Respiratory Mechanics

Critical Care Medicine
Specialty Board Tutorial

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This lecture covers:

1. Basic knowledge: volume, flow, pressure
2. Lung parenchymal condition: compliance
3. Airway condition: FEV1/FVC, Resistance, Flow pattern
4. Chest wall condition: Chest wall compliance
5. Interaction of all factors: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV
6. Work of breathing: Campbell diagram, Pressure-Time Product (PTP)
7. The force of breathing: SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1
8. Other application: Transpulmonary pressure
Basic knowledge: Volume, flow, pressure
Lung volumes

RV can be measured by:
1. gas diffusion method (e.g. multiple N2 washout)
2. Body plethysmography

Volumes can be measured by spirometry
Airflow and Pressures

- Airflow is measured at the airway opening
  - With a pneumotach
  - Integration of flow with time is volume

- Primary pressures
  - Pbs (body surface) = Patm = 0
  - Ppl = Pes
  - Pm (mouth) = Paw at Y-end (during MV)

- Derived pressures
  - Trans-resp system P = Paw – Patm
  - Palv = Paw during no flow
  - Transpulmonary P = Palv (or Paw during no flow) – Pes
  - Transthoracic P = Pes - Patm

Basic primary and derived pressures

Others: Pes and Pgastric P
Actual measurement

- Flow & pressures
  - Pneumotach & airway pressure transducer placed distal to Y-connector
  - Esophageal balloon catheter
  - Signals transformed by an analogue-to-digital converter, recorded by LabVIEW software
- Edi signal
  - Acquired from ventilator at 100 Hz via a RS232 interface to the ServoTracker software
- Time-aligned and analyzed off-line
Lung and chest wall conditions: Compliance

- Two situations:
  - Dynamic compliance (actively breathing, e.g. at peak flow)
  - Static situation (during no flow condition, e.g. at plateau pressure obtained by inspiratory pause; or in a totally relaxed patient, P and V obtained point-by-point)

- Formulae

  Compliance = delta volume / delta P  
  ($P$ is across unit to be measured, unit of compliance is ml/cmH2O)

  - $C_{rs} = \frac{V_t}{(Trans-resp \ system \ P \ at \ end-insp \ - \ Trans-resp \ system \ P \ at \ end-exp)}$
  - $C_{lung} = \frac{V_t}{(Trans-pulmonary \ P \ at \ end-insp \ - \ Trans-pulmonary \ at \ end-exp)}$
  - $C_{cw} = \frac{V_t}{(Trans-thoracic \ P \ at \ end-insp \ - \ Trans-thoracic \ P \ at \ end-exp)}$

  Elastance = $1/\text{Compliance}$
Compliance and Resistance measurement of the respiratory system (Double Occlusion Method, paralyzed patient)

- Compliance if of:
  1. The whole respiratory system (tubings, ETT, patient) if pressure port is in ventilator
  2. The patient and ETT, if pressure port is at Y-end
  3. The patient only, if pressure port is at carina (beyond ETT tip)

Static compliance = TV / (Pplat – PEEP)

The respective data are:

- V'ei = 0.6 l/s
- Vti = 610 ml
- Ppeak = 31 cmH2O
- Pei, st = 17.5 cmH2O
- PEEPtot = 7.5 cmH2O
- PEEPe = 5 cmH2O

Based on these data, we can calculate Rmax, Cstat, and PEEPi according to the formulas of § 4.2., as follows:

- Cstat = 610 / (17.5 - 7.5) = 61 ml/cmH2O
- Rmax = (31 - 17.5) / 0.6 = 22.5 cmH2O/l/s
- PEEPi = 7.5 - 5 = 2.5 cmH2O
### Full compliance study of respiratory system, lungs and chest wall in research setting (paralyzed patient)

Formula: $\frac{1}{C_{\text{lung}}} = \frac{1}{C_{\text{total}}} - \frac{1}{C_{\text{cw}}}$

<table>
<thead>
<tr>
<th>Patient</th>
<th>Total compliance (ml/cmH2)</th>
<th>Chest wall compliance</th>
<th>Lung compliance</th>
<th>Lung (calculated as $C_{\text{total}} - C_{\text{cw}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHF</td>
<td>23.6</td>
<td>84</td>
<td>30.5</td>
<td>32.8</td>
</tr>
<tr>
<td>COPD</td>
<td>84.5</td>
<td>195</td>
<td>142</td>
<td>149</td>
</tr>
</tbody>
</table>

- **Paw**
  - $C_{\text{total}} = \text{Delta} (\text{Paw} - \text{Patm}) / \text{TV}$
  - $C_{\text{cw}} = \text{Delta} (\text{Pes} - \text{Patm}) / \text{TV}$
  - Transpul P = Paw - Pes
- **Pes**
  - $C_{\text{lung}} = \text{Delta} (\text{Paw} - \text{Pes}) / \text{TV}$
  - $\frac{1}{C_{\text{lung}}} = \frac{1}{C_{\text{total}}} - \frac{1}{C_{\text{cw}}}$

