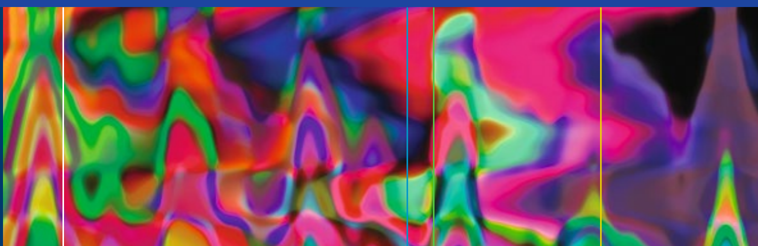
Jean-Michel Arnal



Monitoring Mechanical Ventilation Using Ventilator Waveforms

With Contribution by Robert Chatburn

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Foreword

The study of mechanical ventilation, medicine in general, and perhaps our whole society is struggling under an ominous threat: explosive complexity in technology. It is a threat for the simple reason that the resources spent on technological complexity have increased exponentially over time, while simultaneously, the resources spent on tools to understand and effectively use this technology is holding a constant rate (at best). If you can visualize the graph I have suggested, it would indicate a growing knowledge gap on the part of clinicians and, in particular, physicians using mechanical ventilators. I have been teaching mechanical ventilation for nearly four decades, and I have yet to meet a physician who was provided any substantial training about mechanical ventilation in medical school. This seems astounding, given that life support technologies (resuscitation, intubation, and mechanical ventilation) are critical skills needed by most patients who must endure a stay in an intensive care unit.

As with any advanced medical skill, the road to mastery of mechanical ventilation can be viewed as a hierarchy of specific accomplishments. First, one needs to understand the terminology and then how this terminology is used to describe the technology in terms of both theoretical concepts and a formal taxonomy. In this case, the taxonomy helps us identify modes of ventilation, independent of the names manufacturers coin to sell products. Next, we need to appreciate the specific technological capabilities that different ventilators offer and be able to sort them into advantages and disadvantages. Finally, we need to be able to assess the goal of ventilation for a particular patient (safety, comfort, or liberation) and then match the available technology to the patient's needs. This, of course, involves selecting the most appropriate mode of ventilation. But perhaps the more challenging problem is to select the optimum settings. This is an ongoing challenge because of the constantly changing nature of a patient's condition. Optimizing settings requires that the clinician understand the intricacies of patient-ventilator interactions, particularly in terms of the measured variables as they are displayed by ventilator graphics. In my experience, this is the most difficult skill for clinicians to master. Not only does it require a certain level of theoretical knowledge, but it also requires experience at the bedside.

That brings us to the purpose of this handbook. Consistent, accurate, and practical information regarding ventilator waveform analysis is surprisingly difficult to obtain in book form. To address the need, the author of this book has combined his decades of experience in clinical practice, engineering, and medical education to provide a quick reference work for clinicians at the bedside. The information is presented in short summaries organized in a way that facilitates understanding, using actual ventilator displays and real problems encountered in the daily practice of mechanical ventilation. Each section has a set of self-study questions.

Understanding of the concepts in this resource is a key step in the mastery of the art and science of mechanical ventilation. But remember, knowledge is no substitute for wisdom.

Health and Peace

May, 2017

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Preface

Waveforms are widely available on mechanical ventilator screens and provide clinicians with both precise and important information at the bedside. Ventilator waveforms are produced from measurements of airway pressure and flow, and combine curves and loops. The pressure and flow curves should be interpreted together using different time scales. They represent the interaction between the ventilator and the patient's respiratory mechanics described by the equation of motion. This book is intended for bedside clinicians wanting to assess the effect of ventilator settings on their patients, in order to protect the lung and optimize patient-ventilator synchrony.

The first chapter introduces the basics of respiratory mechanics and interpreting curves. The two main characteristics of respiratory mechanics are compliance and resistance, both of which can be calculated directly from the ventilator waveforms using occlusion maneuvers. The product of compliance and resistance is the time constant, which represents the dynamic respiratory mechanics and is thus very useful at the bedside. Chapters 2–4 detail curves in control modes, during expiration, and in spontaneous modes. In control modes, pressure and flow curves are used to assess respiratory mechanics and measure plateau pressure as a substitute of alveolar pressure. Monitoring of expiration is reliant mainly on the flow curve, which in turn depends on the expiratory time constant. Therefore, monitoring of the expiratory flow provides us with information about the patient's respiratory mechanics and enables detection of dynamic hyperinflation. In pressure support modes, the flow curve informs us about the patient effort and patient-ventilator synchrony, while observation of both the flow and pressure curves helps us to optimize the inspiratory trigger setting, the rise time, and the expiratory trigger setting. Chapter 5 looks at curves in noninvasive ventilation and two particularities of NIV, unintentional leaks and upper airway obstruction, which can also be detected on the flow curve. Chapter 6 covers quasi-static pressure-volume loops used mainly in severe hypoxemic patients to assess lung recruitability, while Chap. 7 describes an esophageal pressure curve that can be added to the airway pressure and flow for several useful applications, such as assessing the risk of stress and atelectrauma. The esophageal pressure can also be used to display a transpulmonary pressure-volume curve and to assess the transpulmonary pressure applied during a recruitment maneuver. In spontaneously breathing patients, the esophageal pressure curve shows the patient effort and patient-ventilator synchrony.

Each page contains a short explanation, a figure, and a quiz question. In most instances, the figures are screenshots taken from real patients with normal artifacts present. The pressure curve is displayed in yellow, and the flow curve in pink. For each question, there is only one correct answer and you will find the answers and comments at the end of each chapter.

I trust you will find the information contained in this book both interesting and useful in your daily work. Should you have comments or additional questions about any of the contents, please don't hesitate to contact me.

