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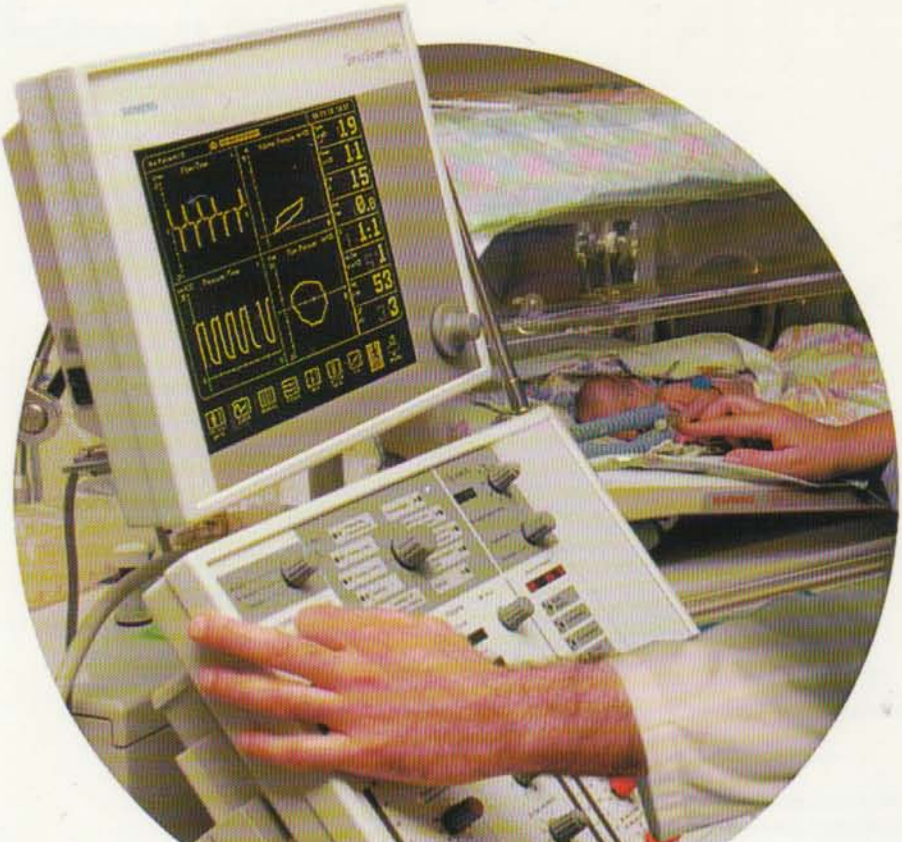
# Waveform and loop analysis in mechanical ventilation

Paul Ouellet, BA, RRT



## Electromedical Systems presents

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One in a series of publications for all who are involved in the treatment of critically ill patients. They are written by, or in collaboration with, doctors and care personnel in intensive care and anesthesia.

The purpose of this series is to convey knowledge and information about new trends in, among other things, respiratory care.

# Waveform and loop analysis in mechanical ventilation

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# Visual display creates a new dimension in ventilatory therapy

Mechanical ventilators have changed significantly over the last decades. They are now equipped with integrated software packages that allow clinicians to actually visualize the delivery of a mechanical breath. Visual display of pressure, volume and flow brings a new dimension to the therapeutic arsenal of ventilators. The clinician thus has access to a multitude of data generated by the new technology.

Nevertheless, delivering effective mechanical ventilation implies an integration of a multitude of physiological concepts surrounded by a rapidly changing technological environment. The critical care specialist, often referred to by one of our colleagues as 'The Educated Hand', now needs both hands educated, one to analyze the underlying pathophysiology and one to keep posted on technological evolution.

This book is intended for all who are involved in the care of patients who need mechanical ventilation. We hope to provide here a comprehensive analysis of factors involved in a rational analysis of waveforms and loops at the bedside of mechanically ventilated patients.

Paul Ouellet, BA, RRT

Department Manager
Respiratory Therapy
Edmundston Regional Hospital
Edmundston, NB, Canada
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# Introduction

The graphic display of curves and loops in mechanical ventilation is emerging rapidly and clinicians find that they must become familiar with a variety of clinical issues surrounding the application.

The graphic display of flow, pressure and volume is generally visualized in two formats; waveforms and loops. In order to benefit from this technology, the clinician must develop a rational sense of interpretation and use this information in selecting appropriate ventilatory strategies. Modes of ventilation directly affect flow, pressure and volume patterns.

During a mechanically generated breath, the inspiratory profile is affected by the mode of ventilation. Expiration being passive, the expiratory profile is not directly affected by the mode of ventilation, but rather by various characteristics of the respiratory system. However, the set inspiratory time can certainly affect the duration of the expiratory profile, as in inverse I:E ratio.

Most ventilators can operate as a flow controller or pressure controller. As a flow controller, the ventilator can deliver a mechanical breath with a constant flow pattern. With this mode, only pressure varies according to the dynamic characteristics of the respiratory system. As a pressure controller, the ventilator delivers mechanical ventilation with a constant pressure pattern. With this mode, both flow and volume vary according to the dynamic characteristics of the respiratory system.

In this text, we focus on the description and analysis of waveforms and loops in three areas of clinical interest.

**The dynamic characteristics of the respiratory system**
**The static characteristics of the respiratory system**
**Patient-ventilator interaction**

As clinicians, we must always remember that although technology can certainly contribute to the delivery of proper care, bedside clinical judgment and discernment should be the golden rule. We must never forget that the patient needs all our attention and compassion. Time spent at manipulating bedside technology should never compromise the caring devotion for the most important person, the patient in need of critical care.

# Contents

# Glossary

| | |
|---|---|
| **Algorithm** | Decision tree illustrating the relationship between various topics or parameters and providing a mode of stepwise action |
| **ARDS** | Acute Respiratory Distress Syndrome |
| **Ascending ramp** | Characteristic to describe a progressively increasing flow pattern during mechanical ventilation |
| **Atelectasis** | Collapse of a lung segment |
| **Bronchodilator** | Pharmaceutical agent stimulating the bronchial smooth muscle, thereby producing a dilatation of the bronchial tree |
| **Compliance** | Volume change produced by a unit pressure change (ml/cm$H_2O$) |
| **COPD** | Chronic Obstructive Pulmonary Disease |
| **Descending ramp** | Characteristic to describe a progressively decreasing flow pattern during mechanical ventilation |
| **EEF** | End Expiratory Flow |
| **EEP** | End Expiratory Pressure |
| **Elastic recoil pressure** | Pressure generated by the recoil properties of the lung/thorax system |
| **Esophageal pressure** | Pressure monitored within the esophagus, approximating the intrapleural pressure |
| **Expiratory dynamic airway compression** | Airway compression during an active expiration often associated with COPD, and causing increased airflow resistance |
| **Exponential decay** | Characteristic of the graphic presentation of an exponential equation when the value of a variable returns to zero |
| **Flow resistive pressure** | Pressure associated with resistance to gas flow |
| **Gas exchange** | Physiological mechanism, whereby the transfer of oxygen and carbon dioxide takes place at the alveolo-capillary or cellular levels |

| | |
|---|---|
| **Intrapleural pressure** | Pressure inside the pleural cavity |
| **IRV** | Inverse Inspiratory:Expiratory Ratio Ventilation |
| **Neuromuscular blocker agent** | Pharmaceutical agent blocking the transmission of an electrical impulse through a myoneural junction of skeletal muscles, causing a temporary paralysis |
| **PEEP** | Positive End Expiratory Pressure |
| **PEEP titration** | Adjustment of PEEP in order to optimize mechanical ventilation |
| **PEF** | Peak Expiratory Flow |
| **PIF** | Peak Inspiratory Flow |
| **PIP** | Peak Inspiratory Pressure |
| **Pneumothorax** | Presence of air inside the pleural cavity, thereby causing a lung collapse |
| **$P_{pause}$** | End Inspiratory Pause Pressure |
| **Pressure gradient** | Difference between two pressure unit values |
| **Pulmonary edema** | Pathological condition associated with the presence of fluid in the lung |
| **Resistance** | Variation of pressure unit per unit flow change (Pressure/Flow; $cmH_2O$/ml/sec) |
| **Sinusoidal** | Often used to describe a curve with distinct inward and outward bends along the edge |
| **Ti** | Inspiratory time |
| **$T_{TOT}$** | Total respiratory cycle time |
| **$VT_e$** | Expired Tidal Volume |
| **$VT_i$** | Inspired Tidal Volume |

# Exponential functions and time constants in mechanical ventilation

**This chapter describes the concept of time constants and exponential functions with reference to the respiratory system during mechanical ventilation.**

**Without having to perform complex calculations, the clinician should be aware of the general concepts of exponential functions when analyzing waveforms during mechanical ventilation. At the bedside, if the pattern of a waveform appears linear rather than its normal exponential form, the clinician must relate the abnormality to the underlying pathophysiology. One good example is the linear appearance of the flow-time waveform found with increased expiratory resistance.**

**Another clinical application of exponential functions in mechanical ventilation is the concept of time constants in resistive and elastic characteristics of the respiratory system. If the duty cycle coupled with resistance and compliance does not allow the expiratory phase to complete at least 3 time constants, air trapping occurs.**

## Exponential functions and time constants

The respiratory system, like most biological systems, is closely associated with exponential functions. An exponential function is a mathematical expression that describes an event where the rate of change of one variable is proportional to its magnitude.

As an example, in a passive breath, expiratory flow will be higher at the beginning of expiration than at the end, as the lung volume decreases toward the functional residual capacity (FRC).

There are various forms of exponential functions, but the two most important ones for the clinician in mechanical ventilation are the rising and the decaying exponential functions.

### Rising exponential function

A rising exponential function expresses an increase of one variable as a function of time: flow vs. time, pressure vs. time, and volume vs. time. In mechanical ventilation with a constant pressure mode, the inspiratory volume-time waveform is an example of a rising exponential function. Figure 1–1 illustrates a typical rising exponential function.

A rising exponential function expresses the behavior of a physical system where the rate of change of one variable is proportional to its magnitude and a constant. In physical systems, the constant is usually the final value of the variable studied. The mathematical form of a rising exponential function is expressed by the following equation:

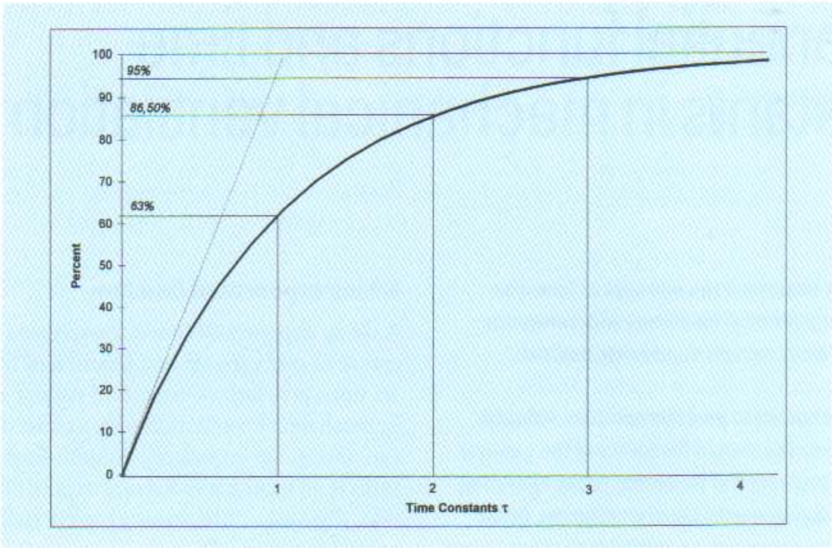
$$\frac{dy}{dt} = \left(\frac{1}{\tau}\right) y_{\text{final}} - y \qquad (1)$$

$\tau$ is the time constant of the system, and is addressed later in the text. Systems governed by equations of this form are called first order systems. We will focus here on exponential functions where the rate of change varies with time.

In this expression, as time progresses, and the function $y$ approaches its final value $y_{\text{final}}$, the rate of change decreases towards zero. The difference between the initial value of y and its final value is always the largest at the beginning of the event. Therefore, the largest rate of change is always observed at the beginning of the event, and the smallest rate of change is always observed at the end of the event. As $y$ approaches its final value ($y_{\text{final}}$) the quantity inside the bracket ($y_{\text{final}} - y$) will approach zero, and the rate of variation of the variable $y$ will be very small. The solution of equation (1) can be obtained and will always be in the following form:

$$y = y_{\text{final}}\,(1 - e^{-t/\tau}) \qquad (2)$$

Figure 1–1. **Typical rising exponential function**



In this equation:

- $y$ is the value of the variable at time $t$,
- $e$ is the base of the natural logarithm (2.71828...),
- $y_{\text{final}}$ is the final value of $y$,
- $t$ is the period of time after the onset of the event,
- $\tau$ is the time constant of the system.

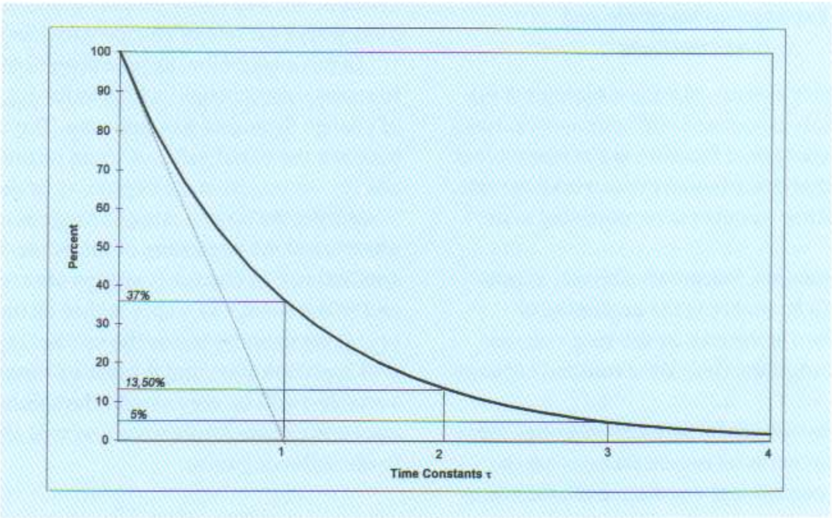
## Decaying exponential function

A decaying exponential function expresses a decrease of one variable as a function of time: flow vs. time, pressure vs. time, and volume vs. time. The pressure decrease during lung deflation in a passive expiration is an example of a decaying exponential function. Flow return to baseline during a passive expiration is an example of a negative decaying exponential function.

Figure 1–2 illustrates a typical decaying exponential function.

A decaying exponential function expresses the behavior of a physical system where the rate

Figure 1–2. **Typical decaying exponential function**



of change of one variable is proportional to its magnitude only. The mathematical form is governed by the following equation:

$$\frac{dy}{dt} = -\left(\frac{1}{\tau}\right) y \qquad (3)$$

In this expression, as time progresses and the function $y$ approaches zero, the rate of change of $y$ decreases toward zero.

Since the function $y$ is always at its largest value at the beginning of the event ($y_0$) its rate of change is also the largest at the beginning of the event, and smallest at the end of the event. The solution of equation (3) can be obtained and will always be of the following form:

$$y = y_0\, e^{-t/\tau} \qquad (4)$$

In this equation:

$y$ is the value of the variable at time $t$,
$e$ is the base of the natural logarithm (2.71828...),
$y_0$ is the final value of $y$,
$t$ is the period of the time after the onset of the event,
$\tau$ is the time constant of the system.

In figures 1–1 and 1–2, if the rate of rising or decaying were constant, a linear curve would reflect the behavior of the function (thin lines). These lines are tangents to the exponential curve at the beginning of the event.

However, in exponential functions the rate of change is not constant over a period of time. The behavior of the exponential functions is shown by the thick curves of figures 1–1 and 1–2.

## Time constant

Exponential functions are often described with time constants, designated by the Greek letter $\tau$ (tau). The time constant characterizes the rate of variation of the function over a period of time. A time constant is a time interval. Short time constants imply a fast rate of change and, vice versa, long time constants imply a slow rate of change.

In figures 1–1 and 1–2, the evolution of the event is shown as a function of time. At $t = 0$, the function is shown at its minimal value in 1–1 and at its maximal value in 1–2. After a period of time, both functions approach their respective final value. During the event, the rate of variation of an exponential function will depend on the value of the time constant of the system.

In a rising exponential function, after one time constant, the value of the variable on the $y$ axis increases to 63.3% of its final value. After two time constants, the value increases to 86.5%, after three time constants it increases to 95.1% of the final value, and after four time constants it increases to 98.2% of its final value.

Mathematically, after an infinity of time constants, the value of the y axis will never reach zero.

In a decaying exponential function, after one time constant, the value of the variable on the y axis decreases to 36.7% of its initial value. After two time constants, the value decreases to 13.5% of the initial value, after three time constants the value decreases to 4.9% of the initial value, and after 4 time constants, the value is only 1.8% of the initial value.

Mathematically, after an infinity of time constants, the value of the y axis will never reach zero.

Table 1–1 illustrates the relative value of five time constants in both a rising and a decaying exponential function encountered in mechanical ventilation.

Table 1–1.
**Percentage change in final or initial values for two types of exponential functions**

| Time constant ($\tau$) | Rising exponential function (%) of final value | Decaying exponential function (%) of initial value |
|---|---|---|
| 0 | 0 | 100 |
| 1 | 63.3 | 36.7 |
| 2 | 86.5 | 13.5 |
| 3 | 95.1 | 4.9 |
| 4 | 98.2 | 1.8 |
| 5 | 99.3 | 0.7 |

As its name implies, the time constant corresponds to a period of time. A system with a short time constant will react very fast to a stimulus, as demonstrated in figure 1–3 A.

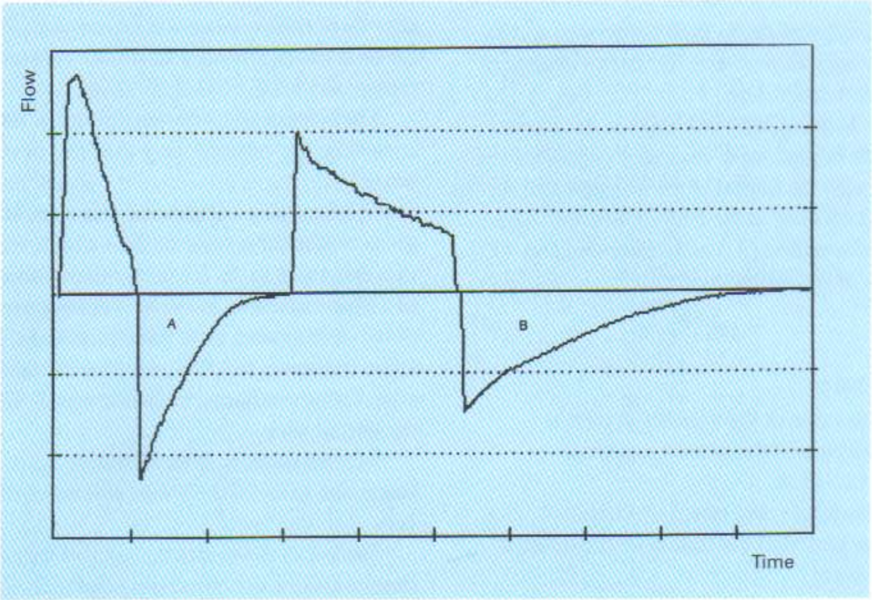
On the other hand, a system with a long time constant will react very slowly to a stimulus, as demonstrated in figure 1–3 B. Both systems reach the same final value, but over a different period of time.

In mechanical ventilation, for practical purposes, an event is considered complete after

Figure 1–3.

**Flow-time waveform from a constant pressure mode of ventilation.**

**A. Exponential function with a short time constant**
**B. Exponential function with a long time constant**



three time constants. For the adult respiratory system the normal time constant is 0.79 seconds.

The actual value of one time constant is obtained through the product of compliance x resistance:

$$\tau = \text{Compliance} \times \text{Resistance}$$
$$[\tau] = \frac{\text{ml}}{\text{cmH}_2\text{O}} \times \frac{\text{cmH}_2\text{O}}{\text{ml} \bullet \text{sec}^{-1}}$$

As an example, a system with a total lung/thorax static compliance of 60 ml/$cmH_2O$, an expiratory resistance of 0.13 $cmH_2O$ per ml and no auto-PEEP, has a time constant $\tau$ of:

$$\tau = \text{Compliance} \times \text{Resistance}$$
$$\tau = 60 \text{ ml/cmH}_2\text{O} \times 0.13 \text{ cmH}_2\text{O per ml per second}$$
$$\tau = 0.78 \text{ seconds}$$

In a decaying exponential function, a time constant of 0.78 seconds means that after one time constant (0.78 s), the value of the variable on the *y* axis decreases to 37% of its final value, after two time constants (1.56 s), it decreases to 13.5% of its final value, and after three time constants (2.34 s) the value of the variable on the y axis decreases to 5% of its final value.

In this example, if the expiratory time is shorter than 2.34 seconds (3 x 0.78), air trapping will be present, causing auto-PEEP.

To prevent auto-PEEP and air trapping, the expiratory time should always be longer than 3 time constants.

Consider figure 1–4 as a pressure-time waveform from a constant flow mode of ventilation. Peak inspiratory pressure is 18 $cmH_2O$, and end expiratory pressure is zero. Compliance is 83 ml/$cm_2O$, and resistance is 8 $cmH_2O$/l/sec.

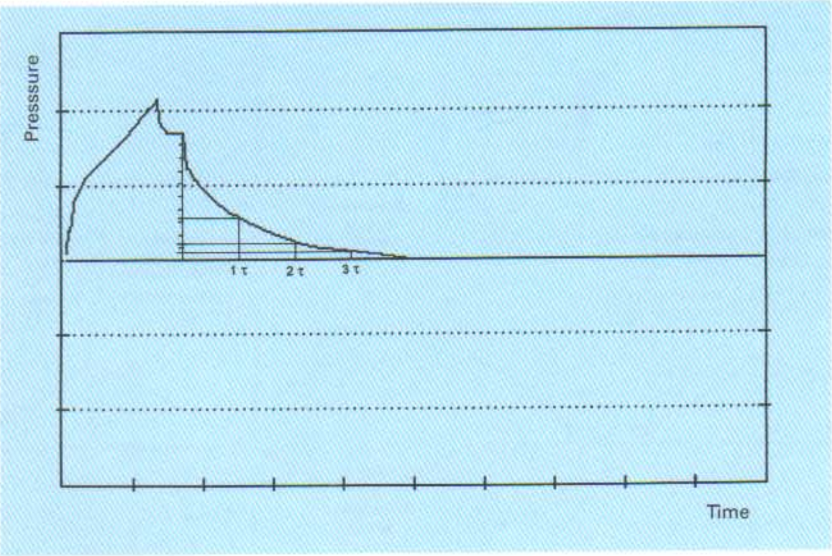
The shape of expiration is a decaying exponential function. The product of compliance x resistance (0.68 seconds) is the value of the time constant $\tau$ for the entire system. Table 1–2 summarizes the data.

During various modes of ventilation, the variables flow, pressure and volume will vary with time as an exponential function. Depending on the mode of ventilation, compliance and resistance will affect both phases of ventilation of each variable. During inspiration, flow and pressure patterns are directly related to the ventilator (generator).

The clinician can control flow and pressure through ventilation strategies in order to optimize ventilation according to the compliance and resistance of the patient's respiratory system.

Figure 1–5 illustrates a flow-time waveform where the expiratory time is shorter than $3\tau$. The expiratory phase of the flow-time waveform is a negative decaying exponential function. Inspiration begins before the cycle completes three time constants. As a result, air trapping is allowed with a resulting auto-PEEP. A flow-time waveform does not allow the clinician to quantify the amount of auto-PEEP produced by air trapping. Auto-PEEP can be measured with the pressure-time waveform, using the end expiratory occlusion technique.

Figure 1–4. **Pressure-time waveform from a constant flow mode**



During expiration, flow, pressure and volume patterns cannot be directly manipulated by the clinician, except for determining the duration of each cycle when using a controlled mode. Passive expiration is then directly governed by elastic and resistive characteristics of the respiratory system.

Table 1–2.
**Summary table of a decaying exponential pressure-time waveform.**

| Time constant ($\tau$) | Real time (Seconds) | Pressure (CmH$_2$0) | % of initial Pressure |
|---|---|---|---|
| 0 | 0.00 | 18 | 100 |
| 1 | 0.68 | 6.48 | 36,7 |
| 2 | 1.36 | 2.43 | 13.5 |
| 3 | 2.04 | 0.882 | 4.9 |
| 4 | 2.72 | 0.324 | 1.8 |

During mechanical ventilation, for practical reasons, the value of the expiratory time constant reflects the characteristics of the global respiratory system. In reality, the respiratory system consists of a multitude of zones, all with different time constants. Various lung pathologies, like ARDS, consist of non-homogeneous lung zones with different compliance and resistance. Diseased zones will have shorter time constants than normal zones with normal compliance. Ventilatory strategies should aim at providing adequate ventilation according to the global time constant of the total respiratory system. It is commonly accepted that slowing end-inspiratory flow may allow better distribution of ventilation among lung units with different time constants.

