Ventilator Waveforms: Interpretation

Albert L. Rafanan, MD, FPCCP
Pulmonary, Critical Care and Sleep Medicine
Chong Hua Hospital, Cebu City
Types of Waveforms

• **Scalars** are waveform representations of pressure, flow or volume on the y axis vs time on the x axis

• **Loops** are representations of pressure vs volume or flow vs volume
Scalar Waveforms

Assisted Mode
(Volume-Targeted Ventilation)

- Pressure (cm H₂O)
  - Control Breath
  - Assist Breath

- Volume (ml)
  - Time

- Flow (L/min)
  - Time
Loop
Common problems that can be diagnosed by analyzing Ventilator waveforms

- Abnormal ventilatory Parameters/ lung mechanics
  E.g., Overdistension, Auto PEEP, COPD

- Patient-ventilator Interactions
  E.g. flow starvation, Double triggering, Wasted efforts, Active expiration

- Ventilatory circuit related problems
  E.g. auto cycling and Secretion build up in the Ventilatory circuit
Lung Mechanics

• Use Scalar
• Pressure Time Waveform with a square wave flow pattern
Understanding the basic ventilator circuit diagram

Essentially, the circuit diagram of a mechanically ventilated patient can be broken down into two parts. The ventilator makes up the first part of the circuit. Its pump-like action is depicted simplistically as a piston that moves in a reciprocating fashion during the respiratory cycle. The patient's own respiratory system makes up the second part of the circuit. The diaphragm is also shown as a second piston, causing air to be drawn into the lungs during contraction. These two systems are connected by an endotracheal tube which we can consider as an extension of the patient's airways.
Understanding airway pressures

The respiratory system can be thought of as a mechanical system consisting of resistive (airways + ET tube) and elastic (lungs and chest wall) elements in series.

**ET tube + Airways** (resistive element)

**Lungs + Chest wall** (elastic element)

Resistive pressure varies with airflow and the diameter of ETT and airways.

Elastic pressure varies with volume and stiffness of lungs and chest wall.

\[ P_{aw} = \text{Flow} \times \text{Resistance} + \text{Volume} \times \frac{1}{\text{Compliance}} \]

**Diaphragm**

**ET Tube**

**Airways**

**P_{PL}** Pleural pressure

**P_{alv}** Alveolar pressure

**P_{aw}** Airway pressure

**Chest wall**

**Pel** = Volume \times \frac{1}{\text{Compliance}}
Let us now understand how the respiratory system’s inherent elastance and resistance to airflow determines the pressures generated within a mechanically ventilated system.

The total ‘elastic’ resistance \( \left( E_{rs} \right) \) offered by the lungs and the chest wall determines the pressure generated by the respiratory system. The total ‘airway’ resistance \( \left( R_{aw} \right) \) in the mechanically ventilated patient is equal to the sum of the resistances offered by the endotracheal tube \( \left( R_{ET\ tube} \right) \) and the patient’s airways \( \left( R_{airways} \right) \). Therefore, to move air into the lungs at any given time \( (t) \), the ventilator has to generate sufficient pressure \( \left( P_{aw}(t) \right) \) to overcome the combined elastic \( \left( P_{el}(t) \right) \) and resistance properties \( \left( P_{res}(t) \right) \) of the respiratory system.

Thus, the equation of motion for the respiratory system is:

\[
P_{aw}(t) = P_{res}(t) + P_{el}(t)
\]
Understanding the pressure-time waveform using a ‘square wave’ flow pattern

The pressure-time waveform is a reflection of the pressures generated within the airways during each phase of the ventilatory cycle. At the beginning of the inspiratory cycle, the ventilator has to generate a pressure $P_{res}$ to overcome the airway resistance. Note: No volume is delivered at this time.

