Advanced Pulmonary Mechanics during Mechanical Ventilation

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Points of Discussion

Basics
- Equation of motion
- Dynamic Compliance
- Pressure-volume loop
- Flow-volume loop
- Work of breathing
- Lower and upper inflection points
- Hysterexis
- Intrathoracic Pressures

Abnormalities
- Air-leak
- Air trapping
- Increased airway resistance
- Inadequate flow support
- Inadequate sensitivity
- Atelectasis
- Inadequate PEEP
- Airway obstruction
- Over-distension
Tube + Spring Model

Elastic Forces

Resistive Forces

Elastic Forces
Static and Dynamic Pressures

- **PEEP**
- **PIP**
- **Pplat**
- **Alveolar Distending (recoil)**
- **Pressure difference (Pres)**
- **Pressure difference (Pdis)**
Airway Resistance

Pressure difference = Flow Rate $\times$ Resistance

\[ dP = Q \times R \]

\[ R = \frac{8 \text{ L (visc.)}}{\pi r^4} \]
Resistive and Elastive Forces

**Dynamic Characteristics:**
\[ dP = \frac{dV}{C_{\text{dyn}}} \]

**Resistance:**
\[ dP_{\text{resistive}} = R \times \text{Flow} \]

**Static Compliance:**
\[ dP_{\text{distensive}} = \frac{dV}{C_{\text{st}}} \]

\[ dP = dP_{\text{resist.}} + dP_{\text{dist.}} \]

\[ dP = R \times \text{Flow} + \frac{dV}{C_{\text{st}}} \]
Basic Calculations

\[ dP = R \times \text{Flow} + \frac{dV}{Cst} \]

\[ \text{Cst} = \frac{dV}{(P_{\text{plat}} - \text{PEEP})} \]

\[ R = \frac{(\text{PIP} - P_{\text{plat}})}{\text{Flow}} \]
Assessment of static P-V curve

Super-syringe method:

- Stepwise inflation from a big syringe with multiply occlusions at each volumes to record recoil pressure
  - Time consuming
  - Cumbersome to perform
  - Difficult to standardize
  - Patient must be paralysed, connected to a special equipment
  - Great risk of oxygen desaturation
Assessment of static P-V curve

Slow Flow Single Inflation Method

- Slow (5-10 lpm) inspiratory flow with large Vt and ZEEP
- The inspiratory curve of the dynamic P-V loop closely approximates the static curve
- The flow-resistive pressure component could be subtracted
- Easy to perform, fast and relatively comfortable

Volume

Pressure

Static curve

LPlflex

UPlflex

S ill AJRCCM 1997
FRC and PV Loop

Normal Compliance

TLC

FRC

FRC

VOLUME

DISTENDING PRESSURE

Negative 0 Positive
Components of Pressure-Volume Loop

- Volume (mL)
- $P_{aw}$ (cm H$_2$O)
- $V_T$

Phases:
- Inspiration
- Expiration

PI P
Pressure-Volume Loop
(Type of Breath)

Vol (ml)

 Controlled

 Assisted

 Spontaneous

 I: Inspiration
 E: Expiration

 $P_{aw}$
 (cm H$_2$O)
PEEP and P-V Loop

Volume (mL)

Paw (cm H₂O)

VT

PEEP

PIP
## Inflection Points

<table>
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<tr>
<th>Inflection Points</th>
<th>Descriptions</th>
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<tr>
<td>Upper Inflection Point</td>
<td>Represents pressure resulting in regional overdistension</td>
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<tr>
<td>Lower Inflection Point</td>
<td>Represents minimal pressure for adequate alveolar recruitment</td>
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![Diagram of Inflection Points](image)
Decreased Compliance

Volume (ml) vs. Pressure (cm H$_2$O)

- Normal
- Patient
Lung Compliance Changes and the P-V Loop

Preset $V_T$

Volume Targeted Ventilation

Volume (mL)

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

$PIP$ levels

Increased
Normal
Decreased
Lung Compliance Changes and the P-V Loop

- Increased
- Normal
- Decreased

Volume (mL)

Paw (cm H₂O)

Preset PIP

VT levels
Flow-Volume Loop

- Inspiration
- PI FR
- VT
- PEFR
- Expiration

Flow (L/min)