Toulon, France Jean-Michel Arnal

Acknowledgments

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Abbreviations

ARDS	Acute respiratory disease syndrome
C_{DYN}	Dynamic compliance of the respiratory system
CO_2	Carbon dioxide
COPD	Chronic obstructive respiratory disease
C_{RS}	Compliance of the respiratory system; $C_{RS} = V_T/\Delta P$
C_{STAT}	Static compliance of the respiratory system
E_{RS}	Elastance of the respiratory system; $E_{RS} = \Delta P/V_T$
ET	Endotracheal
ETS	Expiratory trigger sensitivity
HME	Heat and moisture exchanger
I:E	Inspiratory-expiratory time ratio
NIV	Noninvasive ventilation
P_1	Initial pressure
P_A	Alveolar pressure
P_{AW}	Airway pressure
PC	Pressure control mode
PEEP	Positive end-expiratory pressure
AutoPEEP	Intrinsic PEEP
$PEEP_{TOT}$	Total PEEP measured by an end-expiratory occlusion; $PEEP_{TOT}$ = PEEP + AutoPEEP
P_{EL}	Elastic pressure; the amount of pressure to overcome elastic forces
P_{ES}	Esophageal pressure
P_{INSP}	Preset inspiratory pressure
P_{MUS}	Pressure generated by the patient's muscles
P_{PEAK}	Peak pressure
P_{PLAT}	Plateau pressure measured by an end-inspiratory occlusion
P_{RES}	Resistive pressure: the amount of pressure to overcome resistance

PS	Pressure support mode
P_{TA}	Transalveolar pressure; $P_{TA} = P_{A} - P_{ES}$
P_{TP}	Transpulmonary pressure; $P_{TP} = P_{AW} - P_{ES}$
PV	Pressure-volume
R_{ADD}	Additional resistance
RC_{EXP}	Expiratory time constant
RC_{INSP}	Inspiratory time constant
R_{EXP}	Expiratory resistance
R_{INSP}	Inspiratory resistance
R_{MAX}	Maximum resistance
R_{MIN}	Minimum resistance
VAC	Volume assist control mode
VC	Volume control mode
V_{T}	Tidal volume
ΔP_{TA}	Transpulmonary driving pressure
ΔP	Airway driving pressure
ΔV	Change in volume

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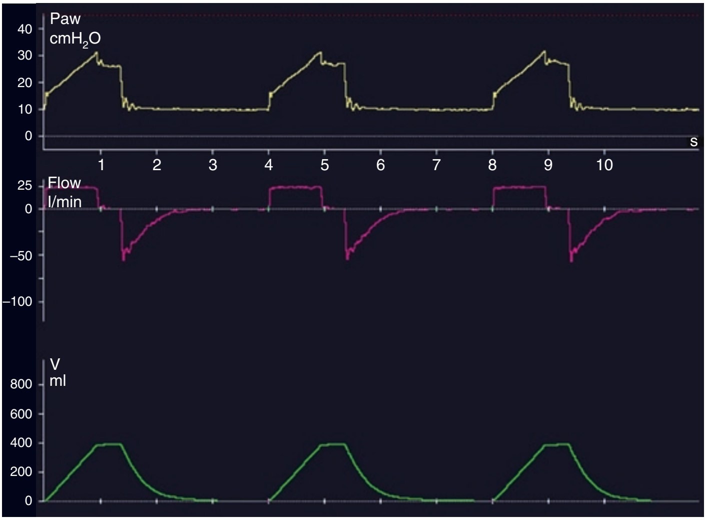
Electronic supplementary material is available in the online version of the related chapter on SpringerLink: http://link.springer.com/

Chapter 1
Basics

1.1 What Is a Curve?

Curves (also known as scalars) are real-time graphical representations of a variable (*pressure, flow*, or *volume*) according to time.



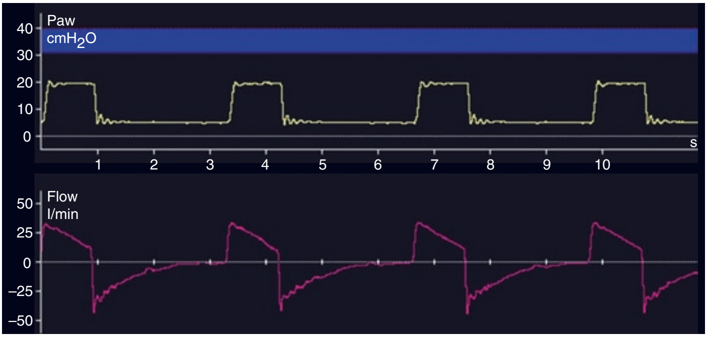
J.-M. Arnal, *Monitoring Mechanical Ventilation Using Ventilator Waveforms*, https://doi.org/10.1007/978-3-319-58655-7_1

On a curve, the x-axis always represents:

1. Flow
2. Pressure
3. Volume
4. Time
5. Points north

1.2 Which Curves Are Relevant?

Ventilators measure airway pressure and airway flow. Volume is derived from the flow measurement. *Pressure and flow* provide all the information necessary to explain the physical interaction between ventilator and patient.

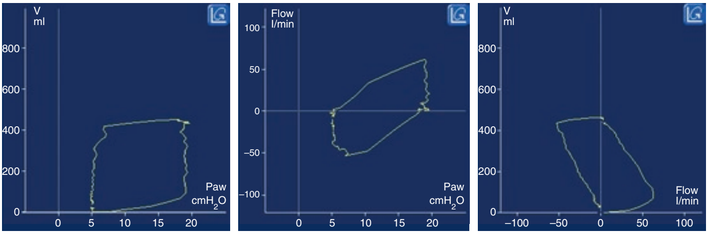


Monitoring of mechanical ventilation relies on the analysis of:

1. The pressure curve
2. The flow curve
3. The volume curve
4. The interactions among pressure and flow
5. The temperature curve

1.3 What Is a Loop?

A loop is a real-time graphical representation of *two variables* (pressure, flow, or volume) plotted against one another. One loop displays the values for one breath.

