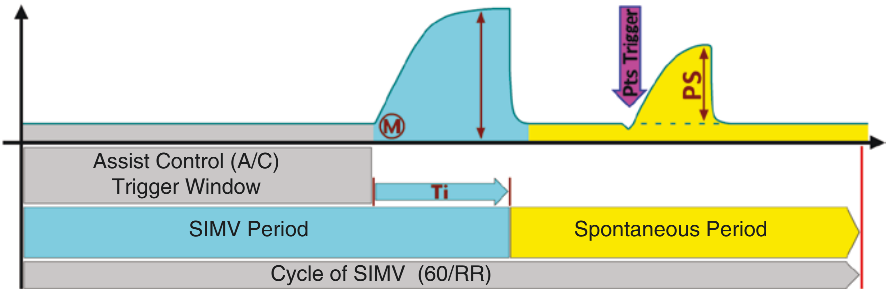


Fig. 4.11 Example with no patient trigger until A/C trigger window has elapsed

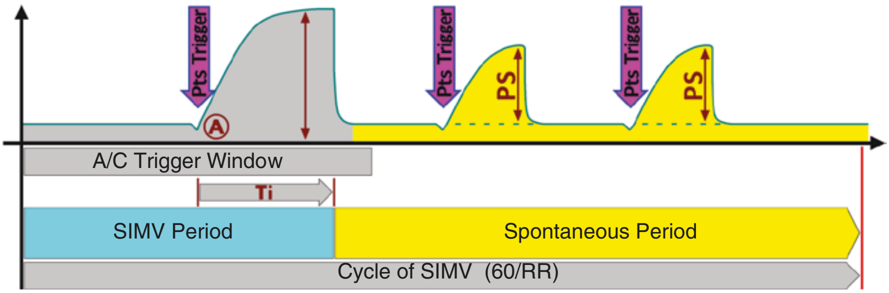


Fig. 4.12 Example with patient trigger in A/C trigger window

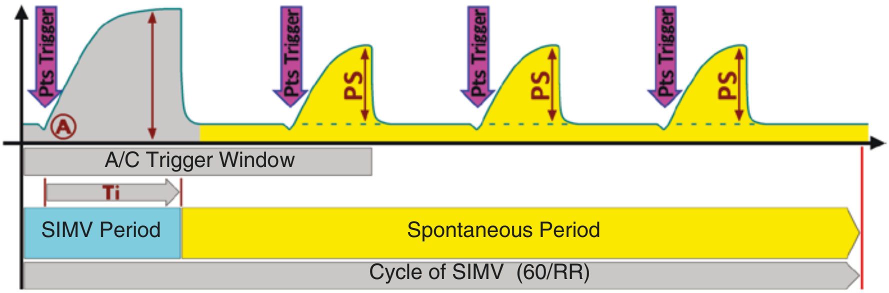


Fig. 4.13 Example of early patient trigger in A/C trigger window

4.3.1 SIMV Mode

Fig. 4.14 shows the cycle of SIMV mode.

Figure 4.15 shows an example of pressure SIMV mode.

Another example of SIMV mode is shown in Fig. 4.16, which is a waveform of volume SIMV mode.

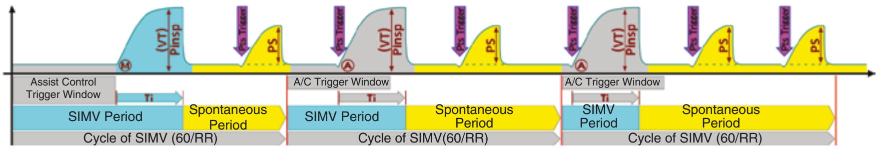


Fig. 4.14 Cycle of SIMV mode

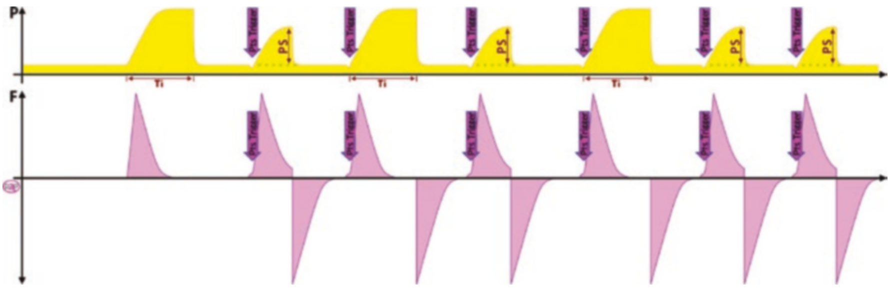


Fig. 4.15 Example waveform of pressure SIMV mode

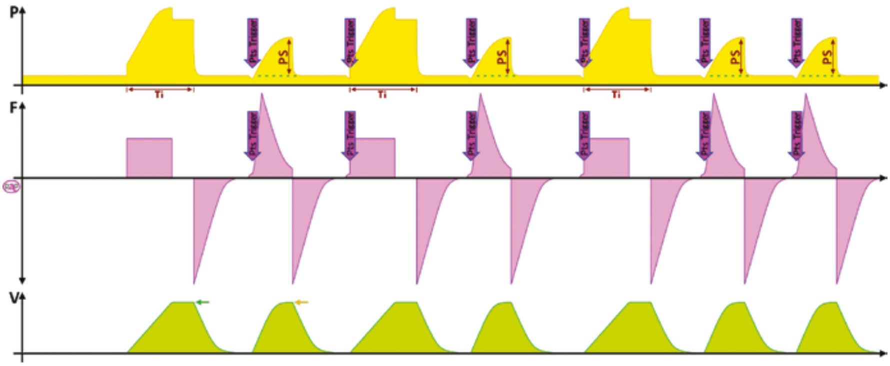


Fig. 4.16 Example of waveform of volume SIMV mode

4.4 Pressure Support and Continuous Positive Airway Pressure (CPAP) Ventilation Modes

4.4.1 Pressure Support Ventilation Mode

In PSV mode, the user set the preset pressure support to support the patient while the respiratory rate, inspiratory time, flow rate, and volume are controlled by the patient himself (see Fig. 4.17). The trigger sensitivity is still activated, which means the patient's breathing is still supported by the ventilator.

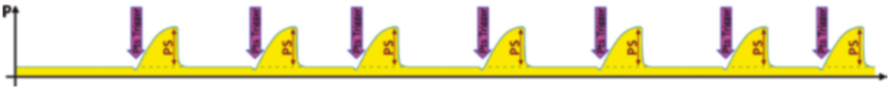


Fig. 4.17 Example waveform of pressure support ventilation mode

Fig. 4.18 Example waveform of CPAP (continuous positive airway pressure) ventilation mode

4.4.2 CPAP Ventilation Mode

In CPAP mode, the patient has spontaneous breathing, which means the volume, flow rate, respiratory rate, and inspiratory time are controlled by the patient himself (see Fig. 4.18). The ventilator still supports the patient by giving PEEP to maintain the inflation of the alveoli.

4.4.2.1 Example of Ventilation Modes Setting

Adult patient with predicted body weight of 75 kg needs support of mechanical ventilator with the following target:

- Lung-protective ventilation with tidal volume of 6–8 mL/kg body weight
- Removal of CO_2 at minute volume of 0.1 L/min/kgBW

Then assist volume-controlled ventilation is calculated as follows, with further setting shown in Table 4.1:

- VT = 450–600 mL
- MV = 7.5 L/min (or greater)
- RR = MV/VT = 17–13 breath/min

Another example setting is the setting of pressure-controlled ventilation which is shown in Table 4.2.

Table 4.1 Example of range setting of assist volume-controlled ventilation mode

Range setting	
Setting –ventilation mode = assist volume controlled –tidal volume = 450 mL –respiratory rate = 17 BPM (breath period = 60 s/17 = 3.5 s) –I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 3.5 × 1/3 = 1.2 s, Te = 2.3 s) –flow pattern = square –inspiratory flow = 36 L/min (600 mL/s) (flow time = VT/600 = 0.75 s) (plateau time = Ti − 0.75 s = 0.75 s) –PEEP = 5 cmH_2O	Setting –ventilation mode = assist volume controlled –tidal volume = 600 mL –respiratory rate = 13 BPM (breath period = 60 s/13 = 4.6 s) –I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 4.6 × 1/3 = 1.5 s, Te = 3.1 s) –flow pattern = square –inspiratory flow = 36 L/min (600 mL/s) (flow time = VT/600 = 1 s) (plateau time = Ti − 1 s = 0.5 s) –PEEP = 5 cmH_2O
Measured parameter –peak pressure = cmH_2O –plateau pressure = cmH_2O	Measured parameter –peak pressure = cmH_2O –plateau pressure = cmH_2O

Table 4.2 Example of range setting of pressure-controlled ventilation mode

Range setting	
Setting –ventilation mode = pressure controlled –Pc (ΔP) = 10 cmH_2O above PEEP Initial setting that needs to be adjusted, for example, breath by breath, to reach tidal volume of 450 mL –respiratory rate = 17 BPM (breath period = 60 s/17 = 3.5 s) –I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 3.5 × 1/3 = 1.2 s, Te = 2.3 s) –slope = 0.2–0.3 s Initial setting that needs to be regulated based on the flow demand of the patient In a patient with higher flow demand (air hunger), shorter slope is needed in order for the inspiratory flow to get bigger. –PEEP = 5 cmH_2O Measured parameter –tidal volume = ?? mL –minute volume = ?? L/min	Setting –ventilation mode = pressure controlled –Pc (ΔP) = 10 cmH_2O above PEEP Initial setting that needs to be adjusted, for example, breath by breath, to reach tidal volume of 600 mL –respiratory rate = 13 BPM (Breath period = 60 s/13 = 4.6 s) –I:E ratio = 1:2 → (1 + 2 = 3) (Ti = 4.6 × 1/3 = 1.5 s, Te = 3.1 s) –slope = 0.2–0.3 s Initial setting that needs to be regulated based on the flow demand of the patient. In a patient with higher flow demand (air hunger), shorter slope is needed in order for the inspiratory flow to get bigger. –PEEP = 5 cmH_2O Measured parameter –tidal volume = ?? mL –minute volume = ?? L/min

Overview of Acid-Base Balance, Oxygenation, Ventilation, and Perfusion

5

5.1 Introduction

It is critical that oxygen delivery through ventilatory support is maintained at adequate physiologic levels. Thus, arterial blood gas examination is needed to find out the oxygen delivery and metabolic status through acid-base balance, oxygenation of the blood, and even ventilation and perfusion. Blood gas data will also help clinician in clinical decision-making and influence therapeutic decision for the patient. Thus, blood gas data must be accurate and free from technical error. Error in blood gas data might affect clinical decision-making, which might cause fatality.

In ABG result, acid-base status can be determined on the measurement of pH. Oxygen can be determined on the measurement of PaO_2 (partial pressure of O_2 in artery). Ventilation can be determined on the measurement of $PaCO_2$ (partial pressure of CO_2 in artery). There are normal levels of each measurement, which by this ABG result can be interpreted. In any fluctuation from the normal physiological range, the body will always compensate to balance the body itself. In case of decreased oxygenation, generally there are two main ways to increase oxygenation. They are by increasing FiO_2 and increasing mean pressure. Ventilation and perfusion can also affect the blood gas result. This chapter will discuss further about acid-base balance, how the body compensates it, oxygenation, ventilation, and perfusion.

The classification of acid-base balance (Fig. 5.1) is used to interpret for arterial blood gas.

R.A. Pupella, *Mechanical Ventilation in Patient with Respiratory Failure*,
DOI 10.1007/978-981-10-5340-5_5

PH Low (<7.35), Acidosis

PH Normal (7.35-7.45)

PH High (>7.45), Alkalosis

		HCO3		
		Low (< 22) Acid	**Normal** (22 – 26)	**High** (> 26) Alka
PaCO2	**Low** (< 35), Alka	**Partially Compensated Metabolic Acidosis** **Fully Compensated PH=7.41-7.45: Respiratory Alkalosis PH=7.35-7.39: Metabolic Acidosis** **Partially Compensated RespiratoryAlkalosis**	**Uncompensated Respiratory Alkalosis**	Mixed Alkalosis
	Normal (35 – 45)	**Uncompensated Metabolic Acidosis**	**Normal**	**Uncompensated Metabolic Alkalosis**
	High (> 45), Acid	Mixed Acidosis	**Uncompensated Respiratory Acidosis**	**Partially Compensated Respiratory Acidosis** **Fully Compensated PH=7.41-7.45: Metabolic Alkalosis PH=7.35-7.39: Respiratory Acidosis** **Partially Compensated Metabolic Alkalosis**

Fig. 5.1 Classification of acid-base balance (blood gas interpretation)

5.1.1 How the Body Compensates

Metabolic: Anion gap analysis to find the root cause.

Respiratoric: Ventilatory support strategy to help regulate $PaCO_2$.

Example effects of high $PaCO_2$ in respiratory acidosis (see Fig. 5.2):

- Increased airway resistance.
- Air trapping → obstruction of airways and/or alveoli surface is too elastic and more sensitive and so cannot exhale completely.
- Low minute volume:
  - Low respiratory rate.
  - Low tidal volume → decreased alveoli capacity.
- Gas exchange problem with the pulmonary capillaries:
  - Alveoli cannot remove CO_2 completely.
  - Pulmonary capillaries are blocked.

Example effects of low $PaCO_2$ in respiratory alkalosis:

- High minute volume:
  - Total respiratory rate is too high (patient is nervous or check if there is auto-trigger if using a ventilator).
  - Tidal volume is too high.

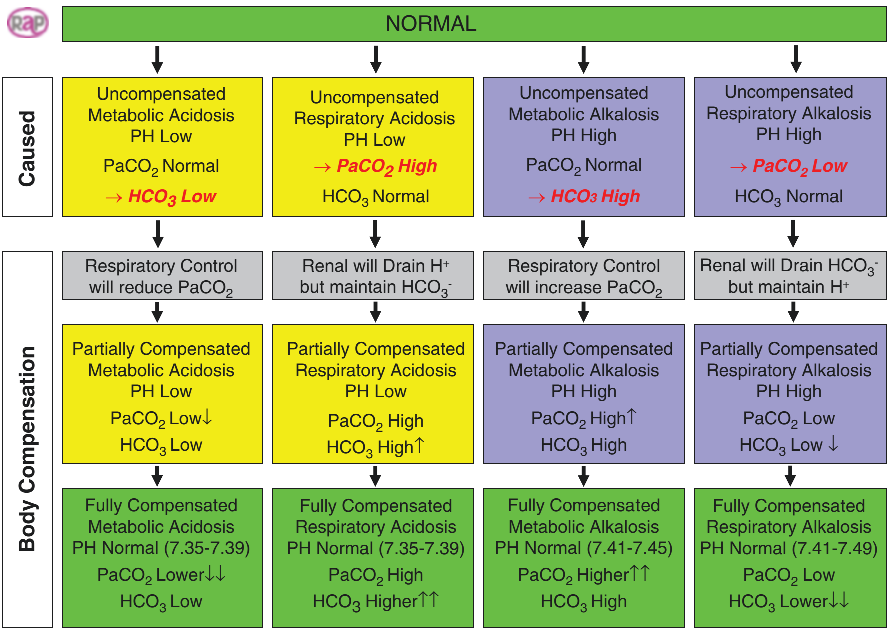


Fig. 5.2 Body compensation

5.2 Oxygenation

There are two main ways to increase oxygenation; they are as follows:

1. Increasing FiO_2 value that is delivered to the patient
   Example: FiO_2 setting = 60% increases to 80%.
2. Increasing mean pressure
   Mean pressure is the average value (area of graphic) of inspiratory pressure that can be increased by increasing PEEP, increasing pressure rise time, increasing PIP, prolonging inspiratory time, and increasing respiratory rate.

By increasing PEEP, the mean pressure which is the area of graphic can be increased because the inspiratory pressure will automatically increase and so is the area of graphic (see Fig. 5.3).

Increasing the inspiratory flow or pressure rise time can also increase the mean pressure (see Fig. 5.4).

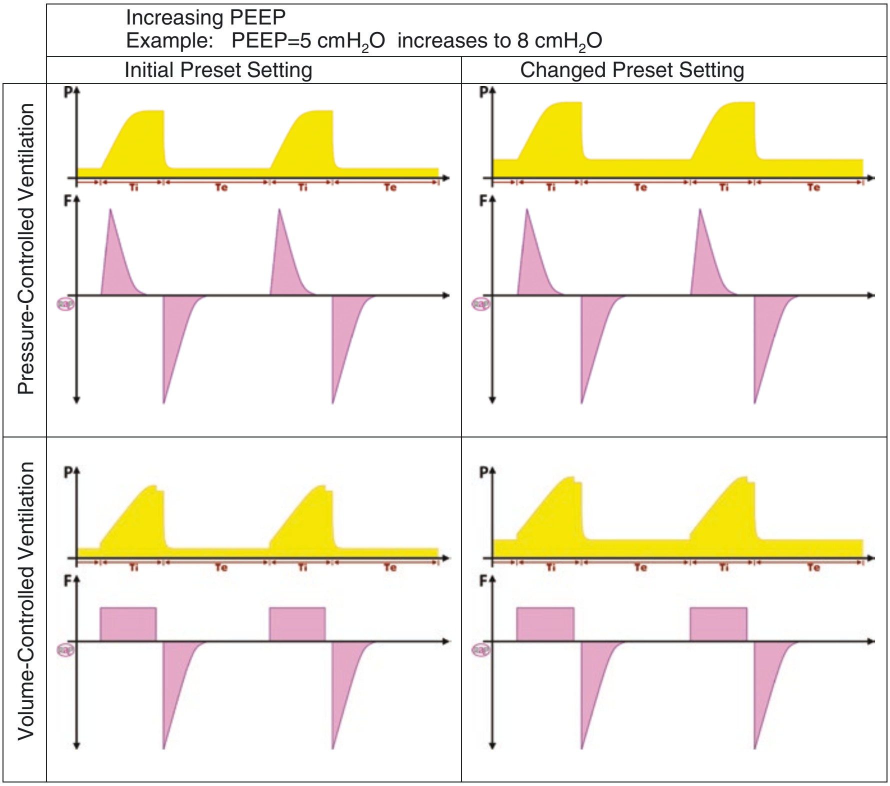


Fig. 5.3 Example of increasing PEEP

Increasing the PIP will also automatically increase the area of graphic which means increased mean pressure (see Fig. 5.5 for example of increased PIP).

Prolonging inspiratory time will also increase mean pressure (see Fig. 5.6 for example of prolonged inspiratory time).

Increasing respiratory rate will result to more breaths per minute which will result to increased mean pressure (see Fig. 5.7 for example of increasing respiratory rate).

Note:

c (Fig. 5.5) → increased driving pressure or increased preset tidal volume value

e (Fig. 5.7) → increased preset respiratory rate value

It is the same as increased inspiratory volume per minute (MVi) (see Figs. 5.8 and 5.9).