Figure 1–6 describes mathematically the various waveforms in mechanical ventilation, as explained with the equation of motion outlined in chapter 2.

Figure 1–5. **Flow-time waveform of a respiratory cycle shorter than 3τ**

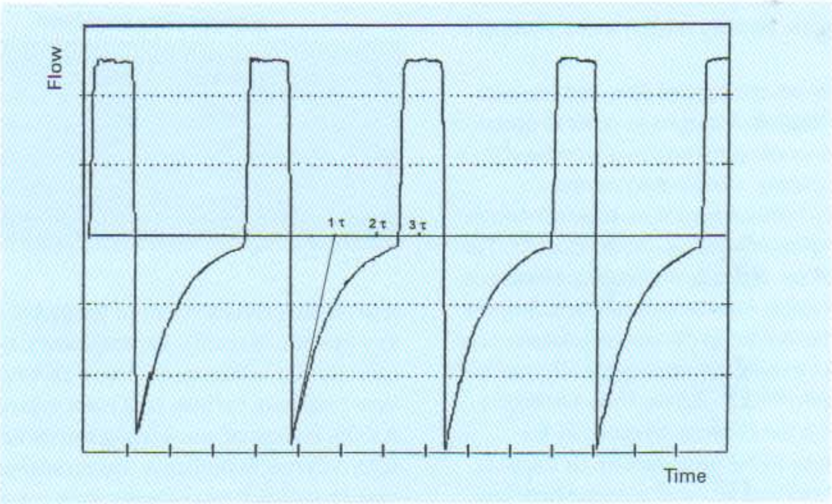


Figure 1–6. **Mathematical description of various waveforms in mechanical ventilation.**

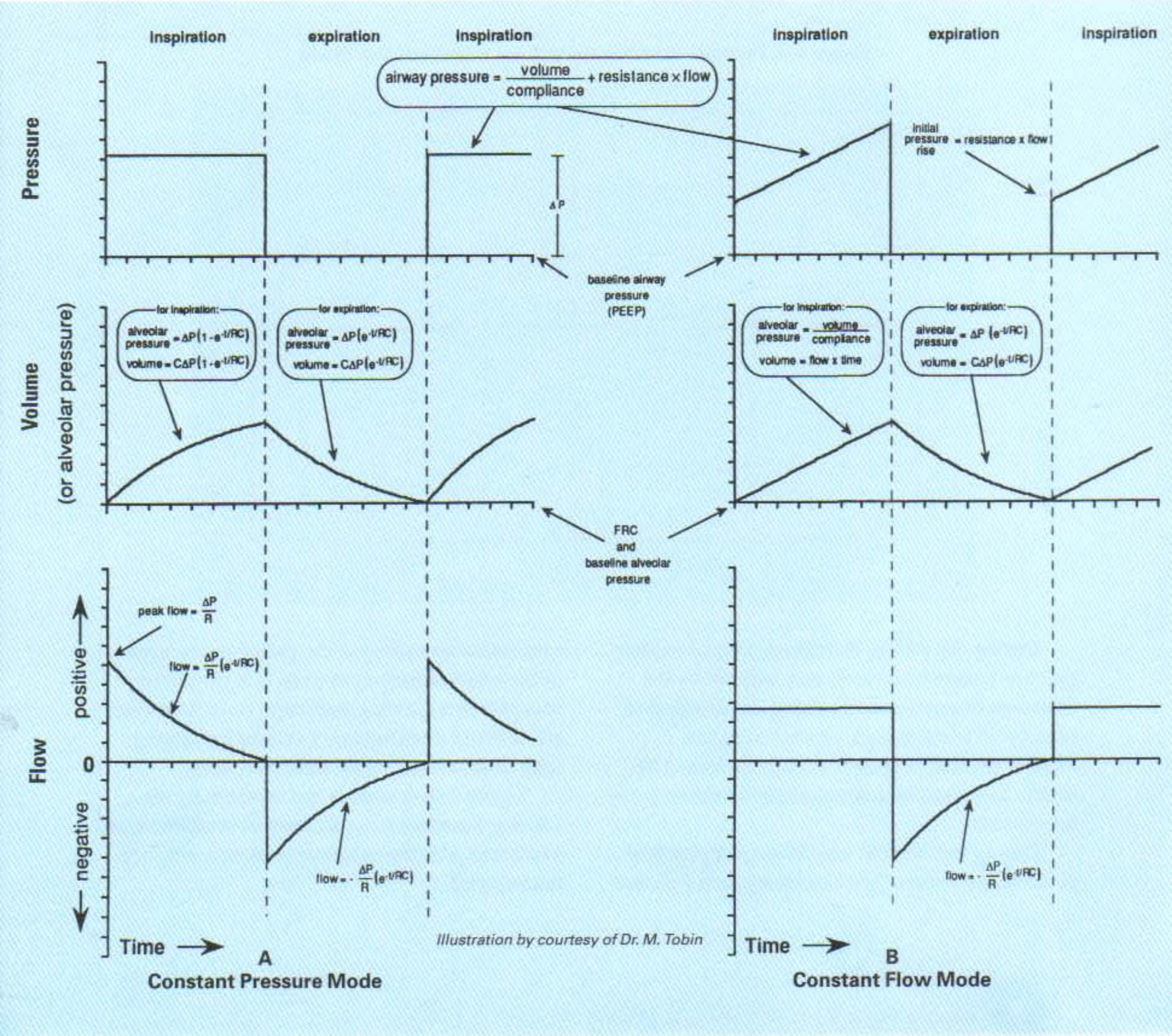


*Illustration by courtesy of Dr. M. Tobin*

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# Equation of motion for the respiratory system

**The respiratory system is governed by various laws of physics. The equation of motion is used throughout physics to describe the dynamic forces involved in the movement of a system. The equation of motion for the respiratory system is similar to that for any mechanical system.**

**In respiratory physiology, the respiratory system must be described through principles that govern movement over three dimensions.**

**To cause a volume displacement, the generating force must overcome elastic and resistive elements inherent to the patient-ventilator interaction. To create such volume displacement, the mechanical ventilator must obey the laws that govern motion. The equation of motion thus becomes an important concept in respiratory mechanics.**

**In this chapter we will focus on exploring the equation of motion to describe the notion of ventilators as a controller of one of three variables described in the equation of motion.**

## Equation of motion for the respiratory system

The equation of motion for the respiratory system is perhaps the single most important equation for the clinician in mechanical ventilation. Not only does it govern the physical principles involved during spontaneous breathing, it also sets the rules for technology in mechanical ventilation. Waveform display of pressure, volume and flow is reflected in the equation of motion and allows the interpretation of various clinical situations.

In mechanical ventilation, a pressure gradient is necessary to produce a volume displacement and a gas flow. To generate a volume displacement, the total forces have to overcome the elastic forces developed inside the lung tissues and chest wall. Also, to generate a gas flow, the total forces have to overcome the resistive forces against the driving pressure gradients. All these concepts are developed in the equation of motion.

At any moment during inspiration, the airway opening pressure ($P_{AWO}$) must exactly balance the forces opposing lung and chest wall expansion. The opposing pressures are the sum of elastic recoil pressure ($P_{elastic}$), flow resistive pressure ($P_{resistive}$) and inertance pressure ($P_{inertance}$) of the respiratory system:

$$P_{AWO} = P_{elastic} + P_{resistive} + P_{inertance} \qquad (1)$$

During conventional ventilation, inertial forces are usually negligible but become significant during high frequency ventilation. For conventional ventilation, the equation of motion for the respiratory system can be simplified as follows:

$$P_{AWO} = P_{elastic} + P_{resistive} \qquad (2)$$

where: $P_{elastic}$ = Elastance x Volume
$P_{resistive}$ = Resistance x Flow

The equation of motion can then be written in a more complete format as follows:

$$P_{AWO} = (\text{Elastance} \times \text{Volume}) + (\text{Resistance} \times \text{Flow}) \qquad (3)$$

By using compliance rather than elastance, equation 3 becomes:

$$P_{AWO} = \frac{\text{Volume}}{\text{Compliance}} + \text{Resistance} \times \text{Flow} \qquad (4)$$

where:

- $P_{AWO}$ is the airway opening pressure.
- Volume/compliance is the quotient of volume displacement and compliance of the respiratory system. This quotient is the pressure necessary to overcome the elastic forces above functional residual capacity (FRC).
- Resistance x flow is the product of maximum airway resistance ($R_{max}$) and inspiratory flow. This product is the pressure necessary to overcome the resistive forces of the respiratory system.

Substituting standard units in equation 4 facilitates the illustration that pressure is the end product of the equation of motion for the respiratory system.

$$\text{cmH}_2\text{O} = \frac{\text{ml}}{\text{ml} \cdot \text{cmH}_2\text{O}^{-1}} + \frac{\text{cmH}_2\text{O}}{\text{ml} \cdot \text{sec}^{-1}} \times \text{ml} \cdot \text{sec}^{-1}$$

In equation 4, for practical reasons, let us designate pressure, volume, and flow as variables because they can be directly controlled by the clinician, as opposed to constants like resistance and compliance, because they are not directly controlled by the clinician, but rather indirectly by manipulating the variables, and according to resistive and elastic properties of the respiratory system.

The way each variable is controlled reflects the way the ventilator delivers a mechanical breath. Every ventilator behaves as a controller of one or more variables. To deliver a mechanical breath, the ventilator has to comply with the elements involved in the equation of motion.

The equation of motion seems appropriate to facilitate the understanding of various principles of operation surrounding the technology of mechanical ventilators.

Figure 2–1.

**Pressure-time, volume-time and flow-time waveforms from a ventilator operating as a pressure controller. Pressure is the independent variable (preset pattern); volume and flow are the dependent variables (function of compliance and resistance).**

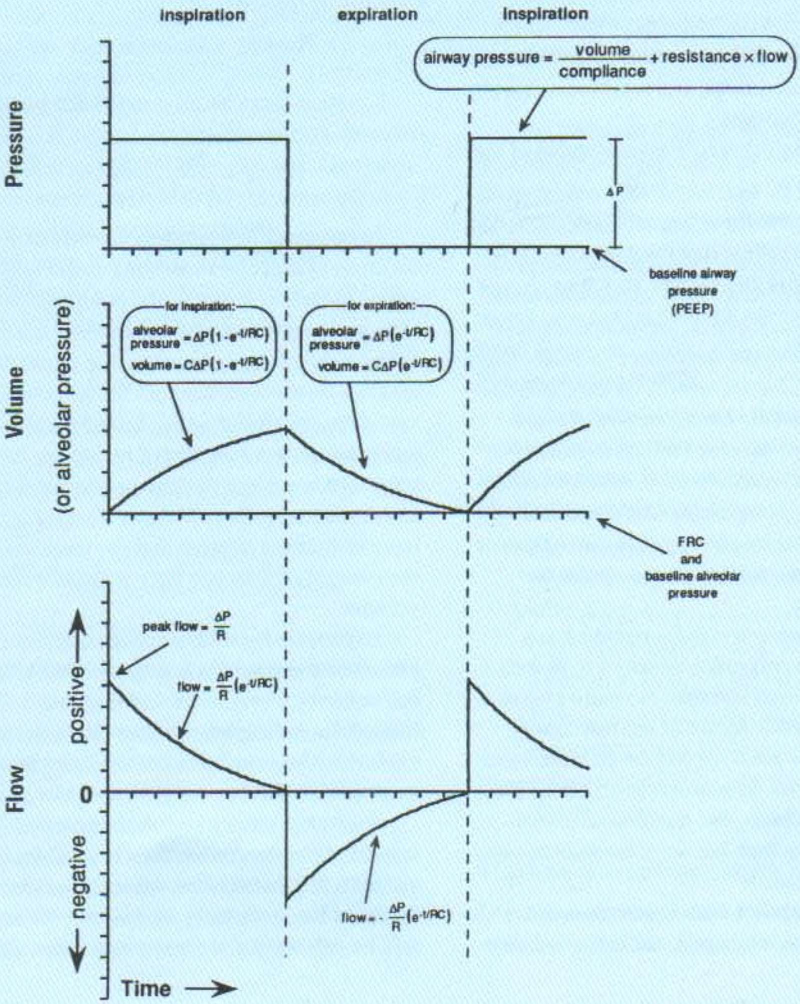


*Illustration by courtesy of Dr. M. Tobin*

### Setting a pressure pattern

Reconsider the equation of motion (4):

$$\text{Airway pressure} = \frac{\text{Volume}}{\text{Compliance}} + \text{Resistance} \times \text{Flow} \qquad (4)$$

For the purpose of simplifying the explanation, let us isolate each element separately, starting with the elastic component of the equation of motion:

$$\text{Pressure} = \frac{\text{Volume}}{\text{Compliance}} \qquad (5)$$

In equation 5, if the clinician sets pressure as a function of time, volume varies with compliance. Pressure is referred to as the independent variable, and volume as the dependent variable. When a pressure pattern is preset, the ventilator operates as a pressure controller. The inspiratory volume-time waveform varies exponentially with time and volume is a function of compliance. Expiration is passive and expiratory waveforms are not directly affected by modes of ventilation, but rather reflect the elastic and resistive elements of the respiratory system.

Let us consider the resistive component of the equation of motion:

$$\text{Pressure} = \text{Resistance} \times \text{Flow} \qquad (6)$$

In equation 6, again if the clinician sets pressure as a function of time, flow varies with resistance. Pressure is referred as the independent variable, and flow as the dependent variable. The inspiratory flow-time waveform varies exponentially with time and flow is a function of resistance. Expiration is passive and the expiratory profile is not directly affected by mode of ventilation, but rather by compliance and resistance, even though the set inspiratory time can influence the expiratory time, and to a certain point the expiratory profile.

Basically, when a ventilator operates as a constant pressure controller, pressure is an independent or controlled variable. No matter what the resistive or elastic forces of the respiratory system are, the set pressure will be delivered and maintained constant throughout inspiration. The delivered tidal volume, and the flow will vary exponentially with time but are a function of compliance and resistance.

Figure 2–1 displays waveforms from the equation of motion when pressure is the independent variable, also known as pressure control ventilation. Volume and flow are the dependent variables, and their pattern will depend on compliance and resistance. When a pressure pattern is preset (constant in a pressure control mode), flow-time and volume-time waveforms vary exponentially with time and are a function of compliance and resistance.

### Setting a flow pattern

Reconsider the equation of motion (4):

$$P_{AWO} = \frac{\text{Volume}}{\text{Compliance}} + \text{Resistance} \times \text{Flow} \qquad (4)$$

By examining equation 4, one can see that flow and resistance are associated only with the resistive component of the equation. The elastic component refers to volume and compliance. So let us isolate the resistive component of the equation of motion:

$$\text{Pressure} = \text{Resistance} \times \text{Flow} \qquad (6)$$

Equation 6 can be rearranged differently as follows:

$$\text{Flow} = \frac{\text{Pressure}}{\text{Resistance}} \qquad (7)$$

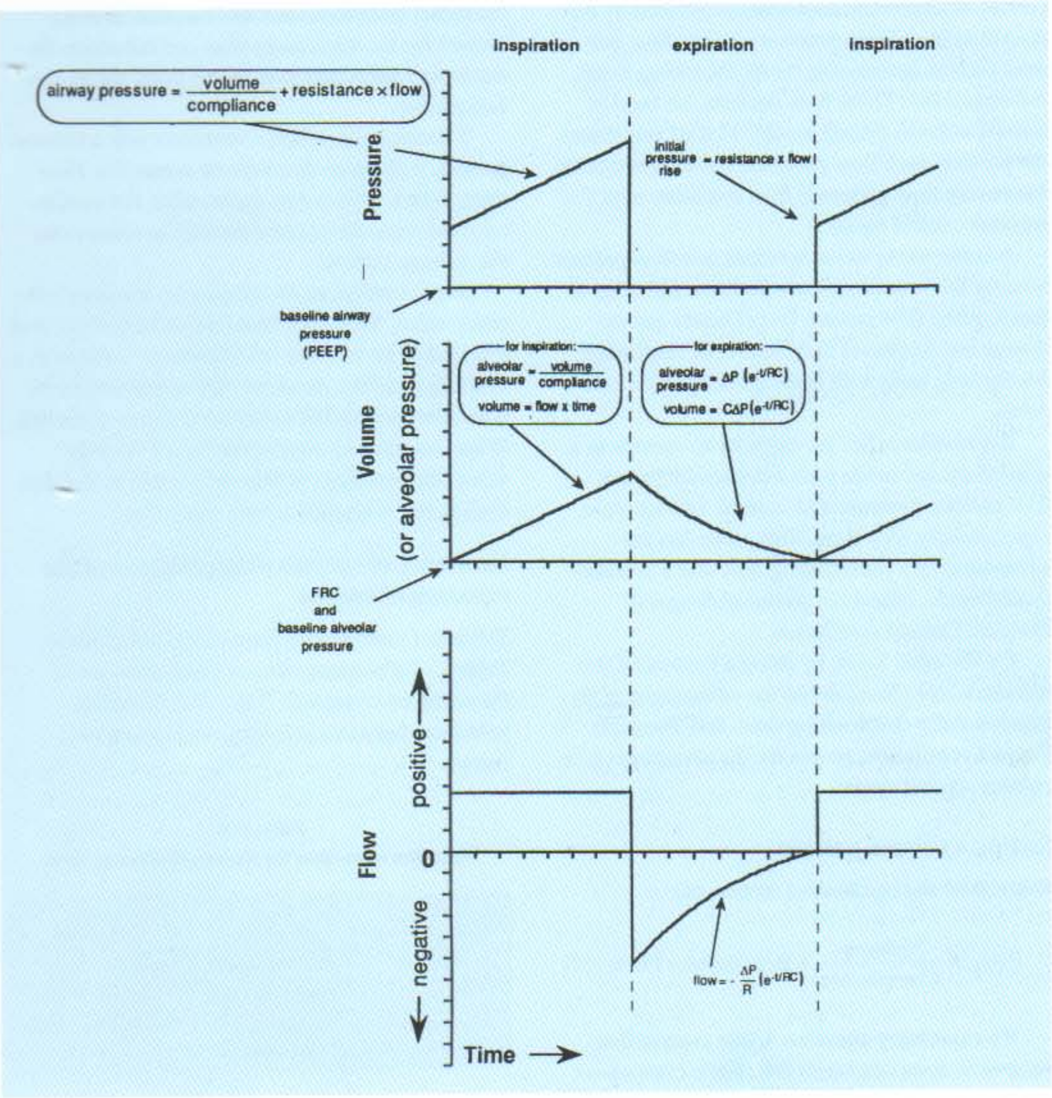
In equation 7, if the clinician sets flow as a function of time, pressure then varies with resistance. Flow is referred as the independent variable, and pressure as the dependent variable. When a flow pattern is preset, the ventilator operates as a flow controller, and the inspiratory pressure-time waveform varies linearly with time and pressure is a function of resistance. Volume increases linearly with time but does not have a direct relation to flow. Volume does nevertheless have an indirect relation to flow, since volume is the integral of flow and flow is the derivative of volume.

Expiration is passive and the expiratory profile is not directly affected by mode of ventilation, but rather by compliance and resistance, even though the set inspiratory time can influence the expiratory time, and to a certain point the expiratory profile.

Basically, when a ventilator operates as a constant flow controller, flow is an independent variable. No matter what the resistive or elastic forces of the respiratory system are, the set flow will be delivered and maintained constant

Figure 2–2.

**Pressure-time, volume-time and flow-time waveforms from a ventilator operating as a flow controller. Flow is the independent variable (preset pattern); Pressure and volume are dependent variables (function of resistance and compliance).**



throughout inspiration. Pressure and tidal volume will vary with time but are functions of compliance and resistance.

Figure 2–2 displays waveforms where flow is the independent variable (controlled variable), pressure and volume are the dependent variables. When a flow pattern is preset (constant in this case), pressure and volume varies linearly with time and are functions of compliance and resistance.

Modern ventilators can operate as a flow controller or a pressure controller. As a flow controller, the most common flow pattern is constant flow, also referred to as a square wave flow pattern. As a pressure controller, the only pressure pattern is constant pressure, also referred to as a square wave pressure pattern.

From the equation of motion, one can stipulate that with a ventilator operating as a constant flow controller, pressure and volume are linear functions of time. Various ventilators have the possibility of delivering various flow patterns.

An important factor here is that in order to have flow patterns different than constant and exponentially decelerating, the ventilator needs to be controlled by a microprocessor which performs a series of sequential adjustments dictated by an algorithm in order to produce various flow patterns such as descending ramp, ascending ramp, and sinusoidal. These flow patterns are used in various volume-cycled modes. Not all ventilators can provide such flow patterns. The exponentially decreasing flow pattern is thus available with a pressure control mode.

A controversy exists whether one flow pattern is better than another. Some authors claim that a decelerating flow pattern favors better gas exchange and improves distribution of ventilation among lung units with heterogeneous time constants.

If a ventilator has the capacity to operate in a volume-cycled mode with a descending ramp flow pattern, pressure and volume will increase exponentially with time. This mode has the advantages of a decelerating flow and a volume-cycled mode, minus the potential danger of Pressure Control ventilation.

On the other hand, by using a Pressure Control mode, the clinician has the advantages of an exponentially decelerating flow, and Pressure Control ventilation, minus the disadvantages of a volume-cycled mode.

## Setting a volume pattern

Reconsider the equation of motion (4):

$$P_{AWO} = \frac{\text{Volume}}{\text{Compliance}} + \text{Resistance} \times \text{Flow} \quad (4)$$

By examining equation 4, one can see that volume is associated with the elastic component of the equation. The resistive component refers to resistance and flow. So let us isolate the elastic component of the equation:

$$\text{Pressure} = \frac{\text{Volume}}{\text{Compliance}} \quad (5)$$

Equation 5 can be rearranged differently as:

$$\text{Volume} = \text{Pressure} \times \text{Compliance} \quad (6)$$

In equation 6, if the clinician sets volume as a function of time, pressure then varies with compliance. Volume is referred to as the independent variable and pressure as the dependent variable. Expiration is passive and the expiratory profile is not directly affected by the mode of ventilation, but rather by compliance and resistance, even though the set inspiratory time can influence the expiratory time, and to a certain point the expiratory profile.

Theoretically, when a ventilator sets a volume pattern, it operates as a volume controller. However, to be truly a volume controller the ventilator must measure volume directly in order to set the volume pattern.

Most ventilators do not directly measure volume; rather, they calculate volume from flow over a period of time. Most ventilators use volume as a limiting variable, meaning that inspiration stops when the preselected value for volume is reached. When inspiration stops at the preset volume value, the ventilator is thus referred to as volume-cycled, but it is really a flow controller.

## Summary of various manipulations of the equation of motion

Table 2–1 summarizes the equation of motion. Table 2–2 illustrates various manipulations of the equation of motion. Table 2–3 illustrates ventilator behavior and relationship to waveforms.

Table 2–1.

**Equation of motion for the respiratory system.**

| Airway opening pressure | = | Elastic components | + | Resistive components |
|---|---|---|---|---|
| Pressure | = | Elastic pressure | + | Resistive pressure |
| Pressure | = | Elastance × Vol. | + | Resistance × Flow |
| Pressure | = | $\frac{\text{Volume}}{\text{Compliance}}$ | + | Resistance × Flow |

Table 2–2.