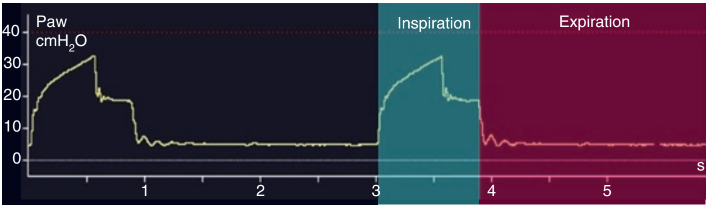


In comparison to curves, loops show:

1. The interaction between variables
2. The same information
3. More information about flow
4. More information about time
5. The dark side of the moon

1.4 Pressure Curve

The pressure curve is always *positive* during mechanical ventilation. Baseline pressure above zero appears when PEEP is applied and assisted inspiration (i.e., work done by the ventilator on the patient) is shown as an increase in pressure above PEEP during volume delivery.

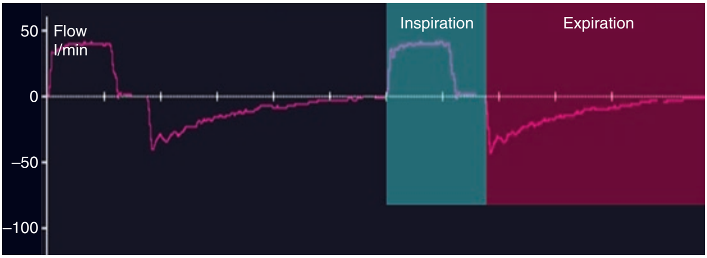


The pressure curve represents the pressure:

1. At the flow outlet of the ventilator
2. At the proximal airway
3. At the end of the endotracheal tube
4. In the alveoli
5. At sea level

1.5 Flow Curve

Flow is displayed above the zero flow line, i.e., *positive values*, *during inspiration* (when gas travels from the ventilator to the patient), and below the zero flow line, i.e., *negative values*, *during expiration* (when gas travels from the patient back to the ventilator). If there is a pause at the end of inspiration, it is considered as part of the inspiratory time. The inspiratory time is therefore measured from the beginning of positive flow to the beginning of negative flow.

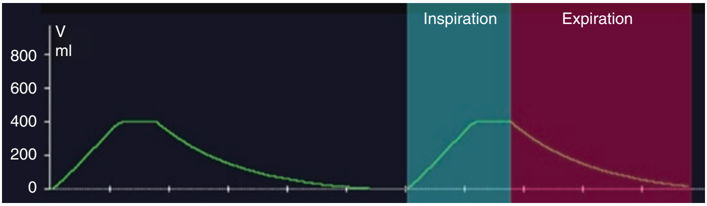


Flow is:

1. Always positive
2. Always negative
3. Positive or negative depending on mode of ventilation
4. Positive or negative depending on the breath phase
5. Dependent on the wind direction

1.6 Volume Curve

Volume is usually not measured directly (except for piston ventilators), but is *derived from the flow* measurement as the area under the flow-time curve. The upslope represents inspiratory volume, while the downslope represents expiratory volume. Any plateau between the two represents an end-inspiratory pause (optional). Inspiratory and expiratory tidal volumes may differ slightly due to the accuracy of the flow measurement, as well as differences in the temperature or humidity of gas. A large discrepancy between inspired and expired tidal volumes may suggest gas leakage. However, the volume display is usually reset to zero at the end of expiration so that errors do not accumulate graphically.



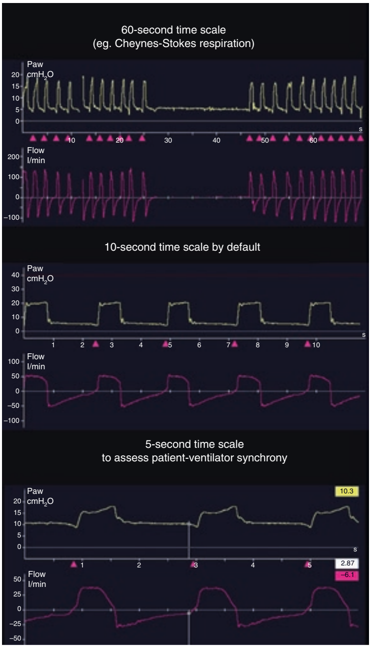
On the volume curve:

1. A volume increase is always linear
2. A volume increase is always exponential
3. The shape of the inspiratory volume waveform is dependent on the shape of the inspiratory flow waveform
4. A volume decrease is exponential if expiration is active
5. Inspiratory and expiratory volume are always the same

1.7 Time Scale

The time scale is often set automatically at 10 s per epoch in order to analyze 3 or 4 breaths. However, it may be useful to manually zoom out to 30 s or more for repetitive events such as obstructive apnea or Cheyne-Stokes respiration or to zoom in for a detailed assessment of patient-ventilator synchrony.

By freezing the curve, it is possible to observe one single event. Using the cursor, pressure or flow can be measured at any point, and synchronization between pressure and flow can be assessed.