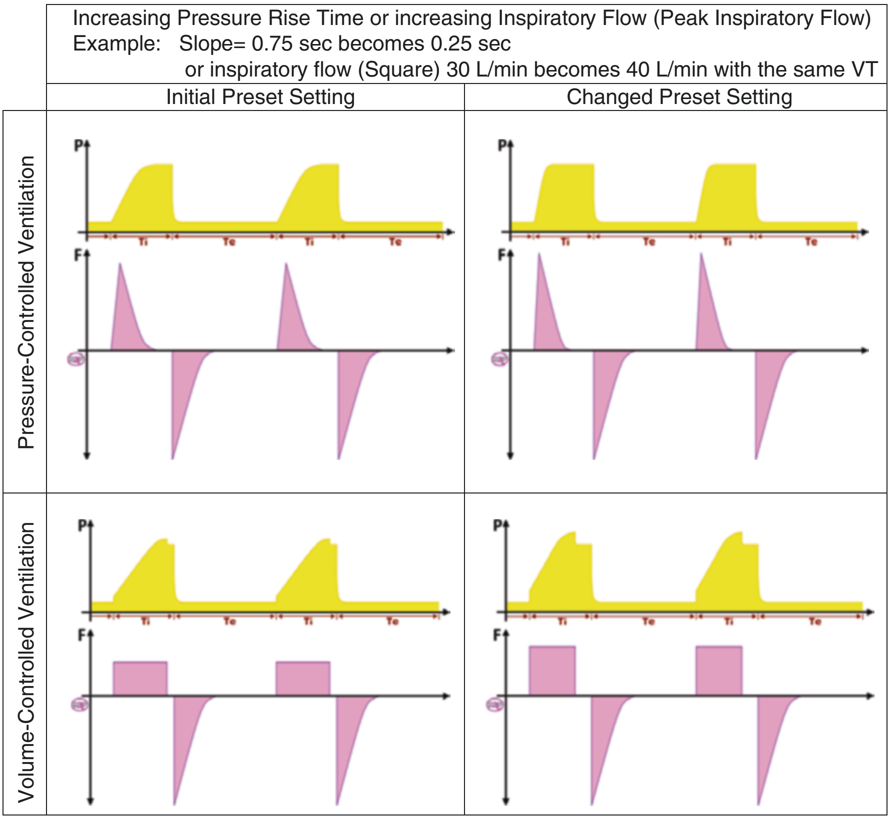


Fig. 5.4 Example of increasing pressure rise time or inspiratory flow

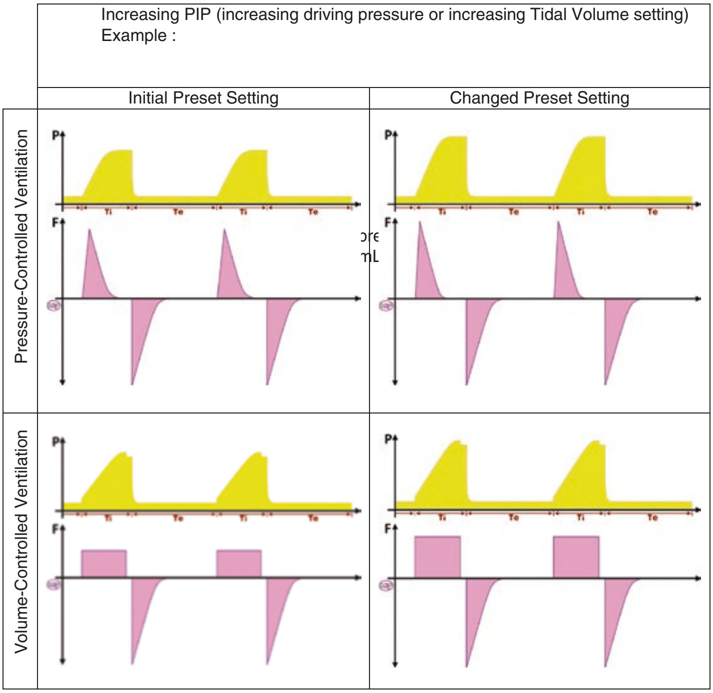


Fig. 5.5 Example of increasing PIP

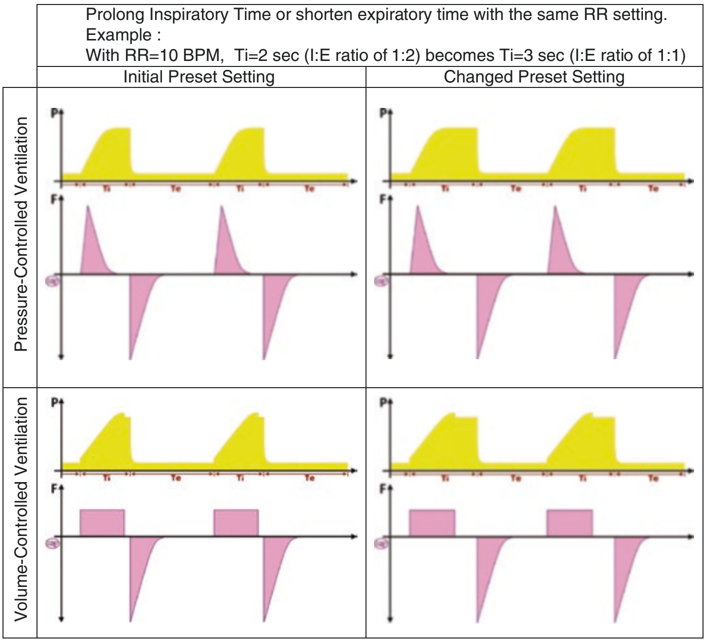


Fig. 5.6 Example of prolonged inspiratory time

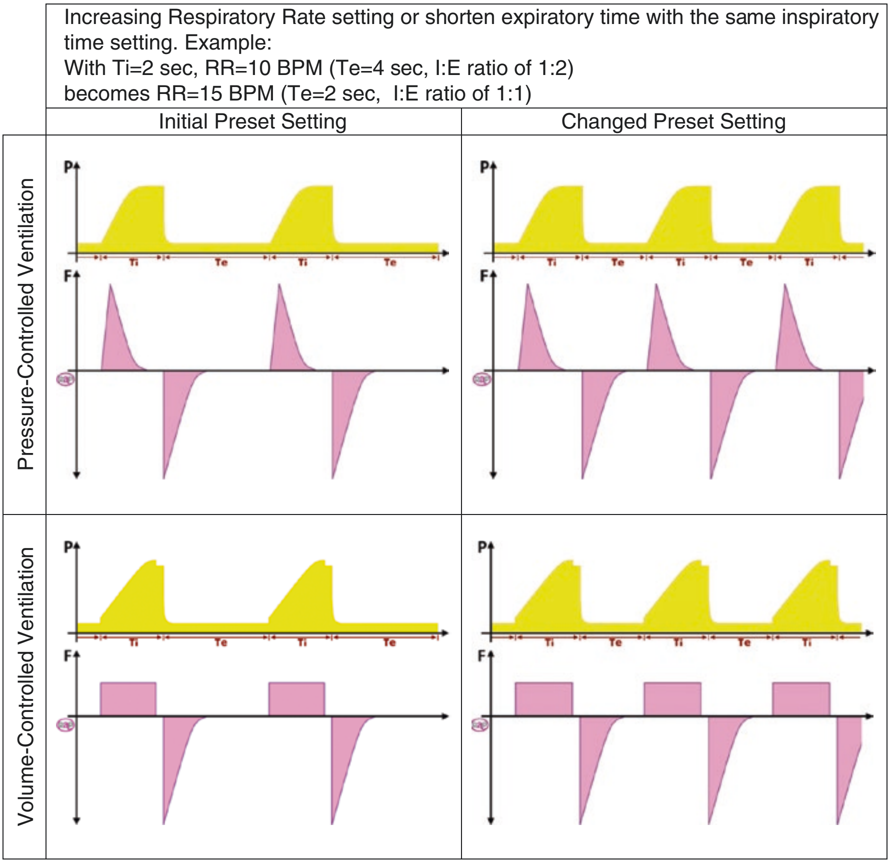


Fig. 5.7 Example of increasing respiratory rate

5.3 Ventilation

5.3.1 Effect of Minute Volume in Ventilation

Expiration is passive from the patient and is not done by the ventilator except HFO (high-frequency oscillatory) ventilation. And thus, the user needs to be sure that exhalation of the patient is completed by expiratory flow which returns to zero. Ventilation or removal of CO_2 can also increase by increasing minute volume, but make sure expiratory flow is completed and returns to zero (Fig. 5.10).

In HFO ventilation, expiration is done by the ventilator because of oscillation that is very fast until 20 frequencies per second, and thus, it does not have enough time to wait for the patient to exhale, particularly neonates with higher airway resistance.

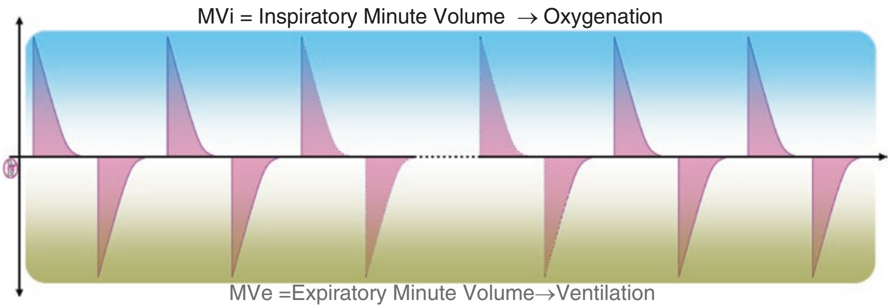


Fig. 5.8 Flow waveform in pressure-controlled ventilation with improving MVi

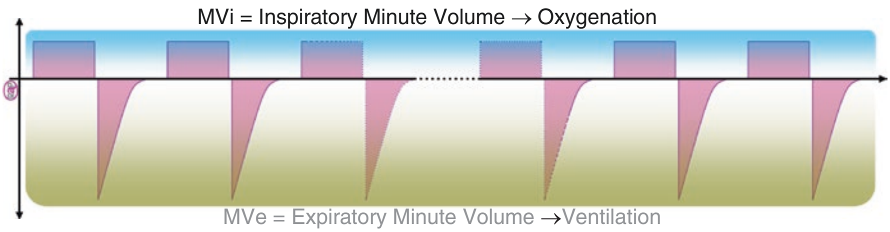


Fig. 5.9 Flow waveform in volume-controlled ventilation with improving MVi

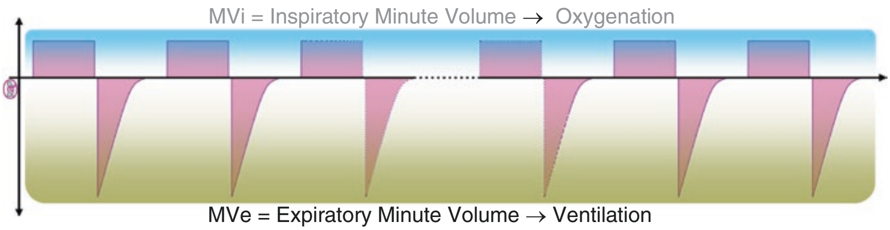


Fig. 5.10 Waveform of inspiratory minute volume

5.4 Perfusion and Ventilation/Perfusion Ratio

See Fig. 5.11 for short explanation of perfusion and ventilation.

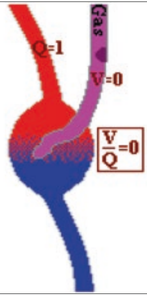
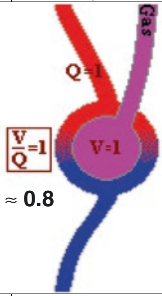
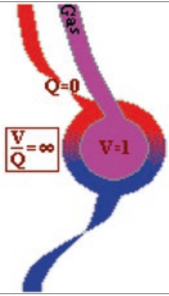
<table>
<tr><th>Alveoli not Ventilated</th><th>Optimal</th><th>Alveoli not Perfused</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>V (gram/min) is the O2 mass per minute.
V=0 can be caused by:
- Airways Problem (for example airway obstruction)
- Alveoli are collapsed or filled with water</td><td></td><td>Q (liter/min) is the blood flow per minute inside the lungs.
Q=0 can be caused by:
- Artery or venous are collapsed
- Blockage of pulmonary veins or arteries (for example pulmonary embolism)</td></tr>
</table>

Fig. 5.11 Illustration of perfusion in alveoli

6 Advanced Ventilation Modes

6.1 Introduction

In every new generation, mechanical ventilator is also developing and upgrading. With this ventilator of each generation, basic ventilation modes are not the only modes available in most advanced ventilators in this generation. Basic ventilation modes have been upgraded, and new modes and variations become available. There now exist different and numerous ventilation modes including advanced ventilation modes from variety of manufacturers of ventilator. These advanced ventilation modes are used often upon their availability and clinician's decision or bias, rather than the fact that they are more advanced than the basic ventilation modes. Most common advanced ventilation modes used and available in advanced ventilator are BiPAP and APRV, Dual Control, Minute Volume Guarantee, and Adaptive Support Ventilation (ASV). This chapter will discuss those advanced ventilation modes.

6.2 BiPAP and APRV and Their Weaning Process

6.2.1 BiPAP: Bi-level Positive Airway Pressure

Background – patient is allowed to inhale and exhale spontaneously without restriction in continuous positive airway pressure (CPAP) mode. See Fig. 6.1.

Inspiratory valve and value of inspiratory flow will be adjusted with patient effort.

Opening of expiratory valve will be adjusted with patient effort in exhaling.

Background – needs concept of CPAP on peak inspiration. See Fig. 6.2.

R.A. Pupella, *Mechanical Ventilation in Patient with Respiratory Failure*,
DOI 10.1007/978-981-10-5340-5_6

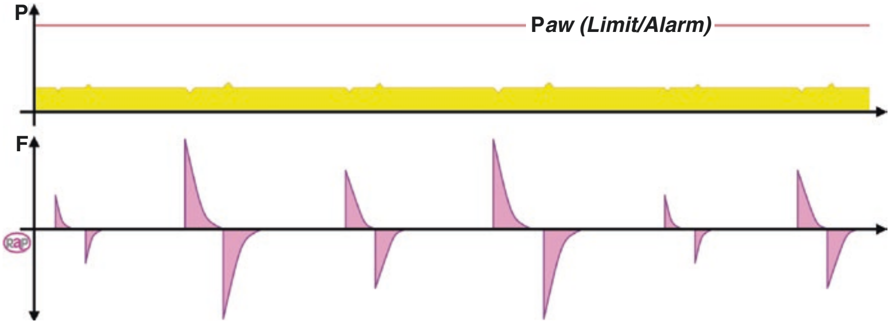


Fig. 6.1 Waveform of CPAP

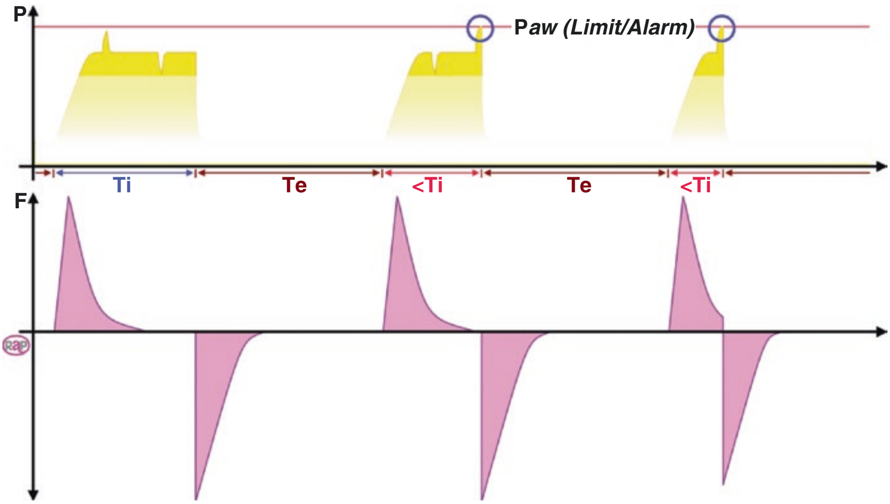


Fig. 6.2 BiPAP waveform with concept of CPAP

With asynchrony of patient with ventilator, then when inspiratory flow is delivered, patient mostly will reject/fight even coughing. This thing will cause fluctuation of PIP or even overshoot. If pressure has reached pressure limit alarm, then patient will be forced to exhale early which makes shortened inspiratory time than that has been set and decreased tidal volume. Shortened Ti and decreased VT will decrease oxygenation and ventilation because mean pressure, inspiratory minute volume, and expiratory minute volume also decrease.

The concept of inhaling and exhaling spontaneously without restriction in CPAP mode needs to be applied in peak inspiration to solve or to prevent the pressure fluctuation and even overshoot due to asynchrony.

BiPAP applies the concept of CPAP on upper level of inspiratory pressure and is sometimes called ***upper CPAP*** (inspiratory pressure) and ***lower CPAP*** (PEEP). See Fig. 6.3 for comparison between waveform of pressure controlled and BiPAP.

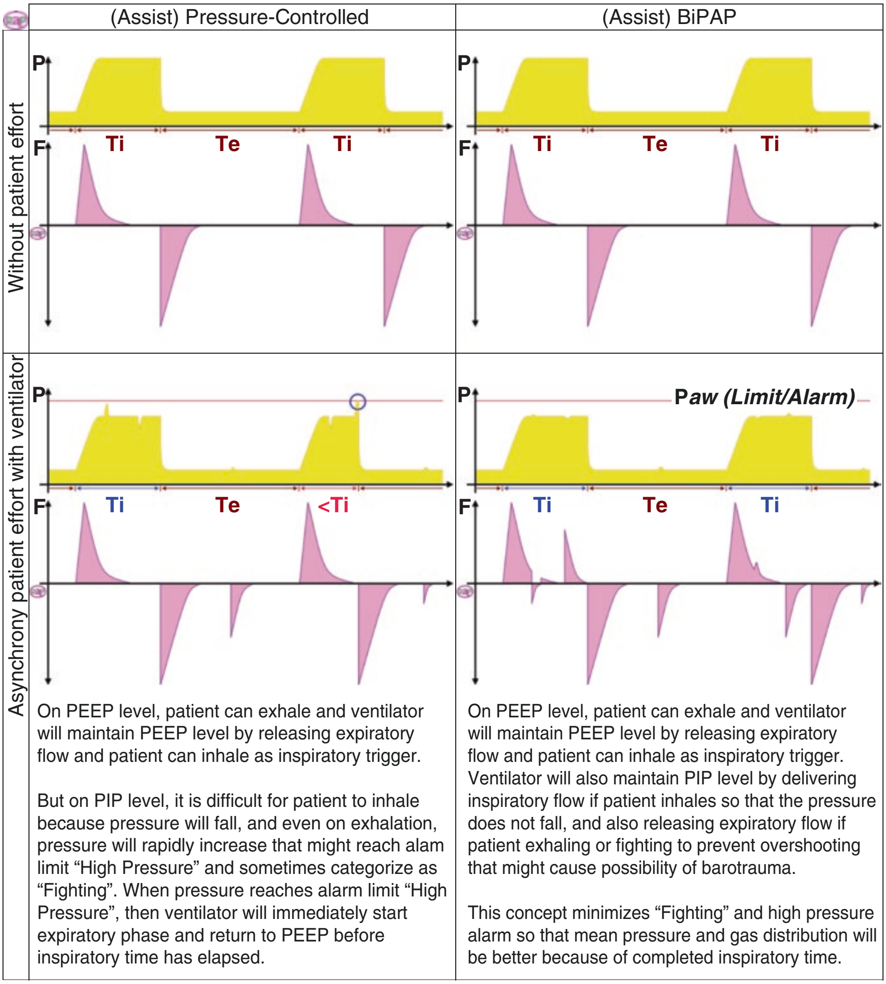


Fig. 6.3 Comparisons of pressure controlled and BiPAP

6.2.1.1 Weaning of BiPAP: Decreasing Peak Inspiratory Pressure

Weaning of BiPAP could be done by decreasing peak inspiratory pressure.

Because BiPAP is categorized to two CPAP or pressure levels which are lower CPAP (PEEP) and upper CPAP (inspiratory pressure), then weaning is done by decreasing the inspiratory pressure (upper CPAP) step by step until it is equal or close to PEEP level (lower CPAP), which then becomes CPAP mode. See Fig. 6.4.