**Manipulation of the equation of motion.**

| Elastic components | Resistive components |
|---|---|
| Pressure = $\frac{\text{Volume}}{\text{Compliance}}$ | Pressure = Resistance × Flow |
| or | or |
| Volume = Pressure × Compliance | Flow = $\frac{\text{Pressure}}{\text{Resistance}}$ |
| or | or |
| Compliance = $\frac{\text{Volume}}{\text{Pressure}}$ | Resistance = $\frac{\text{Pressure}}{\text{Flow}}$ |

## Ventilator behavior and relationship to waveforms

Table 2–3.
**Ventilator behavior as explained using the equation of motion and relationship to waveforms.**

| **Flow Controller**<br>(Constant Flow Controller) | **Pressure Controller**<br>(Constant Pressure Controller) | **Volume Controller**<br>(Variable Flow Controller) |
|---|---|---|
| **Modes:**<br>• Volume Control, SIMV-VC | **Modes:**<br>• Pressure Control, PRVC, SIMV-PC | **Modes:**<br>• Volume Control |
| **Equation:**<br>$\text{Flow} = \frac{\text{Pressure}}{\text{Resistance}}$ | **Equations:**<br>$\text{Flow} = \frac{\text{Volume}}{\text{Compliance}}$<br>Pressure = Resistance x Flow | **Equation:**<br>Flow = Pressure x Compliance |
| **Independent variable:**<br>• Flow | **Independent variable:**<br>• Pressure | **Independent variable:**<br>• Volume |
| **Dependent variable:**<br>• Pressure | **Dependent variables:**<br>• Volume<br>• Flow | **Dependent variable:**<br>Pressure |
| **Limiting variable:**<br>• Volume | • **Limiting variable:**<br>Pressure | **Limiting variable:**<br>Volume |
| **Triggering variables:**<br>• Time<br>• Pressure<br>• Flow | **Triggering variables:**<br>• Time<br>• Pressure<br>• Flow | **Triggering variables:**<br>• Time<br>• Pressure<br>• Flow |
| **Waveform analysis**<br>(active phase only)<br>• Pressure-time waveform is affected by resistance changes.<br>• Flow-time waveform is not affected by compliance and resistance changes.<br>• Volume-time waveform is not affected by compliance and resistance changes. | • **Waveform analysis**<br>(active phase only)<br>• Pressure-time waveform is not affected by compliance and resistance changes.<br>• Flow-time waveform is affected by compliance and resistance.<br>• Volume-time waveform is affected by compliance and resistance. | **Waveform analysis**<br>(active phase only)<br>• Pressure-time waveform is affected by compliance changes.<br>• Flow-time waveform is not affected by resistance changes.<br>• Volume-time waveform is not affected by compliance and resistance changes. |

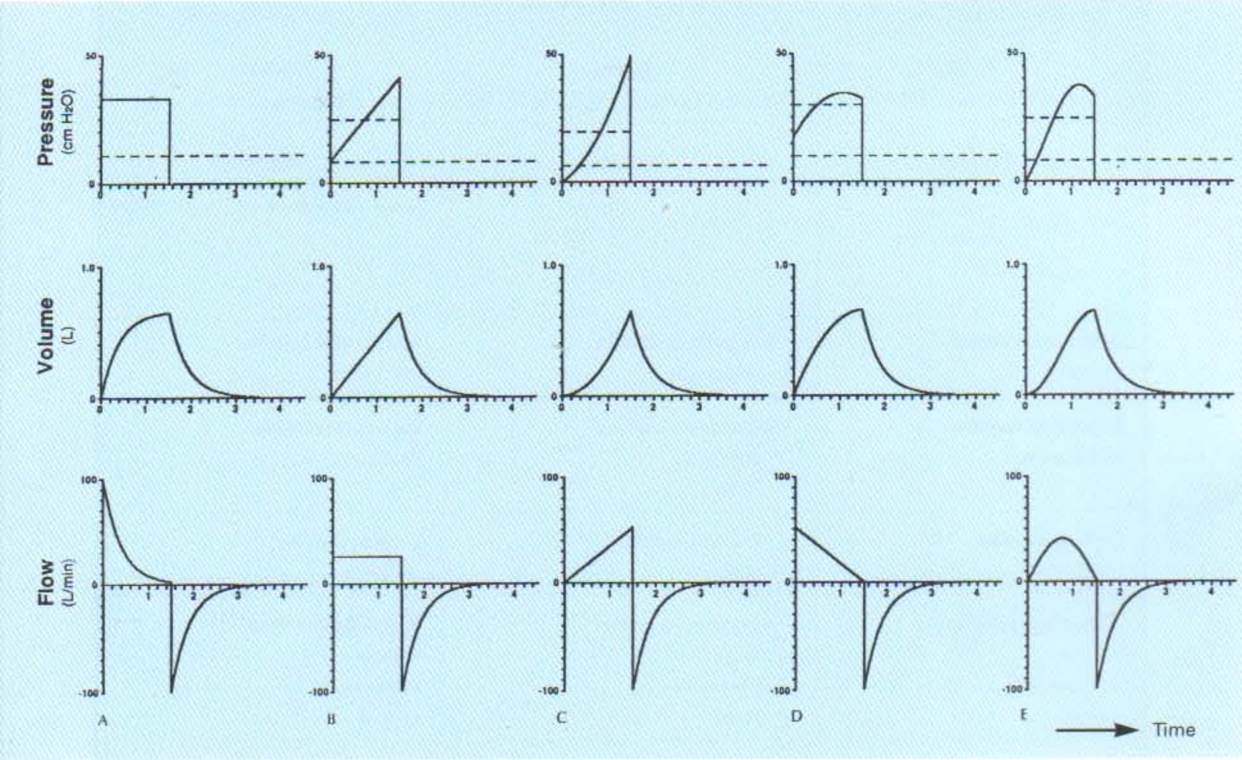
Abbreviations.

SIMV-VC: Synchronized Intermittent Mandatory Ventilation-Volume Control,
SIMV-PC: Synchronized Intermittent Mandatory Ventilation-Pressure Control,
PRVC: Pressure Regulated Volume Control

## Waveforms and the controlled variables

Figures 2–3 illustrates various waveforms associated with different delivery patterns from a flow controller, a pressure controller and a volume controller.

Figure 2–3.
**Theoretical output waveforms.**



**A.**
Pressure-controlled inspiration with rectangular pressure waveform. Note that this is identical to flow-controlled inspiration with an exponential decay flow-waveform.

**B.**
Flow-controlled inspiration with rectangular flow waveform. Note that this is identical to volume-controlled inspiration with an ascending ramp volume waveform.

**C.**
Flow-controlled inspiration with an ascending ramp flow waveform.

**D.**
Flow-controlled inspiration with a descending ramp flow waveform.

**E.**
Flow-controlled inspiration with a sinusoidal flow waveform.

The short dotted lines represent mean inspiratory pressure, and the long dotted lines represent mean airway pressure, assuming in A that the mean inspiratory pressure is the same as the peak inspiratory pressure.

Tables 2–4 and 2–5 summarize the relationship of the various variables of the equation of motion in a concept of waveform analysis through changes in elastic and resistive elements of the respiratory system during mechanical ventilation.

Table 2–4 is associated with a constant flow mode of ventilation, and table 2–5 with a constant pressure mode of ventilation.

## Constant Flow Mode

Table 2–4.

**Elastic and resistive changes noted with a constant flow mode of ventilation.**

| | | Elastic and resistive changes reflected in this waveform | |
|---|---|---|---|
| Pressure-time waveform | Inspiration | Increase to PIP depends on elastic and resistive elements. | Yes |
| | Expiration | Return to EEP depends on elastic and resistive elements. | Yes |
| Volume-time waveform | Inspiration | Increase to $VT_i$ depends on flow, not elastic and resistive elements. | No |
| | Expiration | Return to $VT_e$ depends on elastic and resistive elements. | Yes |
| Flow-time waveform | Inspiration | Increase to PIF is fixed and independent of the elastic and resistive elements. | No |
| | Expiration | Return to EEF depends on elastic and resistive elements. | Yes |
| Volume-pressure loop | Inspiration | Increase to $VT_i$ does not reflect changes, but increase to PIP does. | Yes |
| | Expiration | Return to $VT_e$ and EEP depends on elastic and resistive elements. | Yes |
| Flow-volume loop | Inspiration | Increase to PIF and $VT_i$ does not reflect changes in elastic and resistive elements. | No |
| | Expiration | Return to EEF and $VT_e$ depends on elastic and resistive elements. | Yes |

## Constant Pressure Mode

Table 2–5.

**Elastic and resistive changes noted with a constant flow mode of ventilation.**

| | | Elastic and resistive changes reflected in this waveform | |
|---|---|---|---|
| Pressure-time waveform | Inspiration | Increase to PIP is fixed and independent of the elastic and resistive elements. | No |
| | Expiration | Return to EEP depends on elastic and resistive elements. | Yes |
| Volume-time waveform | Inspiration | Increase to $VT_i$ depends on elastic and resistive elements. | Yes |
| | Expiration | Return to $VT_e$ depends on elastic and resistive elements. | Yes |
| Flow-time waveform | Inspiration | Decelerating flow depends on elastic and resistive elements. | Yes |
| | Expiration | Return to EEF depends on elastic and resistive elements. | Yes |
| Volume-pressure loop | Inspiration | Increase to $VT_i$ reflects changes, but increase to PIP does not. | Yes |
| | Expiration | Return to $VT_e$ and EEP depends on elastic and resistive elements. | Yes |
| Flow-volume loop | Inspiration | Decelerating flow and increase to $VT_i$ depend on elastic and resistive elements. | Yes |
| | Expiration | Return to EEF and $VT_e$ depends on elastic and resistive elements. | Yes |

# Selected references and suggested reading

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# Resistance in mechanical ventilation

**This chapter describes the concept of resistance in a context of mechanical ventilation. Resistance indexes are mostly explained and calculated with pressure-time waveforms. Flow-time and volume-time waveforms and flow-volume loops yield qualitative data of the resistive status during mechanical ventilation.**

**In this chapter, various components of the pressure-time waveform are used to explain resistance from a clinical perspective.**

### Resistance

Resistance in mechanical ventilation describes the airflow condition during both inspiration and expiration. Resistance represents the flow resistive elements of the respiratory system. It is expressed as a pressure variation over gas flow using the following general equation:

$$\text{Resistance} = \frac{\Delta\ \text{Pressure}}{\text{Flow}}$$

By substituting standard units, it becomes

$$[\text{Resistance}] = \frac{\text{cm } H_2O}{\text{ml} \bullet \text{sec}^{-1}}$$

Airway resistance is affected by flow, tidal volume and the network dimension. The size of the endotracheal tube is an important element in gas flow through the breathing circuit, and thus affects resistance.When delivering a set tidal volume at a set flow, smaller and longer tubes will produce larger resistance to gas flow, and vice versa.

### Constant pressure mode of ventilation

When a ventilator operates in a constant pressure mode, the resistive elements of the respiratory system/breathing circuit can be visualized with the flow-time and volume-time waveforms. The inspiration part of the pressure-time waveform does not offer any indication of resistance, since pressure is constant throughout inspiration.

However, the flow-time waveform will reflect the resistive elements of the respiratory system since the rate of decay of flow is a function of resistance. For measuring resistance, the flow interrupter technique cannot be used in this mode since flow varies and pressure is constant.

### Constant flow mode of ventilation

Traditionally, resistance has been measured by the interrupter technique. This technique implies that flow is interrupted at the end of inspiration while pressure is kept constant during a period of time (pause time).

The interrupter technique is only valid when the ventilator operates in a constant flow mode which means that flow is constant throughout inspiration.

When a ventilator operates in a constant flow mode, the resistive elements of the respiratory system/breathing circuit can be visualized and calculated with the pressure-time waveform. The pressure-time waveform begins with an exponential rise to a first step, followed by a linear rise to peak inspiratory pressure (PIP).

The first step is a function of flow and resistance during the initial portion of inspiration. The higher the step, the larger the resistance. The second portion of the waveform is a linear increase to peak inspiratory pressure, and is a function of flow being constant throughout inspiration. This second portion represents the elastic properties of the respiratory system.

As peak inspiratory pressure is reached, a pause time or plateau is maintained while pressure inside the airways and the breathing circuit equilibrates at plateau pressure ($P_{\text{plateau}}$). Flow then stops while pressure equilibrates.

Figure 3–1.
**Pressure-time waveform from a constant flow mode illustrating resistive and elastic elements of the respiratory system.**

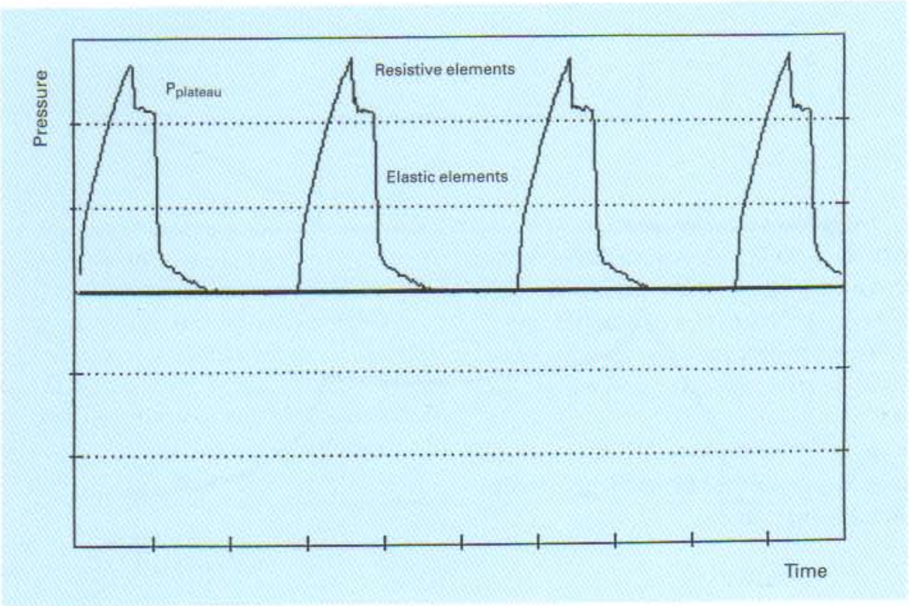


Figure 3–1 is a pressure-time waveform from a constant flow mode of ventilation and illustrates various elements related to resistive and elastic properties of the respiratory system.

Inspiratory resistance is the difference between PIP and $P_{plateau}$ over flow value at PIP, as expressed by the following equation:

$$R_I = \frac{PIP - P_{plateau}}{PIF}$$

Expiratory resistance is the difference between $P_{plateau}$ and total PEEP over flow value at the onset of exhalation, as expressed by the following equation:

$$R_E = \frac{PIP - PEEP_{TOT}}{\text{Flow at onset of exhalation}}$$

Specific measuring conditions must be met for a valid inspiratory and expiratory resistance value:

- Passive tidal volume (inspiration and expiration)
- Constant flow over a fixed inspiratory time (TI) (for inspiratory resistance only)
- The $P_{plateau}$ must have an end-inspiratory pause of at least 1 second with a stable pressure within 0.5 $cmH_2O$ over 2 readings at least 10 ms apart.

The pressure-time waveform under a constant flow mode with a pause time has been extensively documented. The pause time can be analyzed in detail and brings further subdivisions in the resistance concept. The pressure decrease from PIP to the end of $P_{plateau}$ can be magnified. Two segments of resistance can be calculated: the Maximum Resistance Index ($R_{max}$) and the Minimum Resistance Index ($R_{min}$).

Figure 3–2 shows flow-time and pressure-time waveforms from a constant flow mode of ventilation and illustrates various landmarks for resistance calculation.

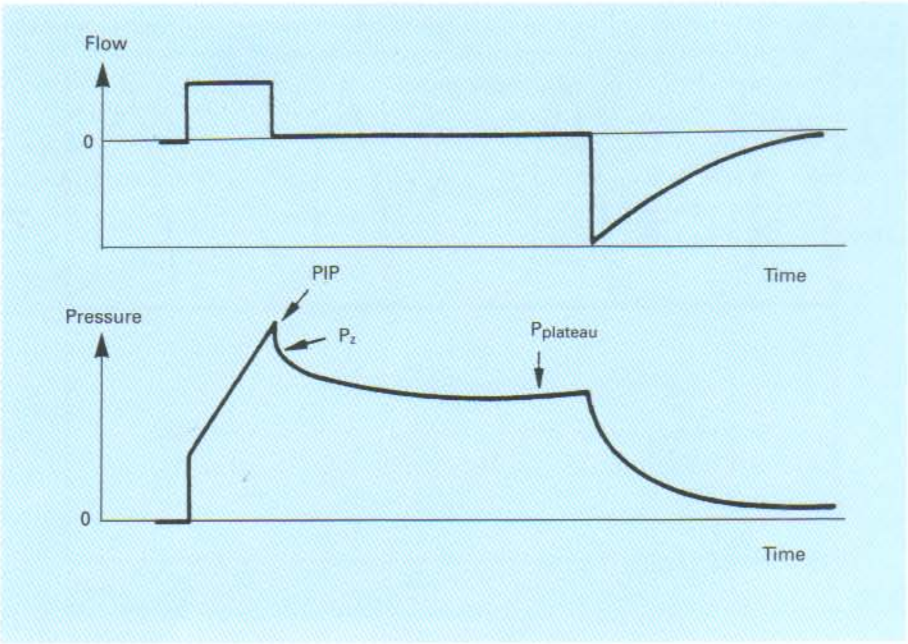
- PIP is the peak inspiratory pressure (representing the peak dynamic pressure)
- $P_z$ is the airway pressure when flow stops (zero flow) during pause time. The exact location of $P_z$ is not yet clearly identified.
- $P_{plateau}$ is the end inspiratory pause pressure representing the static airway pressure and is often referred as a close estimate of the alveolar pressure.

## Maximum resistance index ($R_{max}$)

Maximum resistance index ($R_{max}$) is the difference between PIP - $P_{plateau}$ at peak inspiratory

Figure 3–2.

**Flow-time and pressure-time waveforms (constant flow mode)**



flow. $R_{max}$ represents the resistance caused by the endotracheal tube, the breathing circuit, pulmonary tissues and the thoracic cavity at maximum lung volume.

$R_{max}$ is calculated using the following equation:

$$R_{max} = \frac{PIP - P_{plateau}}{PIF}$$

$R_{max}$ constitutes the overall resistance of the respiratory system/breathing circuit traditionally calculated during mechanical ventilation. Table 3–1 illustrates various values of $R_{max}$ and $R_{min}$ for adults under specific conditions.

Table 3–1.

**Values of $R_{max}$ and $R_{min}$ in adults.**

| Adults | $R_{max}$ (cm $H_2O$/l/s) | $R_{min}$ (cm $H_2O$/l/s) |
|---|---|---|
| Normal | 7 | 2,5 |
| ARDS | 12–15 | 8,0 |
| COPD | 26 | 15 |
| Pulmonary Edema | 7–18 | 4–12 |

Table 3–2 illustrates various $R_{max}$ clinical values for infants under specific conditions.

Table 3–2.

**Values of $R_{max}$ for intubated and extubated infants.**

| | $R_{max}$ (cm $H_2O$/l/s) | |
|---|---|---|
| Infants | Intubated | Extubated |
| 3,0 mm ID | 128 | 75 |
| 3,5 mm ID | 73 | 37 |
| Tube size not specified | 50–150 | 20–30 |

## Minimum resistance index ($R_{min}$)

Minimum resistance index ($R_{min}$) is the difference between PIP - $P_z$ at peak inspiratory flow. $P_z$ is the pressure value when the expiratory valve closes and flow stops. $R_{min}$ describes a specific component of the $R_{max}$ and reflects only the resistance of the airways. $R_{min}$ is calculated by the following equation:

$$R_{min} = \frac{PIP - P_z}{PIF}$$

The calculation of $R_{min}$ in itself presents certain difficulties, as to precisely identify the location of $P_z$. $P_z$ has a value greater than $P_{plateau}$. The difference between $P_z$ and $P_{plateau}$ represents the gas redistribution of alveolar regions with different time constants. Refer to Table 3–1 for $R_{min}$ clinical values.

The difference between $R_{max} - R_{min}$ is an indication of various inhomogeneously ventilated pulmonary zones with different time constants. However, the zones are ventilated even though the flow in larger airways seems to have stopped.

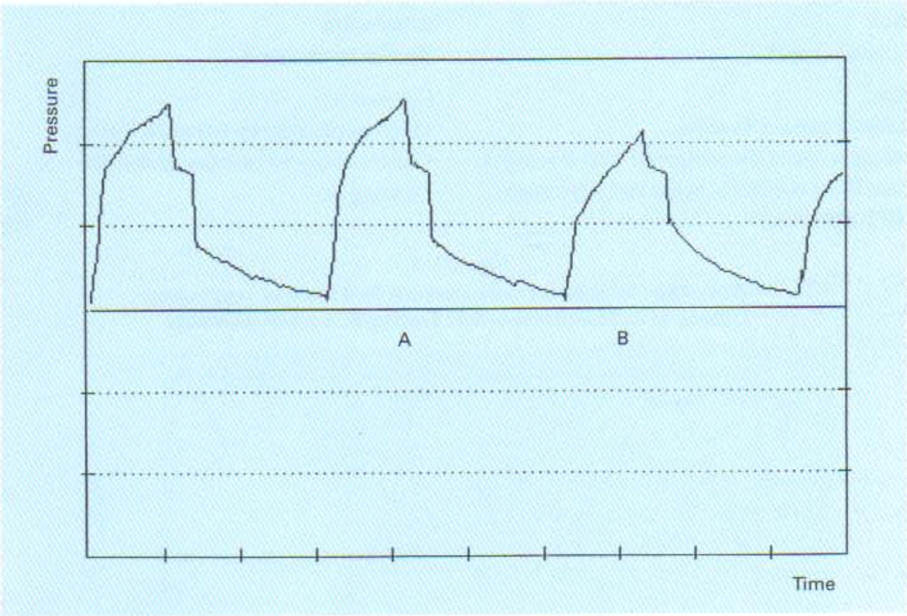
This phenomenon is often referred to as the Pendelluft (German word for pendulum of air); the larger the difference between $R_{max} - R_{min}$, the larger the zones discrepancies. In ARDS, the difference between $P_z$ and $P_{plateau}$ generally differ by 10–20 %.

## Waveforms, loops and resistance

Figures 3–3, 3–4, 3–5, 3–6 and 3–7 illustrate changes in waveforms and loops attributed to resistance changes from a constant flow mode of ventilation.

Figure 3–3.

**Pressure-time waveform from a constant flow mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- The value of the first step is increased compared with tracing B.
- Difference between PIP and $P_{plateau}$ is increased compared with tracing B.
- The slope of the second portion is unchanged compared with tracing B.

*Expiration*

Linear decay to baseline.

**Tracing B: Normal resistance**

*Inspiration*

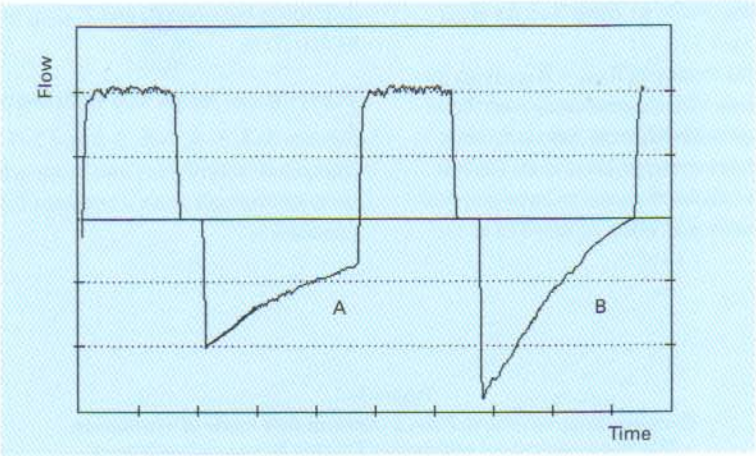
- The value of the first step is smaller compared with tracing A.
- Difference between PIP - $P_{plateau}$ is smaller compared with tracing A.
- The slope of the second portion is unchanged compared with tracing A.

*Expiration*

Exponential decay to baseline.

Figure 3–4.

**Flow-time waveform from a constant flow mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- Linear decay toward baseline.
- Slow decay to baseline compared with tracing B.
- Non Zero Flow condition at the end expiration (auto-PEEP present).

**Tracing B: Normal resistance**

*Inspiration*

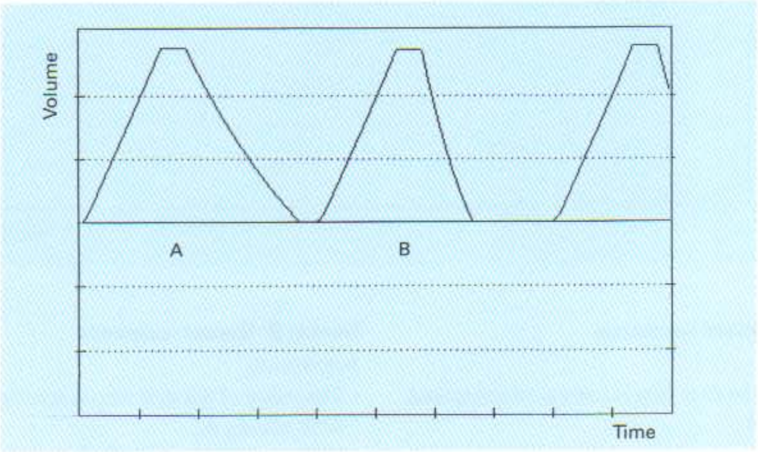
Similar to tracing A.

*Expiration*

- Exponential decay toward baseline.
- Faster decay to baseline compared with tracing A.

Figure 3–5.

**Volume-time waveform from a constant flow mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Linear increase similar to tracing B.

*Expiration*

- Slow decay to baseline compared with tracing B.