Volume (ml)
Positive Pressure Ventilation: The Equation of Motion

- In a passive subject, airway pressure represents the entire pressure (P) applied across the respiratory system.
- The work required to deliver a tidal breath (Wb) = tidal volume (VT) x airway pressure
- The pressure (P) associated with the delivery of a tidal breath is defined by the simplified equation of motion of the respiratory system (lungs & chest wall):

\[
P = \frac{V_T}{C_R} + \frac{V_T}{T_i} \times R_R + PEEP_{total}
\]

Where CR = compliance of the respiratory system, Ti = inspiratory time and \(\frac{V_T}{T_i}\) = Flow, \(R_R\) = resistance of the respiratory system and PEEP total = the alveolar pressure at the end of expiration = external PEEP + auto (or intrinsic) PEEP, if any. Auto PEEP = PEEP total – P extrinsic (PEEP dialed in the ventilator) adds to the inspiratory pressure one needs to generate a tidal breath.
Work of Breathing

A: Resistive Work
B: Elastic Work

Pressure (cm H₂O)
Volume (ml)
Work of Breathing

- WOB is a major source of caloric expenditure and oxygen consumption
- Appr. 70% to overcome elastic forces, 30% flow-resistive work
- Patient work is a one of the most sensitive indicator of ventilator dependency
- Comparison of Ventilator and Patient work is a useful indicator during weaning process
- WOB may be altered by changes in compliance, resistance, patient effort, level of support, PEEP, improper Ti, demand system sensitivity, mode setting
- Elevated WOB may contraindicate the weaning process
WOB Measurements

\[ WOB = \int_{0}^{t_i} P \times V \, dt \]

- Elastic work: ABCA
- Resistive work
  - Inspiratory: ADCA
  - Expiratory: ACEA
Work of Breathing Measurements

\[ WOB = \int_{0}^{t_i} P \times V \, dt \]

- **Paw**: Ventilator Work: The physical force required to move gas into the lung, represents the total work of the resp. system (patient + ventilator)
- **Peso**: Patient Work: done by respiratory muscles, represents the pulmonary work of breathing
- **Paw-Ptr**: Imposed Work by the Endotracheal tube
P-V Loop and WOB

- Normal Compliance
- Increased Resistance

- Decreased Compliance
  - Normal Resistance

- Normal Compliance
  - Normal Resistance
Work per breath is depicted as a pressure-volume area

Work per breath ($W_{\text{breath}}$) = P x tidal volume ($V_T$)

$W_{\text{min}} = w_{\text{breath}} \times \text{respiratory rate}$

The total work of breathing can be partitioned between an elastic and resistive work. By analogy, the pressure needed to inflate a balloon through a straw varies; one needs to overcome the resistance of the straw and the elasticity of the balloon.
Intrinsic PEEP and Work of Breathing

When present, intrinsic PEEP contributes to the work of breaking and can be offset by applying external PEEP.

$\text{PEEPi} = \text{intrinsic or auto PEEP}; \text{green triangle} = \text{tidal elastic work}; \text{red loop} = \text{flow resistive work}; \text{blue rectangle} = \text{work expended in offsetting intrinsic PEEP (an expiratory driver) during inflation}$
The Pressure and Work of Breathing can be Entirely Provided by the Ventilator (Passive Patient)
The Work of Breathing can be Shared Between the Ventilator and the Patient

The ventilator generates positive pressure within the airway and the patient’s inspiratory muscles generate negative pressure in the pleural space.

\[ P_{AW} = \text{Airway pressure}, \ P_{ES} = \text{esophageal pressure} \]
Work of breath

- Resistive Work
- Elastic Work of Lung
- Elastic Work of Chest

Work to inflate the chest wall

Pressure

Volume

P_{aw}

P_{es}

Inflation
Deflation
The changes in Pes (esophageal pressure) and in the diaphragmatic activity (EMG) associated with the increase in the level of mask pressure (Pmask = pressure support) indicate transfer of the work of breathing from the patient to the ventilator.