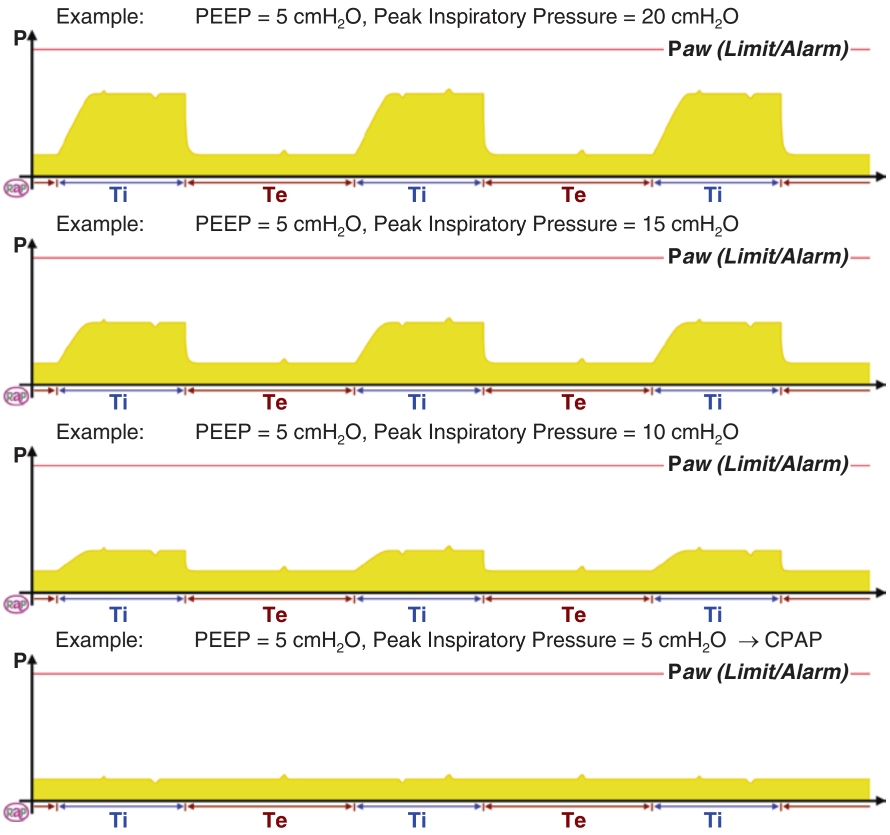


Fig. 6.4 Example of weaning of BiPAP by decreasing PIP

6.2.1.2 Weaning of BiPAP: Increasing Expiratory Time Te (Decreasing RR)

Weaning of BiPAP could be done by decreasing the peak inspiratory pressure.

BiPAP weaning can also be done by increasing expiratory time Te setting or decreasing RR setting step by step until patient breathes totally spontaneously by his own with ventilator or machine support, which then in the end the patient mostly breathes in PEEP level (CPAP). See Fig. 6.5.

6.2.2 APRV: Airway Pressure Release Ventilation

Background – required CPAP with higher pressure. See Fig. 6.6 for an example waveform of APRV.

Several reasons why patient needs higher level of spontaneous breathing (CPAP):

1. Need for higher pressure to maintain the alveoli open to prevent atelectasis and also to prevent atelectrauma due to collapsed alveoli for multiple times because of lack of pressure at the end of expiration
2. Presence of fluid inside the alveoli

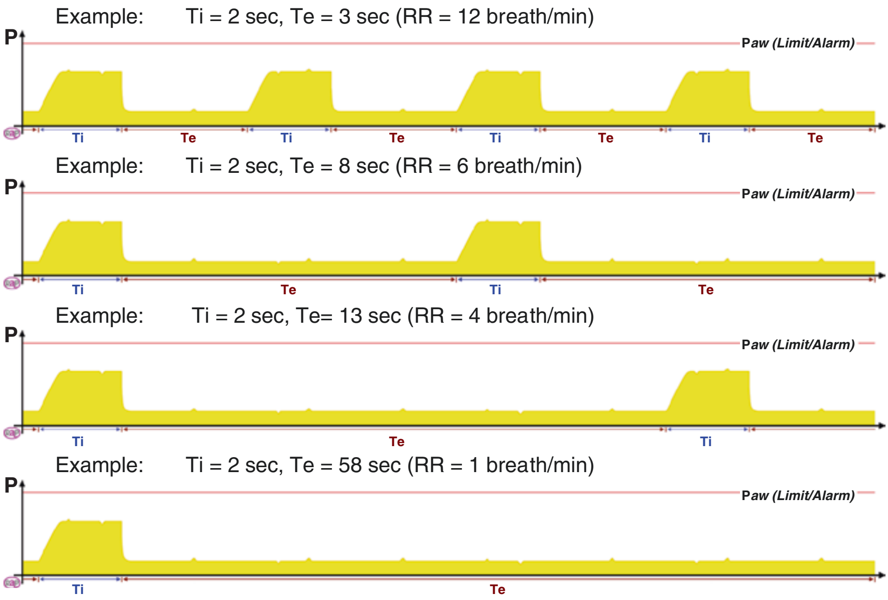


Fig. 6.5 Examples of weaning of BiPAP by increasing expiratory time

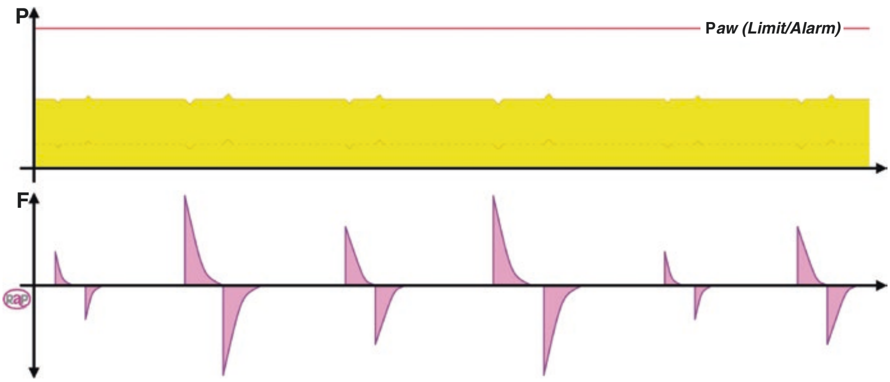


Fig. 6.6 Waveform of APRV

Pressure release – expiratory flow returns to zero, but residual volume of the lungs is maintained by above zero PEEP. Figure 6.7 shows a sample waveform of APRV with pressure release but keeps on maintaining PEEP.

Pressure release – zero PEEP is used to maximize expiration. But TLow, that is being adjusted for the expiratory flow, does not return to zero to maintain residual volume of the lungs. Figure 6.8 shows a sample waveform of APRV with pressure release but with no PEEP at all.

6.2.2.1 Weaning of APRV

APRV is also similar to BiPAP but with inversed ratio which is the upper CPAP level (*PHigh*) that is longer than release level (*PLow*) which is shorter, and so it spends most of the time with the Phigh. Weaning is done by decreasing *PHigh* level

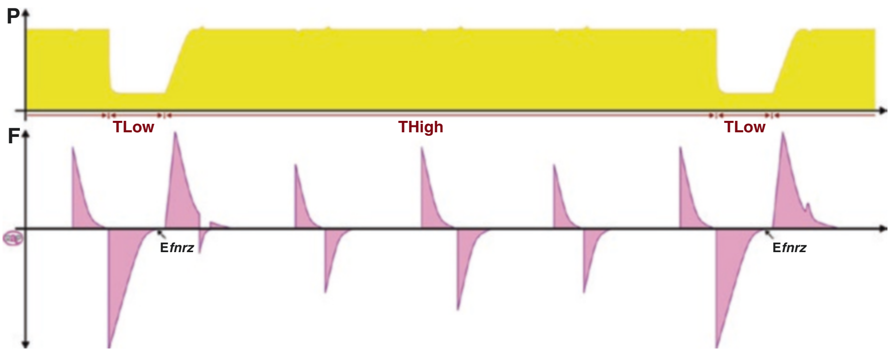


Fig. 6.7 Waveform of APRV with pressure release but maintained PEEP

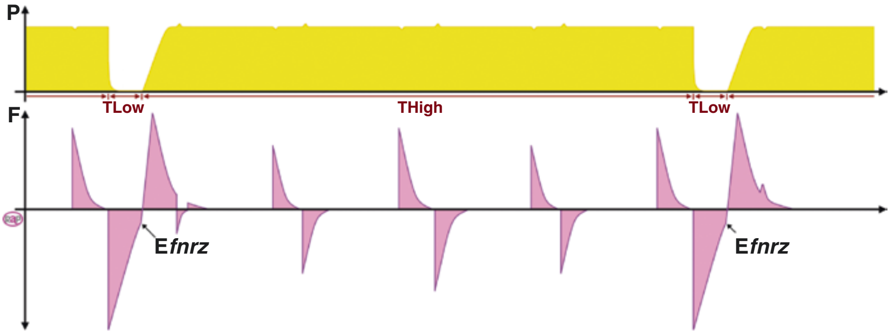


Fig. 6.8 Waveform of APRV with pressure release and zero PEEP

Fig. 6.9 Examples of weaning of APRV mode by PLow value above zero

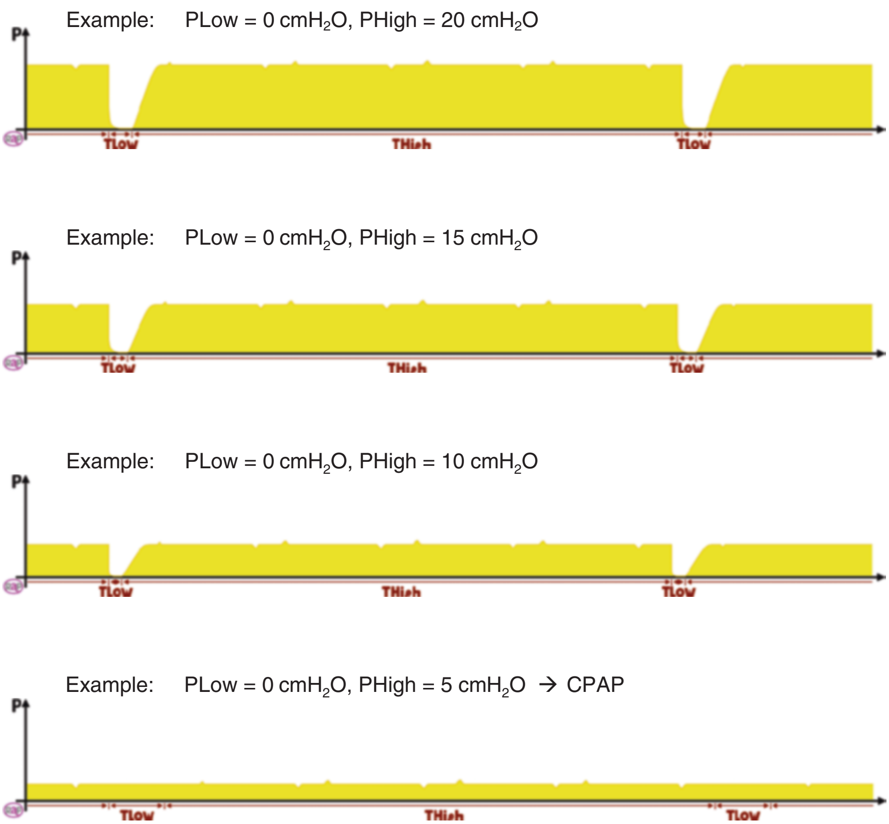


Fig. 6.10 Weaning in APRV mode with PLow of zero

(upper CPAP) gradually until it is the same or close to pressure release level (*PLow*), which then becomes CPAP mode. See Fig. 6.9 for weaning by PLow above zero and Fig. 6.10 for weaning by PLow of zero.

6.2.2.2 Application of APRV in Patient Without Spontaneous Breath

In APRV, patient is expected to breathe spontaneously on PHigh level while in THigh.

Without spontaneous breath on PHigh level then:

$$\text{Respiratory Rate} = \frac{60}{\text{THigh} + \text{TLow}}$$

Inspiratory minute volume and expiratory minute volume are determined by the RR.

The longer the THigh, the smaller minute volume will be because of smaller RR.

The significant effect of this is decreasing of ventilation which is the removal of CO_2 from the blood. But longer THigh and higher PHigh might be needed for "recruitment" which is the opening of alveoli. Which then in patient without spontaneous breath, APRV might also be used in patient which is categorized as *permissive hypercapnia* – where CO_2 level is allowed to be higher.

6.3 Dual Control (Within Breath and Breath-to-Breath) Ventilation Modes

6.3.1 Within Breath: Volume Control Pressure-Limited Ventilation

Volume-controlled pressure-limited breath is different from volume-controlled breath only. Volume-controlled breath does not guarantee that pressure does not reach the high-pressure alarm. See Fig. 6.11.

6.3.2 Within Breath: Pressure Control Volume Guarantee Ventilation (PC VG Within Breath)

In pressure control volume guarantee ventilation within breath, there are criteria for expiratory phases. See Fig. 6.12.

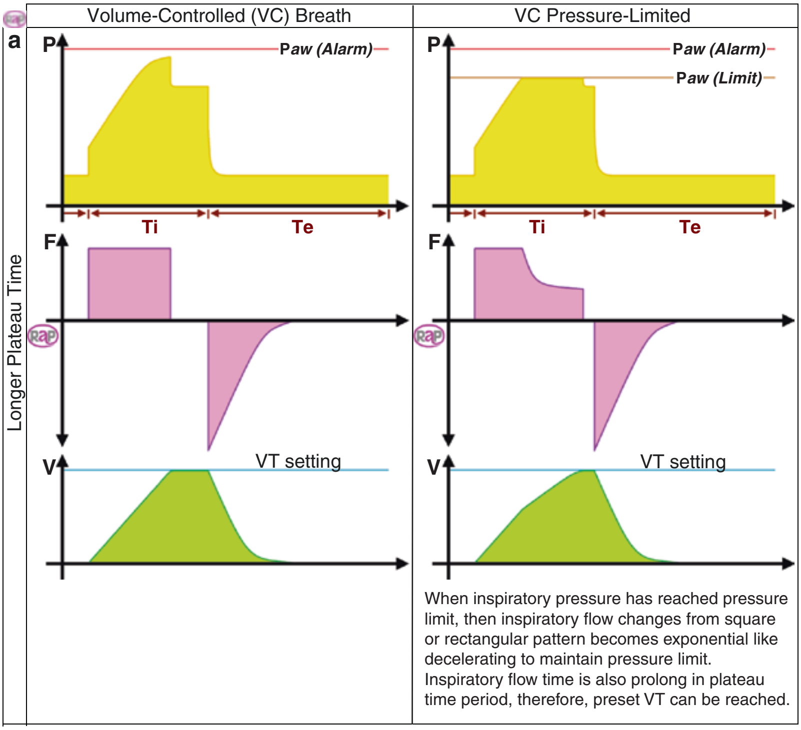


Fig. 6.11 Difference of volume-controlled breath with VC pressure-limited breath

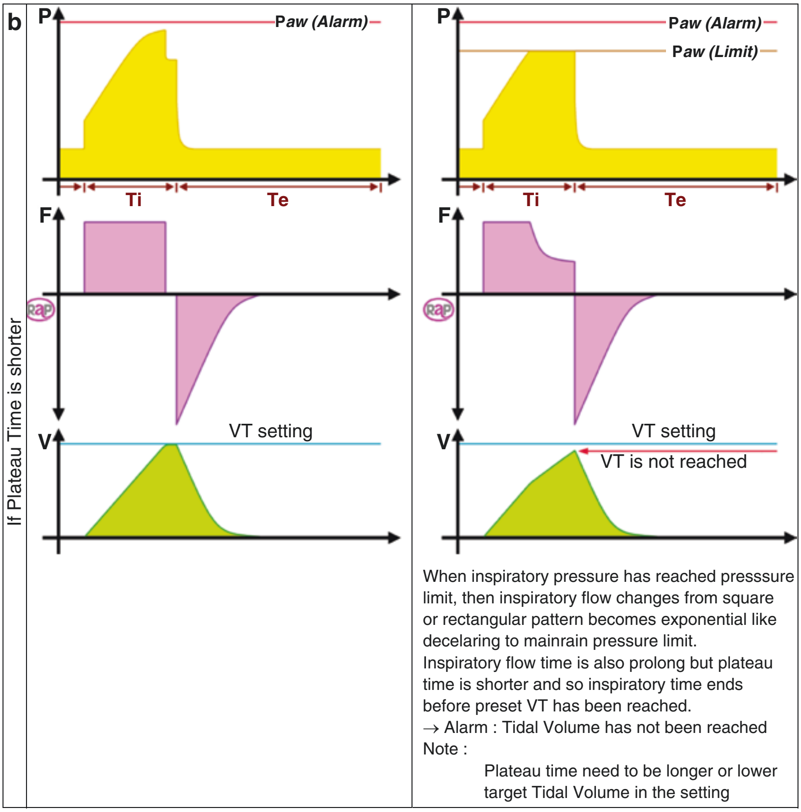


Fig. 6.11 (continued)

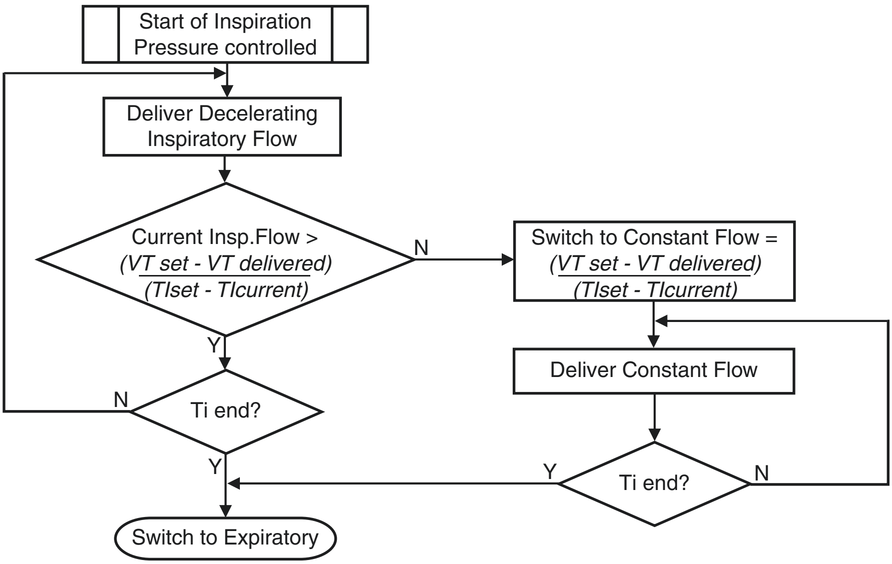


Fig. 6.12 Criteria for expiratory phase in PC VG within breath

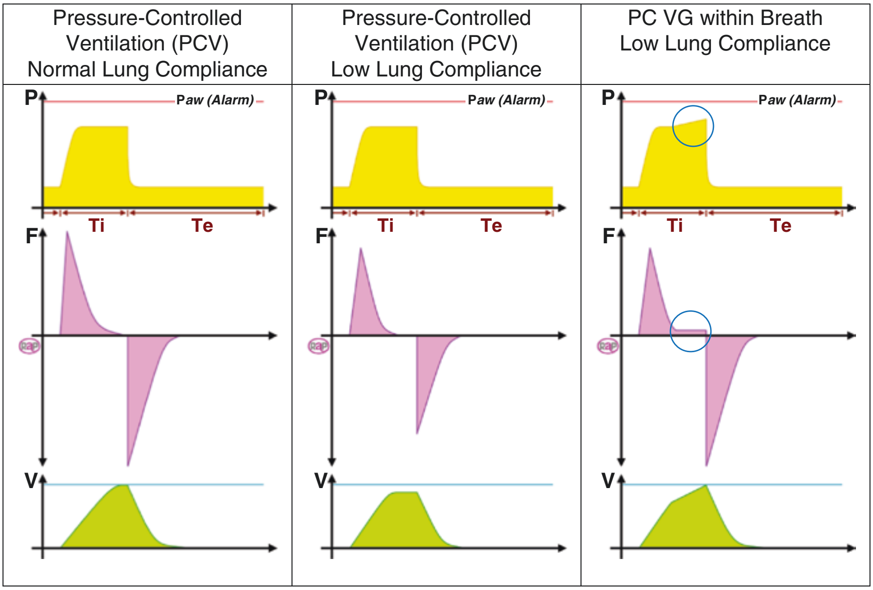


Fig. 6.13 Waveform of PCV and PC VG in different lung conditions

Figure 6.13 shows comparison of pressure-controlled ventilation with pressure control volume guarantee ventilation in normal lung and low lung compliance.

6.3.3 Within Breath: Pressure Support Volume Guarantee Ventilation (PS VG Within Breath)

Criteria for expiratory phase in pressure support volume guarantee ventilation are shown in Fig. 6.14.

Figure 6.15 shows comparison of pressure support ventilation with pressure support volume guarantee ventilation in normal respiratory drive and weak respiratory drive.

6.3.4 Breath-to-Breath: Pressure Control with Volume Guarantee

Background – required changes in airway pressure for every change of lung compliance.