**Tracing B: Normal resistance**

*Inspiration*

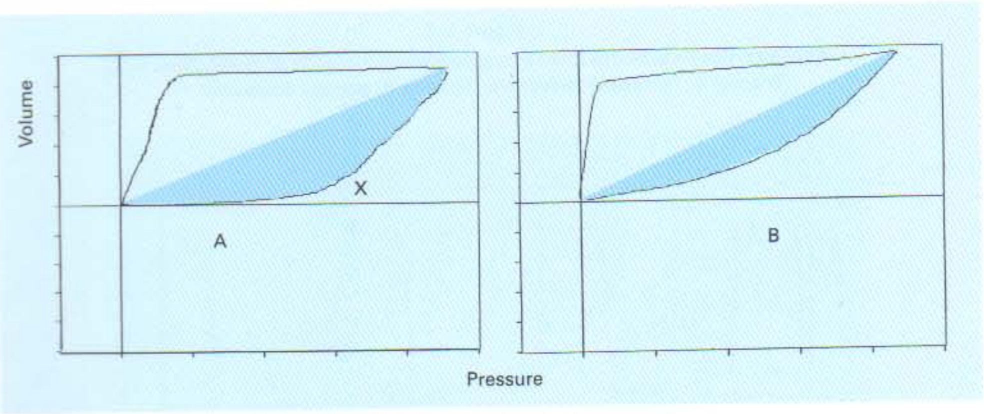
Linear increase similar to tracing A.

*Expiration*

- Rapid decay to baseline compared with tracing A.

Figure 3–6.

**Volume-pressure loop from a constant flow mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- The shaded area is larger than the same area in tracing B.
- X corresponds to the end of the first portion, beginning of the second portion of inspiration.

*Expiration*

- Second portion starts at a higher pressure compared with tracing B.

**Tracing B: Normal resistance**

*Inspiration*

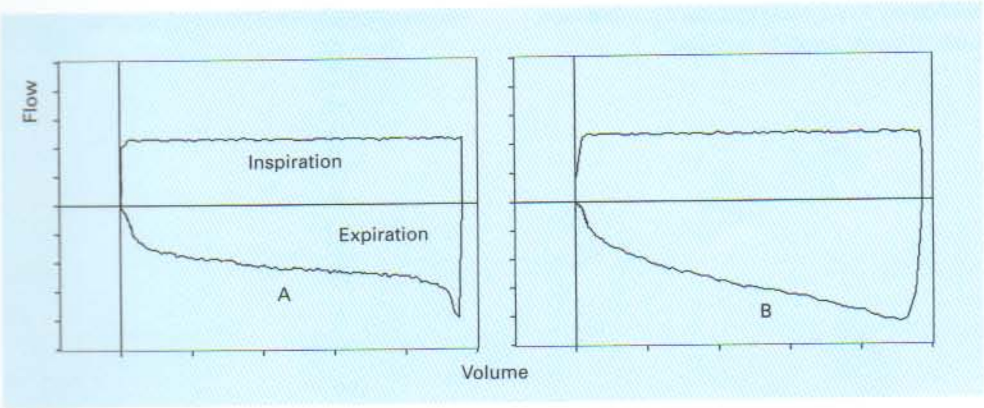
- The shaded area is smaller than the same area in tracing A.

*Expiration*

- Second portion starts at a lower pressure compared with tracing A.

Figure 3–7.

**Flow-volume loop from a constant flow mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- Linear return to baseline.

**Tracing B: Normal resistance**

*Inspiration*

- Similar to tracing A.

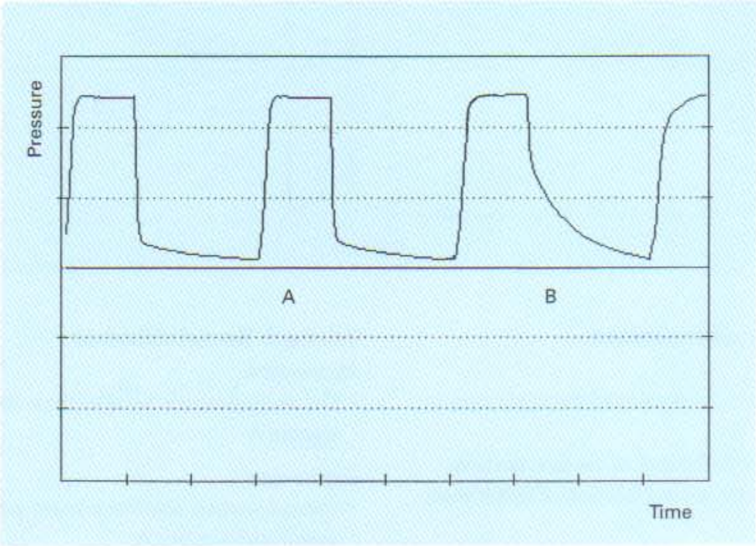
*Expiration*

- Exponential return to baseline.

Figures 3–8, 3–9, 3–10, 3–11 and 3–12 illustrate changes in waveforms and loops attributed to resistance changes from a constant pressure mode of ventilation.

Figure 3–8.

**Pressure-time waveform from a constant pressure mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Peak inspiratory pressure reached rapidly as in tracing B.

*Expiration*

- Rapid decay to second expiratory portion then abnormal linear decay to baseline.

**Tracing B: Normal resistance**

*Inspiration*

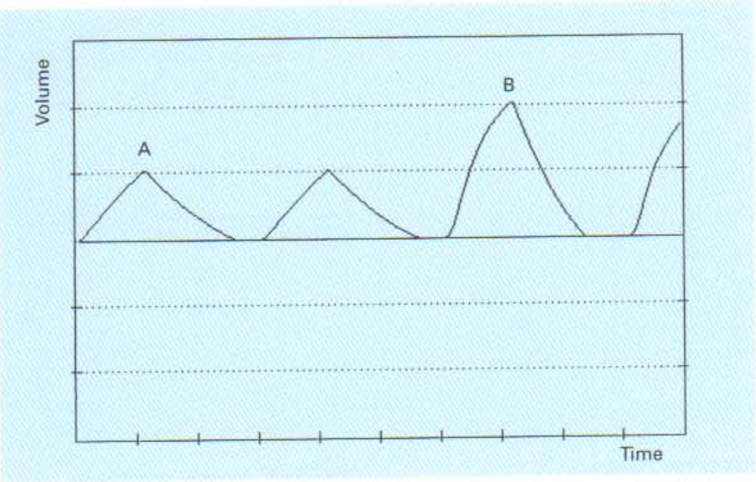
- Peak inspiratory pressure reached rapidly as in tracing A.

*Expiration*

- Normal exponential decay to baseline.

Figure 3–9.

**Volume-time waveform from a constant pressure mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Abnormal linear increase to tidal volume.
- Decreased inspired tidal volume compared with tracing B.

*Expiration*

- Abnormal linear decay to baseline.

**Tracing B: Normal resistance**

*Inspiration*

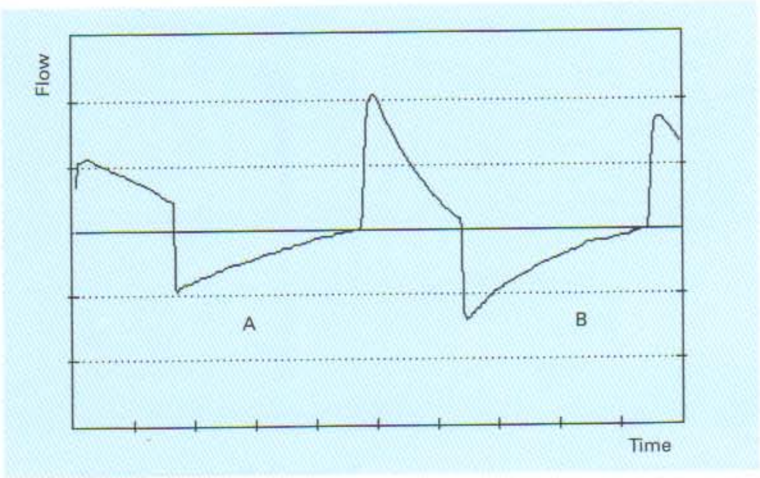
- Normal exponential increase to tidal volume.

*Expiration*

- Normal exponential decay to baseline.

Figure 3–10.

**Flow-time waveform from a constant pressure mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Slow decay throughout inspiration.
- Inspiration stops before baseline is reached.

*Expiration*

- Abnormal linear decay to baseline.

**Tracing B: Normal resistance**

*Inspiration*

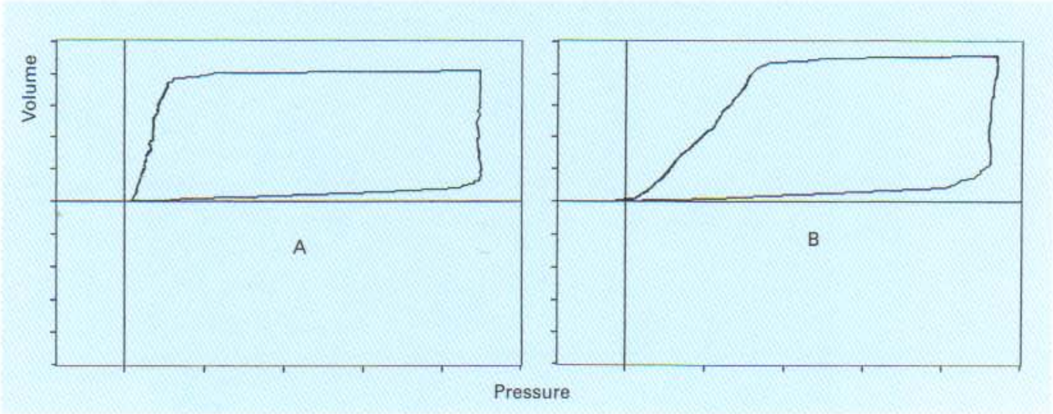
- Normal exponential decay to baseline.

*Expiration*

- Normal exponential decay to baseline.

Figure 3–11.

**Volume-pressure loop from a constant pressure mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Rapid increase to peak inspiratory pressure similar as in tracing B.

*Expiration*

- Second portion starts at a lower pressure compared with tracing B.

**Tracing B: Normal resistance**

*Inspiration*

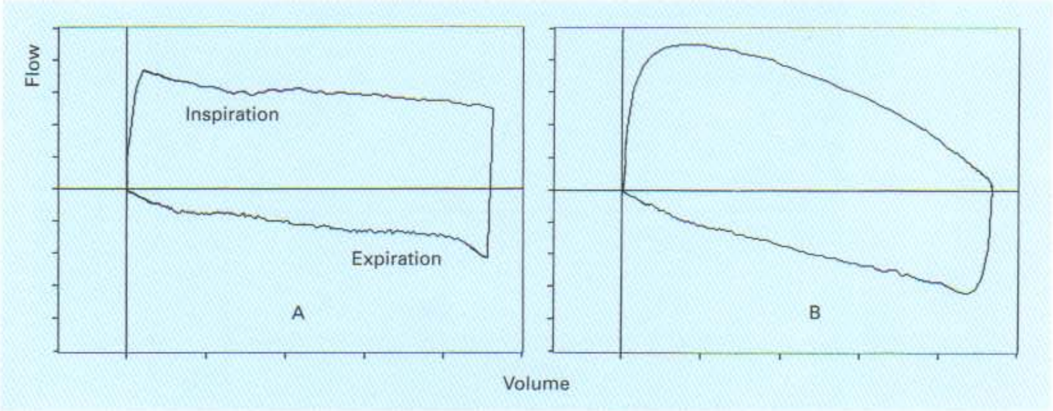
- Rapid increase to peak inspiratory pressure similar as in tracing A.

*Expiration*

- Second portion starts at a higher pressure compared with tracing A.

Figure 3–12.

**Flow-volume loop from a constant pressure mode of ventilation. Tracing A: increased resistance; Tracing B: normal resistance.**



**Tracing A: Increased resistance**

*Inspiration*

- Flow does not reach baseline before set inspiratory time has elapsed.

*Expiration*

- Linear decay to baseline.

**Tracing B: Normal resistance**

*Inspiration*

- Flow decreases to baseline.

*Expiration*

- Normal exponential decay to baseline.

## Constant Flow Mode

Table 3–3.

**Observed changes from a constant flow mode of ventilation.**

| | | Resistance and compliance changes noticed |
|---|---|---|
| Pressure-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Volume-time waveform | Inspiration | No |
| | Expiration | Yes |
| Flow-time waveform | Inspiration | No |
| | Expiration | Yes |
| Volume-pressure loop | Inspiration | Yes |
| | Expiration | Yes |
| Flow-volume loop | Inspiration | No |
| | Expiration | Yes |

## Constant Pressure Mode

Table 3–4.
Observed changes from a constant pressure mode of ventilation.

| | | Resistance and compliance changes noticed |
|---|---|---|
| Pressure-time waveform | Inspiration | No |
| | Expiration | Yes |
| Volume-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Flow-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Volume-pressure loop | Inspiration | Yes |
| | Expiration | Yes |
| Flow-volume loop | Inspiration | Yes |
| | Expiration | Yes |

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# Compliance in mechanical ventilation

**This chapter describes the concepts of static compliance and dynamic characteristics of the respiratory system during mechanical ventilation.**

**With today's technology the clinician can easily monitor meaningful bedside data involved in the understanding of the elastic and resistive characteristics of the disease process.**

**Serial observations of the volume-pressure loop in mechanical ventilation are perhaps as important as the exact quantification of various volume-pressure relationships.**

## Compliance

Compliance describes the elastic properties of various parts of the respiratory system. Compliance represents a volume change over a pressure change, and can be expressed by the following general equation:

$$\text{Compliance} = \frac{\Delta\ \text{Volume}}{\Delta\ \text{Pressure}}$$

By substituting standard units, it becomes

$$[\text{Compliance}] = \frac{\text{ml}}{\text{cmH}_2\text{O}}$$

Total respiratory system compliance ($C_{rs}$) is related to lung compliance and chest wall compliance by the following equation:

$$\frac{1}{C_{rs}} = \frac{1}{C_{pulm}} + \frac{1}{C_{CW}}$$

$C_{rs}$ is used to evaluate and modify various therapeutic interventions such as tidal volume and PEEP titration, paralysis and patient positioning.

Total static compliance (during no flow activity at the end of inspiration and expiration) and total dynamic characteristics (during active inspiration) are the two conditions when volume-pressure relation is most often monitored in mechanical ventilation.

The status of compliance at the bedside can be observed with flow-time and pressure-time waveforms and the volume-pressure loop.

### Chest wall compliance

Chest wall compliance ($C_{CW}$) is not commonly calculated during mechanical ventilation because dedicated monitors allowing estimation of intrapleural pressure through esophageal pressure are still not easily available at bedside.

Chest wall compliance describes the changes in tidal volume ($V_T$) relative to the pleural pressure, reflected by the esophageal pressure ($P_{eso}$), and is expressed by the following equation:

$$C_{CW} = \frac{V_T}{P_{eso}}$$

To calculate chest wall compliance, the patient should be completely passive. Muscle relaxant must be administered to spontaneously breathing patients. This might constitute a drawback in various clinical situations, jeopardizing patient safety. Chest wall compliance is an essential parameter for the calculation of total work of breathing using the Campbell diagram.

Chest wall compliance can usually be estimated at 4% of the vital capacity per $cmH_2O$. Normal value for chest wall compliance is approximately 200 ml/cm $H_2O$.

### Lung compliance

Lung compliance ($C_{pulm}$) is not commonly calculated during mechanical ventilation for the same reasons as for chest wall compliance.

Lung compliance describes the change in tidal volume relative to the transpulmonary pressure $P_{plateau}$ - $P_{eso}$ where $P_{plateau}$ is the plateau pressure, also referred to as alveolar pressure and

$P_{eso}$ is the esophageal pressure under quasi static condition.

Lung compliance is expressed by the following equation:

$$C_{pulm} = \frac{V_T}{P_{plateau} - P_{eso}}$$

Lung compliance can be obtained on passively or spontaneously breathing patients.

### Total static compliance

Total static compliance of the respiratory system ($Cst_{tot}$) is frequently measured and monitored during mechanical ventilation.

Total static compliance is the pressure required to overcome the elastic forces of the respiratory system for a given tidal volume, and under a zero flow (static) condition. Static compliance thus reflects the elastic properties of the respiratory system.

Specific measuring conditions must be met for a valid static compliance value:

- Passive tidal volume (inspiration and expiration)
- Compressible volume correction for tubing
- The plateau must have an end-inspiratory pause of at least 1 second with a stable pressure within 0.5 $cmH_2O$ over 2 readings at least 10 ms apart.

Total static compliance describes the delivered tidal volume relative to the airway pressure under a static condition ($P_{plateau} - PEEP_{total}$), where tidal volume must be corrected for compressible tubing volume, $P_{plateau}$ is the pressure during the pause time, and $PEEP_{total}$ is the sum of set PEEP + intrinsic PEEP. $Cst_{tot}$ is expressed by the following equation:

$$Cst_{tot} = \frac{V_T}{P_{plateau} - PEEP_{total}}$$

Changes in static compliance are associated with changes in lung elasticity; lung pathology that increases lung recoil or decreases lung volume will decrease the static compliance.

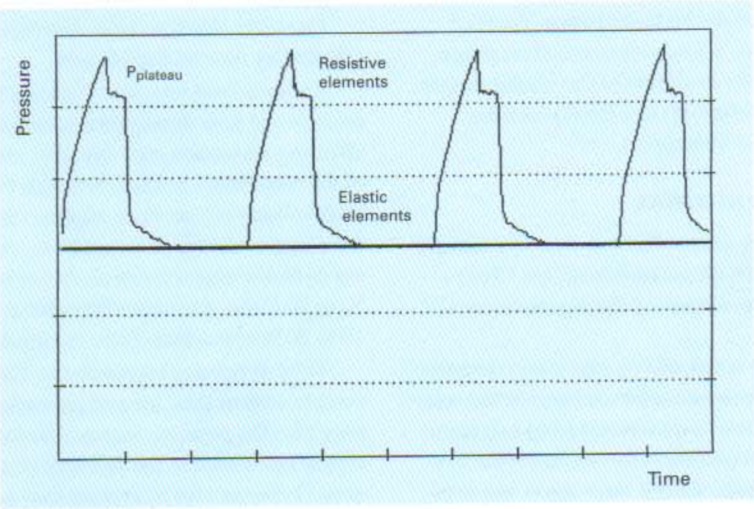
Table 4–1.
**Static compliance values.**

| | Static compliance ($ml/cmH_2O$) |
|---|---|
| Adults | 60–100 |
| Approximately 1 ml per cm $H_2O$ per kg body weight. | |

Static compliance varies with tidal volume and PEEP. Tidal volume and PEEP titration can often be accomplished by monitoring static compliance.

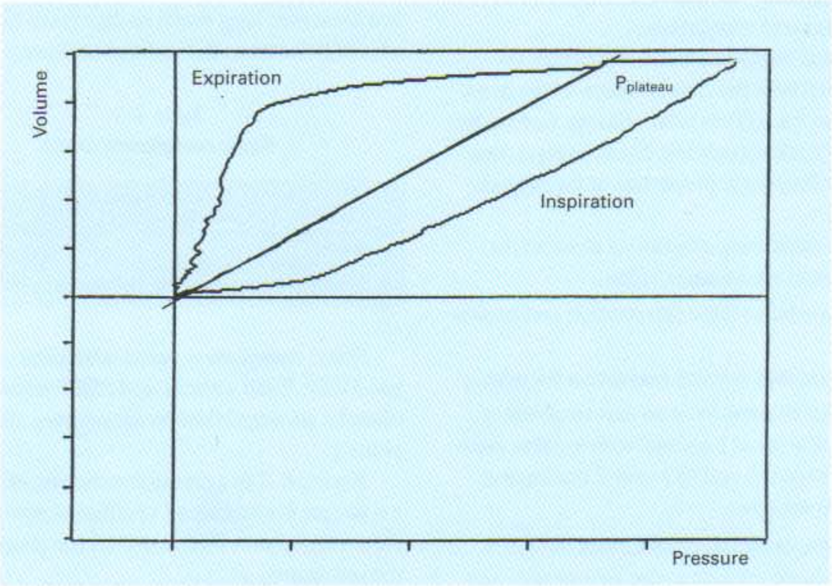
Figure 4–1 is a pressure-time waveform from a constant flow mode of ventilation and illustrates areas related to resistive and elastic properties of the respiratory system.

Figure 4–1.
**Pressure-time waveform from a constant flow mode of ventilation illustrating resistive and elastic elements of the respiratory system.**



The volume-pressure loop from a constant flow mode of ventilation with pause time also allows the clinician to visualize the static compliance status. The slope of this loop (from the origin to $P_{plateau}$) is an estimate of the static compliance. Figure 4–2 is a volume-pressure loop from a constant flow mode of ventilation with a pause time, and illustrates the static compliance slope.

Figure 4–2.
**Volume-pressure loop from a constant flow mode of ventilation illustrating the static compliance slope.**



Compliance values are affected by the patient's size and state of relaxation, lung volume and flow, and caution is thus the rule when interpreting actual values for compliance. Trended values rather than actual values are appropriate for monitoring the evolution of the elastic properties of the respiratory system throughout the period of ventilatory support.

## Dynamic characteristics

Formerly known as the effective dynamic compliance, the dynamic characteristics (Dyn Char) have always been measured during mechanical ventilation.

We prefer to speak of dynamic characteristics rather than dynamic compliance because the relationship of volume vs. pressure during a dynamic event is subject to resistive forces inside the system. In other words, during inspiration and expiration gas flow constitutes a resistive element and volume/pressure is not truly compliance by definition, since resistance is part of the relation.

Dynamic characteristics are thus directly affected by flow and resistance.

Endotracheal tube size is an important element in gas flow through the breathing circuit, affecting resistance, and dynamic characteristics of the respiratory system. When delivering a set tidal volume at a set flow, smaller tubes will produce larger resistance to gas flow, whereby affecting dynamic characteristics. At normal flows of 50 to 80 l/min, dynamic characteristics values are 10 to 20 % lower than static compliance.

Total dynamic characteristics describes the components of total lung or parenchymal compliance plus the pressure required to overcome the airway resistance in the delivery of a tidal volume. Dynamic characteristics thus reflect the resistive and elastic properties of the respiratory system.

Total dynamic characteristics is the tidal volume relative to the peak airway pressure under a dynamic condition, and is expressed by the following relation:

$$\text{Dyn Char} = \frac{V_T}{\text{PIP - PEEP}}$$

Dynamic characteristics data are often displayed continuously breath by breath during mechanical ventilation.

Trended values are thus clinically helpful in reflecting resistive and elastic properties of the respiratory system.

Table 4–2.

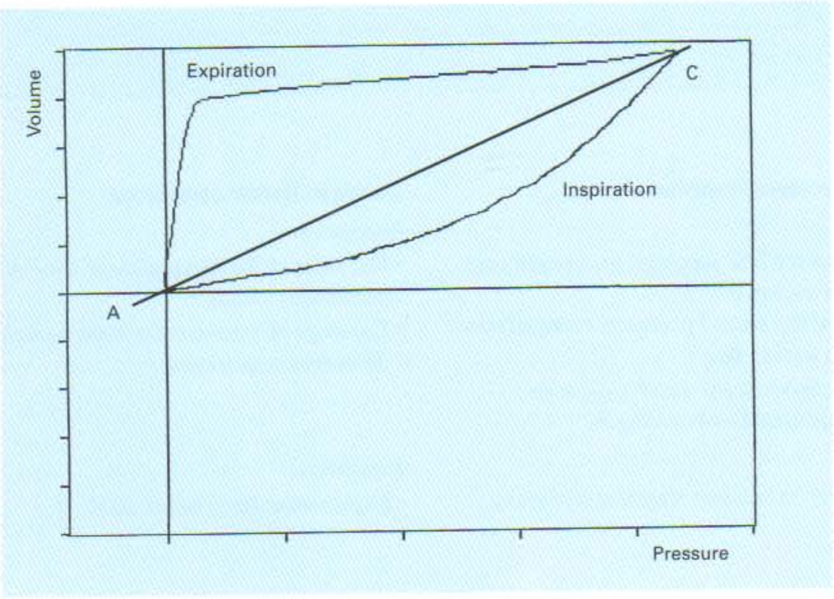
**Dynamic characteristics values.**

| | Dynamic characteristics (ml/cmH$_2$O) |
|---|---|
| Adults | 50–80 |
| Newborns | 5–6 |

Figure 4–3a is a volume-pressure loop from a constant flow mode of ventilation. The slope of AC reflects the total dynamic characteristics of the respiratory system.

Figure 4–3a.