After this, the pressure rises in a linear fashion to finally reach $P_{peak}$. Again at end inspiration, airflow is zero and the pressure drops by an amount equal to $P_{res}$ to reach the plateau pressure $P_{plat}$. The pressure returns to baseline during passive expiration.
Pressure-time waveforms using a ‘square wave’ flow pattern

\[ P_{\text{aw(peak)}} = \text{Flow} \times \text{Resistance} + \text{Volume} \times \frac{1}{\text{Compliance}} \]

This is a **normal** pressure-time waveform
With normal peak pressures \( (P_{\text{peak}}) \);
plateau pressures \( (P_{\text{plat}}) \)and
airway resistance pressures \( (P_{\text{res}}) \)
Waveform showing high airways resistance

\[ P_{aw(peak)} = \text{Flow} \times \text{Resistance} + \text{Volume} \times \frac{1}{\text{Compliance}} + \text{PEEP} \]

Scenario # 2

The increase in the peak airway pressure is driven entirely by an increase in the airways resistance pressure. Note the normal plateau pressure.

This is an abnormal pressure-time waveform.

e.g. ET tube blockage

Square wave' flow pattern
Waveform showing increased airways resistance

'Square wave' flow pattern

$P_{\text{peak}}$

$P_{\text{plat}}$

$P_{\text{res}}$
Waveform showing high inspiratory flow rates

\[ P_{aw(peak)} = \text{Flow} \times \text{Resistance} + \text{Volume} \times \frac{1}{\text{compliance}} + \text{PEEP} \]

Scenario #3

The increase in the peak airway pressure is caused by high inspiratory flow rate and airways resistance. Note the shortened inspiratory time and high flow rates.
Waveform showing decreased lung compliance

The increase in the peak airway pressure is driven by the decrease in the lung compliance. This is an abnormal pressure-time waveform. Increased airways resistance is often also a part of this scenario.

\[ P_{aw(peak)} = \text{Flow} \times \text{Resistance} + \text{Volume} \times \frac{1}{\text{Compliance}} + \text{PEEP} \]
Common problems that can be diagnosed by analyzing Ventilator waveforms

- Abnormal ventilatory Parameters/lung mechanics
  - E.g., Overdistension, Auto PEEP, COPD

- Patient-ventilator Interactions
  - E.g., flow starvation, Double triggering, Wasted efforts, Active expiration

- Ventilatory circuit related problems
  - E.g., auto cycling and Secretion build up in the Ventilatory circuit
Recognizing Lung Overdistension
Flow-time waveform

- Flow-time waveform has both an inspiratory and an expiratory arm.

- The shape of the expiratory arm is determined by:
  - the elastic recoil of the lungs
  - the airways resistance
  - and any respiratory muscle effort made by the patient during expiration (due to patient-ventilator interaction/dys=synchrony)

- It should always be looked at as part of any waveform analysis and can be diagnostic of various conditions like COPD, auto-PEEP, wasted efforts, overdistention etc.
Recognizing lung overdistension

Suspect this when:

There are high peak and plateau pressures...

Accompanied by high expiratory flow rates

PEARL: Think of low lung compliance (e.g. ARDS), excessive tidal volumes, right mainstem intubation etc
The Stress Index

• In AC volume ventilation using a constant flow waveform observe the pressure time scalar.

• Normal, linear change in airway pressure Stress index = 1

• Upward concavity indicates decreased compliance and lung overdistension Stress index > 1

• Downward concavity indicates increased compliance and potential alveolar recruitment Stress index < 1

Note: Patient effort must be absent
The Stress Index

- Stress index < 1
- Stress index = 1
- Stress index > 1
Pressure-volume loop

Lower inflection point (LIP)
Can be thought of as the minimum baseline pressure (PEEP) needed for optimal alveolar recruitment

Compliance (C) is markedly reduced in the injured lung on the right as compared to the normal lung on the left

Upper inflection point (UIP)
above this pressure, additional alveolar recruitment requires disproportionate increases in applied airway pressure

Normal lung

ARDS

C = dV/dP

I. de Chazal and R. D. Hubmayr

Note: During normal ventilation the LIP cannot be assessed due to the effect of the inspiratory flow which shifts the curve to the right.
Recognizing Auto-PEEP
Dynamic Hyperinflation (Gas Trapping)