In constant pressure, tidal volume will decrease due to decrease of lung compliance. See Fig. 6.16.

Because of this, pressure is required to be increased to maintain tidal volume and minute volume.

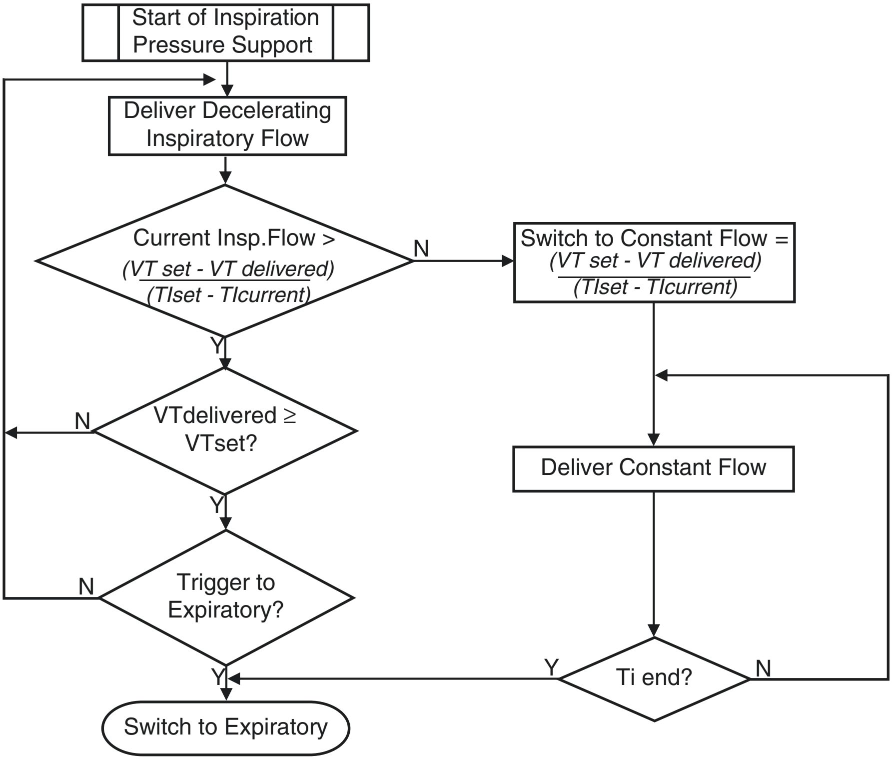


Fig. 6.14 Criteria for expiratory phase in PS VG within breath

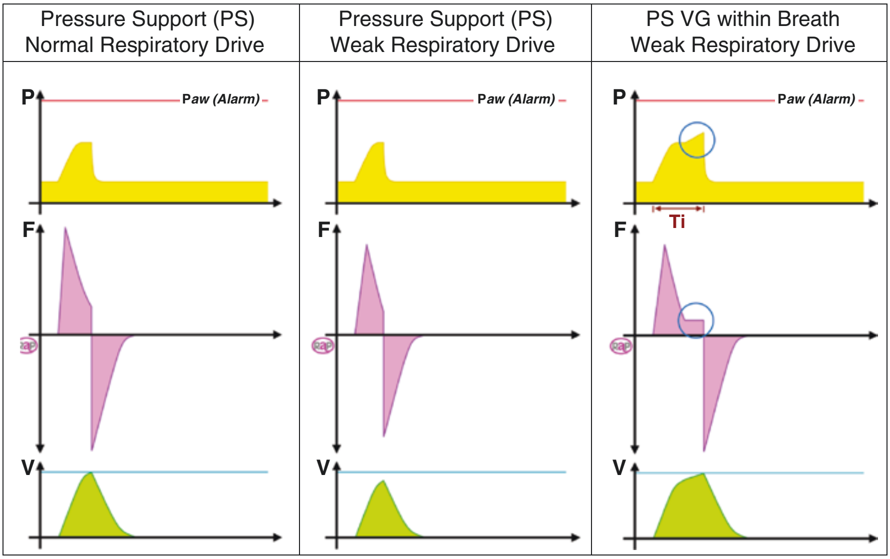


Fig. 6.15 Waveform of PS and PS VG in different lung conditions

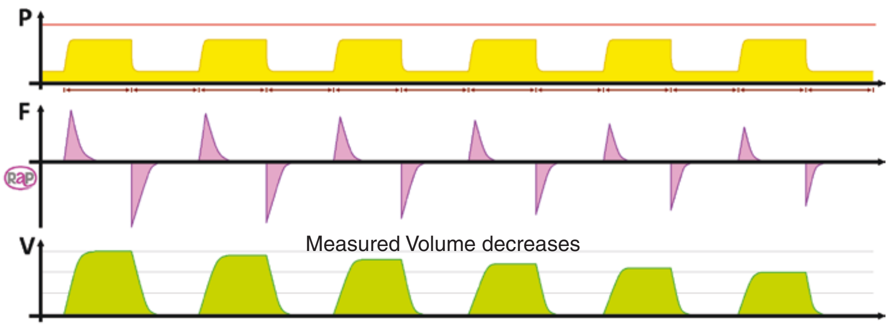


Fig. 6.16 Constant pressure but decreased VT due to decreased lung compliance

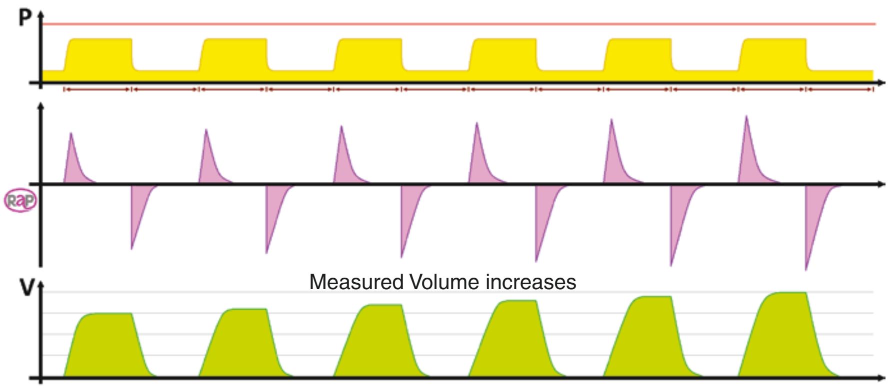


Fig. 6.17 Constant pressure but increased VT due to increased lung compliance

In constant pressure, tidal volume will increase due to increase of lung compliance. See Fig. 6.17.

Because of this, pressure is required to be decreased to maintain tidal volume and prevent lung trauma because of excessive volume.

Thus, in pressure-controlled ventilation (PCV), airway or inspiratory pressure measurement should be adjusted with the changes of lung compliance to reach or to maintain tidal volume and to prevent trauma because of excessive volume – volutrauma. See Fig. 6.18 for phase of pressure control with volume guarantee and Table 6.1 for stages breath-to-breath of the ventilation mode.

Beginning of initiation:

– Previous breath is volume-controlled or pressure-controlled.
– Initial breath is in test of pressure-controlled with pressure of 10 cmH_2O above PEEP.

If measured tidal volume VT is bigger than preset VT (target), then inspiratory pressure will decrease gradually which is breath-by-breath with maximum decrease of 2 cmH_2O until preset VT has been reached. See Fig. 6.19.

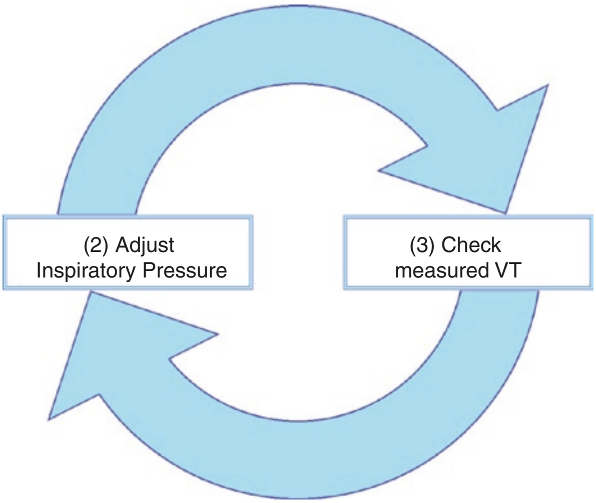


Fig. 6.18 Phase of pressure control with volume guarantee

Table 6.1 Stages breath-to-breath of pressure control with volume guarantee

<table>
<tr><th>No.</th><th colspan="3">The stages</th><th>Notes</th></tr>
<tr><td rowspan="3">1</td><td colspan="3">Initiation of breath:
Measure/compute lung compliance</td><td rowspan="3">Volume-controlled:
$C = \frac{VT(\text{preset})}{\text{plateau pressure}}$
Or pressure-controlled:
$C = \frac{VT(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td colspan="2">From the previous breath</td><td rowspan="2">Or from 1 to 3 test of pressure-controlled breath</td></tr>
<tr><td>Volume-controlled breath</td><td>Pressure-controlled breath</td></tr>
<tr><td>2</td><td colspan="3">Determine and apply the next inspiratory pressure
–Maximum of increase or decrease is 2 cmH_2O
–Maximum of peak pressure is the preset limit</td><td>$\text{Inspiratory pressure} = \frac{VT(\text{preset})}{\text{compliance}}$</td></tr>
<tr><td>3</td><td colspan="3">Measure tidal volume and compute for lung compliance
(VT is inspiratory VT that is compensated by leak or expiratory VT that is compensated by leak)</td><td>$C = \frac{VT(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td>4</td><td colspan="3">Return to step 2</td><td>Loop process is closed</td></tr>
</table>

If measured tidal volume VT is smaller from the preset VT (target), then inspiratory pressure will increase gradually which is breath-by-breath with maximum increase of 2 cmH_2O until preset VT has been reached or until pressure limit has been reached. See Fig. 6.20.

If pressure limit has been reached, but the preset tidal volume VT has not been reached yet, then there will be a notification "Tidal Volume has not been reached, Inspiratory Pressure is limited." See Fig. 6.21.

If compliance decreases, then inspiratory pressure will increase breath-by-breath with maximum increase of 2 cmH_2O until pressure limit to maintain the tidal

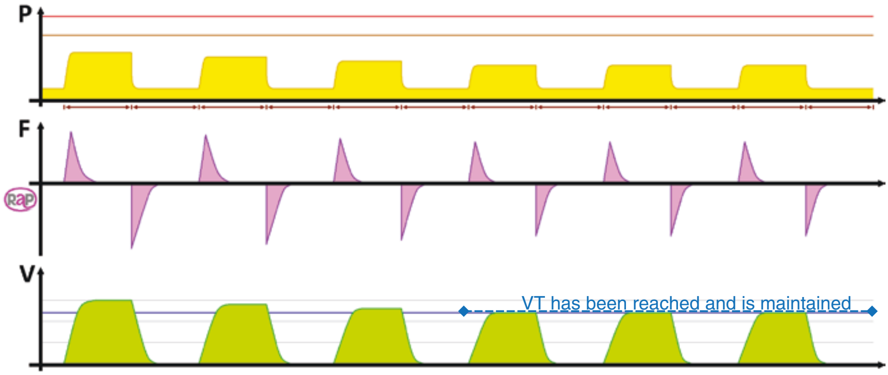


Fig. 6.19 Waveform of decreasing VT by decreasing inspiratory pressure breath-by-breath

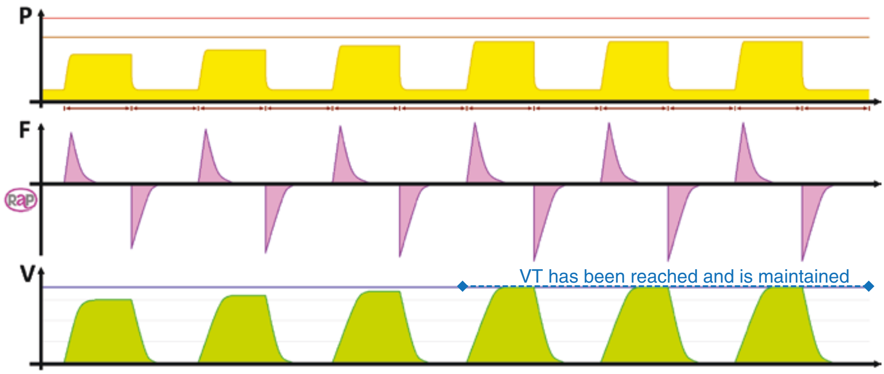


Fig. 6.20 Waveform of increasing VT by increasing inspiratory pressure breath-by-breath

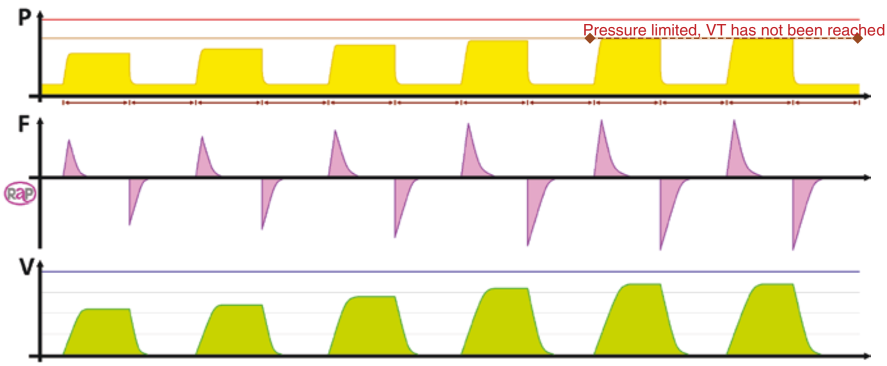


Fig. 6.21 Waveform of pressure limit has been reached, but VT has not been reached

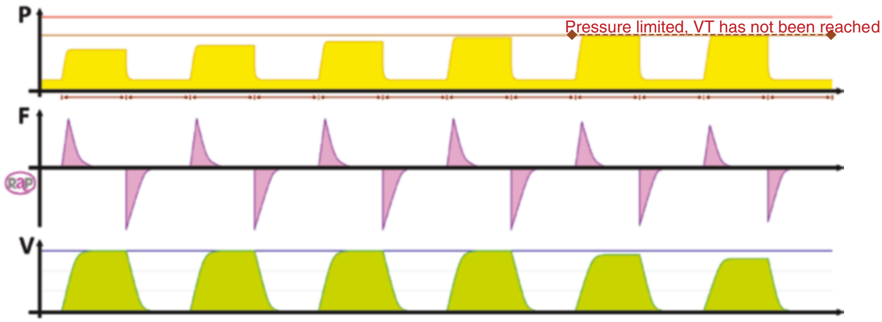


Fig. 6.22 Waveform of maintained pressure and volume but then compliance increases, which then pressure limit has been reached, but VT has not been reached

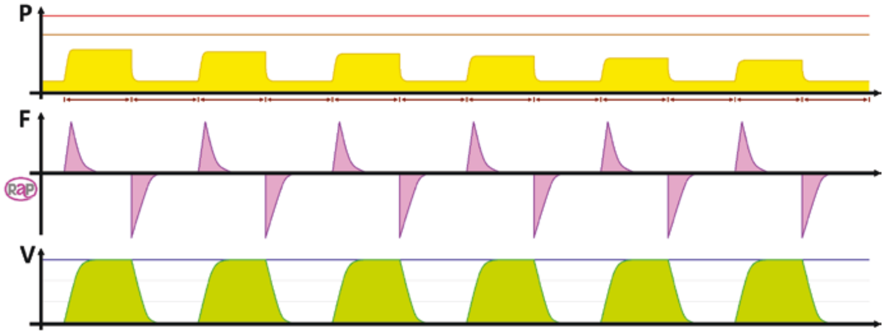


Fig. 6.23 Waveform of decreasing inspiratory pressure breath-by-breath because of increased compliance

volume VT, and if pressure limit has been reached but the preset tidal volume VT has not been reached, then there will be a notification "Tidal Volume has not been reached, Inspiratory Pressure is limited." See Fig. 6.22.

In these two conditions, the following should be considered:

- Preset VT has probably exceeded the lung capacity → consider to decrease preset VT.
- Pressure limit is too low → consider to increase pressure limit but within normal categorization.

If compliance increases, then inspiratory pressure will decrease breath-by-breath with maximum decrease of 2 cmH_2O while still above PEEP to maintain tidal volume VT. See Fig. 6.23.

By maintaining tidal volume VT, it can prevent lung trauma because of excessive tidal volume.

6.3.5 Breath-to-Breath: Pressure BiPAP with Volume Guarantee

Background – required changes in airway pressure for every change of lung compliance and/or change of strength of patient's respiratory drive while breathing. See Fig. 6.24 for phase of pressure BiPAP with volume guarantee and Table 6.2 for stages breath-to-breath of the ventilation mode.

Measured VT depends on lung compliance and/or strength of respiratory drive of the patient while breathing.

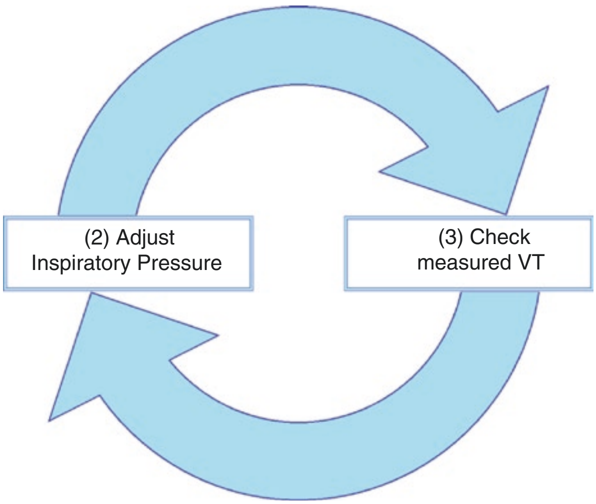


Fig. 6.24 Phase of pressure BiPAP with volume guarantee

Table 6.2 Stages breath-to-breath of pressure BiPAP with volume guarantee

<table>
<tr><th>No.</th><th colspan="3">The stages</th><th>Notes</th></tr>
<tr><td rowspan="3">1</td><td colspan="3">Initiation of breath:
Measure/compute lung compliance</td><td rowspan="3">Volume-controlled:
$C = \frac{\text{VT}(\text{preset})}{\text{plateau pressure}}$
Pressure-controlled:
$C = \frac{\text{VT}(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td colspan="2">From the previous breath</td><td rowspan="2">Or from 1 to 3 test of BIPAP ventilation with pressure of 10 cmH_2O above PEEP</td></tr>
<tr><td>Volume-controlled breath</td><td>Pressure-controlled breath</td></tr>
<tr><td>2</td><td colspan="3">Determine and maintain the next inspiratory pressure
–Maximum increase/decrease is 2 cmH_2O
–Maximum peak pressure until the preset limit</td><td>$\text{Inspiratory pressure} = \frac{\text{VT}(\text{preset})}{\text{compliance}}$</td></tr>
<tr><td>3</td><td colspan="3">Measure tidal volume and compute for lung compliance
(VT is inspiratory VT that is compensated by leak or expiratory VT that is compensated by leak)</td><td>$C = \frac{\text{VT}(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td>4</td><td colspan="3">Return to step 2</td><td>Loop process is closed</td></tr>
</table>

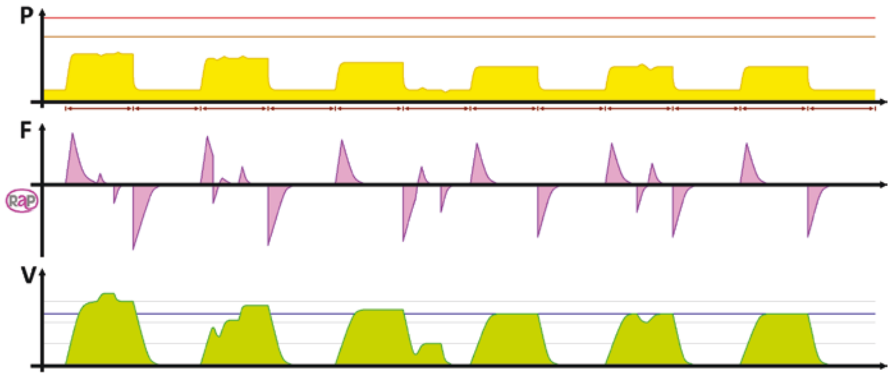


Fig. 6.25 Waveform of decreasing inspiratory pressure breath-by-breath to meet preset VT

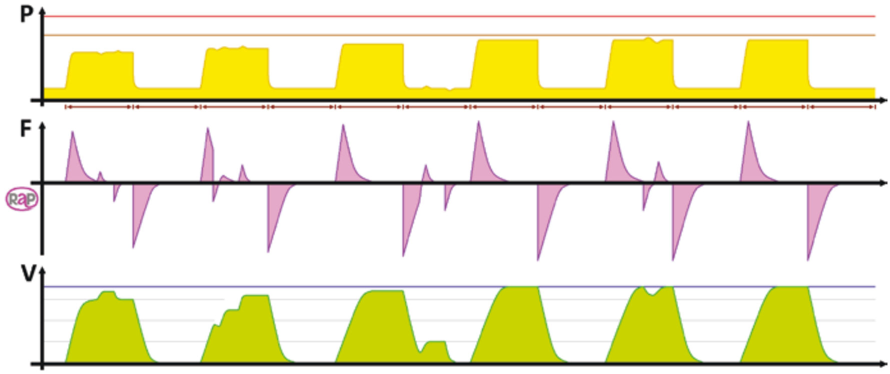


Fig. 6.26 Waveform of increasing inspiratory pressure breath-by-breath to meet preset VT

In Fig. 6.25, inspiratory pressure will decrease gradually breath-by-breath with maximum decrease of 2 cmH_2O to reach the preset VT (measured VT > preset VT) or if there is patient's effort that will be added to the measured VT accumulatively (VTi > VTe in spontaneous breath).

