Primer on

Ventilator Management

ATS Resident Bootcamp 2025

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ATS 2025
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Course Objectives:

1. Distinguish key features of a standard ventilator interface including identifying usual waveforms and the functions of major knobs and buttons on the ventilator.
2. Appreciate the fundamental differences between pressure- and volume-controlled ventilation.
3. Recognize use of 3 fundamental ventilator modes:
   a. PC-CMV (Pressure Control-Continuous Mandatory Ventilation),
   b. VC-CMV (Volume Control-Continuous Mandatory Ventilation), and
   c. PC-CSV (Pressure Control-Continuous Spontaneous Ventilation, AKA "Pressure Support").

--Supplemental Primer--

Indications for mechanical ventilation support:

1. Unstable or unprotected Airway.
   a. Decreases aspiration risk (in the setting of bleeding, vomiting, altered mental status, etc)
   b. Secures the airway (in the setting of laryngeal edema/trauma)
2. Ventilatory Failure (hypercapnea)
   a. Decreases work of breathing and prevents/relieves respiratory muscle fatigue
3. Hypoxemic respiratory failure
   a. Reliably delivers a high inspired oxygen concentration
   b. Improves V/Q mismatch
   c. Decreases shunt by recruiting collapsed alveoli

Physiologic changes which occur after initiating mechanical ventilation:

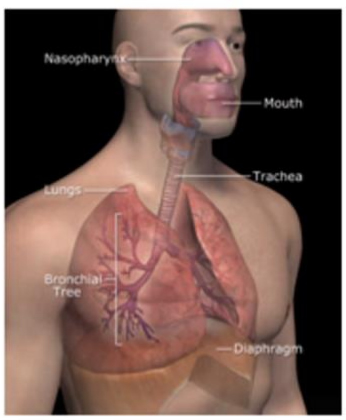
1. Cardiac
   a. Decreased venous return (due to increased lung volume causing increased pleural pressure and increased intramural pressure on the RA and IVC in the thoracic space)
      i. Can give way to worsening hemodynamics in PE, hypovolemia, tamponade, air trapping (autoPEEP), right heart failure, pulmonary hypertension
      ii. Give IV fluids or pressors to increase mean systemic pressure and, subsequently, improve venous return.
   b. Decreased afterload (decrease transmural wall tension in LV with positive pressure).
      i. Helpful in CHF or possibly MI (better coronary perfusion with decreased cardiac O_2 consumption).
   c. The sum of these two above processes can result in either increased or reduced cardiac output, depending on the patient's underlying physiology.
   d. It can also cause hypotension, which needs to be anticipated, especially in states where generous venous return and preload are essential.
      i. An important learning point: do NOT assume that hypotension in a newly mechanically ventilated patient is attributable to sedation—assess for cardiopulmonary sequelae of mechanical ventilation!
2. Pulmonary
   a. May cause:
      i. Ventilator Associated Lung Injury (including barotrauma/volutrauma and atelectrauma)
      ii. Air Trapping (autoPEEP)
      iii. Increased insensible fluid losses
   b. Gas exchange
      i. May increase physiologic dead space (capillary compression or low Vt)
      ii. High PEEP may worsen V/Q matching when used in unilateral lung disease by causing alveolar overdistention and capillary compression of normal lung, resulting in redistribution of blood flow into non-ventilated areas (diseased lung)

