VENTILATOR WAVEFORM ANALYSIS

By
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Seminar Overview

1. Basic Terminology (Types of variables, Breaths, modes of ventilation)
2. Ideal ventilator waveforms (Scalars)
3. Diagnosing altered physiological states
5. Loops (Pressure volume and Flow volume)
Basics phase variables

A. Trigger .......
   What causes the breath to begin?

B. Limit ......
   What regulates gas flow during the breath?

C. Cycle .......
   What causes the breath to end?
1. **TRIGGER VARIABLE**: Initiates the breath
   - Flow (Assist breath)
   - Pressure (Assist Breath)
   - Time (Control Breath)
   - Newer variables (Volume, Shape signal, neural)

Flow trigger better than Pressure trigger.

With the newer ventilators, difference in work of triggering is of minimal clinical significance.

*British Journal of Anaesthesia, 2003*
2. **TARGET VARIABLE**: Controls the gas delivery during the breath
   - Flow (Volume Control modes)
   - Pressure (Pressure Control modes)

3. **CYCLE VARIABLE**: Cycled from inspiration into expiration
   - Volume (Volume control)
   - Time (Pressure control)
   - Flow (pressure Support)
   - Pressure (Safety cycling variable)
## Modes of Ventilation

<table>
<thead>
<tr>
<th>Mode of ventilation</th>
<th>Breath types available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Assist Control</td>
<td>Volume Control, Volume Assist</td>
</tr>
<tr>
<td>Pressure Assist Control</td>
<td>Pressure Control, Pressure Assist</td>
</tr>
<tr>
<td>Volume SIMV</td>
<td>Volume Control, Volume Assist, Pressure Support</td>
</tr>
<tr>
<td>Pressure SIMV</td>
<td>Pressure Control, Pressure Assist, Pressure Support</td>
</tr>
<tr>
<td>Pressure Support</td>
<td>Pressure support</td>
</tr>
</tbody>
</table>
SCALARS
FLOW vs TIME
Flow versus time

Never forget to look at the expiratory limb of the flow waveform.

The expiratory flow is determined by the elastic recoil of the respiratory system and resistance of intubated airways.
Types of Inspiratory flow waveforms

a. Square wave flow
b. Ascending ramp flow
c. Descending ramp flow
d. Sinusoidal flow
e. Decay flow
Which form to use??

- **Pressure control mode**: Always Decelerating or decay flow. Cannot be changed.

- **Volume control mode**: Flow waveform can be changed depending on the ventilator options.
**SQUARE FLOW WAVEFORM:**
- Inspiratory time is shortest for Square wave flow form.
- Highest Peak Inspiratory pressures.
- Low Mean Inspiratory pressure, thus better venous return and cardiac output.

**DESCENDING RAMP FLOW:**
- Increases inspiratory time (if not fixed) or peak inspiratory flow rate (if inspiratory time is fixed).
- Least Peak inspiratory pressures (19% decrease).
- High mean airway pressure helps lung inflation and oxygenation.
Sinusoidal and ascending ramp flow:

- Initial flow rates are slow and hence cause dyssynchrony – FLOW STARVATION.
- Should not be used in assist modes.

Descending ramp and Square wave flow:

- Usually preferred as the initial flow rate meets the flow demand of the patient. Decreases air hunger.
SQUARE WAVE FLOW

DESCENDING RAMP FLOW
Decelerating flow waveform

- **Advantages:**
  - Decreases Peak inspiratory pressures
  - Increases oxygenation, decreases A-aDo2
  - Improves patient ventilator synchrony (more physiological)

- **Disadvantages:**
  - Decreases expiratory time, potential for auto PEEP
  - Increases mean airway pressure, decreases cardiac output
  - Increased intracranial pressures

Mechanical Ventilation, Physiological and Clinical Application. 4thed. 2006: 113.
Expiratory flow waveform

- Passive and determined by compliance of the lung and resistance of the airways.