In Fig. 6.26, inspiratory pressure will increase gradually breath-by-breath with maximum increase of 2 cmH_2O to reach the preset VT (measured VT < preset VT) or if patient exhales which decreases measured VT accumulatively (VTi < VTe in spontaneous breath) or lack of patient's spontaneous breath on upper level of inspiratory pressure.

6.3.6 Breath-to-Breath: Pressure Support with Volume Guarantee

Background – required changes in airway pressure for every change of strength of patient's respiratory drive while breathing. See Fig. 6.27 for phase of pressure support with volume guarantee and Table 6.3 for stages breath-to-breath of the ventilation mode.

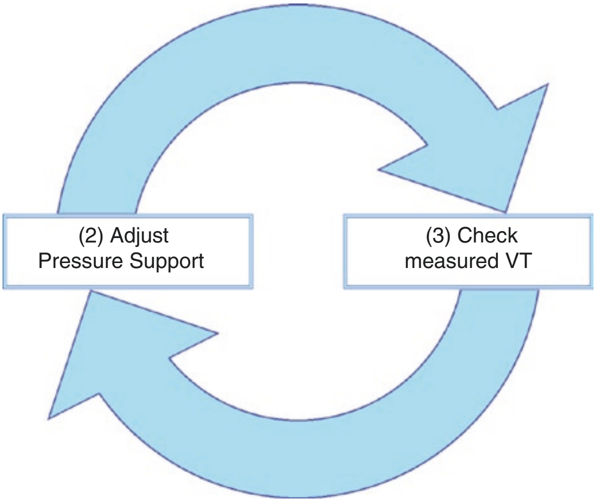


Fig. 6.27 Phase of pressure support with volume guarantee

Table 6.3 Stages breath-to-breath of pressure support with volume guarantee

<table>
<tr><th>No.</th><th colspan="3">The stages</th><th>Notes</th></tr>
<tr><td rowspan="3">1</td><td colspan="3">Initiation of breath:
Measure/compute lung compliance</td><td rowspan="3">Volume-controlled:
$C = \frac{\text{VT}(\text{preset})}{\text{plateau pressure}}$
Pressure-controlled:
$C = \frac{\text{VT}(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td colspan="2">From the previous breath</td><td rowspan="2">Or from 1 to 3 test of pressure support with pressure of 10 cmH_2O above PEEP</td></tr>
<tr><td>Volume-controlled breath</td><td>Pressure-controlled or Pressure support breath</td></tr>
<tr><td>2</td><td colspan="3">Determine and apply the next inspiratory pressure
–Maximum increase/decrease is 2 cmH_2O
–Maximum peak pressure until the preset limit</td><td>$\text{Inspiratory pressure} = \frac{\text{VT}(\text{preset})}{\text{compliance}}$</td></tr>
<tr><td>3</td><td colspan="3">Measure tidal volume and compute for lung compliance (VT is inspiratory VT that is compensated by leak or expiratory VT that is compensated by leak)</td><td>$C = \frac{\text{VT}(\text{measured})}{\text{inspiratory pressure}}$</td></tr>
<tr><td>4</td><td colspan="3">Return to step 2</td><td>Loop process is closed</td></tr>
</table>

Where VT measured depends on the strength of the respiratory muscles while inhaling and also depends on the lung compliance.

In Fig. 6.28, inspiratory pressure will decrease gradually breath-by-breath with maximum decrease of 2 cmH_2O to reach the preset VT (measured VT > the preset VT):

– When starting of breath is PS VG.
– If patient's effort is stronger, that will also add the measured VT, and so to maintain VT to make it the same as the desired/preset VT and does not exceed the VT limit, then pressure support will decrease automatically but breath-by-breath. If pressure support decreases until it is zero (above PEEP), then it is the same as CPAP.

In Fig. 6.29, inspiratory pressure will increase gradually breath-by-breath with maximum increase of 2 cmH_2O to reach the preset VT (measured VT < preset VT):

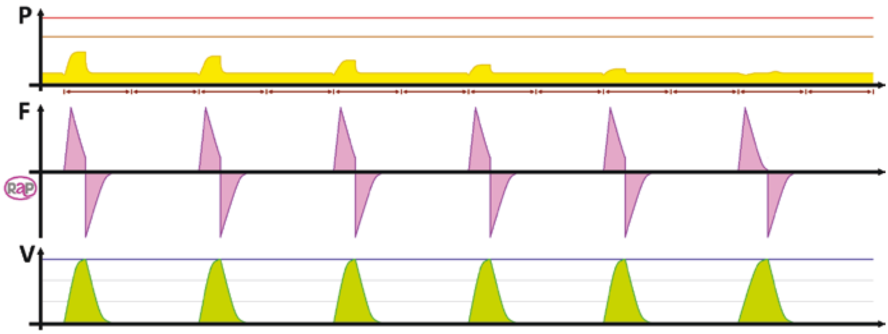


Fig. 6.28 Waveform of decreasing inspiratory pressure breath-by-breath to meet preset VT

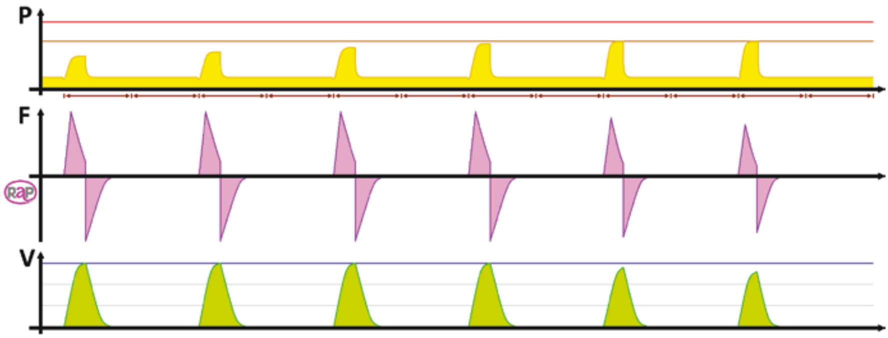


Fig. 6.29 Waveform of increasing inspiratory pressure breath-by-breath to meet preset VT

– When starting of breath is PS VG.
– If patient's effort is getting weaker, that decreases measured VT, and so to maintain VT to make it the same as the desired/preset VT and is enough for the patient, then pressure support will increase automatically but breath-by-breath. If pressure increases until pressure limit but the preset VT has not been reached, then a notification will appear "Tidal Volume has not been reached, Inspiratory Pressure is limited."

6.4 Minute Volume Guarantee and Adaptive Support Ventilation Mode

6.4.1 Guarantee/Mandatory Minute Volume Ventilation Mode

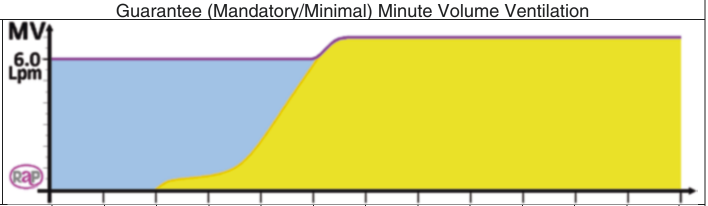
→Spontaneous MV + Mandatory MV ≥ Preset MV

In Fig. 6.30, parameter settings are the following:

- RR (respiratory rate), for example, is 12 breath/min
  – Ti (inspiratory time), for example, is 1.25 s → I:E Ratio = 1:3
- VT (tidal volume), for example, is 500 mL
  – Inspiratory flow, for example, 500 mL/s (30 LPM) → Tplateau = 0.25 s

Guarantee (Mandatory/Minimal) Minute Volume Ventilation

Setting :
Mandatory breath:
MV = 6.0 L/min
- RR = 12breath/min
- VT = 500 mL
Spontaneous breath:
PS = 10 cmH_2O



Spontaneous Breath													
a.	Spontaneous RR(breath/min)	0	0	2	4	10	14	14	14	14	14	14	14
b.	Preset PS (cmH_2O)	10	10	10	10	10	10	8	6	4	2	0	0
c.	Spontaneous VT(mL)	0	0	250	250	400	500	500	500	500	500	500	500
d.	Spontaneous MV(L/min)	0	0	0.5	1.0	4.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Mandatory Breath													
e.	Mandatory RR (breath/min)	12	12	11	10	4	0	0	0	0	0	0	0
f.	Preset VT (mL)	500	500	500	500	500	500	500	500	500	500	500	500
g.	Mandatory MV (L/min)	6.0	6.0	5.5	5.0	2.0	0	0	0	0	0	0	0
Total Breaths													
h.	Total RR (breath/min)	12	12	13	14	14	14	14	14	14	14	14	14
i.	Total MV (L/min)	6.0	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Categorization of mode:		Controlled		Intermittent			Spontaneous					CPAP	

- RR (Respiratory Rate), for example,is 12 breath/min
  - Ti (Inspiratory Time), for example,is 1.25 sec→I:E Ratio = 1:3
- VT (TidalVolume), for example,is 500 mL
  - Inspiratory Flow, for example, 500mL/sec(30 LPM) →Tplateau = 0.25 secC
- Flow Trigger, for example,is 2 LPM
- PS (Pressure Support), for example is10 cmH_2O
  - Slope, for example,is 0.25sec
- PEEP (Positive End Expiratory Pressure), for example,is 5 cmH_2O

Fig. 6.30 Guarantee minute volume with preset tidal volume

- Flow trigger, for example, is 2 LPM
- PS (pressure support), for example, is 10 cmH_2O
  – Slope, for example, is 0.25 s
- PEEP (positive end expiratory pressure), for example, is 5 cmH_2O

With those parameters:

– Preset MV is 6 L/min
– Total MV = spontaneous MV + mandatory MV
– Required: total MV ≥ preset MV, or: (spontaneous MV + mandatory MV) ≥ preset MV
– Result: mandatory MV ≥ preset MV – spontaneous MV, which means:
  every 5 s (60 s/RR) ventilator computes for the total MV then mandatory breath will only be delivered if total MV < preset MV or tends to decrease.

See Fig. 6.31 for different waveforms in different ventilation modes which are based on patient's breath also.

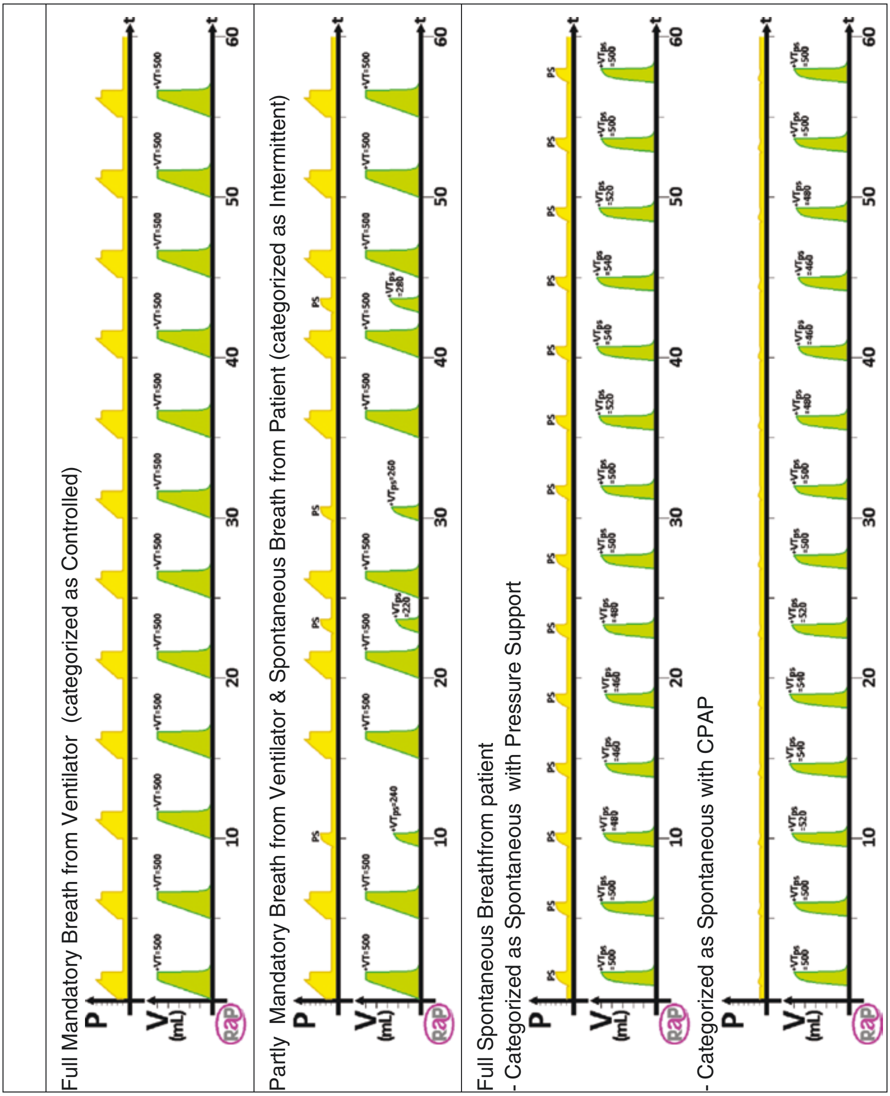


Fig. 6.31 Different waveforms in different ventilation modes

If lung compliance decreases (lung is stiffer):

– In mandatory breath→
  - Delivery of inspiratory tidal volume will be maintained (prevention of collapsed alveoli), but compliance pressure will increase (monitor and limit it with airway pressure limit alarm to prevent barotrauma).
– In spontaneous breath→
  - With the same preset value of pressure support, spontaneous tidal volume on inspiration will decrease with the same patient's effort.

- Required greater patient's effort and strong respiratory muscles to inhale the same tidal volume just before decreasing of lung compliance happens.
- Continuous decrease of spontaneous tidal volume on inspiration can decrease spontaneous MV (minute volume).
- If that also causes decreasing of total MV, then mandatory breath will be delivered, and total mandatory breath will be added.

If lung compliance increases:

– In mandatory breath→
  - Delivery of tidal volume will be maintained (prevention of volutrauma in the alveoli), and compliance pressure will decrease.
  - Monitor changes in expiratory flow which is the cause of increased lung compliance to ensure expiration has ended.
– In spontaneous breath→
  - With the same preset value of pressure support, the spontaneous tidal volume on inspiration will increase with the same patient's effort.
  - Patient could decrease his effort to inhale the same tidal volume just before decreasing of lung compliance happens.
  - Continuous increase of spontaneous tidal volume on inspiration can increase spontaneous MV.
  - If that also causes increasing of total MV, then total mandatory breath will be reduced.
  - Monitor changes in expiratory flow which is the cause of increased lung compliance to ensure expiration has ended.

In changes of respiratory drive of the patient:

– If strength of respiratory drive increases→
  - Spontaneous tidal volume will also increase, because respiratory muscles are getting stronger while inhaling.
  - Increasing spontaneous tidal volume continuously can also increase spontaneous MV.
  - If that also causes increasing of total MV, then total mandatory breath will be reduced.
– If strength of respiratory drive decreases→
  - Spontaneous tidal volume will also decrease, because respiratory muscles are weaker, and the patient inhales shallow breaths.
  - Decreasing of spontaneous tidal volume continuously can decrease spontaneous MV.
  - If that also causes decreasing of total MV, then mandatory breath will be delivered, and total mandatory breath will be added.

Weaning Process (Passive):

1. Step one is to wait for total trigger of spontaneous breath to increase.
2. Pressure support can be decreased when patient's effort is strong enough and is able to inhale deeply.

Change of minute volume:

- Decreasing MV (active weaning process by stimulation in order for total trigger of spontaneous breath to increase)
  1. By decreasing VT and/or RR while monitoring total MV
  2. By decreasing PS if patient's effort is strong enough to be able to inhale deeply while monitoring spontaneous VT and total MV
- Increasing MV (more removal of CO_2)
  1. By increasing RR and/or VT while monitoring total MV and airway pressure limit alarm
  2. By increasing PS while monitoring spontaneous VT and total MV

6.4.2 Adaptive Support Ventilation

In Passive Patients

Adaptive support ventilation is a volume-targeted pressure-controlled mode with automatic adjustment of inspiratory pressure, respiratory rate, and inspiratory/expiratory time ratio or I:E ratio (Table 6.4). Maximum tidal volume is controlled by

Table 6.4 Variables in adaptive support ventilation that is adjustable

Automatic adjustment		
Inspiratory pressure	Respiratory rate	I:E ratio

1. Assess the patient's lung mechanics breath by breath.
2. Optimize the tidal volume/respiratory frequency combination breath by breath based on lung mechanics.
3. Achieve optimum tidal volume / respiratory frequency by automatically adjusting mandatory rate and inspiratory pressure

Fig. 6.32 Steps in operating adaptive support ventilation setting a Pmax (Plimit). Expiratory time is determined according to the expiratory time constant to prevent dynamic hyperinflation.

In Active Patients

In spontaneously breathing patients, adaptive support ventilation is a volume-targeted pressure support mode with automatic adjustment of pressure support according to the spontaneous respiratory rate. There are steps in operating this ventilation which is showed in Fig. 6.32, and the stages to preset the settings are showed in Table 6.5.

Table 6.5 Stages in adjusting setting of adaptive support ventilation

<table>
<tr><th>No.</th><th colspan="2">The stages</th><th>Notes</th></tr>
<tr><td colspan="4">User settings:</td></tr>
<tr><td>1</td><td colspan="2">Set patient height and gender</td><td>Ventilator will calculate:
–Patient’s ideal body weight
–Normal minute volume
Adult = 100 mL/kg/min
Pediatric = 300 mL/kg/min
–Dead space (Vd = 2.2 mL/kg)</td></tr>
<tr><td>2</td><td colspan="2">Set the target minute volume (%MinVol)</td><td>Target MV = %MinVol × normal minute volume</td></tr>
<tr><td>3</td><td colspan="2">Set oxygenation controls (PEEP and oxygen in percent)</td><td></td></tr>
<tr><td>4</td><td colspan="2">Set controls for synchronization and lung protection (pressure ramp, patient trigger sensitivity, expiratory trigger sensitivity, and maximum pressure limit)</td><td></td></tr>
<tr><td colspan="4">Ventilator process in loop:</td></tr>
<tr><td>5</td><td colspan="2">Ventilator will calculate and draw minute volume curve</td><td></td></tr>
<tr><td rowspan="2">6</td><td colspan="2">Ventilator will deliver and/or measure breath</td><td rowspan="2">Ventilator will calculate:
–Airway resistance
–Lung compliance
–Time constant (RCe)
–RR optimal (Otis)
–VT optimal
–Expiratory time</td></tr>
<tr><td>From previous breath</td><td>Or from three initial test breaths</td></tr>
<tr><td>7</td><td colspan="2">Ventilator will calculate and draw safety frame</td><td>Lung protective rules</td></tr>
<tr><td>8</td><td colspan="2">Ventilator will calculate and draw optimal breath pattern (optimal RR and VT) as target circle</td><td>RR based on Otis equation</td></tr>
<tr><td>9</td><td colspan="2">Ventilator will draw current patient values (the cross)</td><td>Current patient values:
–Measured VT
–Current RR</td></tr>
<tr><td>10</td><td colspan="2">Ventilator continuously adjust the settings (approaching the target):
–To keep the patient within the target zone
–To guide the patient to the target point (optimal ventilation)</td><td>Automatic adjustment:
–Inspiratory pressure breath-by-breath to achieve VT, in mandatory breath
–Pressure support breath-by-breath to achieve VT, in spontaneous breath
–Next mandatory breath (if required), based on RR from Otis equation
–Expiratory time of next mandatory breath</td></tr>
<tr><td>11</td><td colspan="2">Return to step 6 (or 5 if %MinVol setting was changed)</td><td>Closed loop process</td></tr>
</table>

Ventilator calculation (Table in Fig. 6.33) and drawing of minute volume curve (Fig. 6.33) with example in Table 6.6.