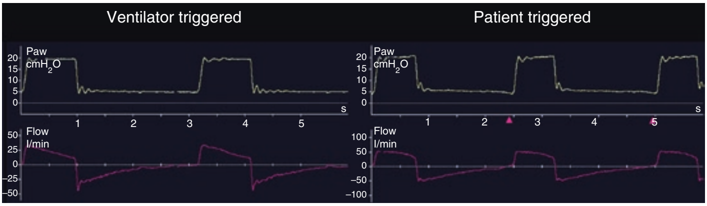


The time scale:

1. Is not really important
2. Is not the same for pressure, volume, and flow
3. Can be manually adjusted depending on requirements
4. Depends on the respiratory rate
5. Depends on ventilation mode

1.8 Mandatory and Triggered Breaths

A *spontaneous breath* is one for which inspiration is both triggered (started) and cycled (stopped) by the patient. A *mandatory breath* is one for which inspiration is either ventilator triggered or ventilator cycled (or both). This is a key concept in understanding the taxonomy for modes of ventilation. A breath triggered by the patient shows a pressure deflection below the baseline (or a flow deflection above baseline) just before the rise in pressure indicating the start of inspiratory flow from the ventilator. Here patient triggering is indicated by the small triangles below each breath. Absence of these triangles indicates ventilator (i.e., time) triggering.



When the patient triggers the breath:

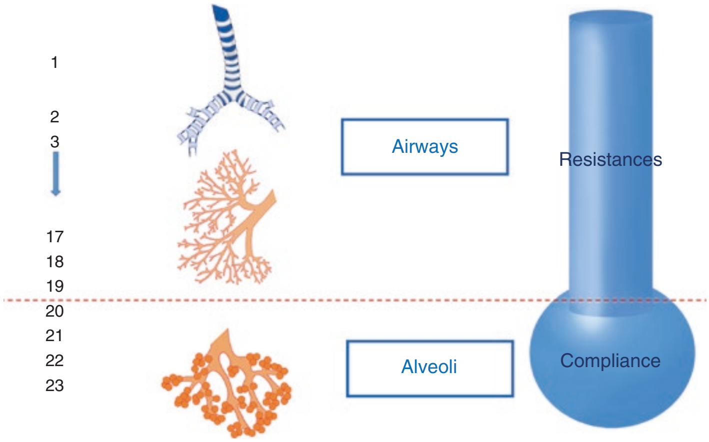
1. There is always a delay between patient effort and flow delivery
2. A small increase in flow before triggering indicates a flow-triggering system
3. A short period of flow at zero before triggering indicates a pressure-triggering system
4. Pressure deflection is deeper if the patient has a high respiratory drive
5. All are correct

1.9 Static Respiratory Mechanics

The respiratory system can be simplified using a linear one-compartment model, which comprises a *tube* representing the airways and a *balloon* representing the alveoli and the chest wall. To ventilate such a system, there are two main forces that oppose inflation of the balloon:

1. The impedance to flow, which represents resistance of the airways:
   - Resistance = Δ pressure/flow
2. The impedance to volumetric expansion, which represents compliance of the lung and chest wall:
   - Compliance = Δ volume/Δ pressure
   - Elastance = Δ pressure/Δ volume

Note that the linear one-compartment model does not take into account the fact that resistance and compliance are not constant in the case of lung and chest-wall disease; instead they exhibit a flow and volume dependency. It also does not include the effects of inertia, which are small for normal respiratory frequencies. Most ventilators ignore these details in their calculations for resistance and compliance.



The two main characteristics of respiratory mechanics during mechanical ventilation are:

1. Lung heterogeneity
2. Airway resistance
3. Inertia
4. Compliance of the lung and chest wall
5. Both 2 and 4

1.10 Equation of Motion in Passive Patients

The graphical, single-compartment model shown above has a *mathematical correlate*, called the equation of motion for the respiratory system. It is essentially a force balance equation. At any point in time during inspiration, airway pressure (P_{AW}) is the sum of:

- The starting pressure: Total PEEP ($PEEP_{TOT}$)
- The resistive pressure (P_{RES}): Pressure to overcome the inspiratory resistance. P_{RES} is the product of inspiratory resistance and inspiratory flow.
- The elastic pressure (P_{EL}): Pressure to overcome the lung and chest-wall compliance. P_{EL} is the ratio of tidal volume to respiratory-system compliance:

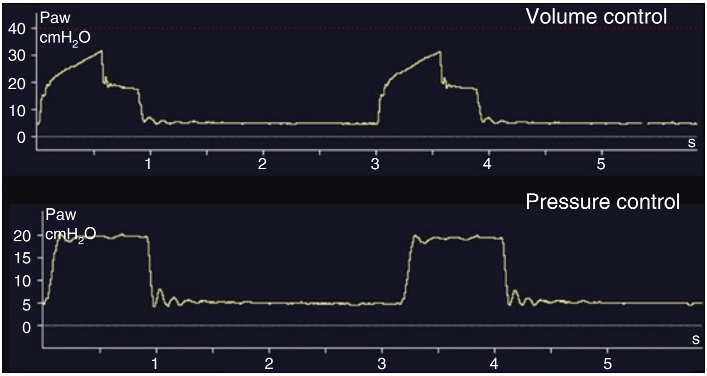
$$P_{AW} = PEEP_{TOT} + P_{RES} + P_{EL}$$

$$= PEEP_{TOT} + (\text{tidal volume} / \text{compliance}) + (\text{flow} \times \text{resistance})$$

or

$$P_{AW} - PEEP_{TOT} = (\text{tidal volume} / \text{compliance}) + (\text{flow} \times \text{resistance})$$

where $PEEP_{TOT}$ is the pressure in the lungs at the end of the expiratory time, which depends both on the PEEP set by the ventilator and how completely the lungs have emptied before the next inspiration. Note that the last form of the equation shows that airway pressure (from the ventilator) must rise above $PEEP_{TOT}$ before inspiratory flow can begin.