- Dynamic hyperexpansion, defined as premature termination of exhalation, often occurs when respiratory rate, inspiratory time, or both have been increased.
- By not permitting exhalation to finish, an increase in mean airway pressure results.
- Gas trapping may occur leading to an elevation in PCO2.
- Careful attention must be paid to dynamic hyperexpansion in patients with obstructive lung disease whose long time constants and slow emptying can result in progressive air trapping, hypercarbia, and eventually decreased cardiac output.
Expiratory flow continues and fails to return to the baseline prior to the new inspiratory cycle.
Detecting Auto-PEEP

Recognize Auto-PEEP when

Expiratory flow continues and fails to return to the baseline prior to the new inspiratory cycle.
The development of auto-PEEP over several breaths in a simulation

Notice how the expiratory flow fails to return to the baseline indicating air trapping (AutoPEEP).

Also notice how air trapping causes an increase in airway pressure due to increasing end expiratory pressure and end inspiratory lung volume.
Understanding how flow rates affect I/E ratios and the development of auto PEEP

Fig. 1. Flow waveform showing air trapping by decreasing flow at equal tidal volume. Progressive reduction in expiratory time generates auto-PEEP when the expiratory time is not long enough to exhale all of the preceding tidal volume.

Decreasing the flow rate

Increase the inspiratory time and consequently decrease the expiratory time (decreased I/E ratio)

Thus allowing incomplete emptying of the lung and the development of air trapping and auto-PEEP
Understanding how inspiratory time affect I/E ratios and the development of auto-PEEP

• In a similar fashion, an increase in inspiratory time can also cause a decrease in the I: E ratio and favor the development of auto-PEEP by not allowing enough time for complete lung emptying between breaths.
Recognizing Expiratory Flow Limitation (e.g. COPD, asthma)
Recognizing prolonged expiration (air trapping)

Recognize airway obstruction when

**Expiratory flow** quickly tapers off and then enters a prolonged low-flow state without returning to baseline (auto-PEEP)

This is classic for the flow limitation and decreased lung elastance characteristic of COPD or status asthmaticus
Common problems that can be diagnosed by analyzing Ventilator waveforms

Abnormal ventilatory Parameters/ lung mechanics
  E.g.. Overdistension, Auto PEEP COPD

Patient-ventilator Interactions
  E.g. flow starvation, Double triggering, Wasted efforts Active expiration

Ventilatory circuit related problems
  E.g. auto cycling and Secretion build up in the Ventilatory circuit
PATIENT-VENTILATOR INTERACTIONS

Wasted efforts
Double triggering
Flow starvation
Active expiration
Ventilator Dyssynchrony: Inaccurate Sensing of Patient’s Effort

• Many modern ventilators sense patient effort
  – by detecting decreases in airway pressure or
  – flow between the inspiratory and expiratory limbs of the circuit.
• Inadequate sensing of patient effort leads to tachypnea, increased work of breathing, ventilator dyssynchrony, and patient discomfort.
• Flow triggering is often used in children, as it is very sensitive to patients with minimal respiratory effort and small endotracheal tubes.
• Dyssynchrony also occurs when an air leak leads to loss of PEEP, resulting in excessive ventilator triggering (auto cycling).
• The unstable pressure baseline that occurs due to leak may be misinterpreted as patient effort by the ventilator.
Recognizing ineffective/wasted patient effort

Patient inspiratory effort fails to trigger vent resulting in a wasted effort

Results in fatigue, tachycardia, increased metabolic needs, fever etc

Causes: High AutoPEEP, respiratory muscle weakness, inappropriate sensitivity settings
Recognizing double triggering

High peak airway pressures and double the inspiratory volume

Continued patient inspiratory effort through the end of a delivered breath causes the ventilator to trigger again and deliver a 2\textsuperscript{nd} breath immediately after the first breath.

This results in high lung volumes and pressures.