The ventilator will deliver three initial test breaths using the following parameters showed in Tables 6.7, 6.8, and 6.9. It is then converted into a curve in Fig. 6.34.

(a) Avoid barotrauma and volutrauma.
  - Avoid barotrauma with Pmax (Plimit) setting, therefore ΔP allowed = Pmax − 10 − PEEP.
  - Avoid volutrauma, VT max = (ΔP allowed) × Cdyn, where VT max <22 mL/kg IBW.
  - With the example above, VT max = (40 − 10 − 5) × 40 = 1000 mL.

(b) Avoid low alveolar ventilation.

MV 6 L/min	
RR	VT (mL)
1	6000.0
2	3000.0
3	2000.0
4	1500.0
5	1200.0
6	1000.0
7	857.1
8	750.0
9	666.7
10	600.0
11	545.5
12	500.0
13	461.5
14	428.6
15	400.0
16	375.0
17	352.9
18	333.3
19	315.8
20	300.0
25	240.0
30	200.0
35	171.4
40	150.0
45	133.3
50	120.0
55	109.1
60	100.0
65	92.3
70	85.7
75	80.0
80	75.0

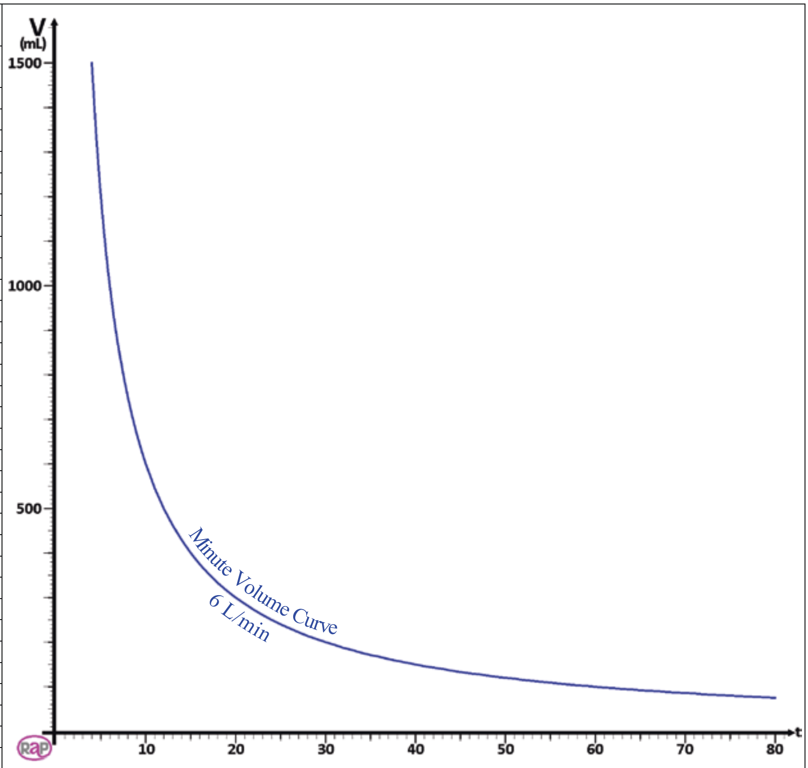


Fig. 6.33 Minute volume curve in ventilator

Table 6.6 Example ASV setting for current case

Settings	Calculated (initially)
Adult, 60 kg IBW	Vd = 60 × 2.2 = 132 mL
%MinVol = 100%	Target minute volume = 100% × 0.1 × 60 = 6 L/min
Plimit = 40 cmH_2O	
PEEP = 5 cmH_2O	
Others	

Table 6.7 Initial breath pattern for pediatric

IBW (kg)	Pinsp (cmH_2O)	Ti (s)	SIMV rate (breath/min)	Minimum target rate (breath/min)
3–5	15	0.4	30	15
6–8	15	0.6	25	12
9–11	15	0.6	20	10
12–14	15	0.7	20	10
15–20	15	0.8	20	10
21–23	15	0.9	15	7
24–29	15	1.0	15	7

Table 6.8 Initial breath pattern for adult

IBW (kg)	Pinsp (cmH_2O)	Ti (s)	SIMV rate (breath/min)	Minimum target rate (breath/min)
30–39	15	1.0	14	7
40–59	15	1.0	12	6
60–89	15	1.0	10	5
90–99	18	1.5	10	5
≥100	20	1.5	10	5

Table 6.9 Parameter for three test breaths based on Tables 6.7 and 6.8

Parameter for three test breaths	Measured values
IBW = 60 kg Pinsp = 15 cmH_2O Ti = 1 s SIMV rate = 10 breath/min Minimum target rate = 5 breath/min	Total resistance =10 cmH_2O/L/s Total compliance =40 mL/cmH_2O =0.04 L/cmH_2O

  - VT min = 2 × Vd, where Vd = 2.2 mL/kg.
  - With the example above, VT min = 2 × 2.2 × 60 = 264 mL.

(c) Avoid dynamic hyperinflation or breath stacking.
  - RR max = (20/RCexp) where RR max <60 breath/min.
  - With current example above:

- RR max = 20/(10 × 0.04) = 50 breath/min
  - (Maximum ventilator rate = MinVol/(2 × Vd) = 22 × %MinVol/100).
  - This limit is for ventilator rate only; not to the patient rate.

(d) Avoid apnea.
  - RR min = 5 breath/min.

In Table 6.10, ventilator will calculate optimal/target breath pattern with Otis equation, with example in Table 6.9.

where ***a*** is a factor that depends on the flow waveform.

For sinusoidal flow, ***a*** is $2\pi^2/60$.

The ventilator will measure/draw actual breath pattern and approach the target (Fig. 6.35).

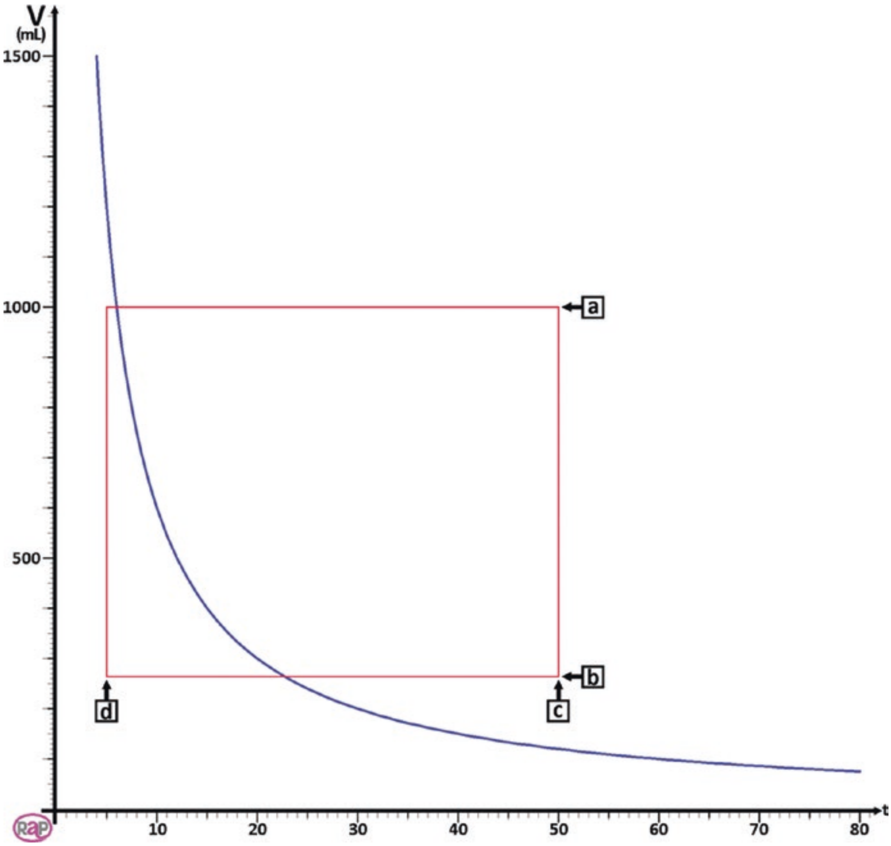


Fig. 6.34 Minute volume curve showing the safety frame. Safety frame defined by lung-protective rules

Table 6.10 Calculated optimal/target breath

Calculated	Measured
MinVol = **6** L/min f from last breaths (which is test breath) = **10** breath/min Vd = 132 mL = **0.132** L	R = 10 $cmH_2O/L/s$ C = 0.04 L/cmH_2O RCe = Re × C = **0.4** s
Optimal/target RR using Otis equation: $$f = \frac{\sqrt{1+2a+RCe\times(MinVol-(f\times VD))/Vd}-1}{a\times RCe} = \frac{\sqrt{1+\left[\frac{4}{60}^{2}\times 0.4\times\frac{(6-(10\times 0.132))}{0.132}\right]}-1}{\frac{2}{60}^{2}\times 0.4} = 16$$ While optimal/target VT = MinVol/16 = 375 mL	

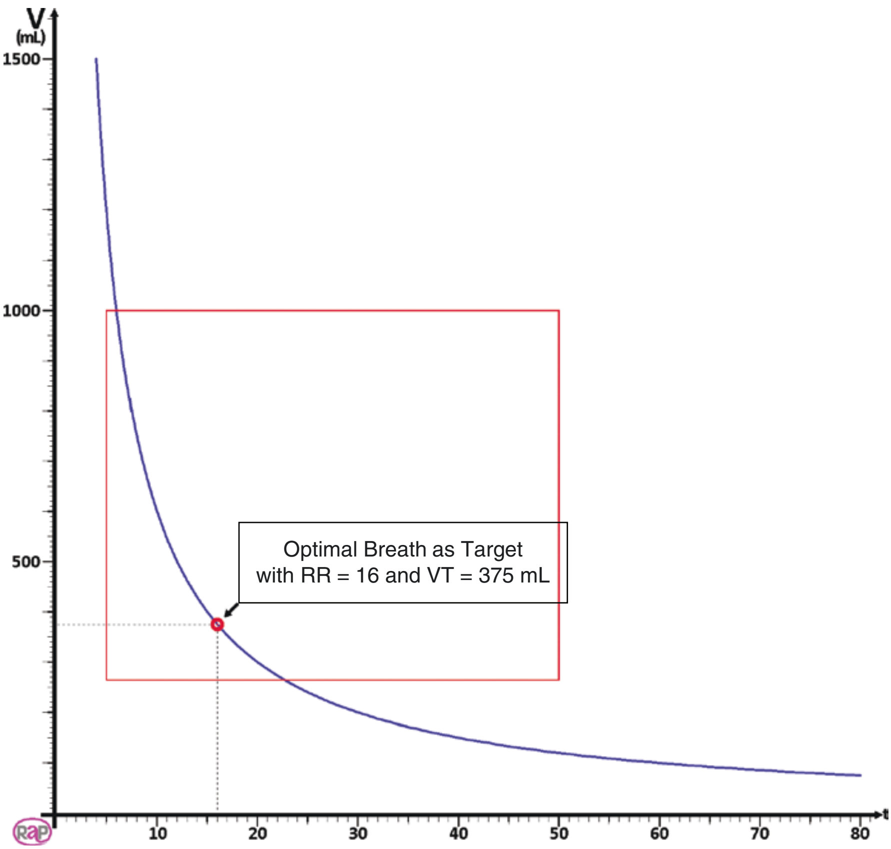


Fig. 6.35 The ventilator will draw optimal breath pattern (optimal RR and VT) as target circle

See Fig. 6.36. The actual breath pattern will be plotted as a cross, which shows clear deviation from the target. The actual VT is calculated as the average of inspiratory and expiratory volumes of the last eight breaths. This definition compensates in part for leaks in the breathing circuit, including the endotracheal tube.

The task of ASV is now to move the cross as close to the circle as possible.

To achieve the target, the strategy in Table 6.11 is used.

As a result, the cross moves toward the circle.

6.4.2.1 Dynamic Adjustment of Lung Protection and Optimal Breath Pattern

If the respiratory system mechanics change, and whether compliance and/or resistance changes, the safety limits and target value (circle) change accordingly. The safety limits and target value (circle) are updated on a breath-by-breath basis. See Fig. 6.37.

(a) Avoid barotrauma and volutrauma.

1. Cdyn = 50 mL/cmH_2O → VT max = (Pmax − 10 − PEEP) × Cdyn = (40 − 10 − 5) × 50 = 1250 mL

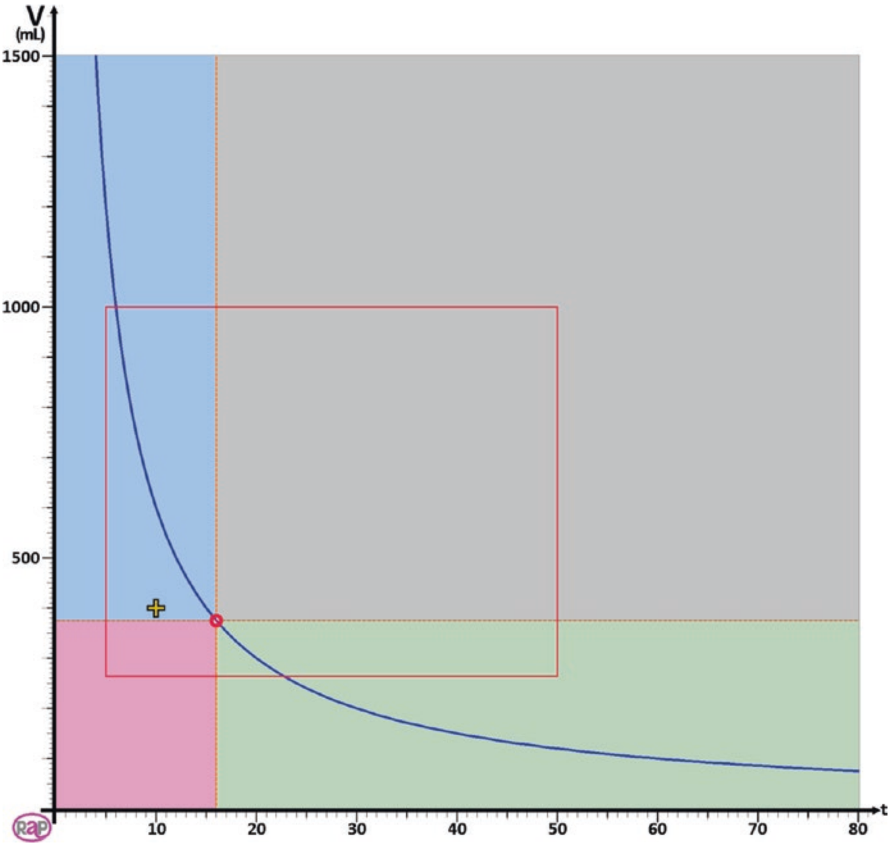


Fig. 6.36 Minute volume curve with optimal breath pattern

Table 6.11 Strategy to achieve target

Actual Vt > target Vt, the inspiratory pressure is decreased	Actual rate < target rate, the SIMV rate is increased
Actual Vt > target Vt, the inspiratory pressure is decreased	Actual rate > target rate, the SIMV rate is decreased
Actual Vt < target Vt, the inspiratory pressure is increased	Actual rate > target rate, the SIMV rate is decreased
Actual Vt < target Vt, the inspiratory pressure is increased	Actual rate < target rate, the SIMV rate is increased
If actual Vt = target Vt, the inspiratory pressure is left unchanged If actual rate = target rate, the SIMV rate is left unchanged	

2. Cdyn = 30 mL/cmH_2O → VT max = (Pmax − 10 − PEEP) × Cdyn = (40 − 10 − 5) × 30 = 750 mL

(b) Avoid low alveolar ventilation.
 – VT min = 2 × Vd = 2 × 2.2 × 60 = 264 mL

(c) Avoid dynamic hyperinflation or breath stacking.

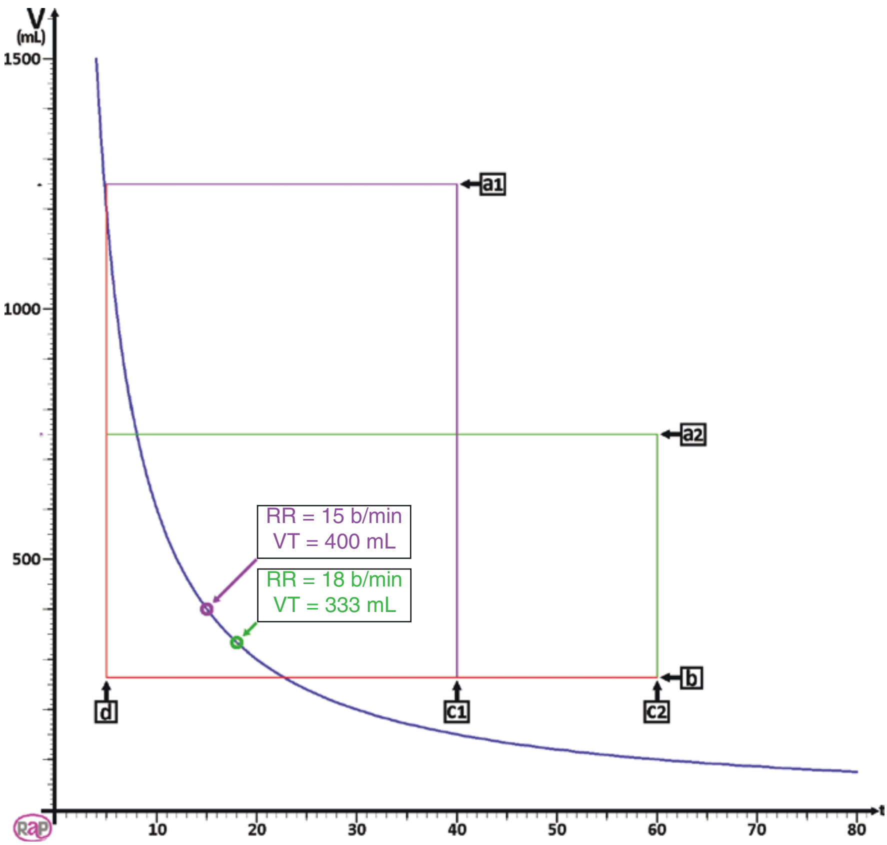


Fig. 6.37 Optimal breath pattern with the safety limits

c1. $R = 10\,cmH_2O$ and $C = 0.05\,L/cmH_2O \rightarrow$ RR max = 20/(10 × 0.05) = 40 breath/min

c2. $R = 10\,cmH_2O$ and $C = 0.06\,L/cmH_2O \rightarrow$ RR max = 20/(10 × 0.03) = 66 ≈ 60 breath/min

(d) Avoid apnea.