**Volume-pressure loop from a constant flow mode of ventilation.**



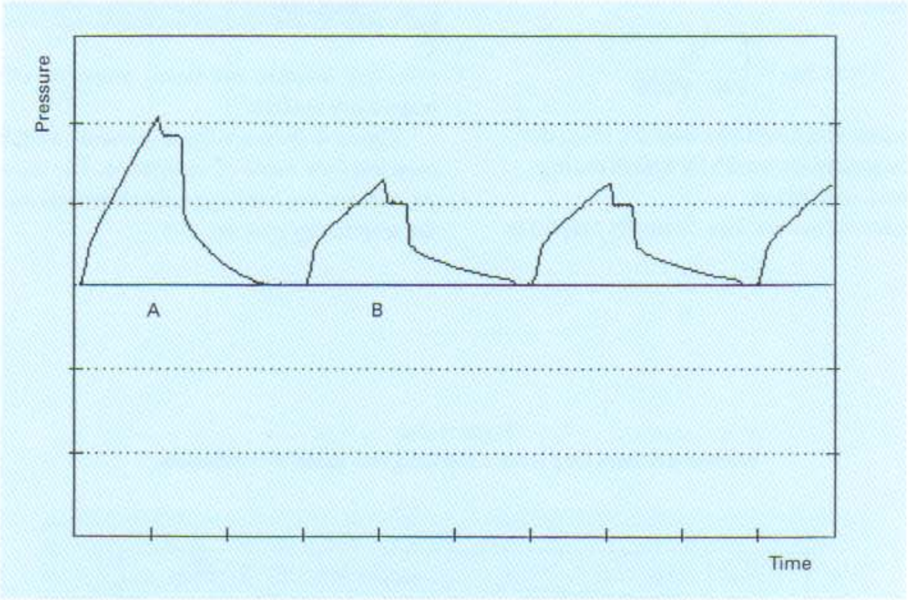
The difference between static compliance and dynamic characteristics can be used as an indirect index of flow-resistive properties of the respiratory system.

In mechanical ventilation, serial measurement of various components of the volume-pressure relationship with the volume-pressure loop after changes in the relaxation state of the patient, tidal volume, and flow can yield useful information on the evolution of airways and parenchymal conditions of the patient.

The volume-pressure loop should be monitored after any modification in ventilatory strategies such as changes in flow, tidal volume, respiratory rate and patient relaxation state.

Figure 4–3b.

**Pressure-time waveform from a constant flow mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- The value of the first portion is unchanged compared with tracing B.
- The slope of the second portion is changed compared with tracing B.
- Difference between PIP and $P_{plateau}$ is unchanged compared with tracing B.

*Expiration*

- Linear decay to baseline after first portion is reached.

**Tracing B: Normal compliance**

*Inspiration*

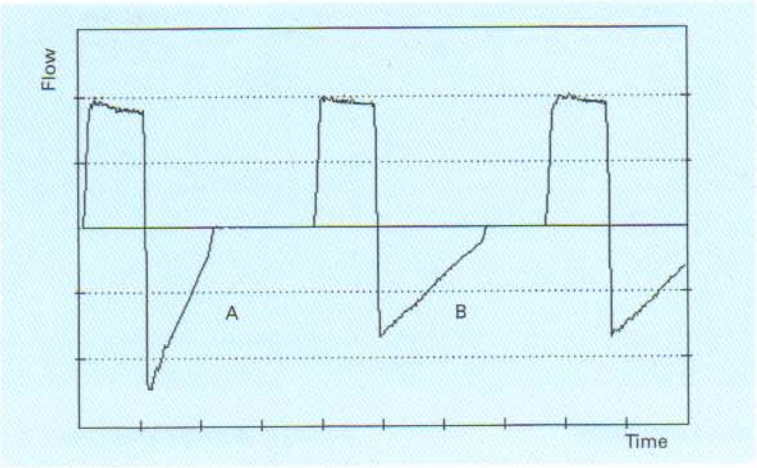
- The value of the first portion is unchanged compared with tracing A.
- The slope of the second portion is unchanged compared with tracing A.

*Expiration*

- Exponential decay to baseline.

Figure 4–4.

**Flow-time waveform from a constant flow mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- Linear decay to baseline.
- The slope of the second portion is sharper than in tracing B.

**Tracing B: Normal compliance**

*Inspiration*

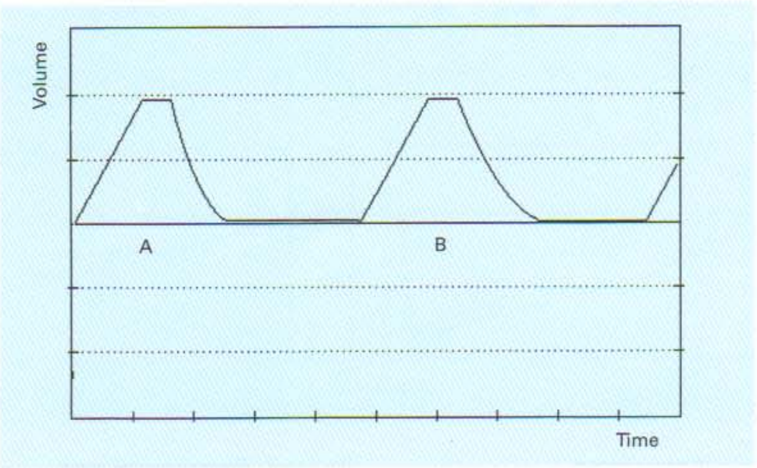
- Similar to tracing A.

*Expiration*

- Exponential decay to baseline.
- The slope of the second portion is less sharp than in tracing A.

Figure 4–5.

**Volume-time waveform from a constant flow mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Linear increase similar to tracing B.

*Expiration*

- Similar decay to baseline as in tracing B.

**Tracing B: Normal compliance**

*Inspiration*

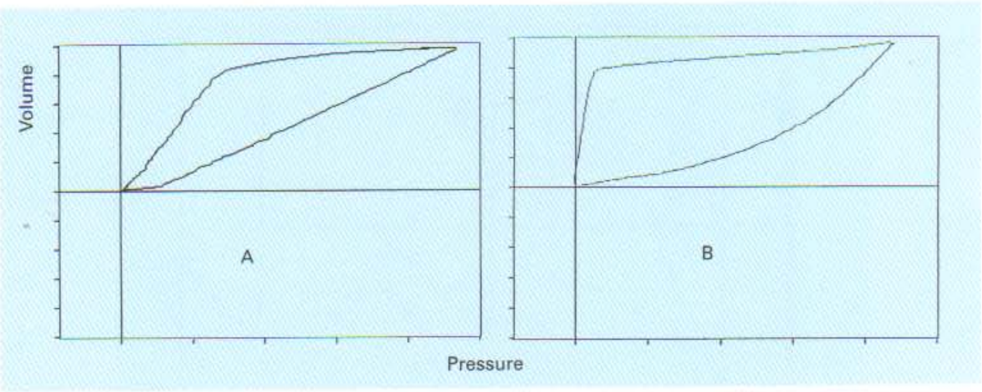
- Linear increase similar to tracing A.

*Expiration*

- Similar decay to baseline as in tracing A.

Figure 4–6.

**Volume-pressure loop from a constant flow mode of ventilation.
Tracing A: Decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Linear increase to peak inspiratory pressure and inspired tidal volume.

*Expiration*

- Second portion of the expiratory profile starts at a higher pressure compared with tracing B.

**Tracing B: Normal compliance**

*Inspiration*

- Exponential increase to peak inspiratory pressure and inspired tidal volume.

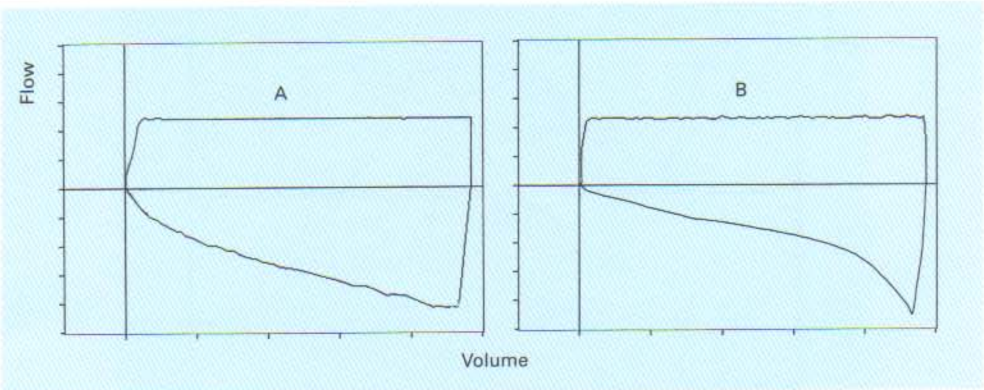
*Expiration*

- Second portion of the expiratory profile starts at a lower pressure compared with tracing A.

*This is more from an academic perspective. Attention should be directed to expiration rather than inspiration.*

Figure 4–7.

**Flow-volume loop from a constant flow mode of ventilation.
Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- Linear to concave expiratory profile.

**Tracing B: Normal compliance**

*Inspiration*

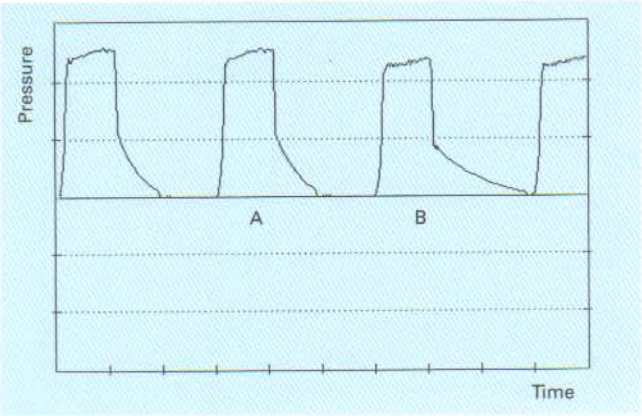
- Similar to tracing A.

*Expiration*

- Linear to convex expiratory profile.

Figure 4–8.

**Pressure-time waveform from a constant pressure mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- The slope of the second portion is steeper than in tracing B.

**Tracing B: Normal compliance**

*Inspiration*

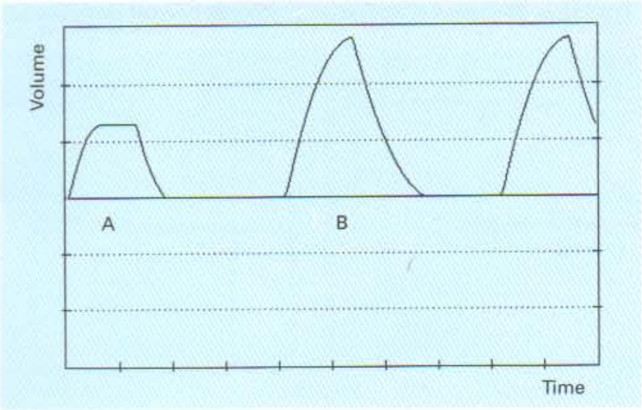
- Similar to tracing A.

*Expiration*

- Normal exponential decay to baseline.

Figure 4–9.

**Volume-time waveform from a constant pressure mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Decreased tidal volume compared with tracing B.
- A plateau is present because flow reached zero before elapsed inspiratory time.

*Expiration*

- Decay to baseline similar to tracing B.

**Tracing B: Normal compliance**

*Inspiration*

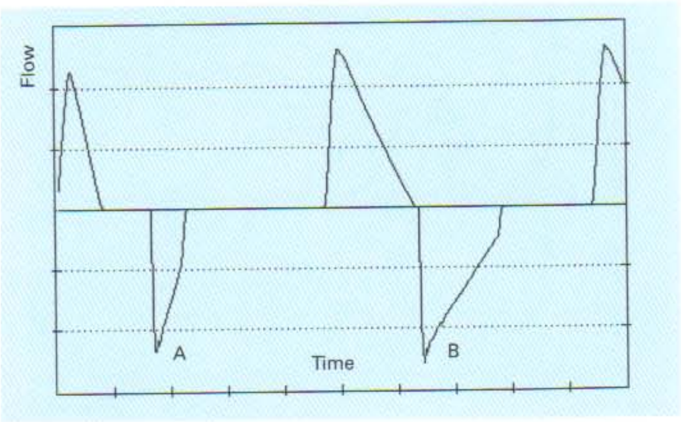
- Increased tidal volume compared with tracing A.

*Expiration*

- Decay to baseline similar to tracing A.

Figure 4–10.

**Flow-time waveform from a constant pressure mode of ventilation Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Rapid decay to baseline before the set inspiratory time has elapsed.
- Tidal volume lower than in tracing B in spite of same peak inspiratory pressure.

*Expiration*

- Rapid decay to baseline.

**Tracing B: Normal compliance**

*Inspiration*

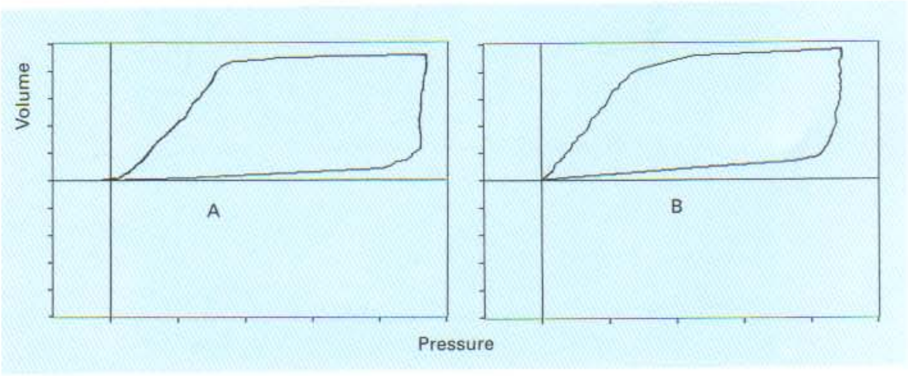
- Slower decay to baseline compared with tracing A.
- Larger tidal inspiratory volume

*Expiration*

- The slope is less steep than the same region in tracing B.

Figure 4–11.

**Volume-pressure loop from a constant pressure mode of ventilation. Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Similar to tracing B.

*Expiration*

- Second portion starts at a higher pressure compared with tracing B.

**Tracing B: Normal compliance**

*Inspiration*

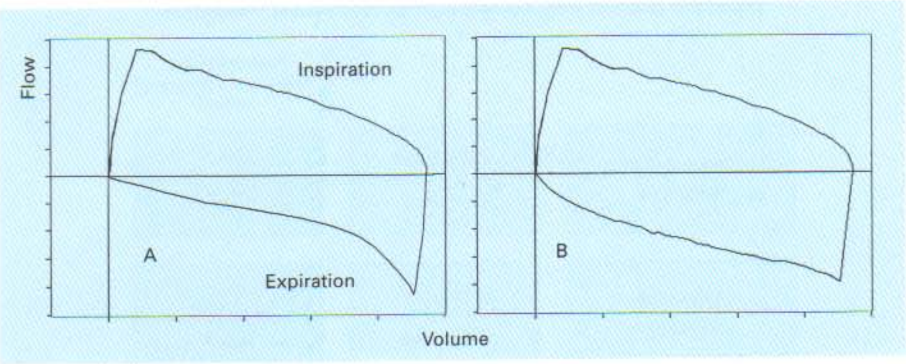
- Similar to tracing A.

*Expiration*

- Second portion starts at a lower pressure compared with tracing A.

Figure 4–12.

**Flow-volume loop from a constant pressure mode of ventilation.**
**Tracing A: decreased compliance; Tracing B: normal compliance.**



**Tracing A: Decreased compliance**

*Inspiration*

- Flow rapidly reaches a peak value then decreases gradually to baseline.
  (Flow decelerates during inspiration)

*Expiration*

- Linear to concave expiratory profile.

**Tracing B: Normal compliance**

*Inspiration*

- Flow reaches a peak value then decreases gradually to baseline.

*Expiration*

- Linear to convex expiratory profile.

### Constant Flow Mode

Table 4–4.

**Observed changes with a constant flow mode of ventilation.**

| | | Resistance and Compliance changes noticed |
|---|---|---|
| Pressure-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Volume-time waveform | Inspiration | No |
| | Expiration | Yes |
| Flow-time waveform | Inspiration | No |
| | Expiration | Yes |
| Volume-pressure loop | Inspiration | Yes |
| | Expiration | Yes |
| Flow-volume loop | Inspiration | No |
| | Expiration | Yes |

## Constant Pressure Mode

Table 4–5.

**Observed changes with a constant pressure mode of ventilation.**

| | | Resistance and Compliance changes noticed |
|---|---|---|
| Pressure-time waveform | Inspiration | No |
| | Expiration | Yes |
| Volume-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Flow-time waveform | Inspiration | Yes |
| | Expiration | Yes |
| Volume-pressure loop | Inspiration | Yes |
| | Expiration | Yes |
| Flow-volume loop | Inspiration | Yes |
| | Expiration | Yes |

# Selected references and suggested reading

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# Work of breathing

**Work of breathing (WOB) is not just another parameter easily calculated and displayed on a screen. Measuring work of breathing involves complex calculations and very specific clinical conditions.**

**Work involves the exertion of a force on a mass with a displacement of the mass. In respiratory physiology, the force is referred to as pressure and the displacement is referred to as volume. Ironically, a patient using all his force trying to breathe through a completely blocked endotracheal tube does not generate any work, yet can generate tremendous efforts. Effort of breathing would perhaps describe more what the clinician needs to know to adapt strategies in mechanical ventilation.**

**Microprocessors can perform complex calculations to quantify what is commonly called work of breathing and it is up to the clinician to use this parameter in a context of better patient care.**

**Various methods are available to measure work of breathing. Every method involves planimetric measurements if displayed by various parameters such as airway pressure, intrapleural pressure, and generated volume.**

## Work of breathing

WOB is a complex concept both at the mathematical and conceptual levels. Work is defined as a product of a force by a displacement. By convention, if a force is applied to a mass in the same direction as the displacement of the mass, work is described as force x distance, and is expressed by the following equation:

$$W = F \times D \qquad (1)$$

Force is measured in Newtons, and distance is measured in meters. In respiratory mechanics, force is the product of pressure x area, expressed as follows:

$$F = P \times A \qquad (2)$$

Substituting equation (2) in equation (1) yields:

$$W = P \times A \times D \qquad (3)$$

The product of area x distance can be associated with a volume and expressed as follows:

$$V = A \times D \qquad (4)$$

Substituting equation (4) in equation (3) yields:

$$W = P \times V \qquad (5)$$

This equation allows the calculation of work for a specific value of pressure and volume. During breathing activities, pressure varies continuously in magnitude and direction while at the same time volume varies continuously as a function of pressure. This condition can be expressed mathematically with calculus, by integrating pressure with respect to the volume variation, as described in the following equation:

$$W = \int P\,dV \qquad (6)$$

This equation implies that work represents the area under the curve of pressure vs. volume. This in itself can create certain terminological confusion because the work of breathing is clinically obtained from a volume vs. pressure loop, rather than a pressure vs. volume loop, as expressed in equation (6).

The equation of motion states that in order to achieve a volume displacement, the driving force (ventilator or patient) has to overcome elastic and resistive elements of the respiratory system. It thus seems appropriate to speak of elastic work of breathing ($WOB_{elastic}$) and resistive work of breathing ($WOB_{resistive}$).

$$WOB = WOB_{elastic} + WOB_{resistive} \qquad (7)$$

During ventilatory support, total work of breathing ($WOB_{tot}$) is the sum of the work performed by the patient ($WOB_{pat}$) and the work performed by the ventilator ($WOB_{vent}$):

$$WOB_{tot} = WOB_{pat} + WOB_{vent}$$

Table 5–1 summarizes the elements involved in the concept of $WOB_{tot}$.

Table 5–1.
**Elements in the concept of total work of breathing.**

| Nature of work | Definition |
|---|---|
| Elastic Work | Work necessary to overcome the elastic properties of the respiratory system. It involves lung and chest wall components. |
| Resistive Work | Work necessary to overcome the resistive properties of the respiratory system. It involves airway resistance. |
| Patient Work | Work performed by the patient during a spontaneous breathing activity. |
| Ventilator Work | Work performed by the ventilator during mechanical breath delivery. |

Figure 5–1 displays a volume-pressure loop (volume vs. pressure) and illustrates $WOB_{elastic}$ and $WOB_{resitive}$. Since there is no patient effort in this breath, WOB is entirely performed by the ventilator. The slope of the volume-pressure loop represents the dynamic characteristics of the respiratory system.

## Elastic work of breathing ($WOB_{elastic}$)

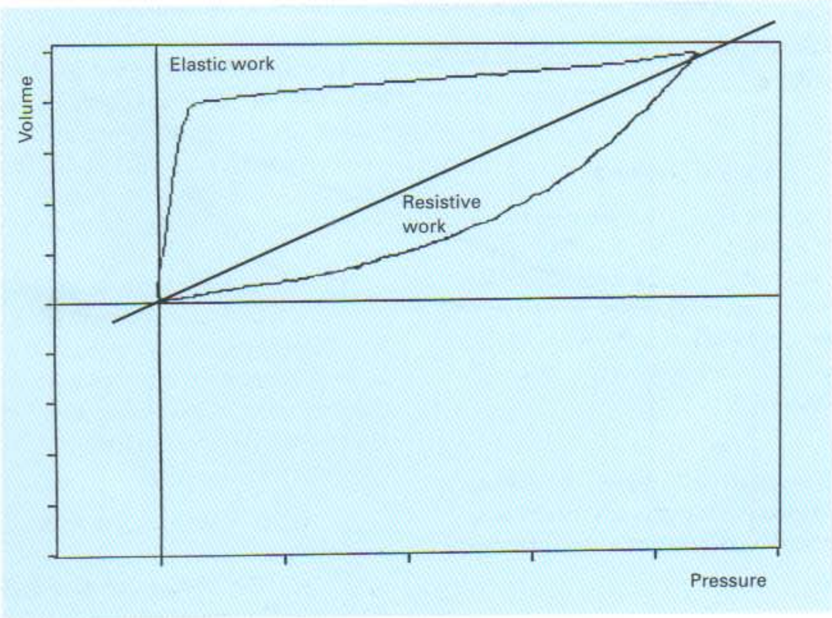
$WOB_{elastic}$ refers to the work generated by the patient or ventilator to overcome the elastic properties of the respiratory system. The volume-pressure loop allows the clinician to interpret the elastic properties of the respiratory system, and also the $WOB_{elastic}$. Elastic properties of the respiratory system are reflected in the slope of the volume-pressure loop.

Patient $WOB_{elastic}$ is not easily obtained at bedside. Lung and chest wall compliances must be measured, thus requiring the value of the intrapleural pressure indirectly assessed with the esophageal pressure.

To measure lung and chest wall compliances, the patient must be completely relaxed or paralyzed. This implies that a muscle relaxant must be administered prior to measurement and can jeopardize the patient's safety.

$WOB_{elastic}$ can be affected by sudden changes in chest wall compliance, as in gastric distention and intra-abdominal bleeding. Chest wall compliance is often approximated at 200 ml/cm$H_2O$.

Figure 5–1.
**Volume-pressure loop from a constant flow mode of ventilation, illustrating elastic and resistive components of the work of breathing.**



Ventilator $WOB_{elastic}$ can be easily obtained when a patient is completely passive during mechanical ventilation.

In figure 5–2A and 5–2B, triangle ABCA represents only $WOB_{elastic}$. Figure 5–2A is a volume-pressure graph from a patient with a normal compliance value.

Figure 5–2B is a volume-pressure graph from a patient with a decreased compliance value. Note that the area in 5–2B is larger than 5–2A. Since the elástic forces are larger in 5–2B, ventilator $WOB_{elastic}$ is thus larger.

As described in Figure 5–2, ventilator $WOB_{elastic}$ is the area subtended by a triangle ABCA.

In Figure 5–3, the ventilator $WOB_{elastic}$ can be easily calculated using the following equation:

$$\text{Area} = \text{Base} \times \text{Height} : 2$$

The area of ABCA is calculated as follows:

$$\text{Area} = \text{Tidal volume} \times \text{Peak Inspiratory Pressure} : 2$$

As an example, let's calculate the ventilator $WOB_{elastic}$ on a passive patient ventilated with a tidal volume of 880 ml and a peak inspiratory pressure of 23 cm $H_2O$.

Figure 5–2.