- Four points to be observed:
  1. Peak Expiratory Flow
  2. Slope of the expiratory limb
  3. Expiratory time
  4. Does the waveform reach the baseline?
PRESSURE vs TIME
No active breathing
Treats lung as single unit

Driving Pressure
(PIP-PEEP)

PIP

resistance
flow

Pplat
end-inspiratory
alveolar pressure

compliance
tidal volume

PIP - PEEP = (Flow x Resistance) + (Vt/ Compliance RS)
Respiratory System Compliance

\[ C = \frac{\text{tidal volume}}{P_{\text{plat}} - P_{\text{PEEP}}} \]

Decreased with:

Pulmonary Disorder:
- mainstem intubation
- congestive heart failure
- ARDS
- Atelectasis, consolidation
- fibrosis
- Hyperinflation
- Tension pneumothorax
- pleural effusion

Extra Pulmonary Disorder:
- abdominal distension
- chest wall edema/Obesity
- thoracic deformity

Normal: 100 mL/cm H₂O
Pplat - PEEP = Vt/ Compliance

- Pplat increased by
  a) Decreasing compliance of lung: Pulmonary edema, ARDS, Atelectasis, Pneumonia
  b) Decreasing compliance of the chest wall: Morbid obesity, ascites, stiff chest wall
  c) Increasing Tidal volume
  d) Patient ventilator dyssynchrony
**Inspiratory Resistance**

\[ R_i = \frac{\text{PIP} - \text{Pplat}}{\text{flow}} \]

**Increased with:**
- Airways: Secretions, Mucus plugging, Bronchospasm
- ET tube: Small size, ET block
- Ventilator Circuit: Kinking, Clogged HME

**Normal:** 5 - 10 cm H$_2$O/L/s for intubated ventilated adults measured with 60 L/min (1 L/s) constant flow
\[ P_{\text{peak}} - P_{\text{plat}} = \text{Flow} \times \text{Resistance} \]

- Increased by
  a) Increasing resistance: Bronchospasm, Mucus plugging/secretions, ET block, Biting the ET tube, Tube kinking, Clogged HME.
  b) Increasing flow: Increasing Vt, Increasing Insp. pause, Increasing I:E ratio
\[
\begin{align*}
\text{Crs} &= \frac{\text{tidal volume}}{P_{\text{plat}} - \text{PEEP}} \\
\text{CcW} &= \frac{\text{tidal volume}}{\Delta \text{Peso}} \\
\text{CL} &= \frac{\text{tidal volume}}{(P_{\text{plat}} - \text{PEEP}) - \Delta \text{Peso}} \\
R_i &= \frac{\text{PIP} - P_{\text{plat}}}{\text{flow}}
\end{align*}
\]
STRESS INDEX (ARDS)

Flow

Pao

Stress index < 1

Stress index = 1

Stress index > 1

Increase PEEP (Recruitment)

Ideal PEEP

Decrease PEEP (Overdistension)

Chest 2010;137;1203-1216
SQUARE WAVE FLOW

DECEASING RAMP FLOW
VOLUME vs TIME
### Information derived from Volume Time Scalar

<table>
<thead>
<tr>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal Volume</td>
<td>Volume on y axis</td>
</tr>
<tr>
<td>Air leak</td>
<td>Expiratory limb fails to return to x axis</td>
</tr>
<tr>
<td>Active Expiration</td>
<td>Tracing continues beyond the baseline</td>
</tr>
<tr>
<td>Auto PEEP</td>
<td>Expiratory limb fails to reach the baseline</td>
</tr>
</tbody>
</table>
HOW TO USE THE GRAPHS FOR DIAGNOSIS OF DISEASE STATES?
Which waveforms to monitor?