– RR min = 5 breath/min

RCe = 0.5 → f (Otis) = 15 breath/min, VT = 6000/15 = 400 mL
RCe = 0.3 → f (Otis) = 18 breath/min, VT = 6000/18 = 333 mL

7 Advanced Ventilation Graph

7.1 Introduction

Nowadays, there are many ventilators that have improved. There are ventilators without screen or even touch screen, rather just the buttons or knob to set the ventilator. As the previous two chapters have talked about the basic ventilation modes and advanced ventilation modes, in this chapter, it will show those graphs of basic ventilation modes and even some of advanced ventilation modes. These basic ventilation and advanced ventilation graphs can help more to understand modes showed on the screen of mechanical ventilator.

Generally, it is important for the clinician or user to understand what those graphs mean or clinician can even tell what mode the ventilator has been set by looking at those graphs. In this chapter, graphs that will be showed are graphical loops of full-controlled, assist-controlled, and spontaneous graphical loops in airway resistance and lung compliance change and graphical loops of leakage indication and upper or lower inflection. For example, in volume-controlled mode, the flow graph is often square, while in pressure-controlled mode, the pressure graph is often square. This chapter will further show and describe those graphs above.

7.2 Graphical Loops of (Full/Assist) Controlled Breath and Spontaneous Breath

There are many different graphs and loops we would usually encounter on ventilator. For example, in Fig. 7.1, it shows waveforms of volume-time and pressure-time and pressure-volume loop. The pressure-volume loop is made from those two waveforms. While in Fig. 7.2, it shows the waveforms of full-controlled breath which are volume-controlled and pressure-controlled, in Fig. 7.3, it shows their respective graphical loops.

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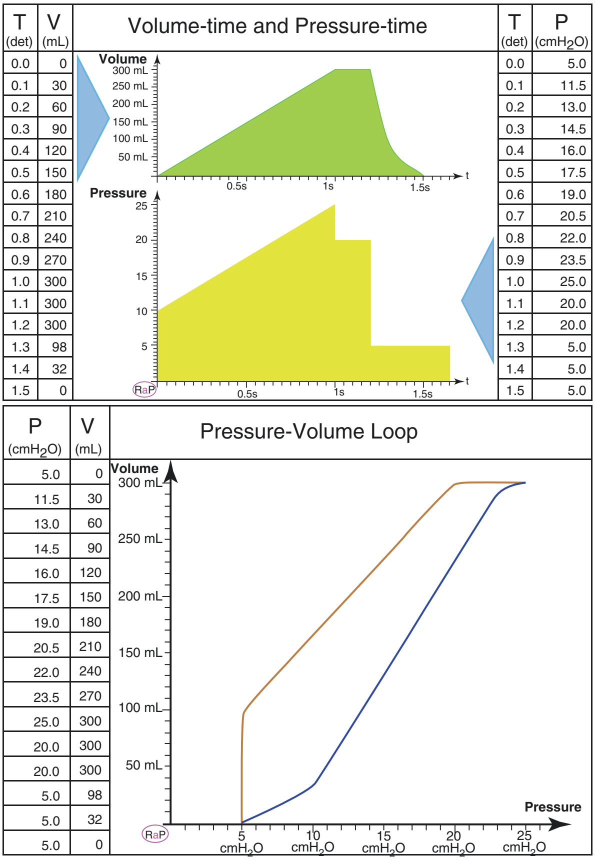
DOI 10.1007/978-981-10-5340-5_7



T (det)	V (mL)
0.0	0
0.1	30
0.2	60
0.3	90
0.4	120
0.5	150
0.6	180
0.7	210
0.8	240
0.9	270
1.0	300
1.1	300
1.2	300
1.3	98
1.4	32
1.5	0

T (det)	P (cmH_2O)
0.0	5.0
0.1	11.5
0.2	13.0
0.3	14.5
0.4	16.0
0.5	17.5
0.6	19.0
0.7	20.5
0.8	22.0
0.9	23.5
1.0	25.0
1.1	20.0
1.2	20.0
1.3	5.0
1.4	5.0
1.5	5.0

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

Fig. 7.1 Example of volume-time and pressure-time waveform and also pressure-volume loop

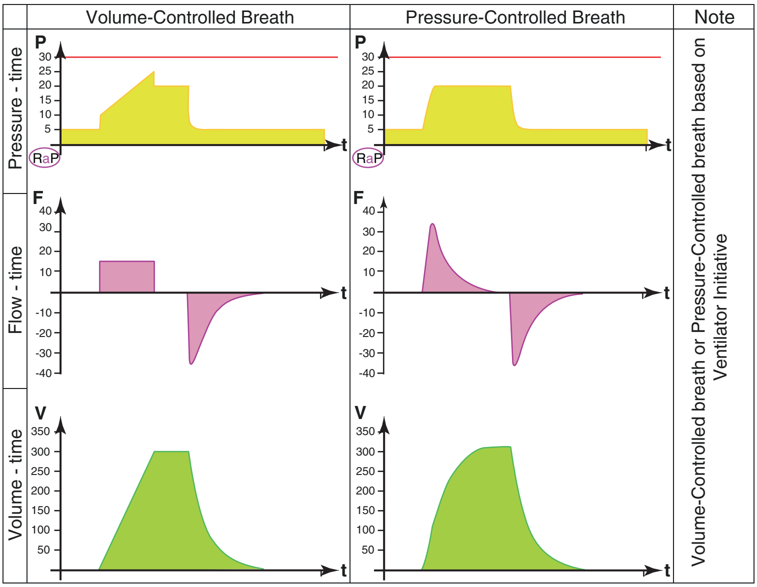


Fig. 7.2 Waveform of full-controlled breath

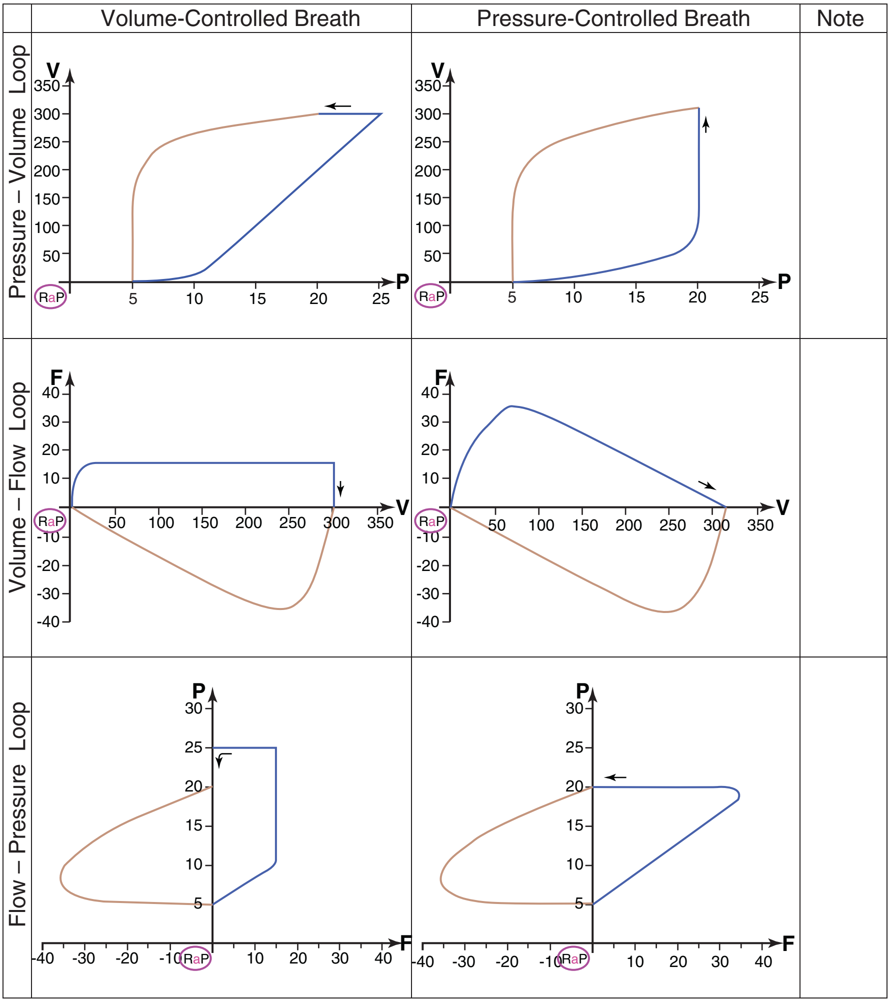


Fig. 7.3 Graphical loops of full-controlled breath

In Fig. 7.4, it shows the waveforms of assist-controlled breath and their respective graphical loops, while in Fig. 7.5, it shows waveforms of pressure support breath with lower and higher respiratory drive with their respective graphical loops.

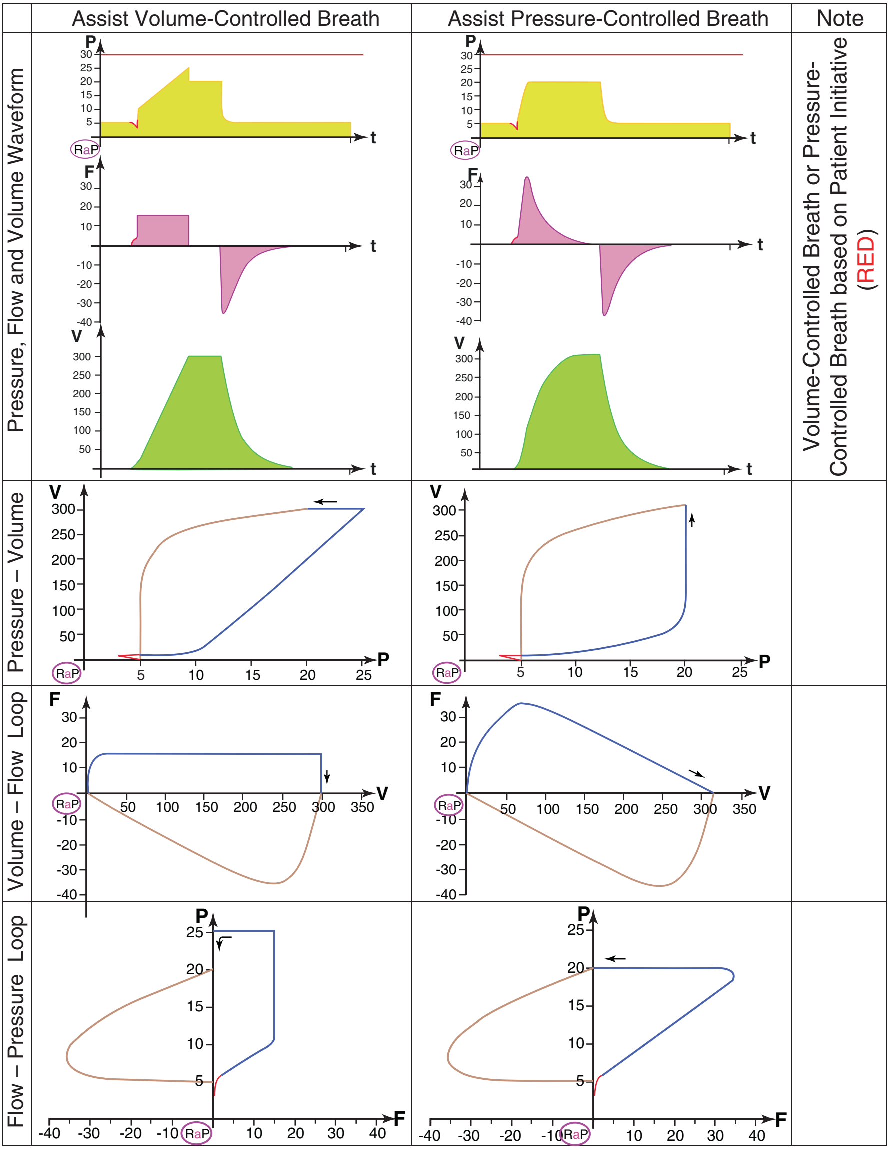


Fig. 7.4 Waveform and graphical loop of assist-controlled breath

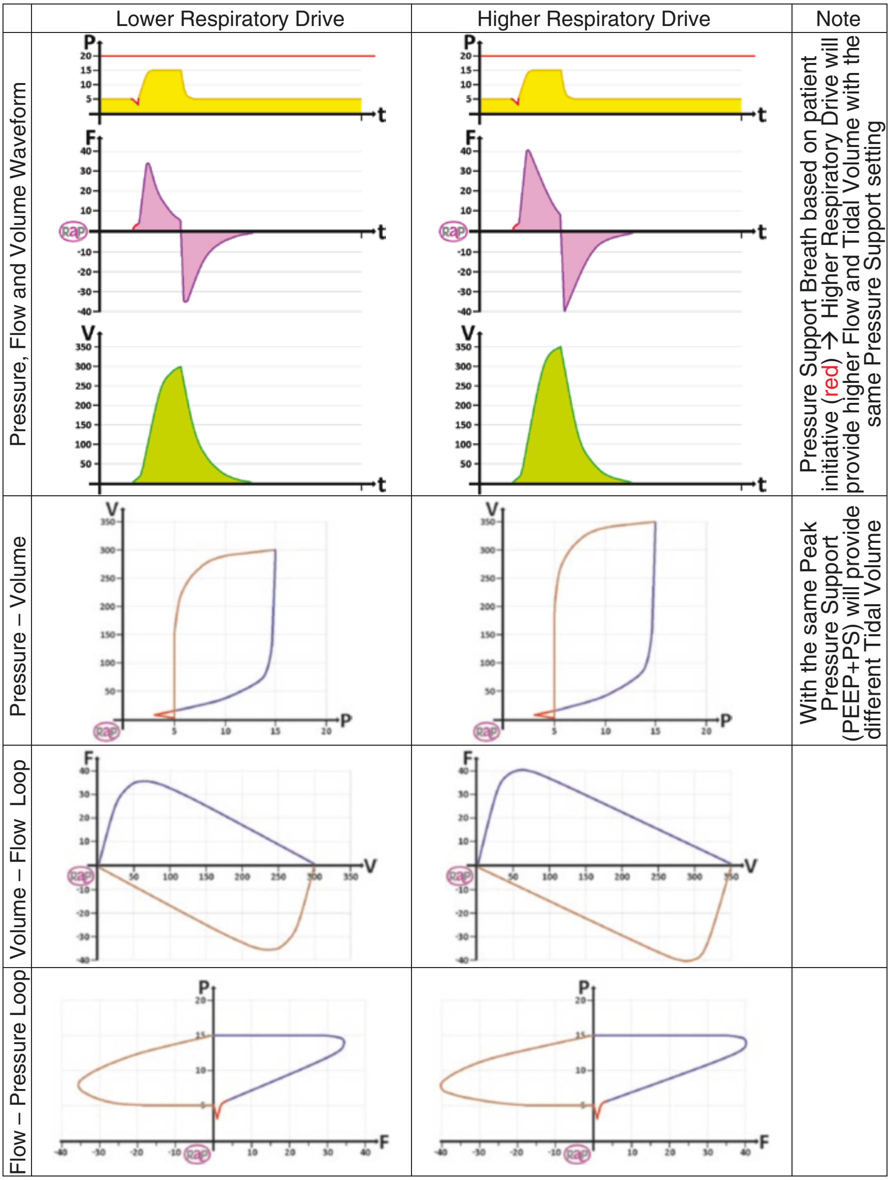


Fig. 7.5 Waveform and graphical loop of pressure support breath

7.3 Graphical Loops in Airway Resistance and Lung Compliance Change

In Fig. 7.6, it shows the waveforms of volume-controlled and pressure-controlled ventilation modes when airway resistance increases with their respective graphical loops.

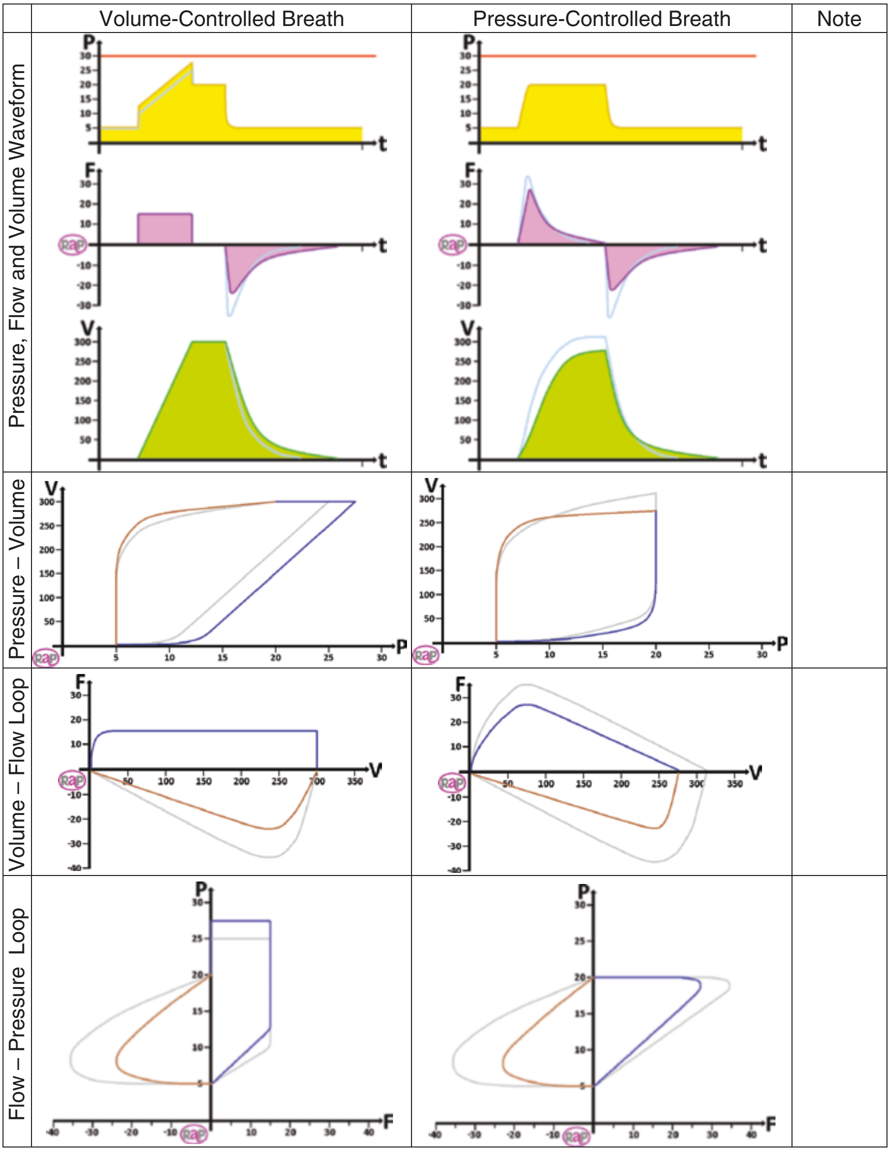


Fig. 7.6 Graphical loops in case of increased airway resistance

In Fig. 7.7, it shows the same ventilation mode waveforms but when the lung compliance decreases with their respective graphical loops.