**Elastic work of breathing. 'A' represents $WOB_{elastic}$ on a patient with normal compliance. 'B' represents $WOB_{elastic}$ on a patient with decreased compliance.**

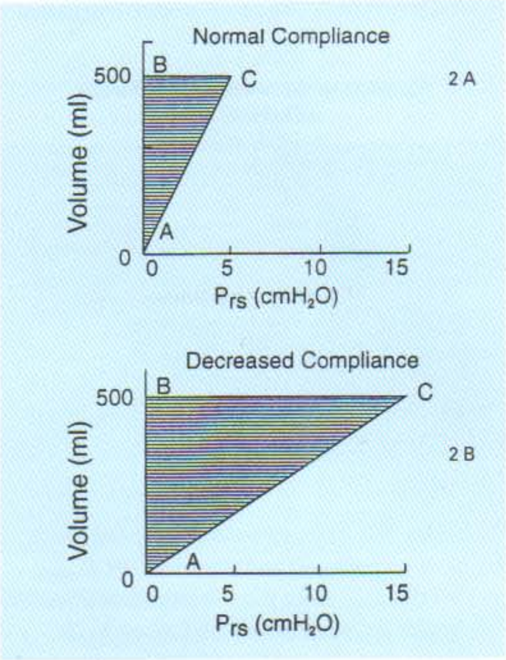
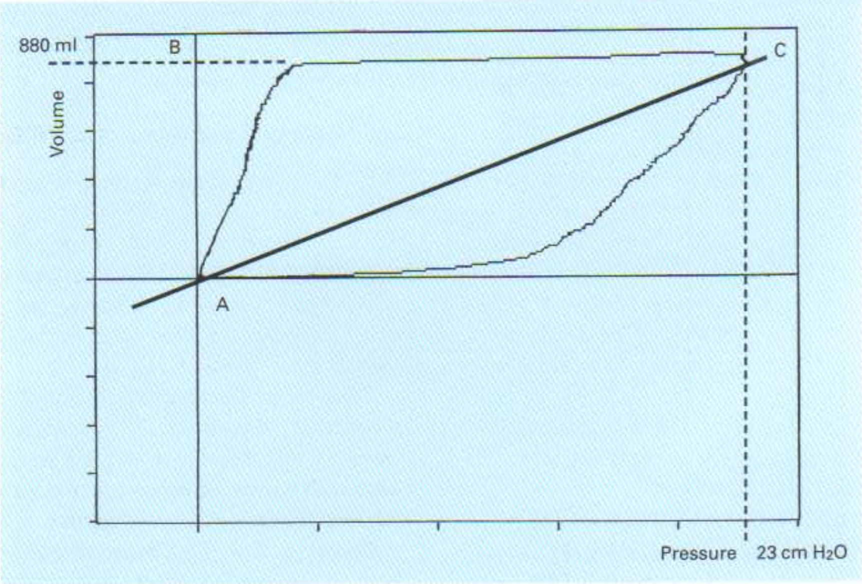


Figure 5–3.

**Elastic work of breathing on a patient ventilated with a constant flow mode. Tidal volume 880 ml, and peak inspiratory pressure 23 cm $H_2O$. In this case the $WOB_{elastic}$ is the work performed by the ventilator.**



$$\begin{aligned}\text{Ventilator WOB}_{\text{elastic}} &= \text{Tidal volume} \times \\ &\quad \text{Peak Inspiratory Pressure} \\ &= \frac{880}{2}\text{ ml} \times 23 \text{ cm H}_2\text{O} : 2 \\ &= 440 \times 23 \\ &= 10\,120 \text{ cmH}_2\text{O} \bullet \text{ml}\end{aligned}$$

Since the units for work is in joules/l or joules/min, various conversions are necessary. First, $\text{cmH}_2\text{O} \bullet \text{ml}$ must be converted into Kg • m and then Kg • m must be converted into joules. The following conversion factors are used:

$$1 \text{ cmH}_2\text{O} \bullet \text{ml} = 10^{-5} \text{ Kg} \bullet \text{m}$$
$$10\,120 \text{ cmH}_2\text{O} \bullet \text{ml} = 10.12 \times 10^{-2} \text{ Kg} \bullet \text{m}$$
$$1 \text{ Kg} \bullet \text{m} = 9.8 \text{ joules}$$
$$10.12 \times 10^{-2} \text{ Kg} \bullet \text{m} = 0.10 \text{ joules}$$

To obtain the $\text{WOB}_{\text{elastic}}$ in joules/l, the total number of joules for each breath is transposed on a 1 liter value.

0.10 joules/0.880 l *(Tidal volume of 880 ml)*

Ventilator $\text{WOB}_{\text{elastic}} = 0.11$ joules/l

This method of calculation is only valid on ventilated patients and thus represents only the ventilator $\text{WOB}_{\text{elastic}}$. When a patient breathes spontaneously, chest wall and lung compliances must be measured.

## Resistive work of breathing ($\text{WOB}_{\text{resistive}}$)

$\text{WOB}_{\text{resistive}}$ refers to the work generated by the patient or ventilator to overcome the resistive (non-elastic) properties of the respiratory system. The volume-pressure loop allows the clinician to interpret resistive properties of the respiratory system, visualized as a bowing in the inspiratory limb of the volume-pressure loop generated by a constant flow controller.

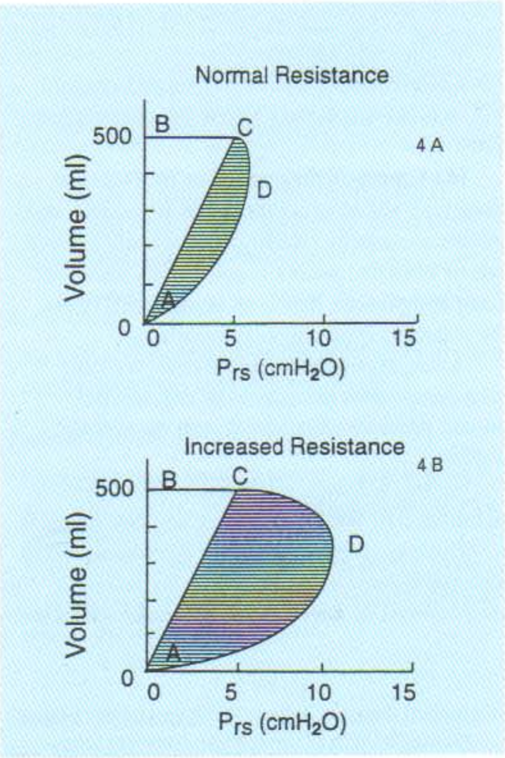
In figure 5–4A and 5–4B, area ACDA represents only the $\text{WOB}_{\text{resistive}}$. Figure 5–4A is a volume-pressure graph from a patient with a normal resistance value. Figure 5–4B is a volume-pressure graph from a patient with an increased resistance value.

Note that the area in 5–4B is larger than 5–4A. Since the resistive forces are larger in 5–4B $\text{WOB}_{\text{resistive}}$ is thus larger.

The area of the geometric figure ACDA is rather complex for free-hand calculation. Calculation of such a geometric area is done by a method known as a planimetric method of calculation, and is explained later in the text.

Figure 5–4.

**Resistive work of breathing. 4 A represents $\text{WOB}_{\text{resistive}}$ on a patient with normal resistance. 4 B represents $\text{WOB}_{\text{resistive}}$ on a patient with increased resistance.**



### Units of measurement for WOB

WOB can be quantified in joules/min and in joules/l. Some authors feel WOB should be described in both units. WOB is not indexed to body surface area, but the work per liter tends to be less in large individuals compared with smaller individuals, since resistance and elastance decrease with increasing body size.

Work per liter describes pulmonary mechanics properties, like increased resistance, and decreased compliance and work per minute is associated with minute ventilation, and correlates less with lung mechanical characteristics.

Normal values of WOB for normal resting individuals, are 0.47 J/l or 3.9 J/min.

### Calculation of $WOB_{total}$

The literature generally speaks of two different methods for assessing $WOB_{total}$:

- Planimetric measurement of the pressure-volume loop
- Electronic integration of pressure-flow product

## Planimetric measurement of the volume-pressure loop using the Campbell diagram

The Campbell diagram, as illustrated in Figure 5–5, was developed in 1958 by the physiologist CAMPBELL.

The Campbell diagram takes into account chest wall and lung compliances. Chest wall compliance is measured during a completely passive breath while the patient is completely paralyzed. Lung compliance, however, is measured while the patient is spontaneously breathing.

As explained in chapter 4, chest wall and lung compliance measurement requires the pleural pressure value rather than the airway pressure.

Various software applications allow bedside calculation of WOB using the Campbell diagram.

This planimetric method of calculating WOB with the volume-pressure loop is based on the area covered by the loop, the delivered tidal volume and the peak inspiratory pressure. The measured area is converted to work units, according to the work equation:

$$W = \int P\,dV \qquad (6)$$

Figure 5–5.

**Campbell diagram, where WOB can be calculated using the area of the volume-pressure loop, lung and chest wall compliance curves.**

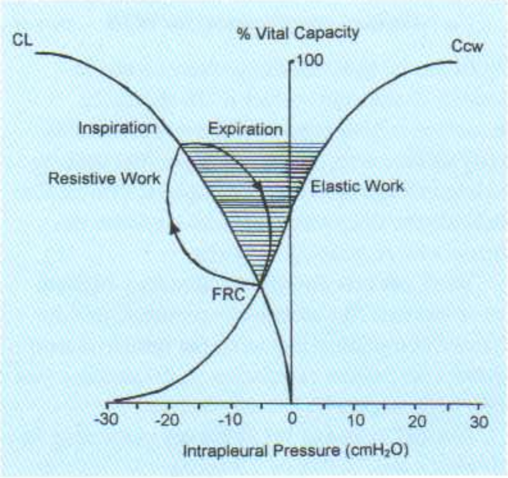
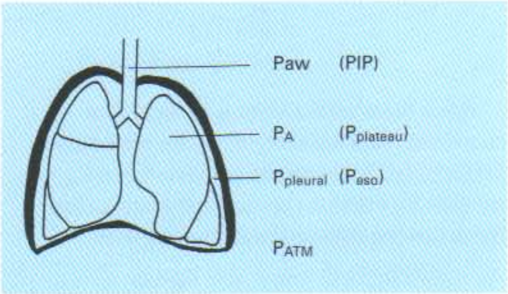


Figure 5–6.

**Pressure interactions during passive mechanical ventilation.**



Inspiratory elastic WOB is the area in square mm that is then converted to joules per liter or joules per minute.

## Pressure-flow integration

Various authors describe another method for calculating the WOB using the equation of motion. This method is known as pressure-flow integration, and involves the measurement of pressure gradients at four different sites throughout the respiratory system, as illustrated in Figure 5–6.

For the purpose of describing the method, let's recall the equation of motion (chapter 4):

$$P_{total} = P_{elastic} + P_{resistance} \qquad (8)$$

Also, $WOB_{total}$ is thus the sum of $WOB_{elastic}$ and $WOB_{resistive}$ of the respiratory system:

$$WOB_{total} = WOB_{elastic} + WOB_{resistive} \qquad (7)$$

As expressed mathematically in equation 6, WOB is the integral of pressure-volume product:

$$WOB = \int P\,dV \qquad (6)$$

Airway resistance is expressed as a relation of a pressure gradient ($PIP\text{-}P_{plateau}$) and flow. Resistive work can thus be represented as follows:

$$WOB_{resistive} = \int (PIP\text{-}P_{plateau})\,\dot{V}dt \qquad (9)$$

In equation 9, flow as a function of time ($\dot{V}dt$) is volume.

Elastic forces include lung and chest wall components, and $WOB_{elastic}$ can be expressed as follows:

$$WOB_{elastic} = WOB_{pulm} + WOB_{cw} \qquad (10)$$

Lung elastic properties are expressed as a relation of a pressure gradient ($P_{plateau}$ - $P_{eso}$) and tidal volume. Lung elastic work of breathing ($WOB_{pulm}$) can be expressed as follows:

$$WOB_{pulm} = \int (P_{plateau} - P_{eso})\,\dot{V}dt \qquad (11)$$

Chest wall elastic properties are expressed as a relation of a pressure gradient ($P_{eso}$ - $P_{atm}$) and tidal volume. Chest wall elastic work of breathing ($WOB_{cw}$) can thus be expressed as follows:

$$WOB_{cw} = \int (P_{eso} - P_{atm})\,\dot{V}dt \qquad (12)$$

Equation 11 and 12 can be combined in equation 10 to become equation 13.

$$\begin{aligned} WOB_{elastic} &= \int (P_{plateau} - P_{eso})\,\dot{V}dt \\ &+ \int (P_{eso} - P_{atm})\,\dot{V}dt \qquad (13) \end{aligned}$$

$WOB_{total}$ (equation 7) thus combines equations 9 and 13 to become equation 14:

$$\begin{aligned} WOB_{total} &= \underbrace{\int (PIP\text{-}P_{plateau})\,\dot{V}dt}_{\text{(airway resistive properties)}} \\ &+ \underbrace{\int (P_{plateau} - P_{eso})\,\dot{V}dt}_{\text{(Lung elastic properties)}} + \underbrace{\int (P_{eso} - P_{atm})\,\dot{V}dt}_{\text{(Chest wall elastic properties)}} \qquad (14) \end{aligned}$$

Equation 14 can be simplified as follows:

$$WOB_{total} = \int (PIP\text{-}P_{atm})\,\dot{V}dt \qquad (15)$$

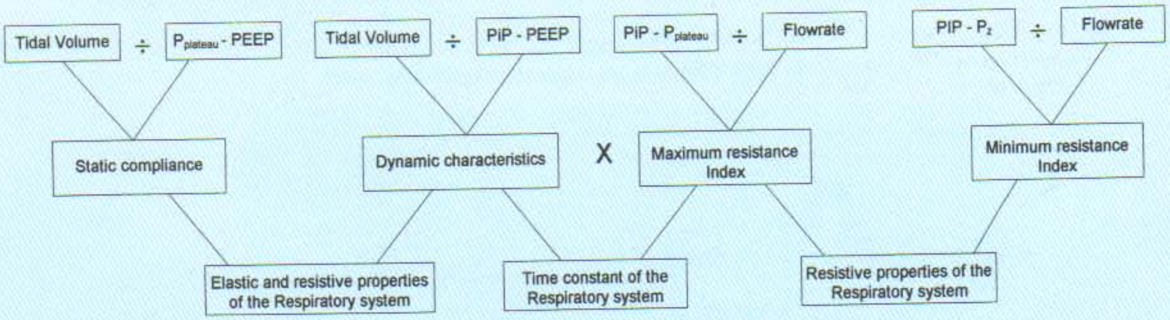
Patient work of breathing ($WOB_{patient}$) is obtained by subtracting the ventilator work of breathing ($WOB_{vent}$) from $WOB_{total}$.

In a completely paralyzed patient, $WOB_{total}$ equals $WOB_{vent}$ and $WOB_{patient}$ is thus zero. At first glance, equation 15 seems relatively simple.

However, to calculate $WOB_{total}$, the patient must generate a breath of exactly the same flow, tidal volume and resistance as the ventilator. This condition is rather difficult to obtain clinically.

Figure 5–7

**Volume-pressure relationship and pressure-flow relationship.**



# Selected references and suggested reading

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# Normal waveforms and loops

**This chapter describes normal waveforms and loops from constant flow and constant pressure controllers.**

**The following conditions can be monitored through waveform and loop analysis at bedside:**

- **Dynamic characteristics of the respiratory system**
- **Static characteristics of the respiratory system**
- **Patient-ventilator interaction**

## Flow-time waveform

*From a constant flow mode of ventilation (Fig. 6–1)*

### Description of a normal flow-time waveform

*Inspiratory phase*

- Rapid increase to peak inspiratory flow.
- Flow is constant until pause time is reached.
- Flow stops during the pause time.

*Expiratory phase*

- Rapid decrease to peak expiratory flow.
- Exponential decay to baseline.
- End expiratory flow should be zero.

### Clinical interests of the flow-time waveform from a constant flow mode of ventilation

*Dynamic characteristics*

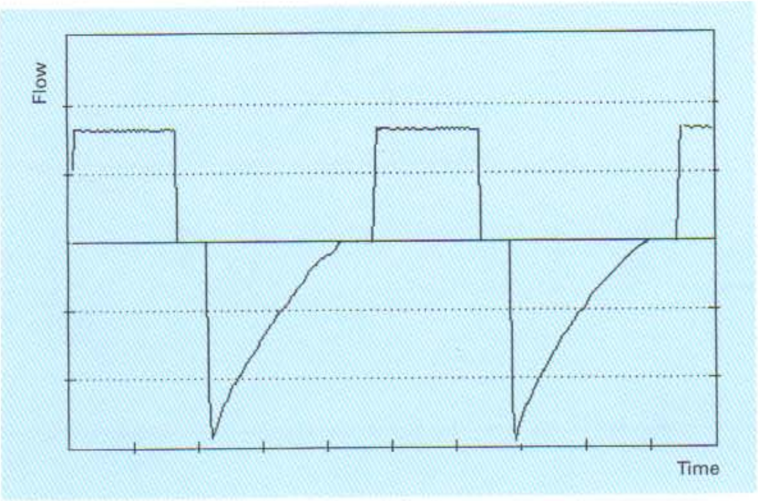
- Elastic and resistive changes are not reflected in the inspiratory profile.
- Auto-PEEP is present when flow is not zero at the end of expiration and when the expiratory time is shorter than at least 3 expiratory time constants.
- Slow and linear expiratory decay to baseline is a sign of expiratory airway flow obstruction.

*Static characteristics*

- No static characteristic of the respiratory system can be described with this waveform.

Figure 6–1.

**Flow-time waveform from a constant flow mode of ventilation**



*Patient-ventilator interaction*

- A sawtooth pattern during inspiratory and expiratory profile can be associated with secretions or water condensation in the breathing circuit.
- Active use of respiratory muscles during expiration can affect the duration and pattern of the expiratory flow profile.

**Checklist**

Flow-time waveform from a constant flow mode of ventilation

| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Auto-PEEP | Adjusting respiratory rate if indicated<br>Adding external PEEP if indicated |
| Dynamic airway compression | Bronchodilator therapy if indicated<br>Suctioning if indicated |
| Increased insp. resistance ($R_{max}$, $R_{min}$) | Adjusting inspiratory time if indicated<br>Changing mode of ventilation if indicated |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing patient relaxation status<br>Reviewing triggering modality if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

# Flow-time waveform

*From a constant pressure mode of ventilation (Fig. 6–2)*

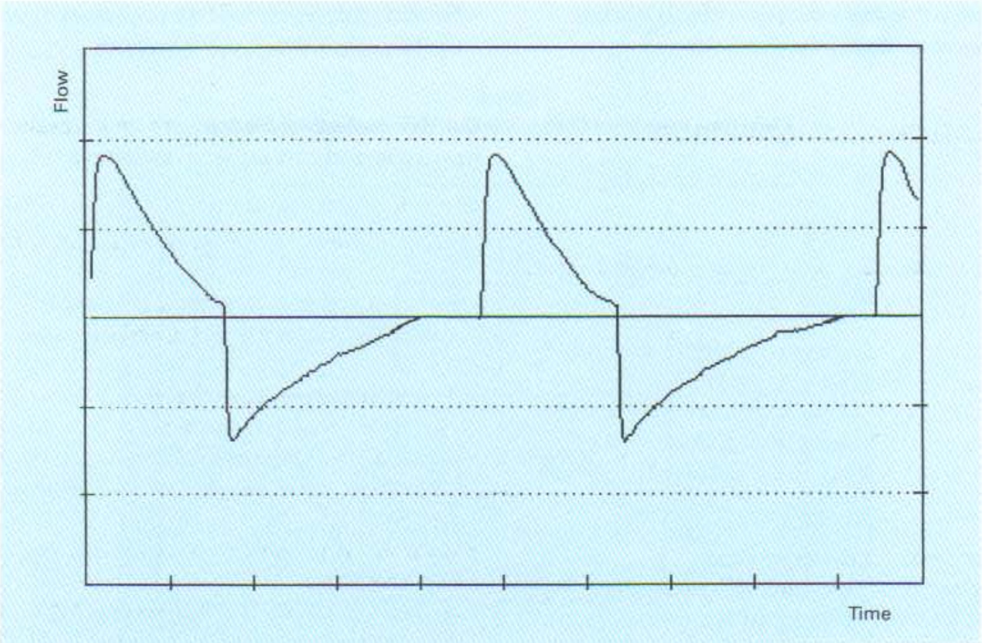
## Description of a normal flow-time waveform

*Inspiratory phase*

- Rapid increase to peak inspiratory flow followed by exponential decay to baseline.

Figure 6–2.

**Flow-time waveform from a constant pressure mode of ventilation**



- Rate of decay depends upon:
    - elastic and resistive properties of the respiratory system.
    - Set inspiratory time % and set inspiratory pressure above PEEP.

*Expiratory phase*

- Exponential decay to baseline.
- Short time constants decay rapidly to baseline, long time constants decay slowly to baseline.
- The value of the time constant is determined by compliance and resistance.

### Clinical interests of the flow-time waveform from a constant pressure mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are reflected in the inspiratory profile.
- An inspiratory flow reaching zero before the set inspiratory time has elapsed can be associated with:
    - Low compliance conditions,
    - Increased inspiratory time,
    - High peak inspiratory flow.
- Inspiratory time modifies the flow waveform.
- A low flow at end inspiration allows alveolar recruitment for long time constant zones.

**Checklist**

Flow-time waveform from a constant pressure mode of ventilation

| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Auto-PEEP | Adjusting respiratory rate if indicated<br>Adding external PEEP if indicated |
| Dynamic airway compression | Adjusting inspiratory time if indicated<br>Changing mode of ventilation if indicated |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing patient relaxation status<br>Reviewing triggering modality if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

- Expiratory dynamic airway compression is associated with a linear appearing rather than exponential decay to baseline.

*Static characteristics*

- No static characteristic of the respiratory system can be described with this waveform.

*Patient-ventilator interaction*

- Excessive rapid peak inspiratory flow is associated with patient discomfort and premature termination of expiration.
- Active use of respiratory muscles during expiration may affect the magnitude, duration and pattern of expiratory flow profile.

---

## Pressure-time waveform

*From a Constant Flow mode of ventilation (Fig. 6–3)*

### Description of a normal pressure-time waveform

*Inspiratory phase*

- The inspiratory phase is divided in three parts:
    - Exponential rise from zero to first step,
    - Linear rise to peak inspiratory pressure.
    - Exponential decay from peak inspiratory pressure to $P_{pause}$ at the end of the pause time.

*Expiratory phase*

- Exponential decay to baseline.
- End expiratory pressure will remain above base line when PEEP is applied.

### Clinical interests of the pressure-time waveform from a constant flow mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are reflected in the inspiratory profile.
- Increased expiratory resistance is associated with a linear rather than exponential decay to baseline.
- The difference between PIP and $P_{pause}$ is an index of inspiratory resistance.
- The larger the difference between $R_{max}$ and $R_{min}$, the larger are the zones of unequal time constants.
- Mean airway pressure is directly affected by inspiratory time.
- An increase in PIP without changes in $P_{pause}$ reflects an increase in inspiratory resistance.

### *Static Characteristics*

- $P_{pause}$ is an estimate of the alveolar pressure.
- $P_{pause}$ reflects the elastic properties of the respiratory system.
- An increase in $P_{pause}$ without changes in tidal volume and PEEP is associated with atelectasis, pneumothorax and decrease in functional residual capacity.

### *Patient-ventilator interaction*

- Fluctuations in peak inspiratory pressure and triggering efforts are suggestive of asynchrony between patient needs and flow delivery system.

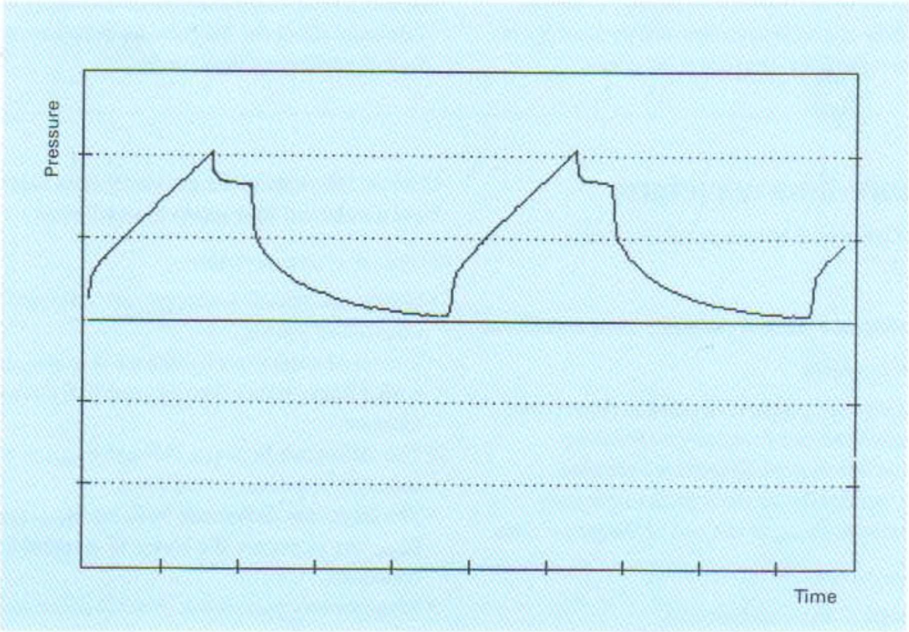
## Checklist

Pressure-time waveform from a constant flow mode of ventilation

| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Auto-PEEP | Adjusting respiratory rate if indicated<br>Adding external PEEP if indicated |
| Increased insp. resistance $(R_{max}, R_{min})$ | Changing mode of ventilation if indicated<br>Bronchodilator therapy if indicated<br>Changing mode of ventilation if indicated |
| Increased expiratory resistance | Bronchodilator therapy if indicated<br>Changing mode of ventilation if indicated |
| Static alveolar pressure | Maintaining $P_{pause} < 30$ cm $H_2O$ if possible |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing relaxation status of patient if indicated<br>Reviewing the triggering modality if indicated |
| Effort of breathing | Adjusting triggering sensitivity if indicated<br>Correcting Auto-PEEP<br>Changing mode of ventilation if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

Figure 6–3.