<table>
<thead>
<tr>
<th>Mode of ventilation</th>
<th>Independent variables</th>
<th>Dependent variables</th>
<th>Waveforms that will be useful</th>
<th>Waveforms that normally remain unchanged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Control/</td>
<td>Tidal volume, RR, Flow rate, PEEP, I/E ratio</td>
<td>( P_{aw} )</td>
<td><strong>Pressure-time:</strong> Changes in ( P_{ip} ), ( P_{plat} ) \nFlow-time (expiratory): Changes in compliance \nPressure-volume loop: Overdistension, optimal PEEP</td>
<td>Volume-time \nFlow time (inspiratory)</td>
</tr>
<tr>
<td>Assist-Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Control</td>
<td>( P_{aw} ), Inspiratory time (RR), PEEP and I/E ratio</td>
<td>( V_t ), flow</td>
<td><strong>Volume-time and flow-time:</strong> Changes in ( V_t ) and compliance \nPressure-volume loop: Overdistension, optimal PEEP</td>
<td>Pressure-time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure support/CPAP</td>
<td>PS and PEEP</td>
<td>( V_t ) and RR, flow, I/E Ratio</td>
<td><strong>Volume-time</strong> \nFlow-time (for ( V_t ) and ( V_E ))</td>
<td></td>
</tr>
</tbody>
</table>
Increased airway resistance
(ACMV- VC)

- **Pressure Time Waveform:**
  - Increased difference between Ppeak and Pplat
  - Normal P plat

- **Expiratory flow waveform:**
  - Decreased PEFR
  - Increased expiratory time
  - Scooped out appearance of expiratory limb
  - Potential for auto PEEP
  - Loss of peak (emphysema)

- **Volume Time Waveform:**
  - Expiratory limb long
A patient with Endotracheal Tube block (When received from Dialysis room)
A patient with acute severe asthma on ventilator
Decreased Compliance of Respiratory System

- **Pressure Time Waveform:**
  - Increased $P_{\text{plat}}$ and $P_{\text{peak}}$.
  - Normal $P_{\text{peak}} - P_{\text{plat}}$

- **Flow Time Waveform:**
  - Increased PEFR
  - Shortened expiratory time
Auto PEEP/Intrinsic PEEP

Positive end-expiratory pressure (PEEP) is defined as pressure in the alveoli at the end of exhalation that is greater than the atmospheric pressure.

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

Also notice how air trapping causes an increase in airway pressure due to increasing end expiratory pressure and end inspiratory lung volume.
A patient of acute severe asthma. Note failure of expiratory limb to return to baseline.
Physiologic mechanisms of auto-positive end-expiratory pressure

Dynamic hyperinflation
plus intrinsic expiratory flow limitation
Chronic obstructive pulmonary disease

Dynamic hyperinflation
without intrinsic expiratory flow limitation
Breathing pattern and ventilator settings
  Rapid breaths
  High tidal volume
  Inspiration greater than expiration
  End-inspiratory pause
Added flow resistance
  Fine-bore endotracheal tube
  Ventilator tubing and devices

Without dynamic hyperinflation
Recruitment of expiratory muscles
**AUTO-PEEP: Consequences**
- Increases the work of Triggering
- Ineffective triggering
- Worsens Oxygenation
- Lung Hyperinflation - barotrauma
- Hemodynamic Compromise

**AUTO PEEP: Recognition**
- Analysis of ventilator graphics:
  - Pressure wave: while performing an expiratory hold, the waveform rises above baseline.
  - Flow wave: the expiratory flow doesn’t return to baseline before the next breath begins.
  - Volume wave: the expiratory portion doesn’t return to baseline.
  - Flow/Volume Loop: the loop doesn’t meet at the baseline
  - Pressure/Volume Loop: the loop doesn’t meet at the baseline
- Delay between start of Inspiratory effort and Pressure drop
- No increase in P peak with increase in Applied PEEP
Treatment of auto-positive end-expiratory pressure

Change ventilator settings
  Increase expiratory time
  Decrease respiratory rate
  Decrease tidal volume

Reduce ventilatory demand
  Reduce anxiety, pain, fever, shivering
  Reduce dead space
  Give sedatives and paralytics

Reduce flow resistance
  Use large-bore endotracheal tube
  Suction frequently
  Give bronchodilators

Counterbalance expiratory flow limitation
  External positive end-expiratory pressure
VENTILATOR PATIENT SYNCHRONY

VS

DYS-SYNCHRONY
What is Ventilator Patient Synchrony?