Partitioning of the Workload Between the Ventilator and the Patient

How the work of breathing partitions between the patient and the ventilator depends on:

- Mode of ventilation (e.g., in assist control most of the work is usually done by the ventilator)
- Patient effort and synchrony with the mode of ventilation
- Specific settings of a given mode (e.g., level of pressure in PS and set rate in SIMV)
Intrathoracic pressures

- TRACHEAL PRESSURE
- PROX. AIRWAY PRESSURE
- TRACHEAL PRESSURE
- ALVEOLAR PRESSURE
- PLEURAL PRESSURE
3 Levels of Lung Mechanics

**DYNAMIC CHARACTERISTICS:**
\[ \frac{dP}{dV} = \frac{1}{C_{dyn}} \]

**RESISTANCE:**
\[ \frac{dP}{dV} = R \times \text{Flow} \]

**STATIC COMPLIANCE:**
\[ \frac{dP}{dV} = \frac{1}{C_{stat}} \]

**AIRWAY RESISTANCE:**
\[ \frac{dP}{dV} = \text{Raw} \times \text{Flow} \]

**IMPOSED RESISTANCE:**
\[ \frac{dP}{dV} = \text{Rimp} \times \text{Flow} \]

**LUNG COMPLIANCE:**
\[ \frac{dP}{dV} = \frac{1}{CL} \]

**CHEST WALL COMPLIANCE:**
\[ \frac{dP}{dV} = \frac{1}{C_{cw}} \]
A closer look at lung mechanics

\[ \text{Crs} = \frac{\text{Vt}}{\text{dP}_{\text{dist}} (\text{aw})} \]

\[ \text{Ccw} = \frac{\text{Vt}}{\text{dP}_{\text{dist}} (\text{pl})} \]

\[ \text{CL} = \frac{\text{Vt}}{\text{P}_{\text{dist}} (\text{aw} - \text{pl})} \quad \text{or} \quad \frac{\text{Vt}}{\text{P}_{\text{dist}} (\text{tr} - \text{pl})} \]

\[ \text{Rrs} = \frac{\text{P}_{\text{resist}} (\text{aw})}{\text{Flow}} \]

\[ \text{RL} = \frac{\text{P}_{\text{resist}} (\text{tr})}{\text{Flow}} \]

\[ \text{Rimp} = \frac{\text{P}_{\text{resist}} (\text{aw} - \text{tr})}{\text{Flow}} \]
Respiratory Mechanics in ARF*

- Reduced range of volume excursion:
  
  **Low compliance**

- Flattening at low and high volumes:
  
  **Lower and upper inflection points**

*Bigatello: Br J Anaest 1996*
Lung Protective Strategy

1. Set **PEEP** above the lower Pflex to keep the lung open and avoid alveolar collapse
2. Apply small **Vt** to minimize stretching forces
3. Set **Pplat** below the upper Pflex to avoid regional overdistension
Abnormalities

- Air-leak
- Air trapping
- Increased airway resistance
- Inadequate flow support
- Inadequate sensitivity
- Atelectasis
- Inadequate PEEP
- Airway obstruction
- Over-distension
Air Leak

Volume (ml) vs. Pressure (cm H2O)

Air Leak
Air Leak

Volume (mL) vs. Time (sec)
Air Trapping

Inspiration

Expiration

Flow (L/min)

Time (sec)

Normal

Patient

Air Trapping

Auto-PEEP

↑
Air Trapping

Inspiration

Expiration

Flow (L/ min)

Volume (ml)

Does not return to baseline

Normal
Abnormal
Response to Bronchodilator

Before

Flow (L/min)

PEFR

Time (sec)

After

Long $T_E$

Higher PEFR

Shorter $T_E$
Increased Airway Resistance

Inspiration

Expiration

Flow (L/min)

Volume (ml)

“Scooped out” pattern

Decreased PEFR

Normal
Abnormal
Increased Raw

Vol (mL)

Pressure (cm H$_2$O)

Higher $P_{TA}$

Normal Slope

Lower Slope
Inadequate Inspiratory Flow

Volume (ml)

Inappropriate Flow

P_{aw} (cm H_2O)

Active Inspiration
Airway Secretions/Water in the Circuit

Inspiration

Expiration

Flow (L/min)

Volume (ml)

Normal

Abnormal
Airway Obstruction

Before Suction

After Suction
Optimising PEEP

PEEP: 3 cmH$_2$O

PEEP: 8 cmH$_2$O
Inadequate Sensitivity

- Volume (mL)
- $P_{aw}$ (cm H$_2$O)
- Increased WOB
Atelectasis

Lost FRC

Replaced FRC
Overdistension

With little or no change in VT

Pressure (cm H₂O)
Overdistension

- Overdistension occurs when the volume limit of some components of the lung has been exceeded
- Abrupt decrease in compliance at the termination of inspiration
- Results in a terminal “Beaking” of the P/V Loop
Overdistension Index

Volume

Pressure

0.8 \text{P}_{\text{max}} \quad \text{P}_{\text{max}}

\text{C}_{20}

\text{C}_{\text{dyn}}
Thank You