**Pressure-time waveform from a constant flow mode of ventilation**



# Pressure-time waveform

*From a constant pressure mode of ventilation (Fig. 6–4)*

## Description of a normal pressure-time waveform

*Inspiratory phase*

- Rapid and linear rise to peak inspiratory pressure.
- Constant peak pressure throughout inspiration.

*Expiratory phase*

- Exponential decay to baseline.
- End expiratory pressure remains above baseline when PEEP is applied.

## Clinical interests of the pressure-time waveform from a constant pressure mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are not detected in the inspiratory profile.
- Increased expiratory resistance is associated with a linear appearing rather than exponential decay to baseline.

**Checklist**

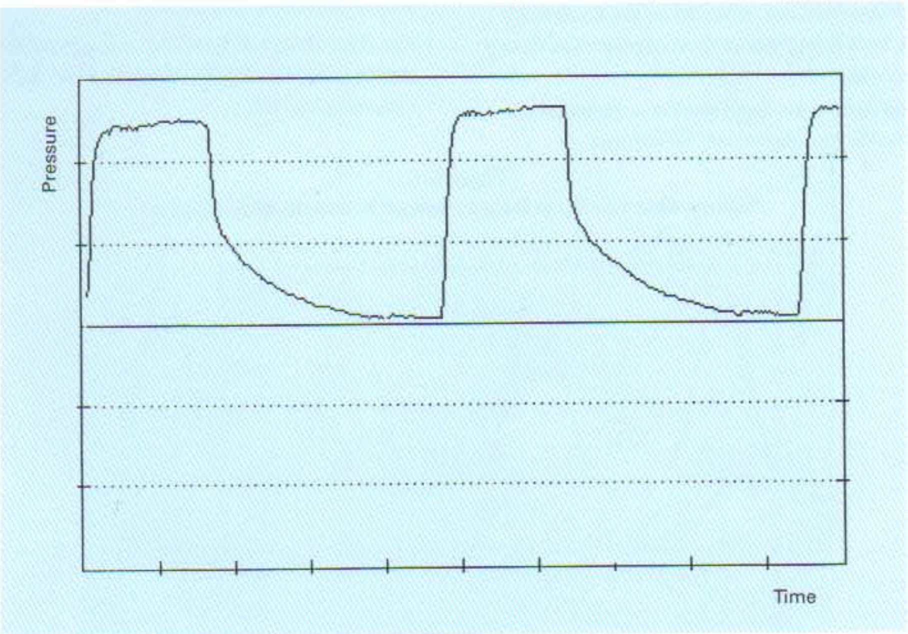
Pressure-time waveform from a constant pressure mode of ventilation

| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Auto-PEEP | Adjusting respiratory rate if indicated<br>Adding external PEEP if indicated |
| Increased exp. resistance | Bronchodilator therapy<br>Changing mode of ventilation if indicated |
| Static alveolar pressure | Maintaining alveolar pressure $< 30$ cm $H_2O$ if possible |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing relaxation status of patient if indicated<br>Reviewing triggering modality if indicated |
| Effort of breathing | Adjusting triggering sensitivity if indicated<br>Correcting auto-PEEP<br>Changing mode of ventilation if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

- End-expiratory pressure will not return to baseline with external PEEP applied, but will return to baseline with auto-PEEP.

Figure 6–4.

**Pressure-time waveform from a constant pressure mode of ventilation**



*Static characteristics*

- No static characteristic can be described with this waveform.

*Patient-ventilator interactions*

- The degree of deformity during the plateau is an index of patient effort.
- An unreached pressure limit is associated with leakage inside the patient breathing circuit.
- Excessive scalloping during the plateau is associated with an inadequate flow.
- A fast rise to peak inspiratory pressure can be associated with an excessively high flow.

---

## Volume-time waveform

*From a constant flow mode of ventilation (Fig. 6–5)*

### Description of a normal volume-time waveform

*Inspiratory phase*

- Linear rise to inspired tidal volume.
- Plateau during pause time.

*Expiratory phase*

- Exponential decay to baseline.

### Clinical interests of volume-time waveform from a constant flow mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are not reflected in the inspiratory profile.
- Elastic and resistive changes like dynamic airway obstruction are reflected in the expiratory profile by a linear rather than exponential decay to baseline.
- Volume-time waveform profile is identical to the alveolar pressure-time waveform.

**Checklist**

Volume-time waveform from a constant flow mode of ventilation

| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Increased exp. resistance | Bronchodilator therapy<br>Changing mode of ventilation if indicated |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing relaxation status of patient if indicated<br>Reviewing triggering modality if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

*Static characteristics*

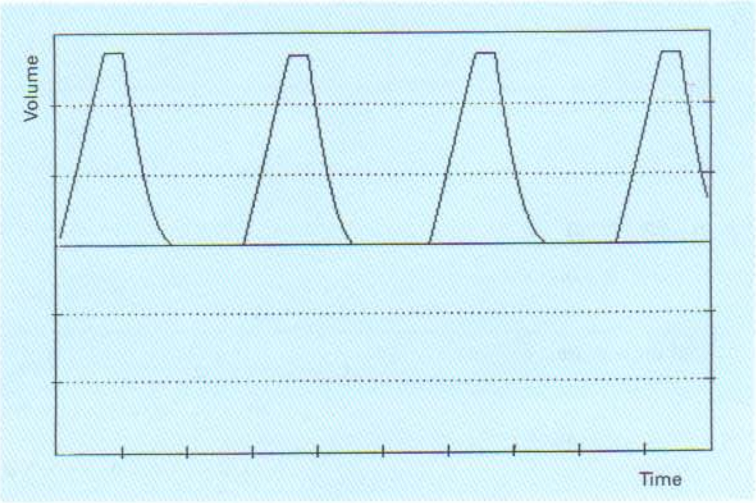
- A pause time allows volume redistribution during a zero flow condition.

*Patient-ventilator interaction*

- A sudden return to baseline as inspiration starts can be associated with leakage in the patient breathing circuit.

Figure 6–5.

**Volume-time waveform from a constant flow mode of ventilation**



## Volume-time waveform

*From a constant pressure mode of ventilation (Fig. 6–6)*

### Description of a normal volume-time waveform

*Inspiratory phase*

- Exponential rise to inspired tidal volume

*Expiratory phase*

- Exponential decay to baseline.

### Clinical interests of the volume-time waveform from a constant pressure mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are reflected in the inspiratory and expiratory profiles.
- The volume-time waveform is identical to the alveolar pressure-time waveform.

*Static characteristics*

- No static characteristics of the respiratory system can be described with this waveform.

**Checklist**

Volume-time waveform from a constant pressure mode of ventilation

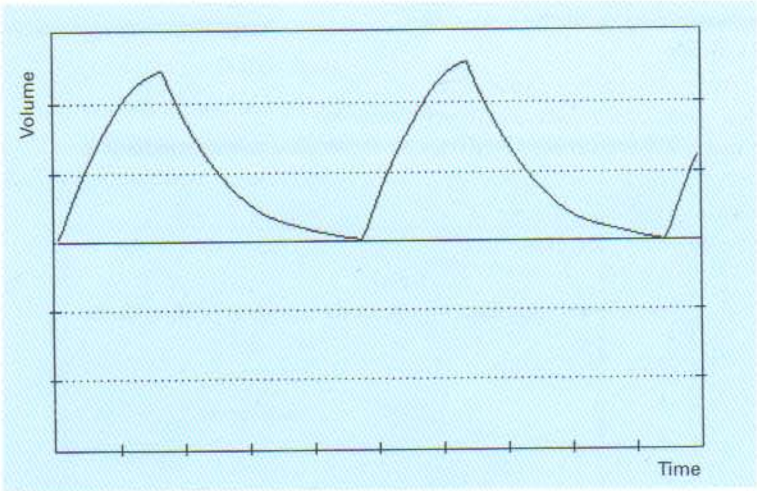
| Characteristics | Consider |
|---|---|
| Dynamic hyperinflation | Adjusting respiratory rate if indicated<br>Adjusting inspiratory time if indicated<br>Checking for auto-PEEP |
| Increased exp. resistance | Bronchodilator therapy<br>Changing mode of ventilation if indicated |
| Patient-ventilator asynchrony | Changing mode of ventilation if indicated<br>Reviewing relaxation status of patient if indicated<br>Reviewing triggering modality if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

*Patient-ventilator interaction*

- A sudden return to baseline as inspiration starts is associated with leakage in the patient breathing circuit.

Figure 6–6.

**Volume-time waveform from a constant pressure mode of ventilation**



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## Volume-pressure loop

*From a constant flow mode of ventilation (Fig 6–7)*

### Description of a normal volume-pressure loop

*Inspiratory phase*

- Exponential rise to peak inspiratory pressure and inspired tidal volume.
- Drop in pressure but not in volume during pause time.
- If external PEEP is applied, the loop moves to the right.

*Expiratory phase*

- Rapid pressure decrease at the beginning of expiration.
- Volume and pressure decay to baseline, express-

ing the expired tidal volume and end expiratory pressure.

### Clinical interests of volume-pressure loop from a constant flow mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are reflected in the inspiratory and expiratory profile.
- An inflection point in the first third of the loop can be associated with early ARDS.
- Overdistention is associated with a deflection point in the upper part of the inspiratory loop.
- Increasing inspiratory resistance is associated with bowing of the inspiratory limb.

*Static characteristics*

- The slope of the loop during the pause time represents the static compliance.
- A shift to the right (slope) is associated with a decreased compliance.
- A shift to the left (slope) is associated with an increased compliance.

*Patient-ventilator interaction*

- The volume-pressure loop should be evaluated after any modification in the ventilatory strategies such as:
  - a change in flow
  - a change in tidal volume
  - a change in respiratory rate
  - a change in patient relaxation state

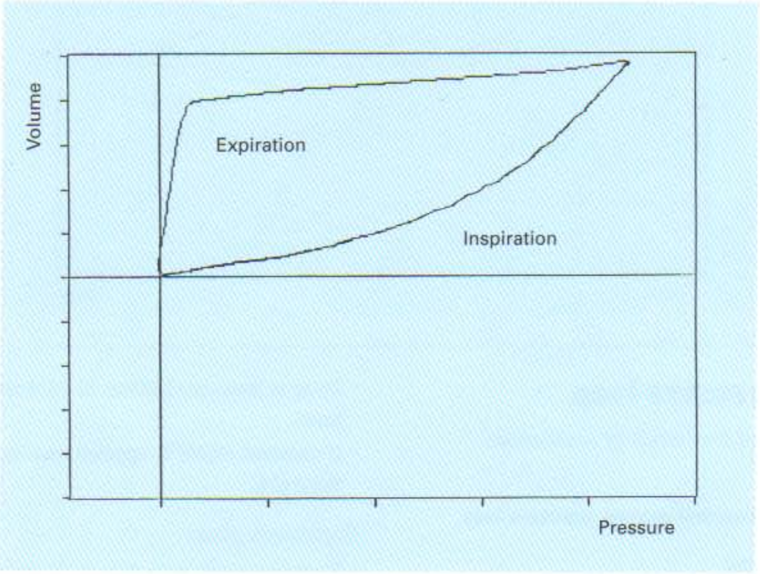
### Checklist

Volume-pressure loop from a constant flow mode of ventilation

| Characteristics | Consider |
|---|---|
| Airway collapse | Adding external PEEP if indicated<br>Reviewing mode of ventilation if indicated |
| Overdistention | Decreasing Tidal volume if indicated<br>Reviewing mode of ventilation if indicated |
| Effective compliance | Adjusting tidal volume if indicated<br>Reviewing mode of ventilation if indicated |
| Static alveolar pressure | Maintaining $P_{pause} < 30$ cm $H_2O$ if indicated |
| Static Lung compliance | Adjusting tidal volume if indicated<br>Consider adjusting PEEP for optimal compliance<br>Reviewing mode of ventilation if indicated |
| Effort of breathing | Adjusting triggering modality if indicated<br>Correcting auto-PEEP, if indicated<br>Reviewing mode of ventilation if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

Figure 6–7.

**Volume-pressure loop from a constant flow mode of ventilation**



# Volume-pressure loop

*From a constant pressure mode of ventilation (Fig. 6–8)*

### Description of a normal volume-pressure loop

*Inspiratory phase*

- Rapid pressure rise to peak inspiratory pressure followed by a constant pressure throughout inspiration.
- Volume rise is proportional to compliance and resistance.

*Expiratory phase*

- Rapid pressure decay during the first portion.
- Volume and pressure decay to baseline.

### Clinical interests of the volume-pressure loop from a constant pressure mode of ventilation

*Dynamic characteristics*

- Elastic and resistive changes are reflected in the inspiratory and expiratory profile.
- The slope of this loop represents the dynamic characteristics of the respiratory system.
- Overdistention is associated with a deflection point in the upper part of the inspiratory loop.

**Checklist**

Volume-pressure loop from a constant pressure mode of ventilation

| Characteristics | Consider |
|---|---|
| Effective compliance | Adjusting tidal volume if indicated<br>Reviewing mode of ventilation if indicated |
| Effort of breathing | Adjusting triggering sensitivity if indicated<br>Correcting auto-PEEP, if indicated<br>Reviewing mode of ventilation if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

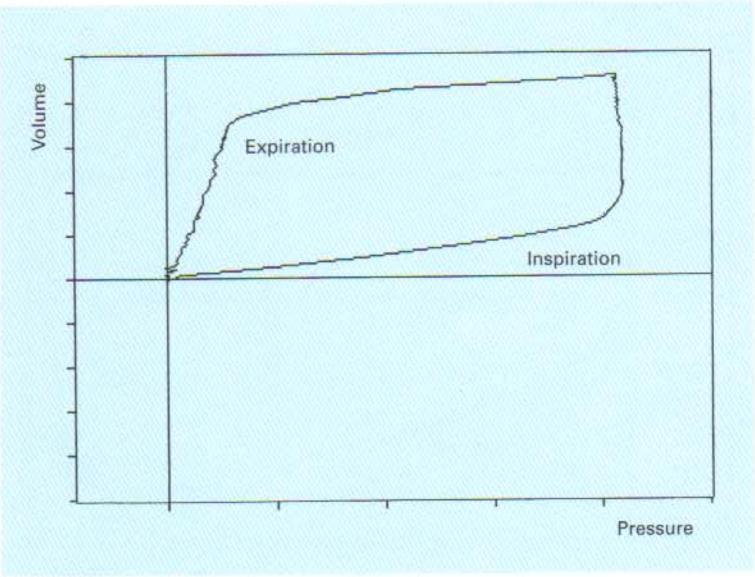
*Static characteristics*

- No static characteristics can be described with this waveform.

*Patient-ventilator interactions*

- The volume-pressure loop should be evaluated after any modification in the ventilatory strategies such as:
  - – a change in flow
  - – a change in tidal volume
  - – a change in respiratory rate
  - – a change in patient relaxation state

Figure 6–8.
**Volume-pressure loop from a constant pressure mode of ventilation**



## Flow-volume loop

*From a constant flow mode of ventilation (Fig. 6–9)*

### Description of a normal flow-volume loop

*Inspiratory phase*

- Rapid rise to peak inspiratory flow throughout inspiration.
- Rapid decay from peak inspiratory flow to baseline.

*Expiratory phase*

- Rapid decay to peak expiratory flow, then progressive return to baseline.

### Clinical interests of the flow-volume loop from a constant flow mode of ventilation

*Dynamic characteristics*

- Resistive changes are not reflected in the inspiratory profile.
- Auto-PEEP is associated with an abrupt expiratory flow termination.
- Airflow limitation is associated with a convex (to the volume axis) shape of the second phase of the expiratory profile of the loop.

| Characteristics | Consider |
|---|---|
| Increased exp. resistance | Bronchodilator therapy if indicated<br>Reviewing mode of ventilation if indicated |
| Sawtooth pattern | Suctioning patient if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

- A fixed obstruction is associated with both decreased peak inspiratory flow and peak expiratory flow.

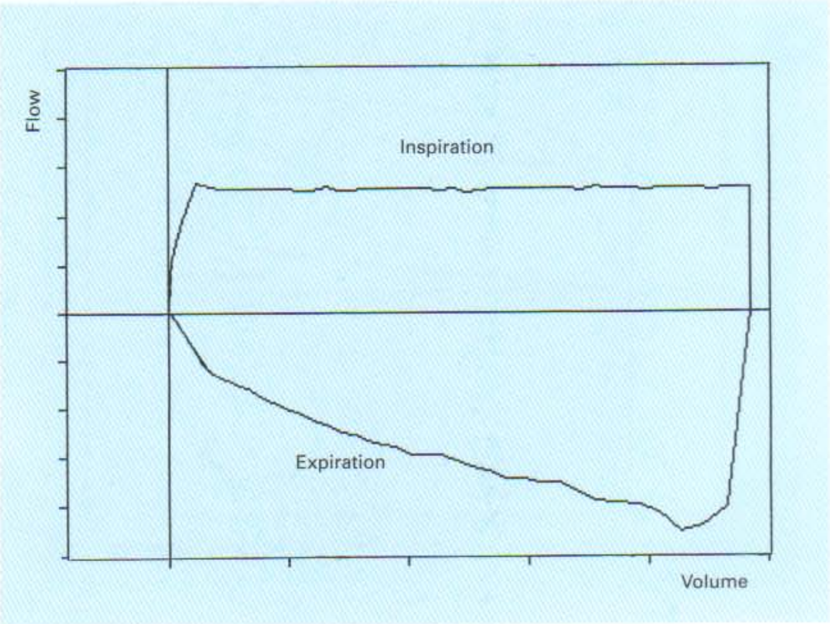
*Static characteristics*

- No static characteristic of the respiratory system can be described with this loop.

*Patient-ventilator interactions*

- A leakage in the breathing circuit is associated with an open loop at the end of a cycle.
- A sawtooth pattern on spontaneous breathing is associated with the presence of secretions.
- A positive therapeutic response to bronchodilators is present when the peak expiratory flow increases and the expiratory profile becomes less convex to the volume axis.

Figure 6–9.
**Flow-volume loop from a constant flow mode of ventilation**



# Flow-volume loop

*From a constant pressure mode of ventilation (Fig. 6–10)*

### Description of a normal flow-volume loop

*Inspiratory phase*

- Rapid rise to peak inspiratory flow, then decay to baseline.

*Expiratory phase*

- Rapid decay to peak expiratory flow, then progressive return to baseline.

### Clinical interests of the flow-volume loop from a constant flow mode of ventilation

*Dynamic characteristics*

- Resistive changes are reflected in the inspiratory and expiratory profile with peak inspiratory flow and peak expiratory flow (fixed obstruction).
- Auto-PEEP is associated with an abrupt expiratory flow termination.
- Airflow limitation is associated with a convex (to the volume axis) shape of the second portion of the expiratory profile.
- Flow-volume loops in mechanical ventilation are at tidal volume and not at vital capacity.

| Characteristics | Consider |
|---|---|
| Increased exp. resistance | Bronchodilator therapy if indicated<br>Reviewing mode of ventilation if indicated |
| Sawtooth pattern | Suctioning patient if indicated |
| Leakage | Faulty breathing circuit connections<br>Anatomical leakage |

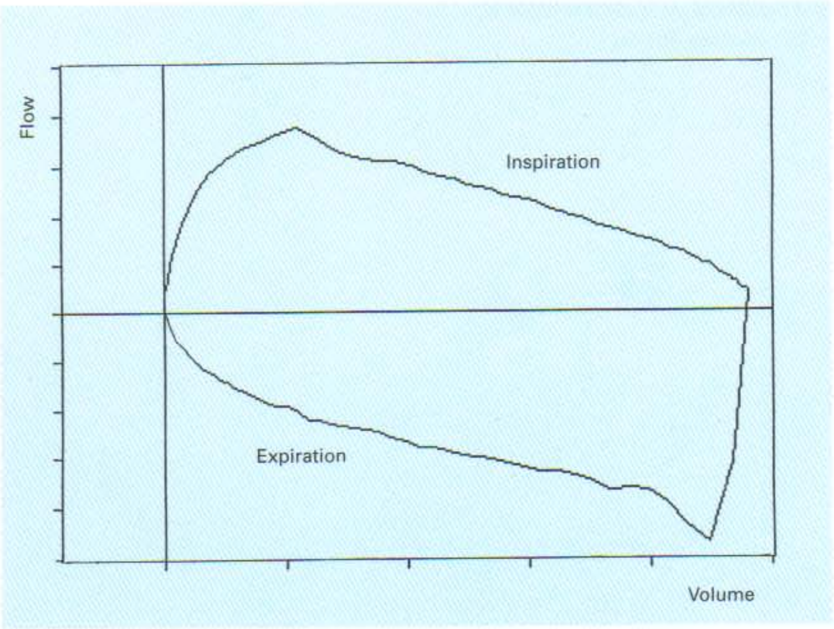
*Static characteristics*

- No static characteristic of the respiratory system can be described with this loop.

*Patient-ventilator interactions*

- Gas leakage in the breathing circuit is associated with an open loop at the end of a cycle.
- A sawtooth pattern in spontaneous breathing is associated with the presence of secretions.
- A positive therapeutic response to bronchodilators is present when the peak expiratory flow increases and the expiratory profile becomes less convex to the volume axis.

Figure 6–10.
**Flow-volume loop from a constant pressure mode of ventilation**



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# Nomenclature and terminology

**This appendix describes various expressions consistently used throughout literature on waveforms and loops in mechanical ventilation. Most of the terms described in this chapter are addressed in their respective context throughout this book.**

### Auto-PEEP (Intrinsic PEEP)

Auto-PEEP is an expression used to designate an inadvertent positive pressure remaining inside the lungs after an expiration, also designated as intrinsic PEEP.

The factors that determine its development include tidal volume, expiratory time constant and shortened expiratory time.

If inspiration starts before the end of the previous expiration, some air will remain trapped inside the lungs.

Consequently, the end expiratory lung volume will be larger than the normal relaxed volume.

If allowed to equilibrate, by preventing the next breath to happen, the trapped gas volume will generate a positive pressure. This pressure is the auto-PEEP or intrinsic PEEP, because it is not directly set by the clinician.

The presence of auto-PEEP will underestimate the calculated static compliance. When adjusting a PEEP level, functional residual capacity (FRC) will increase only after auto-PEEP is exceeded.

Auto-PEEP is present if flow does not reach zero before the beginning of inspiration. The flow waveform can identify the presence of auto-PEEP, but does not allow the clinician to quantify the value.

Only on a completely relaxed patient can auto-PEEP be measured with a pressure waveform during an expiratory hold; on spontaneously breathing patients an esophageal catheter system must be used.

Auto-PEEP can occur under two conditions:

- Auto-PEEP without dynamic hyperinflation: This condition occurs with an active expiration, where vigorous expiratory muscle contraction persists to the end of expiration.
- Auto-PEEP with dynamic hyperinflation: This condition occurs with a passive expiration, where dynamic hyperinflation equals auto-PEEP. Auto-PEEP with dynamic hyperinflation can occur with or without expiratory flow limitation.

Auto-PEEP increases work of breathing (WOB) on spontaneously breathing patients by affecting the triggering threshold.

However, the impact of auto-PEEP on WOB can be attenuated by applying levels of external PEEP lower than the auto-PEEP value.

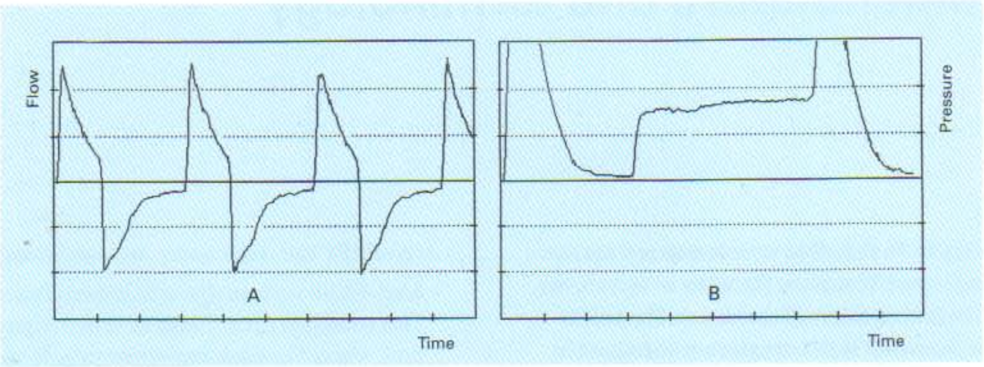
Auto-PEEP can be reduced by adopting a strategy which allows a normal expiration. This could be done through bronchodilation, using a large endotracheal tube, decreasing the minute ventilation, decreasing the duty cycle, or increasing the flow.

Figure A–1 illustrates a flow-time waveform identifying a non zero end expiratory zone, and a pressure-time waveform quantifying the value of auto-PEEP during expiratory hold.