During mechanical ventilation, airway pressure depends on:

1. Lung and chest-wall compliance
2. The flow
3. AutoPEEP
4. The tidal volume
5. All the above

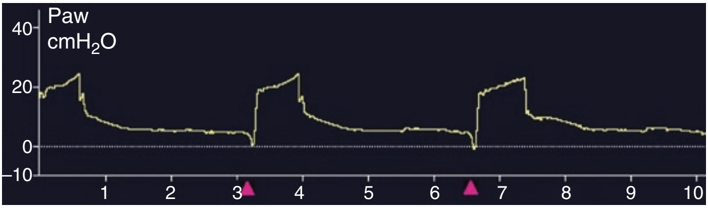
1.11 Equation of Motion for Spontaneously Breathing Patients

In spontaneously breathing patients, the pressure generated by the *patient's muscle* (P_{MUS}) is added to the *pressure applied by the ventilator*:

$$P_{AW} + (P_{MUS} - PEEP_{TOT}) = (\text{tidal volume} / \text{compliance}) + (\text{flow} \times \text{resistance})$$

There are two implications of this equation:

- First is that for PC modes, increasing P_{MUS} does not affect P_{AW} (because this is preset), but it increases volume and flow (i.e., it deforms the volume and flow curves). For VC modes, increasing P_{MUS} decreases P_{AW} (i.e., it deforms the pressure curve), but it does not affect volume or flow (because they are preset).
- Second, it follows that P_{MUS} must exceed $PEEP_{TOT}$ in order for P_{AW} to drop (or flow to increase) enough to trigger inspiration. Otherwise a patient-ventilator asynchrony occurs, known as an "ineffective trigger effort."



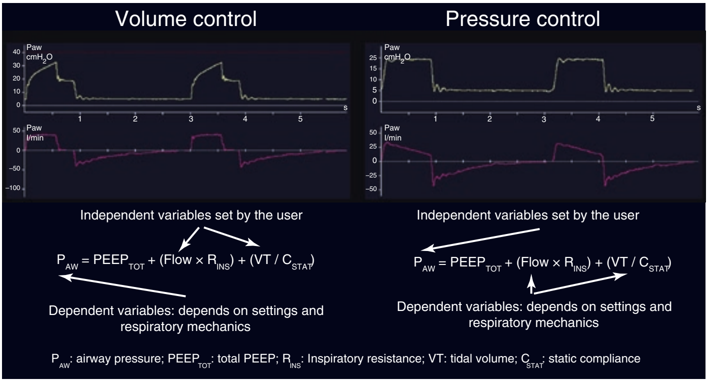
When the patient makes an inspiratory effort:

1. P_{MUS} distorts the pressure waveform in PC modes and the volume waveform in VC modes
2. P_{MUS} distorts the flow waveform in PC modes and the pressure waveform in VC modes
3. P_{MUS} must be greater than $PEEP_{TOT}$ to trigger inspiration
4. Both 2 and 3
5. None of the above

1.12 Independent and Dependent Variables

The equation of motion is the *theoretical basis for classifying modes* as "pressure control" (PC) or "volume control" (VC). Pressure control means that the left-hand side of the equation is predetermined (i.e., preset inspiratory pressure and time or inspiratory pressure is adjusted by the ventilator to be proportional to inspiratory effort) with volume and flow delivery dependent on the patient's respiratory mechanics. Hence, pressure is considered the independent variable, while volume and flow are dependent variables.

Volume control means that the right-hand side of the equation is predetermined (preset tidal volume and flow) making pressure delivery dependent on the patient's respiratory mechanics. Thus, volume and flow are considered independent variables in the equation of motion, and pressure is the dependent variable.

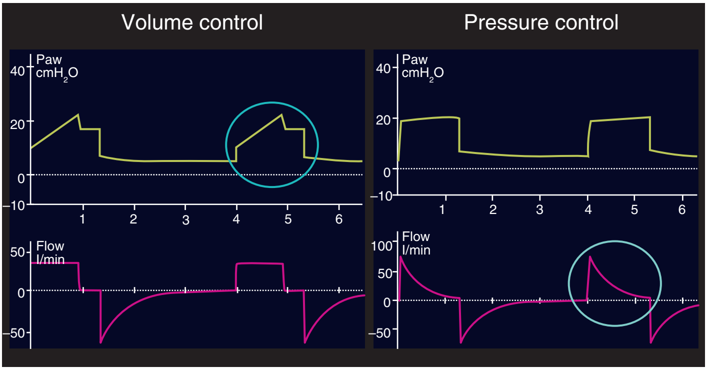


To identify the control variable:

1. A constant inspiratory pressure indicates PC
2. A constant inspiratory flow indicates VC
3. If tidal volume and flow are both preset, this indicates VC
4. If inspiratory pressure is preset, this indicates PC
5. All of the above

1.13 Which Curves Should Be Monitored During Inspiration?

The independent-variable curve provides information on the control variable of the ventilator. The dependent-variable curve indicates the response of the respiratory system. Thus, for monitoring the patient, the essential information is obtained by looking at the *dependent-variable curve*.

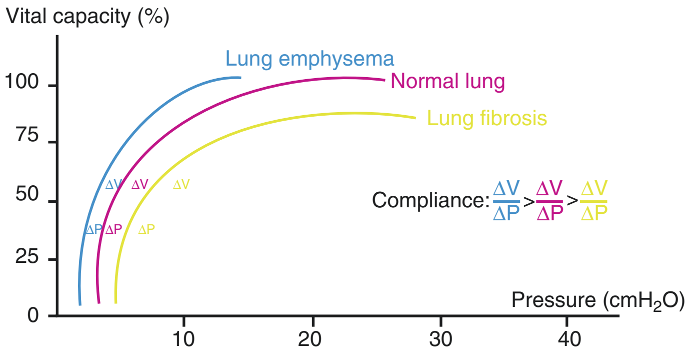


The dependent variable is:

1. The pressure curve in VC modes
2. The pressure curve in PC modes
3. The flow curve in PC modes
4. Both 1 and 3
5. The flow curve in VC modes

1.14 Compliance

Respiratory-system compliance is the ratio between a *change in volume and the associated change in pressure*. Elastance is the reciprocal of compliance ($E_{RS} = 1/C_{RS}$). Respiratory-system elastance is the sum of lung elastance and chest-wall elastance.