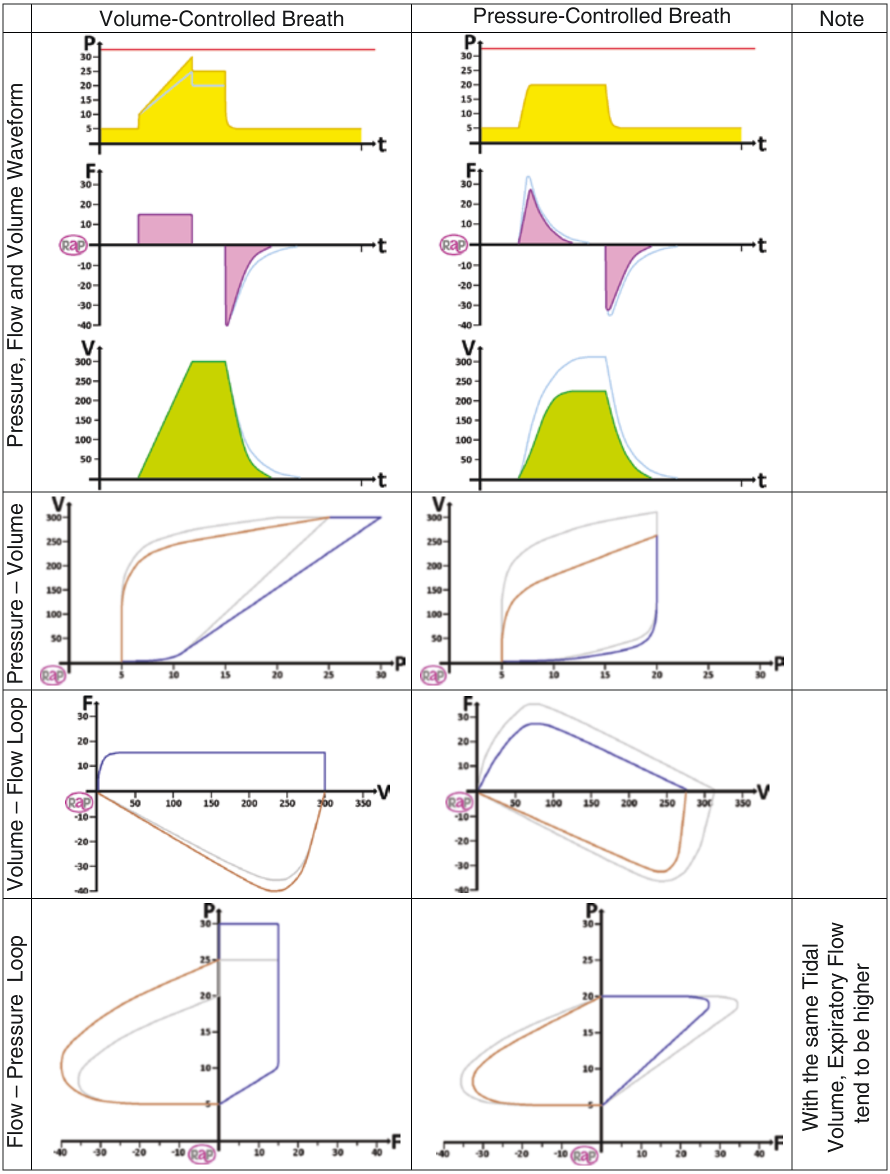


Fig. 7.7 Graphical loops in case of decreased lung compliance

7.4 Leakage Indication and Upper/Lower Inflection Points on Graphical Loops

Inspiratory volume from the ventilator inspiratory port may have a leak during inspiration especially on high pressure which causes received inspiratory volume by the patient to be smaller.

Expiratory volume produced by the patient may have a leak during expiration, even just a small leak, because of the lowest pressure which is PEEP, which causes expiratory volume to the ventilator expiratory port to be smaller (Figs. 7.8 and 7.9).

Patient inspiratory VT < VT from ventilator inspiratory port

VT to ventilator expiratory port < patient expiratory VT

Therefore, VT that returns to the expiratory port is smaller than VT from the inspiratory port.

See Fig. 7.10. It shows the lower and upper inflection point graphic loop.

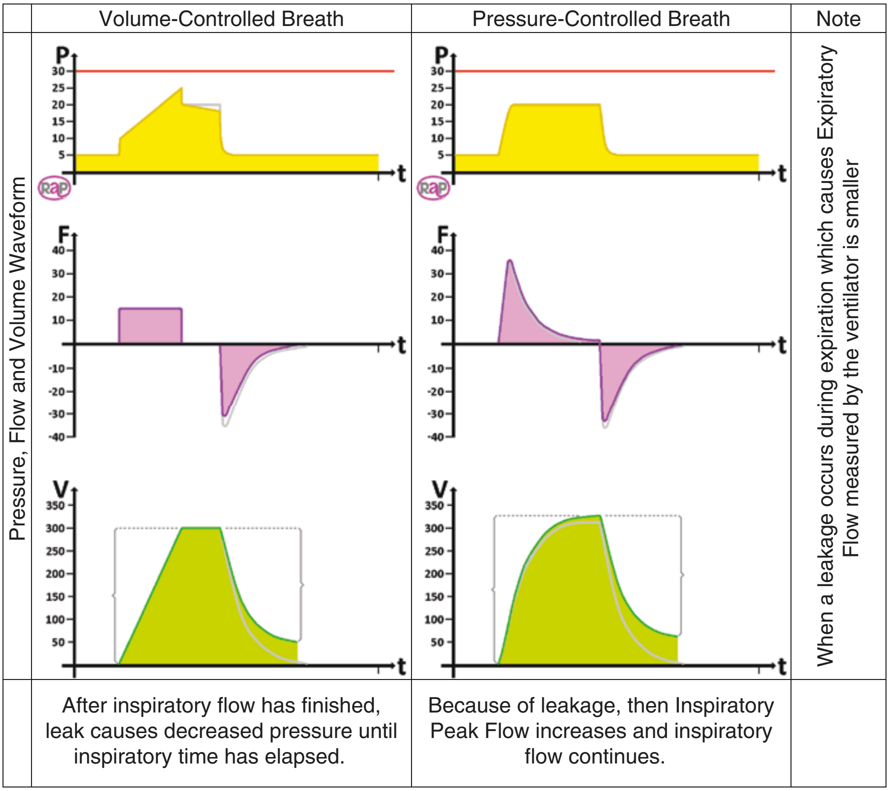


Fig. 7.8 Leakage indications on waveforms or graphs

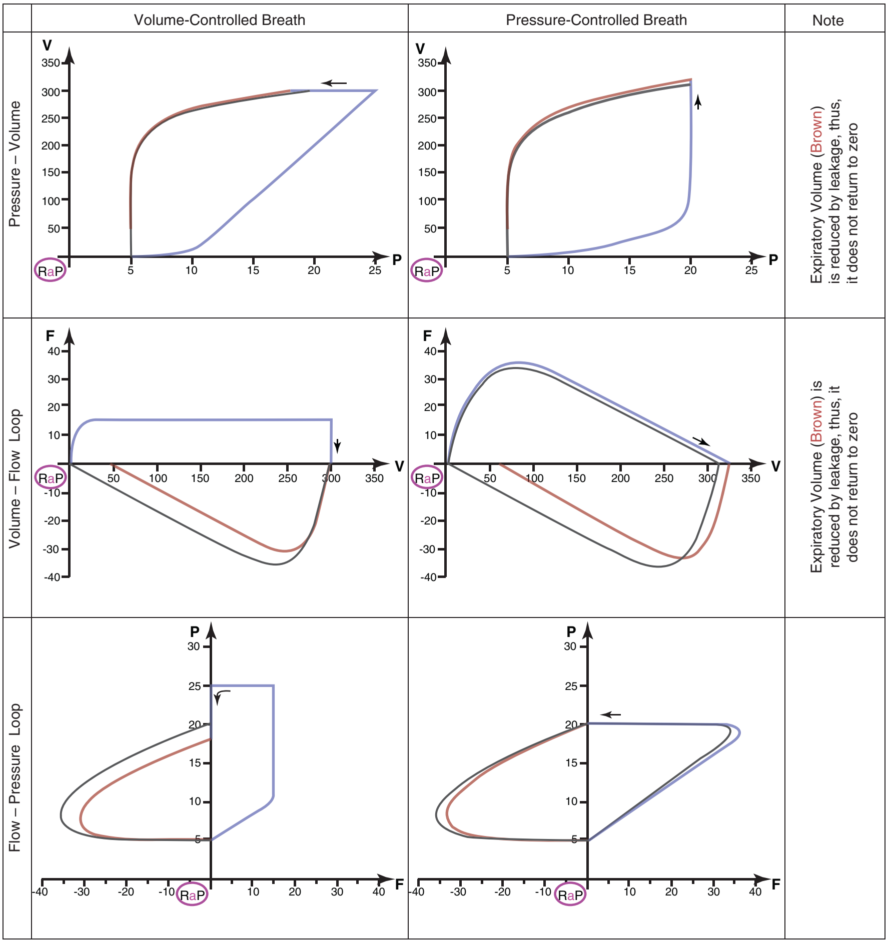


Fig. 7.9 Leakage indications on graphic loops

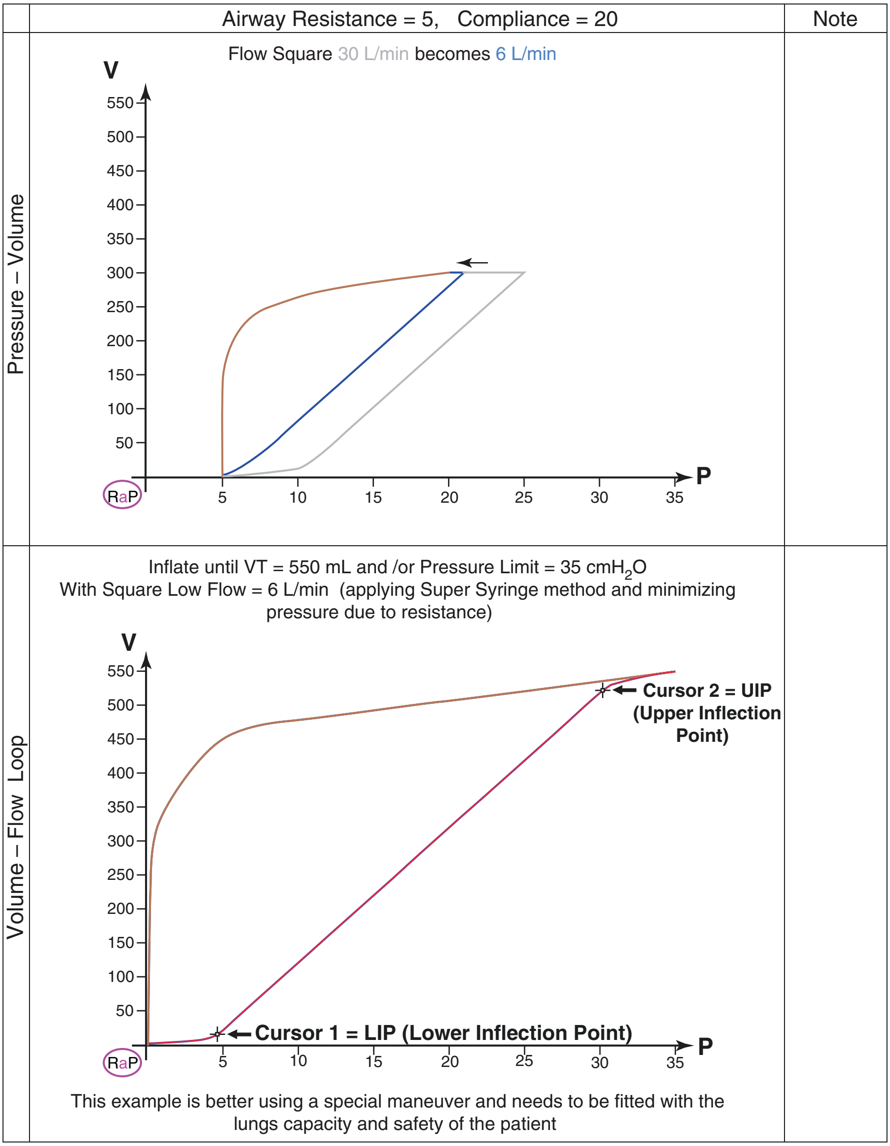


Fig. 7.10 Lower and upper inflection point graphic loop

Troubleshooting 8

8.1 Introduction

The ventilator system, especially when it is used by patient, should be evaluated periodically related to the technical problem of the ventilator system and even the condition of the patient. The patient-ventilator system should be checked and evaluated. This is for the evaluation of a ventilator and to check for the patient's response to mechanical ventilatory support. Checking of patient-ventilator system should be done regularly or at certain regular intervals. In hospital, respiratory therapist often does the rounds for the ventilator check. This is to make sure the ventilator works well and the patient's condition is stable.

Advanced ventilators from different manufacturers now are required to be calibrated before they are hooked to patient, or other ventilators are calibrated regularly in a specific interval of time. This calibration is critically important to make sure for the operation of the system of the ventilator itself.

Alarms in ventilator are one of the most important settings in a ventilator and in mechanical ventilation. If there is an alarm during mechanical ventilation, clinician and most specifically respiratory therapist should check on both the patient and the ventilator to know what the reason is for the ventilator to sound the alarm. Alarms in ventilator can be classified as immediately life-threatening, which is a possible source of patient harm. This is where the troubleshooting is needed. This chapter will show some example waveforms that need troubleshooting and will be discussed how to solve them.

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DOI 10.1007/978-981-10-5340-5_8

8.2 Troubleshooting

To make sure of good function of the ventilator, then user needs to do the following:

- Check source of electricity and/or battery.
- Check gas inlet – quality, pressure, and flow that can be given.
- Check internal ventilator functions including sensors.
- External circuit check – by using test lung and check for leakage.

If the user has already checked for the function of the ventilator for the purpose of well operation of the ventilator system, there are still possibilities of ventilator alarm while it is being used by the patient. This ventilator alarm might be a sign of patient harm. Some ventilator alarms and their examples of waveform will be showed and discussed further and the steps to solve or troubleshoot these problems.

Example 1:

Based on waveform in Fig. 8.1, it is shown:

- On the pressure waveform, plateau pressure on several early breaths is mostly constant, but pressure on resistance is increasing. Plateau pressure on several breaths at the end is mostly increasing because of presence of air trapping. On the pressure waveform, it was shown that the pressure has reached the high-pressure airway alarm limit which makes the ventilator to start expiration immediately. Because the expiration is started before the inspiration time has elapsed, then that might be possible that inspiratory gas has not been filled fully into the lungs, and mean pressure decreases. Minute volume also decreases which causes bad oxygenation and ventilation.
- On the flow waveform, peak expiratory flow continues on decreasing, and expiratory flow time becomes longer, which often is caused by increased airway resistance. Expiratory time can be set longer, but expiratory flow is expected to

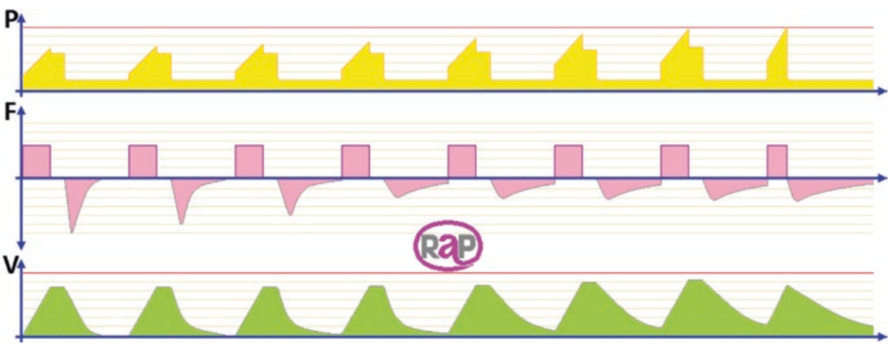

Fig. 8.1 Example of troubleshooting with increased resistance

end at point zero or do other solutions that can decrease airway resistance, for example, bronchodilator. Unfinished expiration can decrease minute volume (expiration) and possibly also ventilation or bad removal of CO_2.

– On the volume waveform, dynamic hyperinflation is shown, where inspiratory volume is constant in every breath, while there is increased residual volume due to air trapping from unfinished expiration.

Example 2:
Based on waveform in Fig. 8.2, it is shown:

– On the pressure waveform, peak pressure of breaths is constant. Peak inspiratory pressure should be decreased if VT increases too high.
– On the flow waveform, peak flow on inspiration and expiration keeps on increasing without significant decreasing of expiratory time to return to zero. So it is possible that it can be caused by increased compliance.
– On the volume waveform, it was shown increased VT because of increased inspiratory flow which also increases minute volume. Increased removal of CO_2 needs to be monitored to prevent worsening removal of CO_2 which can cause apnea due to too low or absence of CO_2.

Example 3a:
Based on waveform in Fig. 8.3, it is shown:

– On the pressure waveform, pressure on resistance on few breaths at the beginning mostly looks constant but can also decrease slightly due to decreased flow that passes by the airway resistance. Plateau pressure inclines downward during holding of inspiration that indicates there is presence of escaped flow which means presence of leak. And so, during holding of inspiration, air escapes from the lungs because of presence of leak even if it is not the time yet for expiration. Leak can also cause decreasing PEEP level that might cause "low pressure"

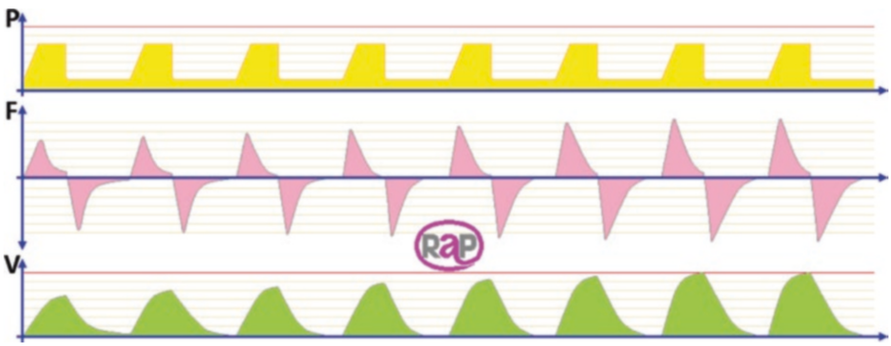

Fig. 8.2 Example of troubleshooting with increased inspiratory flow and VT but constant inspiratory pressure

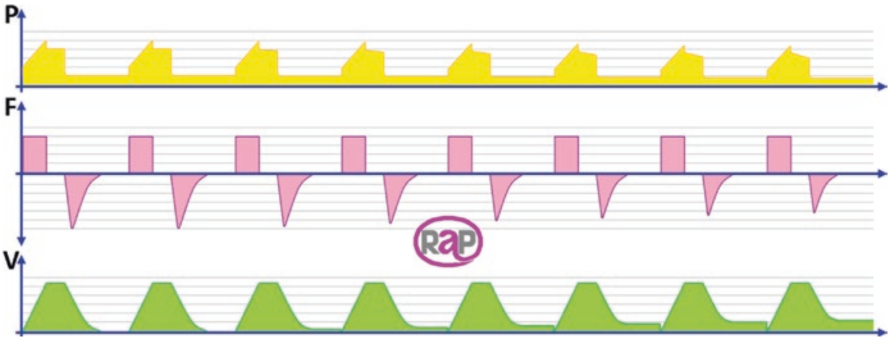

Fig. 8.3 Example of troubleshooting because of suspect presence of leak

Fig. 8.4 Example of troubleshooting with suspect presence of leak which causes decreased PEEP level

alarm or "pressure drop below PEEP" alarm. Mean pressure decreases that might cause decreased oxygenation.

– On the flow waveform, inspiratory flow looks constant just like in the setting of flow or tidal volume. Peak expiratory flow continuously decreases, and expiratory flow time is shortened because expiratory volume is getting smaller due to escaped air. Difference of inspiratory and expiratory flow is the leak of flow.
– On the volume waveform, inspiratory volume is constant in every breath, but expiratory volume continuously decreases, and the difference of inspiratory and expiratory volume is the total of leak. Total leak = leak on inspiratory + leak on expiratory.

The next example will discuss how to check and solve the leak.
Example 3b:
Based on waveform in Fig. 8.4, it is shown:

– On the pressure waveform, leak will cause decreased PEEP level which then will cause "low pressure" alarm or "pressure drop below PEEP" alarm to appear.

With setting of constant delta pressure or driving pressure, peak airway pressure decreases. Mean pressure decreases also gradually that might cause decreases in oxygenation.

– On the flow waveform, inspiratory flow continuously increases, peak expiratory flow continuously decreases, and expiratory flow time is also shortened because expiratory volume is getting smaller due to escaped air. And so, inspiratory flow is getting higher but not because of increased lung compliance, but rather because it needs additional flow to reach and maintain inspiratory pressure. Difference of inspiratory and expiratory flow is the leak of flow. Leak of flow will get bigger based on the increased airway pressure. So, leak of flow is basically bigger during inspiration.
– On the volume waveform, inspiratory volume increases because inspiratory flow also increases due to leak. Expiratory volume continuously decreases also due to leak, and the difference is the total of leak. Total of leak = leak on inspiratory + leak on expiratory.

Troubleshooting on circuit leak:

1. Check and fix leak on breathing circuit on ventilator by using test lung based on the procedure in ventilator manual book.
2. Check and fix tube (ETT/tracheostomy) of patient or the balloon of ETT that might cause the leak.

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DOI 10.1007/978-981-10-5340-5