### Bias flow

On the Servo Ventilator 300, bias flow is a gas flow generated by the ventilator inside the breathing circuit, and participates in flow triggering. At the start of expiration, a constant flow is delivered from the ventilator. The flow is maintained during the entire expiratory phase, even if the patient's exhaled gas flow ceases. At the start of the next inspiration, triggered by the patient or mandatory from the ventilator, the bias flow stops. The bias flow is delivered during both pressure and flow triggering.

Figure A–1.
**Auto-PEEP with waveforms.**



A: Flow-time waveform with a non zero end expiratory zone
B: Pressure-time waveform measuring auto-PEEP during expiratory hold

The bias flow is automatically set according to the selected patient range:

Adult: 32 ml/s (2 l/min), Pediatric 16 ml/s (1 l/min), Neonates 8 ml/s (0.5 l/min).

### Constant flow generator

A constant flow generator is a mechanical ventilator that generates a constant flow pattern regardless of the lung/thorax conditions, while pressure varies with lung/thorax conditions. The inspiratory profile of the flow-time waveform is square. The inspiratory part of the pressure-time waveform begins with an exponential rise to a first step, then becomes linear until peak inspiratory pressure is reached. In a constant flow pattern, the flow-time waveform is square throughout inspiration.

Figure A–2 illustrates various waveforms and loops from a constant flow mode of ventilation.

### Constant pressure generator

A constant pressure generator is a mechanical ventilator that generates a constant pressure pattern, regardless of the lung/thorax conditions, while the flow waveform varies with the lung/thorax conditions. The inspiratory profile of the flow-time waveform decelerates to zero through an exponential function. The inspiratory profile of the pressure-time waveform is square.

The major characteristic of a constant pressure generator is that the ventilator pressure is allowed to equilibrate with the lung pressure. This implies that the generated pressure should be relatively low in order to equilibrate with the alveolar pressure.

Figure A–3 illustrates various waveforms and loops from a constant pressure generator.

### Duty cycle

The duty cycle describes the inspiratory period of a breath, or $Ti/T_{TOT}$ where Ti is the inspiratory time and $T_{TOT}$ is the total cycle time. It is another way to express the I/E ratio. The normal value of a duty cycle varies between 0.2 to 0.4. A value above 0.5 is indicative of an inverse ratio condition. Prolongation of the duty cycle means increasing the inspiratory time.

### Dynamic airway compression

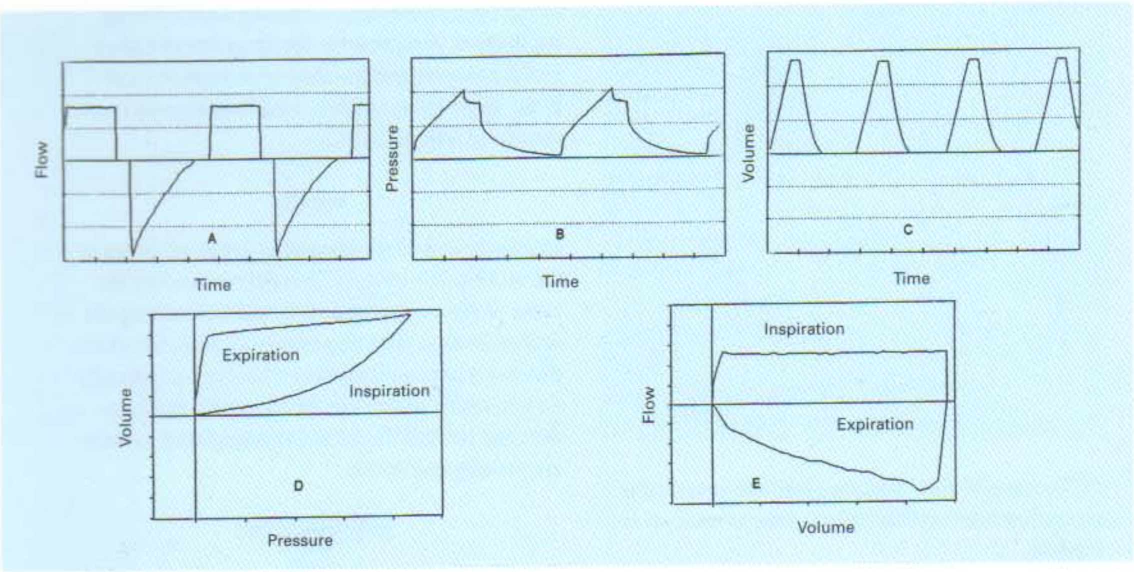
Associated with a condition where pleural pressure is greater than the atmospheric pressure, as for example with forced expiration or coughing. During this forced expiration, the intrapleural pressure will narrow or collapse airways where the pressure inside is lower than the pressure outside the airway.

### Dynamic hyperinflation

Dynamic hyperinflation is an expression to designate a state where end expiratory lung volume exceeds the predicted functional residual capac-

Figure A–2.

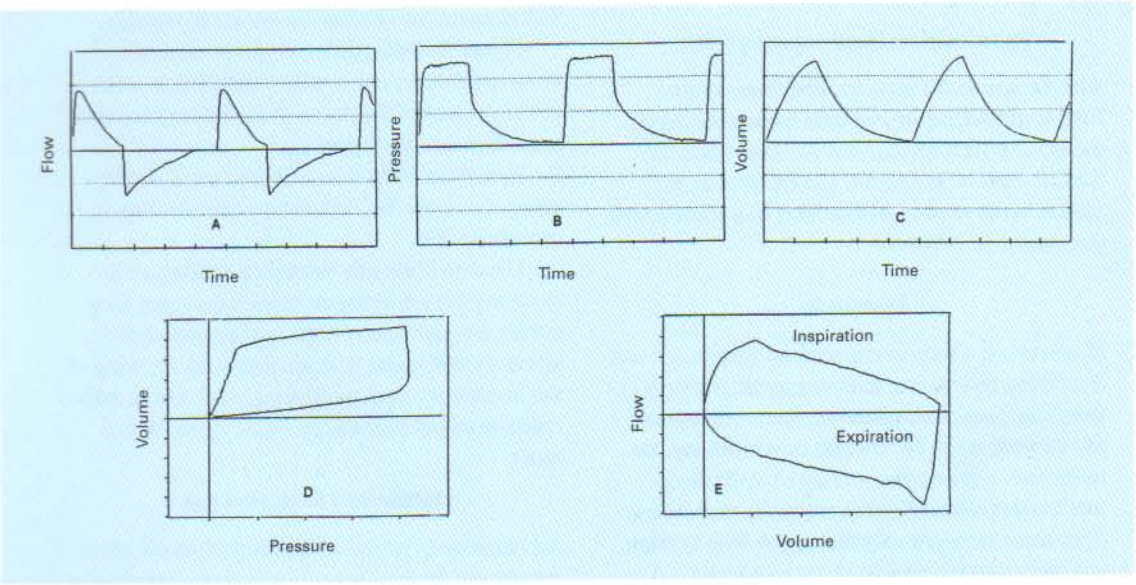
**Waveforms and loops from a constant flow mode of ventilation**



A: Flow-time waveform.
B: Pressure-time waveform
C: Volume-time waveform
D: Volume-pressure loop
E: Flow-volume loop

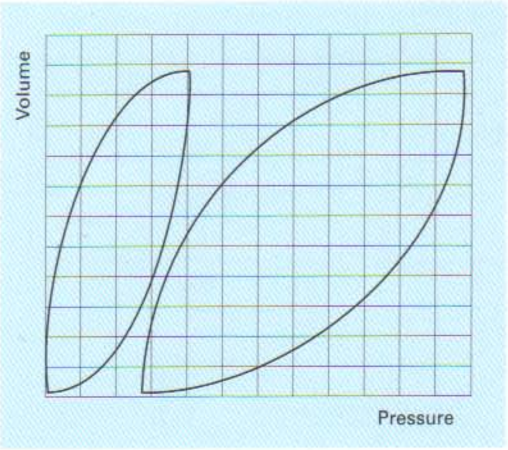
Figure A–3.

**Waveforms and loops from a constant pressure mode of ventilation.**



A: Flow-time waveform.
B: Pressure-time waveform
C: Volume-time waveform
D: Volume-pressure loop
E: Flow-volume loop

Figure A–4.
**Two different sizes of hysteresis.**



ity, because of slow deflating rate and premature expiration interruption before static relaxation is reached.

### Dynamic condition

A dynamic condition describes an activity taking place during ventilation and when the lung/thorax system is moving.

As an example, dynamic characteristics is the measurement of volume-pressure interaction during an active phase of the respiratory cycle.

### Functional residual capacity (FRC)

Also known as the static equilibrium volume, FRC is the pulmonary volume remaining inside the lungs after a normal passive expiration. In ARDS, FRC is decreased, and PEEP is usually used in order to re-establish FRC to a point where gas exchange is better.

### Hysteresis

Hysteresis is a loop characteristic. Inspiration and expiration follow two different paths, but both extremities meet. This phenomenon is common in elastic bodies. In the volume-pressure loop, the hysteresis is the surface occupied by the loop, and is often referred as the elastic hysteresis and represents the work of breathing. A loop is often characterized by the size of the hysteresis. An increased hysteresis is associated with a loss of lung volume. Figure A–4 displays two different sizes of hysteresis.

### Impedance

Impedance describes the total forces of the respiratory system exerting a limiting factor during inspiration. It represents the lung/thorax elastic recoil pressure and the airway resistance to airflow. Impedance is often used to designate resistance and compliance.

### Inertia

Inertia describes the state of opposition forces to the motion of a system. It is determined by the mass of the system and its distribution along the axis of motion. The respiratory system, for example, has a low inertia because it offers practically no resistance to motion. In the equation of motion, the inertial forces of the respiratory system are usually negligible.

### Inflection point

An inflection point describes a location in a loop where the slope of the curve changes abruptly. In a static volume-pressure loop, an inflection point at the lower part of the inflation limb seems to represent the reopening of the closed units during deflation. A static volume-pressure loop is very different from a dynamic volume-pressure loop seen during mechanical ventilation. A static condition is necessary in order to eliminate the resistive elements of volume-pressure relationship.

Figure A–5 illustrates a typical inspiratory volume-pressure curve with an inflection point in the lower part of the curve and a deflection point located in the upper part.

Below the inflection point the small airways close and above the deflection point the lung is overdistended.

Caution is the rule when interpreting an inflection point. A dynamic volume-pressure loop contains resistive elements, and an increased inspiratory resistance will accentuate the bowing of the inspiratory limb, producing what can be mistaken as an inflection point due to alveolar collapse.

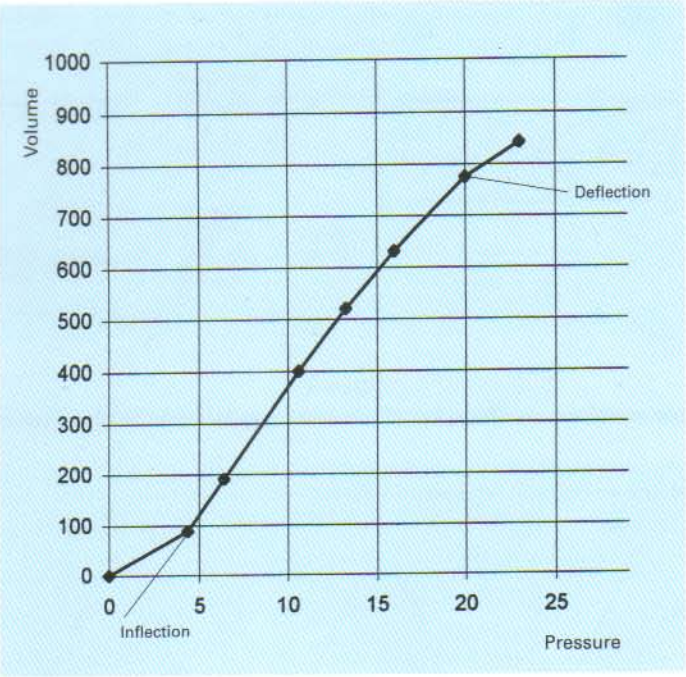
### Inspiratory occlusion test

An inspiratory occlusion test is performed when measuring the total lung/thorax static compliance during mechanical ventilation.

To achieve a static condition, an occlusion valve is involved. The valve closes at the end of

Figure A–5.

**Semi-static volume-pressure curve with an inflection and deflection point.**



inspiration, flow stops and a constant pressure is maintained during a pause time, thus prolonging the inspiratory time.

Certain clinical conditions must be met for a valid occlusion test and can be verified by various waveforms and loops:

- Flow-time waveform:
  Zero flow during the occlusion period (pause)
  Occlusion should be at the end of inspiration
- Pressure-time waveform:
  Stable pressure during the occlusion period (pause)
  Occlusion should be at the end of inspiration
- Volume-time waveform:
  % Leak should be < 20%
- Flow-volume loop:
  Flow and volume must remain at zero during the occlusion period (pause)

### Laminar and turbulent flows

Laminar and turbulent flows are used to describe various characteristics of fluid or gas movements. They represent two possibilities of fluid flow movements.

A laminar flow is a flow pattern obtained when the velocity of the airflow travels in one direction with little mixing activity.

A turbulent flow is a flow pattern obtained when the velocity of the airflow travels in one direction with large mixing activity.

Another flow pattern, the transition flow, is a flow regime that characterizes the transition from a laminar flow to a turbulent flow. In a transition flow regime, complex flow movements are taking place.

In mechanical ventilation, laminar and turbulent flows are seen with the flow-time waveform, and the flow-volume loop. The pressure-time waveform can provide some clues to the airflow status. Figure A–6 illustrates examples of laminar and turbulent flows.

### Leakage

Leakage describes the difference between inspired tidal volume and expired tidal volume expressed as a percentage (% leak). According to most clinicians, a value < 20% is not conclusive and acceptable. Values > 20% are significant and the clinician should find the cause. In a completely passive breathing patient, the major

Figure A–6.
**Flow characteristics. A: Laminar flow; B: Turbulent flow**

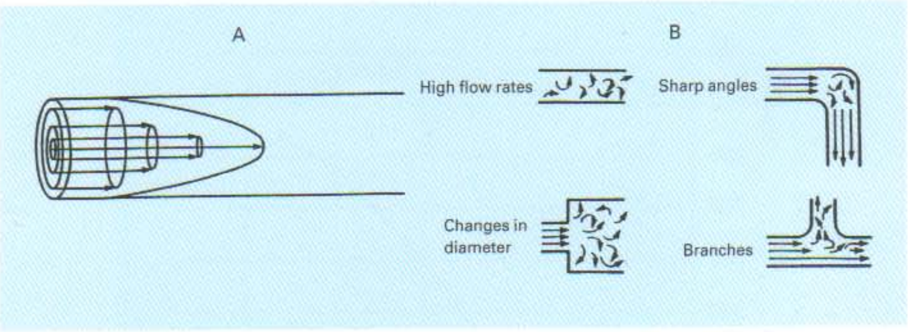
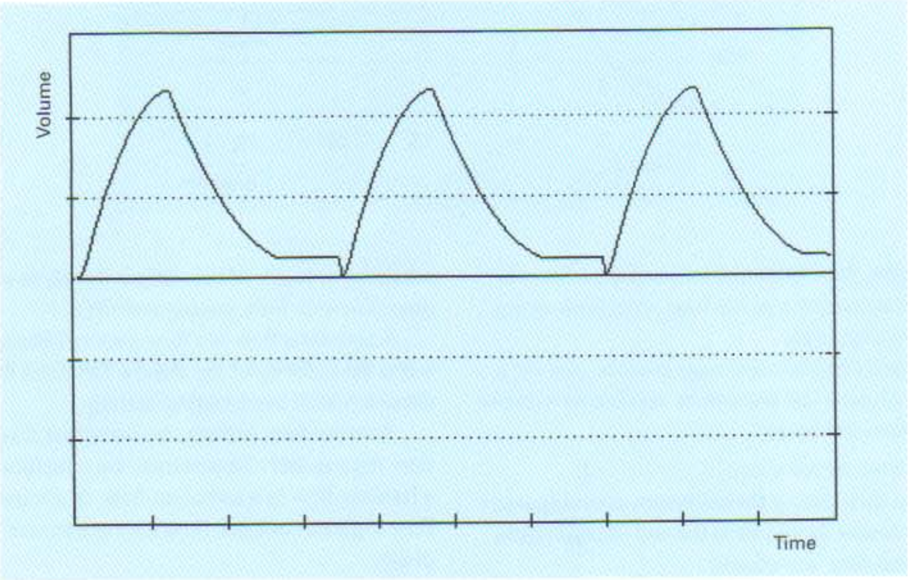


Figure A–7.
**Volume-time waveform showing a loss of volume as seen by a truncated expiratory profile**



causes of increased % leak are cuff and circuit leakage.

% leak during a spontaneous breath is often erroneous, due to tidal volume variation from breath to breath. The % leak can be evaluated with the volume-time waveform and flow-volume loop.

A volume-time waveform that stops abruptly before the next breath is a sign of leakage inside the patient-breathing circuit. A loop that does not return to its origin can also be associated with leakage and air trapping. Figure A–7 illustrates a sign of % leak > 20% in a volume-time waveform.

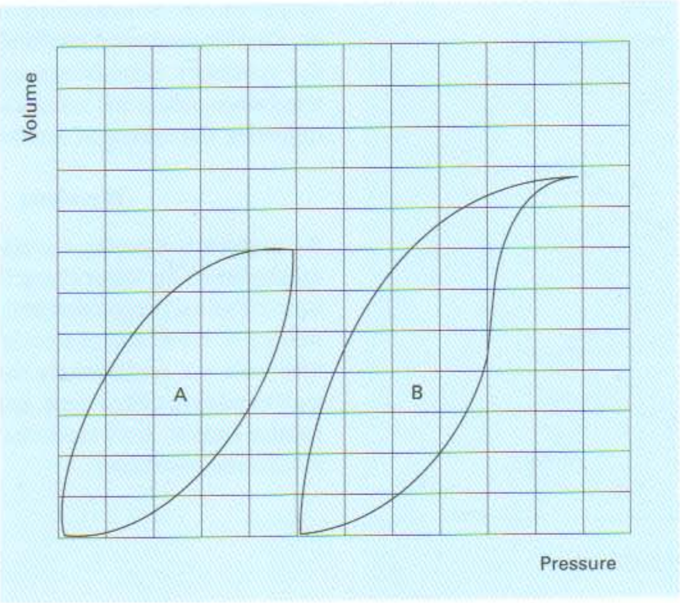
### Loop

A loop is a graphic display of two variables against each other. One major characteristic of a normal loop is that the progression of the event always returns to its origin. In mechanical ventilation, inspiration usually follows a different path from expiration. Loops are also used in pulmonary function testing (PFT).

In PFT, loops are produced on spontaneously breathing patients, with maximal efforts. In mechanical ventilation, loops are produced on mechanically breathing patients, without any efforts.

Figure A–8.

**Volume-pressure loops. A: Normal distention, B: Overdistension**



### Overdistention

Overdistention is a term used to express a situation in which the lungs are inflated past their level of optimal compliance. In mechanical ventilation, overdistention can be identified with the volume-pressure loop.

A distinct deflection point located in the last third of the inspiratory limb of the loop is associated with overdistention. Figure A–8 illustrates two volume-pressure loops; one with normal distention, and one with a deflection point at the last third of inspiration, associated with overdistension.

### Planimetry

The technique used to measure the area of a plane figure. Planimetry is used to calculate the area of various curves. As an example, the area of the volume-pressure loop can be converted to work of breathing.

### Quadratic function

A quadratic function is a mathematical expression that relates parameters according to the following equation:

$$y = ax^2 + bx + c$$

The curve displayed according to a quadratic function is a parabola. In Fig. A–9 this is used to describe total WOB versus breathing frequency.

### Signal to noise ratio (ringing and oscillating)

Monitoring a biological function with an electronic device requires an amplification of the biological signal to be displayed. While picking up the biological signal, the amplifier also picks up and amplifies artifacts. Artifacts are also designated as noise.

The signal to noise ratio is an expression to designate how much amplification of a signal an amplifier can provide as compared to the amount of noise that it introduces during measurement. A high signal to noise ratio is excellent to reproduce accurately a biological function with the least artifacts. Conversely, a low signal to noise ratio is associated with limited accuracy.

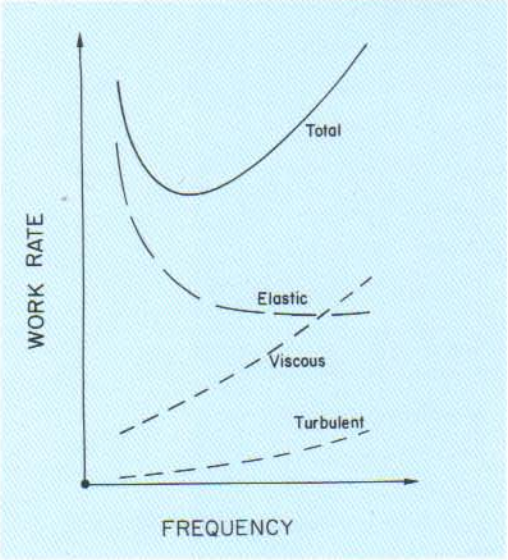
### Static condition

A static condition describes an activity taking place during ventilation and when the lung/thorax system is not moving.

A valid static compliance measurement requires the following conditions:

Figure A–9.

**Quadratic function as expressed by the parabola of total work rate as a function of frequency.**



- Passive tidal volume (inspiratory and expiratory)
- Compressible volume correction for tubing
- The plateau must have an end-inspiratory pause of at least 1 second with a stable pressure within 0.5 $cmH_2O$ over 2 readings at least 10 ms apart.

As an example, static compliance is the measurement of compliance during an inspiratory occlusion test (see inspiratory occlusion test and dynamic characteristics).

Resistance measurement as described by the flow interrupter technique also requires a static condition:

- Passive tidal volume (inspiratory and expiratory)
- Constant flow over a fixed inspiratory time (Ti) (for inspiratory resistance only)
- The plateau must have an end-inspiratory pause of at least 1 second with a stable pressure within 0.5 $cmH_2O$ over 2 readings at least 10 ms apart.

### Synchrony and asynchrony

Expressions that describe the interaction between the patient and the mechanical ventilator. Flow is the variable most often involved in synchrony and dys-synchrony. Signs of asynchrony are monitored when patient and ventilator interact in the triggering and cycling of ventilation

### Waveform

A waveform is a graphic display of a variable against time. One major characteristic of a waveform is that the progression of the event is always moving in one direction, from left to right. The time scale will determine the sweep time of the monitored event. Flow-time, pressure-time and volume-time are the waveforms used during mechanical ventilation.

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# Acute respiratory failure with reference to waveforms and loops

**This appendix describes the concept of acute respiratory failure (ARF) in a context of waveforms and loops during mechanical ventilation.**

**ARF has been described by some authors as a four-stage process in which the respiratory system undergoes physiological changes. These changes affect the dynamic properties of the respiratory system and gas exchange.**

## Clinical stages in ARF

The pathophysiology of ARF has been described in four clinical stages:

| | |
|---|---|
| Stage 1 | Injury and resuscitation |
| Stage 2 | Subclinical respiratory distress |
| Stage 3 | Established respiratory distress |
| Stage 4 | Severe respiratory failure |

These stages describe ARF according to clinical signs such as gas exchange, clinical evidence of respiratory distress, chest radiographic appearance. Four separate groups corresponding to the traditional stages according to characteristics of the static volume-pressure loop have been proposed. Despite a small population group, the findings are indicative of a pathophysiological process that can be easily monitored at bedside. These findings certainly need more clinical verifications, but are nevertheless promising.

Table A-1 shows the four clinical stages of ARF.

Table A–1. **Description of ARF stages adapted from Wilson and Matamis**

| Stage | Respiratory distress | Gas exchange (mmHg) | Chest X-ray | Dynamic characteristics | Hysteresis in V-P Loop | Inflection point in V-P Loop |
|---|---|---|---|---|---|---|
| 1 | None | $P_aO_2$ 70–90<br>$P_aCO_2$ 30–40<br>$A\text{-}_aDO_2$ 20–40<br>Qs/Qt 10–20% | Normal | Normal | Small | Absent |
| 2 | Mild to moderate tachypnea | $P_aO_2$ 60–80<br>$P_aCO_2$ 25–35<br>$A\text{-}_aDO_2$ 30–50<br>Qs/Qt 15–25% | Minimal or no infiltrate | Reduced | Medium | Present |
| 3 | Increasing tachypnea | $P_aO_2$ 50–60<br>$P_aCO_2$ 20–35<br>$A\text{-}_aDO_2$ 40–60<br>Qs/Qt 20–40% | Increasing edema and infiltrates | Reduced | Large | Marked |
| 4 | Obvious respiratory failure | $P_aO_2$ 40–50<br>$P_aCO_2$ 35–50<br>$A\text{-}_aDO_2$ 55–85<br>Qs/Qt 50–70% | Increasing opacification | Reduced | Absent | Absent |

To convert mmHg mercury to kPa divide by 7.5

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