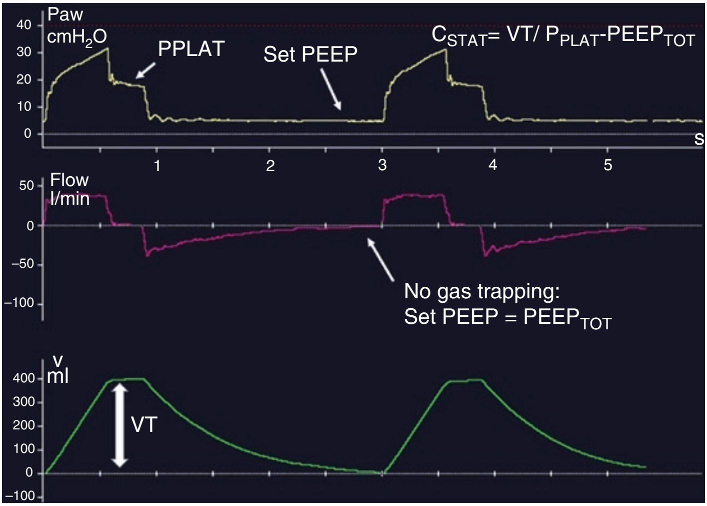
Compliance is expressed in:

1. cm H_2O/L
2. mL/cm H_2O
3. hPa
4. L/min
5. cm H_2O/L/s

1.15 Static and Dynamic Compliance

Static compliance is the ratio of tidal volume to driving pressure and represents the elasticity of the respiratory system. It is calculated as the ratio of volume change to pressure change ($\Delta V/\Delta P$) between two points in time when flow throughout the respiratory system is zero (e.g., during an inspiratory pause maneuver): $C_{STAT} = V_T/(P_{PLAT} - PEEP_{TOT})$.

Dynamic compliance is the estimation of C_{STAT} during dynamic conditions (i.e., during active inspiration without the use of an inspiratory hold). Thus, it is the ratio of volume change to pressure change between two points in time when flow at the airway opening is zero. This is accomplished by fitting multiple data points (e.g., pressure, volume, and flow measured every 20 ms) to the equation of motion and then solving for compliance. For the single-compartment model of the respiratory system, $C_{STAT} = C_{DYN}$ and is independent of respiratory rate. For a multiple-compartment model of the lungs, as the distribution of resistance and compliance become less homogeneous, C_{STAT} becomes greater than C_{DYN} because flow persists among lung units with different mechanical properties (pendelluft) and this flow increases ΔP for the same ΔV. In this case, C_{DYN} decreases as respiratory rate increases. Unfortunately, some authors have propagated an old idea that dynamic compliance can be calculated using peak inspiratory pressure (i.e., P_{PEAK} rather than P_{PLAT}): $C_{DYN} = V_T/(P_{PEAK} - PEEP)$. Because P_{PEAK} is a function of both R and C, clearly this metric is not a form of "compliance." This outdated definition of C_{DYN} is both clinically irrelevant and theoretically misleading.



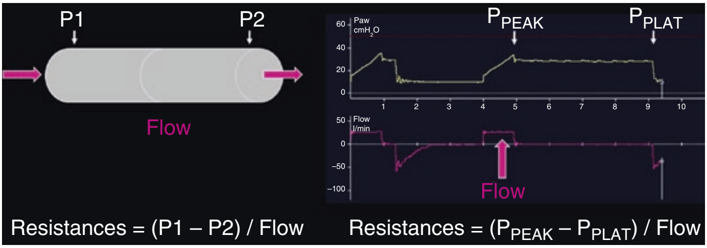
Static compliance is:

1. ΔV/ΔP
2. ΔP/ΔV
3. Not affected by gas trapping
4. Calculated using peak inspiratory pressure
5. Increased when respiratory rate increases

1.16 Resistance

Airway resistance is the ratio between the pressure driving a given flow, i.e., transairway pressure, and the resulting flow rate.

In passive patients ventilated in VC modes with a square flow waveform, airway resistance including the resistance of the endotracheal tube can be calculated as $(P_{PEAK} - P_{PLAT})$/flow.



Inspiratory resistance depends on:

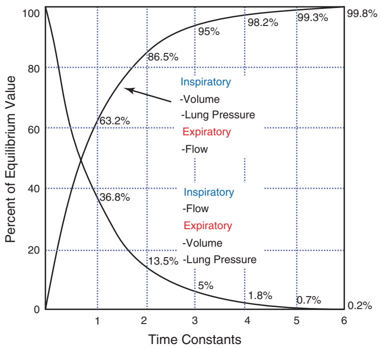
1. Inspiratory flow
2. The caliber of the endotracheal tube
3. The density of the gas
4. The use of HME or heated humidification
5. All of the above

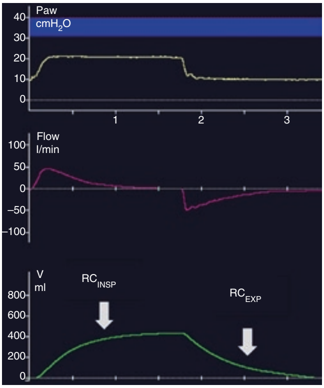
1.17 Dynamic Respiratory Mechanics: Time Constant

When a step change in pressure is applied to the respiratory system, the change in volume (and flow and alveolar pressure) follows an exponential curve that is initially fast, but slows down progressively as it reaches a new equilibrium. The *speed of the volume change* is described by the time constant, which has the dimension of time. Mathematically, one time constant is equal to the product of resistance and compliance and describes the time needed to increase or decrease volume by 63% of the total volume change.