### Time tracings of the paralyzed CHF patient

### Static relaxation pressure-volume curve
Compliance measurement of the respiratory system in research situation: Static PV curve by the Low Constant Flow method

- Compliance is of the whole respiratory system if Paw is used.
- Tiny irregularities correspond to cardiac oscillations.
- Slope of straight portion = best compliance of the resp system.
- ARDS: Lower (LIP) and upper inflection points (UIP) in ARDS.
- Lung fibrosis: No lower inflection point implies no recruitable alveoli, B represents start of upper inflection zone and implies overdistension.
At lung volumes above \( \sim 70\% \) of the vital capacity, the chest wall no longer tends to spring out but instead to spring in.

- relaxation pressure of the lung plus chest wall is simply the sum of the relaxation pressures of the two components.
Application: Open lung tool to look for the best dynamic compliance for PEEP setting.
Airway condition

- Awake patient: FEV1/FVC by forced spirometry
- Intubated patient: Resistance by inspiratory hold
Forced spirometry: in non-intubated patients

1. **FEV1/FVC ratio**
   - If $<70\%$, means there is airflow obstruction (GOLD Guideline criteria)
   - If $<lower\ 5^{th}\ percentile$, means there is airflow obstruction (more stringent statistical criteria, HK local reference equation: Ip MS et al. *Updated spirometric reference values for adult Chinese in Hong Kong and implications on clinical utilization*. Chest. 2006 Feb;129(2):384-92.)

2. **FEV1**
   - The predicted percentage reflects the severity of the airflow obstruction, if present
   - Severity of obstruction is based on FEV1
     - $<35\%$ predicted: severe
     - $35\ –\ 50\%$ predicted: moderate
     - $50\ –\ 80\%$ predicted: mild
Compliance and Resistance measurement of the respiratory system (Double Occlusion Method, paralyzed patient)

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Static compliance = TV / (Pplat – PEEP)

The respective data are:

<table>
<thead>
<tr>
<th>Vei</th>
<th>Vti</th>
<th>Ppeak</th>
<th>Pei,st</th>
<th>PEEPot</th>
<th>PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>610</td>
<td>31</td>
<td>17.5</td>
<td>7.5</td>
<td>5</td>
</tr>
<tr>
<td>l/s</td>
<td>ml</td>
<td>cmH2O</td>
<td>cmH2O</td>
<td>cmH2O</td>
<td>cmH2O</td>
</tr>
</tbody>
</table>

Based on these data, we can calculate Rmax, Cstat, and PEEPi according to the formulas of § 4.2., as follows:

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Volume control mode

Exp hold  Ins p hold

Exp hold  Ins p hold
Inspiratory hold, volume control mode: Distinguish among resistance, compliance and flow problem.
Interaction of all factors

Interaction of lung, airway and chest wall: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV
Time Constant

- \( R \times C = \frac{\delta P}{\text{Flow}} \times \frac{\delta \text{vol}}{\delta P} \)
- \( \delta \text{Volume}/\text{Flow} \) (can be read at expiration of passive flow-volume loop)

Flow-Volume Loop in an actively breathing COPD Patient: Shows Time Constant and End-Exp Lung Volume (EELV)
Clinical implications

- To avoid hyperinflation, we must allow an expiratory time of 4, or at least 3, time constants.

<table>
<thead>
<tr>
<th>Duration of step change in pressure (s)</th>
<th>Resulting change in volume (% of ΔVol.max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x Time Constant</td>
<td>63</td>
</tr>
<tr>
<td>2 x Time Constant</td>
<td>86.5</td>
</tr>
<tr>
<td>3 x Time Constant</td>
<td>95</td>
</tr>
<tr>
<td>4 x Time Constant</td>
<td>98</td>
</tr>
<tr>
<td>5 x Time Constant</td>
<td>99</td>
</tr>
<tr>
<td>Infinite x Time Constant</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Resistance</th>
<th>Compliance</th>
<th>RC</th>
<th>Te required</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARDS</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Acute Asthma</td>
<td>High</td>
<td>Normal</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Emphysema</td>
<td>High (exp)</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
Ventilator tracing of incomplete emptying due to AFO

Actually what happens is: Volume vs time curve
(without zero resetting before each breath)

PEEP_{tot} = PEEP_e + PEEP_i; i.e. PEEP_i = PEEP_{tot} - PEEP_e

Static and dynamic intrinsic PEEP: Static and dynamic refers to the method of measurement, not whether the patient is actively breathing or paralyzed.
Static intrinsic PEEP