Causes: patient flow or volume demand exceeds ventilator settings
Consider: Increasing tidal volume, switching modes i.e. pressure support, increasing sedation or neuromuscular paralysis as appropriate
Ventilator Dyssynchrony: Inadequate Ventilatory Support

- Inadequate ventilatory support occurs when patient effort is not satiated by the inspiratory flow of the mechanical breath.
- As a result, patients attempt to initiate breaths during a mechanical breath.
- This phenomenon is seen as a reduction of airway pressure, seen as a decrease in airway pressure tracing during inspiration (flow dyssynchrony).
- In volume-limited ventilation a reduction of the inspiratory pressure as a result of dyssynchronous patient effort can translate into a higher PIP.
- Titration of flow rate, decreasing inspiratory time, or changing the mode of ventilation can help meet a patient’s inspiratory demand.
Another example of double triggering
Recognizing flow starvation

Look at the pressure-time waveform

If you see this kind of scooping or distortion instead of a smooth rise in the pressure curve....

Diagnose flow starvation in the setting of patient discomfort, fatigue, dyspnea, etc on the vent
Recognizing active expiration

Look at the flow-time & pressure-time waveform

Notice the high and variable expiratory flow rates due to varying expiratory muscle effort

The patient’s active expiratory efforts during the inspiratory phase causes a pressure spike.

PEARL: This is a high drive state where increased sedation/paralysis and mode change may be appropriate for lung protection.
Common problems that can be diagnosed by analyzing Ventilator waveforms

- Abnormal ventilatory Parameters/lung mechanics
  E.g., Overdistension, Auto PEEP, COPD

- Patient-ventilator Interactions
  E.g., flow starvation, Double triggering, Wasted efforts, Active expiration

- Ventilatory circuit related problems
  E.g., auto cycling and Secretion build up in the Ventilatory circuit
Recognizing Airway Secretions & Ventilator Auto-Cycling
Recognizing airway or tubing secretions

Normal flow-volume loop

Flow volume loop showing a ‘saw tooth’ pattern typical of retained secretions

Bedside Detection of Retained Tracheobronchial Secretions in Patients Receiving Mechanical Ventilation: Is It Time for Tracheal Suctioning?
Jean Guglielminotti, Marc Alzieu, Eric Maury, Bertrand Guidet and Georges Offenstadt

CHEST 2000; 118:1095–1099
Characteristic scalars due to secretion build up in the tubing circuit.
Recognizing ventilator auto-cycling

• Think about auto-cycling when
  – the respiratory rate increases suddenly without any patient input and
  – if the exhaled tidal volume and minute ventilation suddenly decrease.
• Typically occurs because of a leak anywhere in the system starting from the ventilator right up to the patients lungs
  – e.g. leaks in the circuit, ET tube cuff leak, lungs (pneumothorax)
• May also result from condensate in the circuit
• The exhaled tidal volume will be lower than the set parameters and this may set off a ventilator alarm for low exhaled tidal volume, low minute ventilation, circuit disconnect or rapid respiratory rate.
Take home points

- Ventilator waveform analysis is an integral component in the management of a mechanically ventilated patient.
- Develop a habit of looking at the right waveform for the given mode of patient ventilation.
- Always look at the inspiratory and expiratory components of the flow-time waveform.
- Don’t hesitate to change the scale or speed of the waveform to aid in your interpretation.
Thank You
Where is the plateau pressure?
Components of Inflation Pressure

$P_{aw}$ (cm H$_2$O)

Time (sec)
Components of Inflation Pressure

A

\[ P_{aw} \text{ (cm H}_2\text{O)} \]

Transairway resistance
Transthoracic pressure

Time (sec)

B

\[ P_{aw} \text{ (cm H}_2\text{O)} \]

Transairway resistance
Transthoracic pressure

PIP

Pplat

PEEP

Time (sec)
2. Which of the following waveforms indicate an increased resistance and a decreased compliance?
Waveform showing decreased lung compliance

'Square wave' flow pattern

- $P_{peak}$
- $P_{plat}$
- $P_{res}$
3. What is the best Stress Index?

This is on AC volume ventilation using a constant flow waveform. The graph is a pressure time scalar.

Note: Patient effort must be absent
4. Which waveform shows autopeep?
5. What is shown by the Red Arrow

A. Auto Peep
B. Retained Secretions
C. Ineffective Patient Effort
D. Double Triggering
SIMV+ PS
(Volume-Targeted Ventilation)
SIMV
(Volume-Targeted Ventilation)

Pressure (cm H₂O)

Volume (ml)

Flow (L/min)