- The ventilator should start inspiration at the time of onset of patients inspiration.
- The flow provided by the ventilator should meet the flow demand of the patient.
- The Ventilator Inspiratory time should match with the patients inspiratory time.
Ventilator Patient Dys-synchrony

**Trigger Asynchrony**
1. Ineffective Triggering
2. Auto Triggering
3. Double Triggering
4. Delayed triggering

**Flow Asynchrony**
1. Delayed Cycling
2. Premature Cycling

**Cycle Asynchrony**
INEFFECTIVE TRIGGERING

- One of the most common asynchronies
- Failure of the patient's inspiratory effort to initiate a ventilator breath.
- Identified by
  - Visual inspection of patients expanding thoracic volume but without delivery of ventilator breath.
  - Ventilator graphics which show a decrease in airway pressure with an increase in flow but no initiation of breath.
Ineffective triggering

- What causes this?
  - Improper sensitivity of trigger threshold
  - Respiratory muscle weakness (disease related, critical illness, neuromyopathy, electrolyte imbalances)
  - Intrinsic PEEP in COPD patients
  - Decreased respiratory drive (Excessive sedatives)
  - Alkaline pH
  - External nebulizers
  - High Tidal volumes/High Pressure support decrease respiratory drive
AUTO TRIGGERING

Definition: Ventilator delivers an assisted breath that was not initiated by the patient

Causes:
1. Circuit leaks (ET cuff, ICTD with BPF etc)
2. Fluid in the circuit
3. Cardiac oscillations (High cardiac output states)
4. Very low trigger threshold
DOUBLE TRIGGERING

- Patients inspiration continues after the ventilator inspiration and triggers another breath immediately after the inspiration.
- Also called Breath Stacking

**Causes:**

1. High Ventilatory demand of the patient (ARDS)
2. Inappropriate settings (Low tidal volume, Short inspiratory time, High cycle threshold)
A case of Morbid Obesity with Obesity hypoventilation syndrome.

Note the low tidal volumes generated on PSV mode.
DELAYED TRIGGERING

Components of Triggering:

- Trigger threshold: The pressure/flow that must be attained by the patient's breath to trigger the ventilator.
- Inspiratory Trigger Time (ITT): Time from the initiation of effort to the trigger threshold.
- Rise Time to Baseline Pressure (RTBP)

Inspiratory Delay Time (IDT) = ITT + RTBP
DELAYED TRIGGERING

- An inherent problem with all the conventional modes of ventilation

- Can be overcome by
  - Newer modes of ventilation (NAVA)
  - Newer methods of triggering (Shape signal triggering)
Neurally Adjusted Ventilatory Assist (NAVA)

Diaphragmatic Electrical activity is sensed by an electrode placed in the esophagus and is used to trigger the breath and cycle into expiration.
FLOW ASYNCHRONY

Causes:
- High ventilatory demand (ALI/ARDS)
- Low ventilatory settings (Flow rate, Tidal volume, Pramp)

What to do:
- Treat reversible causes of air hunger (fever, acidosis)
- Increase the tidal volume (if feasible)
- Increase the flow rate (directly, or by decreasing inspiratory time, increasing pause)
- Change to pressure control mode with variable flow
- Sedate/Paralyze the patient (last resort)
Patient of ARDS being ventilated using ARDS Network strategy
(Tidal volume = 6 ml/kg, Body weight = 66 kg)
Tidal volume increased to 440 ml from 400 ml to improve the flow synchrony
Same patient during a spike of fever 39.2°C showing severe flow dyssynchrony
CYCLING ASYNCHRONY

- **Delayed Cycling**: \( \text{Ventilator } Ti > \text{Patient Ti} \)
  
  Ventilator continues Inspiration when actually expiration has started.