- In a paralyzed patient
  - End-exp occulsion manoeuvre (i.e. Based on PEEPi, \( st = PEEP_{tot} - PEEPe \))

- In actively breathing patient
  - 7-sec end exp occlusion manoeuvre, PEEPtot is the Paw between two successive periods of muscular activation

Real-life tracing

Zero PEEPi

Pseudo-relaxation period too short and not flat: Not fit for analysis
Dynamic PEEPi

Based on Pes drop to initiate flow, therefore refers to actively breathing patients only

\( \text{Dynamic PEEPi} = \text{Negative deflection of Pes from the onset of inspiratory effort to onset of flow from zero} \)

When displayed in a Pes-Vol loop:

\[ \text{TV} \]

Pressure (cmH2O) or Flow (L/min)

Pes generated to initiate flow
Dynamic PEEPi

Based on the Pes drop to initiate flow, in a spontaneously breathing patient.
Work of breathing

Campbell’s Diagram, Pressure-Time Product
Campbell’s Diagram

**Fig. 1** Campbell’s diagram. Work of breathing measured by the esophageal pressure: resistive WOB ($W_{\text{resist}}$), elastic WOB ($W_{\text{elast}}$), WOB related to active expiration ($WOB_{\text{expiratory}}$) and WOB related to intrinsic PEEP ($W_{\text{PEEPi}}$). *Chest wall*: this thick line (the chest wall compliance) represents the pleural (esophageal) pressure obtained when muscles are totally relaxed and lung volume increases above functional residual capacity, measured in static conditions.
Campbell’s Diagram in practice

Pressure-time product

- PTP that reflects the exertion of the respiratory muscles for inspiration (PTP$_{insp,pat}$) = time interval between the inspiratory effort start and the end of the inspiratory phase of a cycle
  - PTP/breath × RR = PTP per minute (cmH$_2$O.s/min)
The Force of Breathing

SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1
Monitoring
### SVC, MIP, MEP in spontaneously breathing patient

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Predictive of respiratory failure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slow Vital Capacity (SVC)</strong></td>
<td>50 ml/kg</td>
<td>&lt; 20 ml/kg</td>
</tr>
<tr>
<td><strong>Maximal Inspiratory Pressure (MIP) – from RV</strong></td>
<td>-70 cm H2O</td>
<td>Less neg than – 30 H2O</td>
</tr>
<tr>
<td><strong>Maximal Expiratory Pressure (MEP) -from TLC</strong></td>
<td>150 cm H2O</td>
<td>&lt; 40 cm H2O</td>
</tr>
</tbody>
</table>
MIP in intubated patient

- Negative pressure generated by the inspiratory muscles during a maximal inspiratory effort, performed during temporary occlusion of the airway opening

  \[ \text{PIMax, } \text{NIP} = \text{PIMax, } \text{NIP} = \text{NIP} \text{, expressed as a positive number} \]

- Unit is cmH2O

- Two methods (after removal of any PEEPe applied by the ventilator):
  1. at the end-expiratory volume
  2. below the end-expiratory volume
Method 1

End-expiratory occlusion

Method 2

Requires a one-way valve that limit occlusion to inspiration only, but free to exhale
Transdiaphragmatic pressure = Pes – Pgastric

Pgastric is measured by a gastric balloon.
Occlusion pressure at 0.1 sec

- Corresponds to the drop in Paw, or in Pes, observed during the first 100ms of an inspiratory effort performed against the occluded airway opening, with the occlusion performed at the end of exhalation.
- In conscious patients, no relevant reaction to an unexpected occlusion before 200ms from start of inspiratory effort.
- P0.1: A mechanical index of respiratory drive, directly expresses the force applied by the inspiratory muscles, an index of the motor output of the respiratory centres.
- Since gas flow is zero during occlusion, P0.1 is independent from resistance and compliance.

Interpretation:
1. High: high patient workload and high central respiratory drive.
2. Low: if alveolar V normal, then it’s normal; if alveolar V is low, it means motor output is low.
Other applications OF respiratory mechanics
The primary endpoint of this study was improvement in oxygenation c/w ARDS Network protocol, not recruitment of recruitment per se.

Critique: absolute value of Pes may not be equal to actual Ppl, also different at different levels of the lung, cannot be ascertained

Talmor D et al. 2008 NEJM
Summary

1. Basic knowledge: volume, flow, pressure, their derivation and relationship
2. Lung parenchymal condition:
3. Airway condition: FEV1/FVC, Resistance, Flow pattern
4. Chest wall condition: Chest wall compliance
5. Interaction of all factors: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV
6. Work of breathing: Campbell diagram, Pressure-Time Product (PTP)
7. The force of breathing: SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1
8. Other application of respiratory mechanics: Transpulmonary pressure
End
Thank you