The time constant can be calculated during inspiration or expiration. Because the time constant represents the response to a step change (i.e., a square pressure waveform), the inspiratory time constant (RC_{INSP}) will be inaccurate to the extent that rise time is not zero (and it never is for a mechanical system). The expiratory time constant (RC_{EXP}) is almost completely dependent from the patient (assuming passive expiration so that $P_{MUS} = 0$) and independent of settings, to the extent that the pressure drops instantaneously to PEEP (which is never quite true because of resistance in the ventilator's expiratory circuit). RC_{EXP} is therefore the preferred metric of the patient's dynamic respiratory mechanics, provided there is no active expiratory effort.

The time constant is important because it determines the amount of inspiratory time required for complete tidal volume delivery during PC modes.





In terms of the time constant:

1. The inspiratory and expiratory time constants are equal
2. Three expiratory time constants equal the time required to exhale 95% of the tidal volume
3. The time constant depends primarily on compliance
4. A short time constant means increased resistance
5. The inspiratory time constant depends on the inspiratory time

1.18 Expiratory Time Constant

Some ventilators provide a measurement of the RC_{EXP} in all ventilation modes, including NIV. This measurement is accurate if there is no active expiratory effort and no leakage.

For an intubated patient with normal lungs, the RC_{EXP} is usually between 0.5 and 0.7 s.

A decrease in the lung and/or the chest-wall compliance (e.g., ARDS) is associated with a short RC_{EXP} (< 0.5 s).

An increase in airway and/or endotracheal tube resistance (e.g., COPD) is associated with a long RC_{EXP} (> 0.7 s).

The expiratory time constant determines the time required for complete exhalation during any mode. Thus, if expiratory time is set less than five time constants, gas trapping will occur and $PEEP_{TOT}$ increases above set PEEP (i.e., autoPEEP >0).

	Normal lung	**ARDS**	**COPD**
C_{STAT} (ml/cm H_2O)	45–65	< 45	50–80
R_{INS} (cm H_2O s/l)	10–15	10–15	16–33
RC_{EXP} (s)	0.5–0.7	< 0.5	> 0.7

The expiratory time constant:

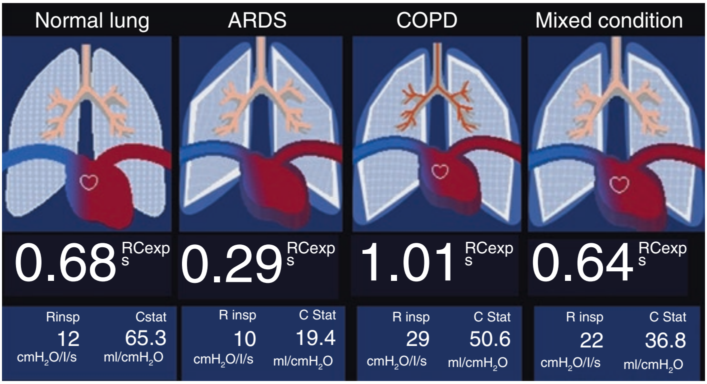
1. Is accurate only in passive patients
2. Reflects the disease state of the respiratory system
3. Is expressed in seconds
4. Is slightly different in intubated patients and those receiving NIV
5. All of the above

1.19 Clinical Application of the Expiratory Time Constant

A normal RC_{EXP} (0.5–0.7 s) means a normal lung or a mixed condition (COPD + ARDS).

A short RC_{EXP} (< 0.5 s) means there is decreased compliance due to the lung and/or the chest wall: ARDS, lung fibrosis, atelectasis, kyphoscoliosis, increased abdominal pressure, etc.

A long RC_{EXP} (> 0.7 s) means there are increased resistances due to the patient and/or the endotracheal tube: COPD, asthma, bronchospasm, endotracheal tube obstruction, etc.

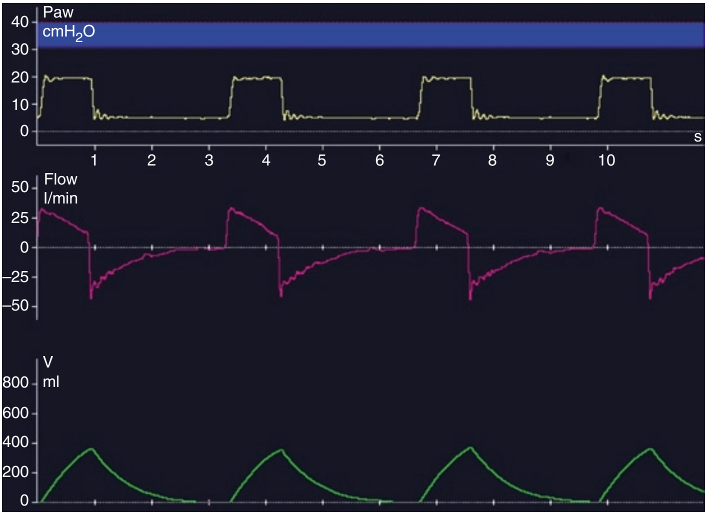


The expiratory time constant:

1. Is approximately 0.6 s in normal-lung patients
2. Is approximately 0.3 s in the case of ARDS
3. Is long in COPD and asthmatic patients
4. Can be normal in the case of a mixed-disease condition
5. All of the above

1.20 Rationale Behind Curve Analysis

Airway flow and pressure curves display the *complex interaction* between the ventilator settings and the patient's respiratory mechanics. In fact, pressure, volume, and flow curves displayed by the ventilator are nothing more than graphical representations of the equation of motion.