- **Premature Cycling**: \( \text{Ventilator } Ti < \text{Patient Ti} \)
  
  Patients inspiratory effort continue into the expiratory phase of ventilator breath.
DELAYED CYCLING

Patient while weaning. Expiratory trigger sensitivity of 25%
How to Manage:

- Decrease Inspiratory time
- Decrease Tidal volume (SCMV mode)
- Increase Expiratory Trigger Sensitivity (PSV mode)
Expiratory trigger sensitivity increased to 60 % to improve cycling synchrony.
A case of Acute severe asthma on SCMV mode.

I : E ratio kept at 1: 3.3 to avoid auto PEEP.

Ventilator shows double triggering.
I : E ratio decreased to 1 : 2.5 along with control of bronchospasm. None of the other parameters changed. No further double triggering.

Illustrates double triggering due to short inspiratory time and premature cycling.
PATIENT VENTILATOR DYS-SYNCHRONY
CLINICAL SIGNIFICANCE ??

- Increases Work Of Breathing
- Causes Ultrastructural damage to the respiratory muscles
- Worsens Respiratory mechanics (Auto PEEP)
- Alters gas exchange (Auto, double triggering – lower CO2)
- Increased need for sedation
- Longer duration of mechanical ventilation
- Difficulty in weaning
- Confounds lung protective ventilation (Double breaths)
- Sleep Fragmentation
- Inability to tolerate NIV
Loops

- Pressure-Volume Loops
- Flow-Volume Loops
Pressure-Volume Loop

$V_T$
LITERS

Paw
cmH$_2$O

-60  40  20  0  20  40  60
Spontaneous Breath

Clockwise

Inspiration

Expiration

Pressure

cmH₂O

-60  40  20  0  20  40  60

CPAP

0.6

0.4

0.2

Vₜ
Controlled Breath

Anticlockwise

Paw

cmH₂O

-60 40 20 0 20 40 60

PEEP

0 20 40 60

Vₜ

LITERS

0.2 0.4 0.6

Expiration

Inspiration

P-V loop and PEEP.....
Assisted Breath

V

LITERS

VT

0.6

0.4

0.2

Expiration

Inspiration

Assisted Breath

Paw

cmH₂O

-60

40

20

0

20

40

60

PEEP

Clockwise to Counterclockwise
Lung Compliance Changes and the P-V Loop... (Volume mode)

Preset VT

Volume

Pressure

Constant VT ........ Variable Pressure

↑C

C

↓C

PIP levels
Lung Compliance Changing in P-V Loop (pressure mode)........

1. With surfactant
2. Emphysematous L

RDS...lung

Constant PIP........... variable $V_T$
Overdistension

A = inspiratory pressure
B = upper inflection point
C = lower inflection point

A

B

C

V_T
LITERS

Paw
cmH_2O

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60

-60 -40 -20 0 20 40 60
Insufficient flow

Normal

Insufficient Flow

Volume

Pressure

Cusping
Flow – Volume Loops ....
Flow-Volume Loop

- **PIFR**
- **FRC**
- **PEFR**
- **VT**

Inspiration:

Expiration:
Air Trapping

Inspiration

PIFR

Flow (L/min)

Does not return to baseline

Expiration

PEFR

Volume (ml)

VT
Bronchodilator Response.... F-V loop

Normal

Bronchospasm

Relief

AFTER
SUMMARY

- Identify the correct waveforms to monitor
- Spend more time at the bedside
- Never ignore any ventilator alarm

- Monitor P peak, P plat and expiratory limb of flow volume loop to diagnose changes in lung resistance or compliance.

- Identify Dysynchrony early and correct the cause.