An analysis of the curves is used to:

1. Assess the patient's respiratory mechanics
2. Optimize the ventilator settings
3. Both 1 and 2
4. Predict the gas exchange
5. Learn the geography

Responses

1.1 4

1.2 4

1.3 1

1.4 2: Some ventilators measure airway pressure directly at proximal airways, between the Y piece and the endotracheal tube. Others measure it remotely at the inspiratory compartment (between the inspiratory valve and the inspiratory gas outlet) and at the expiratory compartment (between the expiratory gas inlet and the expiratory valve). Then, proximal airway pressure is calculated taking into account the breathing circuit resistances

1.5 4

1.6 3

1.7 3

1.8 5

1.9 5

1.10 5: AutoPEEP if any is part of total PEEP. Total PEEP = external PEEP + autoPEEP

1.11 4

1.12 5

1.13 4

1.14 2

1.15 1

1.16 5

1.17 2: Inspiratory and expiratory time constant are not equal because airway resistances are usually lower during inspiration as compared to expiration. Thus, inspiratory time constant is shorter than expiratory time constant

Time constant	Change in volume (% of total change)
1	63%
2	86.5%
3	95%
4	98%
5	99%

1.18 5: RC_{EXP} is slightly different in intubated and NIV patients because of the ET resistance

1.19 5

1.20 3

Suggested Readings

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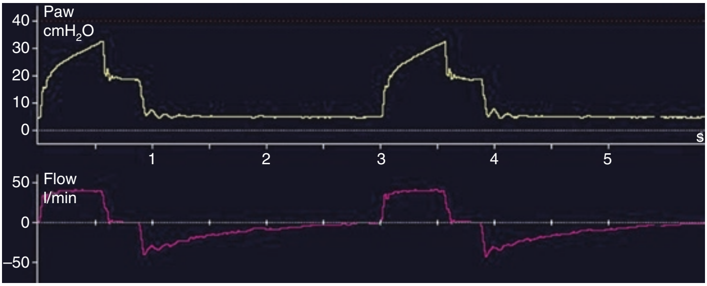
Chapter 2
Controlled Modes

2.1 Volume-Controlled Modes

2.1.1 Shape of the Pressure Curve

During VC, *flow and tidal volume* are the independent variables set by the user. In the simplest case, the flow waveform is square (constant flow) during inspiration. Pressure is the dependent variable. Pressure increases during insufflation to reach a maximum at the end of inspiration. If an end-inspiratory pause is set by the user, the flow will be zero and pressure will reach a plateau (Video 2.1).



Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-319-58655-7_2) contains supplementary material, which is available to authorized users.

J.-M. Arnal, *Monitoring Mechanical Ventilation Using Ventilator Waveforms*, https://doi.org/10.1007/978-3-319-58655-7_2

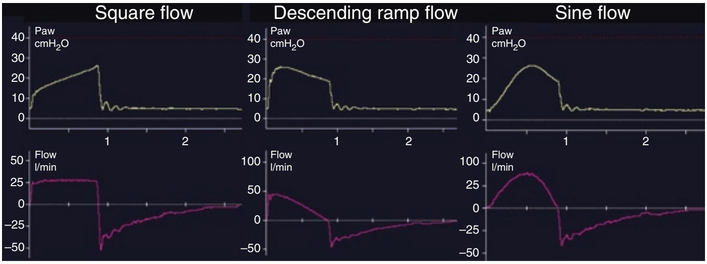
In VC modes with constant flow:

1. The flow curve provides information about respiratory mechanics
2. Pressure is the independent variable
3. Pressure reaches its maximum at the end of the inspiratory time
4. The pressure curve shows always a plateau
5. The pressure curve has a square shape

2.1.2 Flow Pattern

Different flow waveforms can be set in during VC on some ventilators:

- *Square*: Flow is constant throughout the inspiratory phase. This pattern is associated with the highest peak pressure.
- *Descending ramp*: Flow is at its maximum at the beginning of inspiration and decreases linearly during the inspiratory phase.
- *Sine*: Flow gradually increases to a maximum at mid-inspiratory time and then decreases back down to zero (Video 2.2)

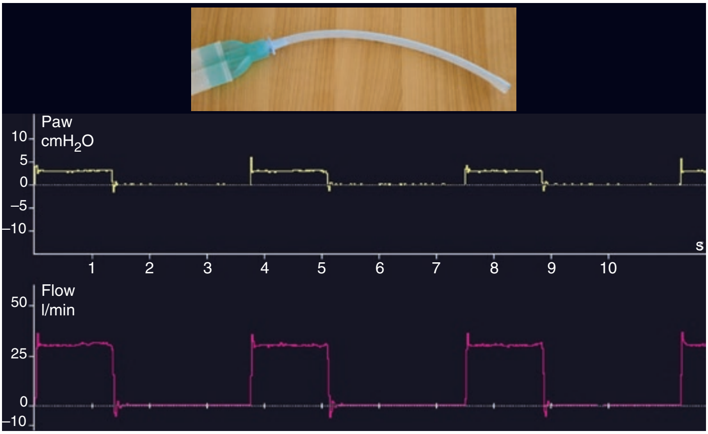


In VC, the preset flow waveform affects all these variables *except*:

1. The tidal volume delivered
2. The inspiratory time
3. The peak pressure
4. The shape of the pressure curve
5. The gas distribution within the lung

2.1.3 Resistive Component of the Pressure Curve

If only the resistive component of the linear one-compartment model (namely the tube) is ventilated in VC with a square flow pattern, the pressure curve will show a *square* with constant pressure throughout the inspiratory phase. The pressure will be higher if tube resistance or flow increase. Therefore, the initial rapid increase in pressure in VC is due to resistance and is reproduced at the end of inspiration by the difference between peak and plateau pressure.



In VC, the initial increase in pressure depends on:

1. Airway resistance and flow
2. The inspiratory time
3. The size of the endotracheal tube
4. Both 1 and 3
5. Respiratory-system compliance