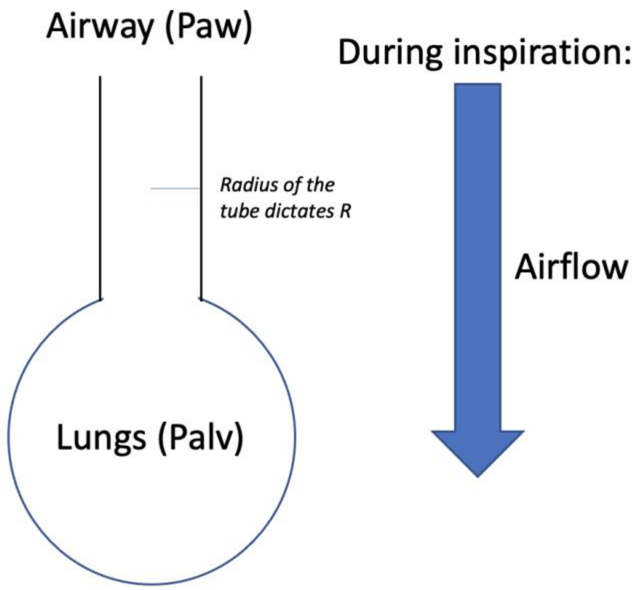
Basic Respiratory Mechanics:

1. Flow
    a. Airflow is dictated by Ohm's Law, which states that flow is driven by a pressure gradient. More specifically, air flows from an area of high pressure to an area of lower pressure.
    b. <u>Δ Pressure</u>: At the onset of a positive pressure breath (inspiration), air flows from an area of high pressure (from the ventilator at the level of the airway, Paw = airway pressure) to an area of lower pressure (in the lungs, Palv = alveolar pressure)
    c. Ohm's Law specifically states that a pressure gradient is equal to flow x resistance. With regards to mechanical ventilation:

        Δ Pressure = Paw – Palv = F x R

    d. <u>Resistance</u> is primarily dictated by Poiseuille's Law, which states: $R = 8\ nL / \pi r^4$
        i. R = resistance, n = viscosity of gas, L = length of the tube, r = radius of the tube. In other words, resistance is primarily impacted by the radius of the tube. As the radius r decreases, R significantly increases
        ii. Major factors that may impact the resistance include factors that impact the radius of the tube/airway (ETT size, secretions, mucous plugs, bronchoconstriction, etc)





2. <u>Compliance</u>
    a. Recall that compliance is equal to change in volume / change in pressure
        $C = \Delta V / \Delta P$
        i. Here, the pressure gradient more specifically refers to the plateau pressure and PEEP. (This compliance is known as static compliance, since it is obtained during an inspiratory pause (no flow).
3. The Equation of Motion and Newton's 3^{rd} law of motion.
    a. The relationship among the variables pressure, volume, and flow is expressed by the **Equation of Motion** for the respiratory system. A simplified version of the equation for **passive ventilation** (no inspiratory effort on the part of the patient) is:

        Paw = F x R + V/C + PEEP

        i. The equation may be derived by rearranging our equations for Ohm's Law and compliance:

Note that this ΔP is the gradient between the vent and the lungs (airways + alveoli)

Note that this ΔP is the gradient between the highest pressure in the alveolus at end inspiration (Palv) and lowest pressure in the alveolus at end expiration (PEEP $_{total}$)

$$\Delta P = F \times R$$
$$Paw - Palv = F \times R$$
$$Paw = F \times R + Palv$$

$$C = \Delta V / \Delta P$$
$$C = V / Palv - PEEP_{Total}$$
$$Palv - PEEP_{Total} = V/C$$
$$Palv = V/C + PEEP_{Total}$$

$$Paw = F \times R + Palv$$
$$Paw = F \times R + \underbrace{V/C + PEEP_{Total}}_{Palv}$$

4. The equation of motion is the basis for defining **pressure control** and **volume control** modes of ventilation. Here, we will categorize clinician-controlled variables in purple and patient-controlled variables in orange. **Please note that the following examples describe passive patients (no respiratory effort) with no autoPEEP** (more on that to come…).

   a. <u>If the ventilator is set to control the pressure (PC)</u>, the clinician will control the left side of the equation.
      i. As the clinician (purple), you control the pressure-time waveform. This means that you set the pressure above PEEP and the set PEEP, as well as the rise time (time to pressurize) and inspiratory pressure.
      ii. As a result, the flow and volume delivered are <u>patient-dependent variables</u> (orange) and will vary with the compliance and resistance of the respiratory system.

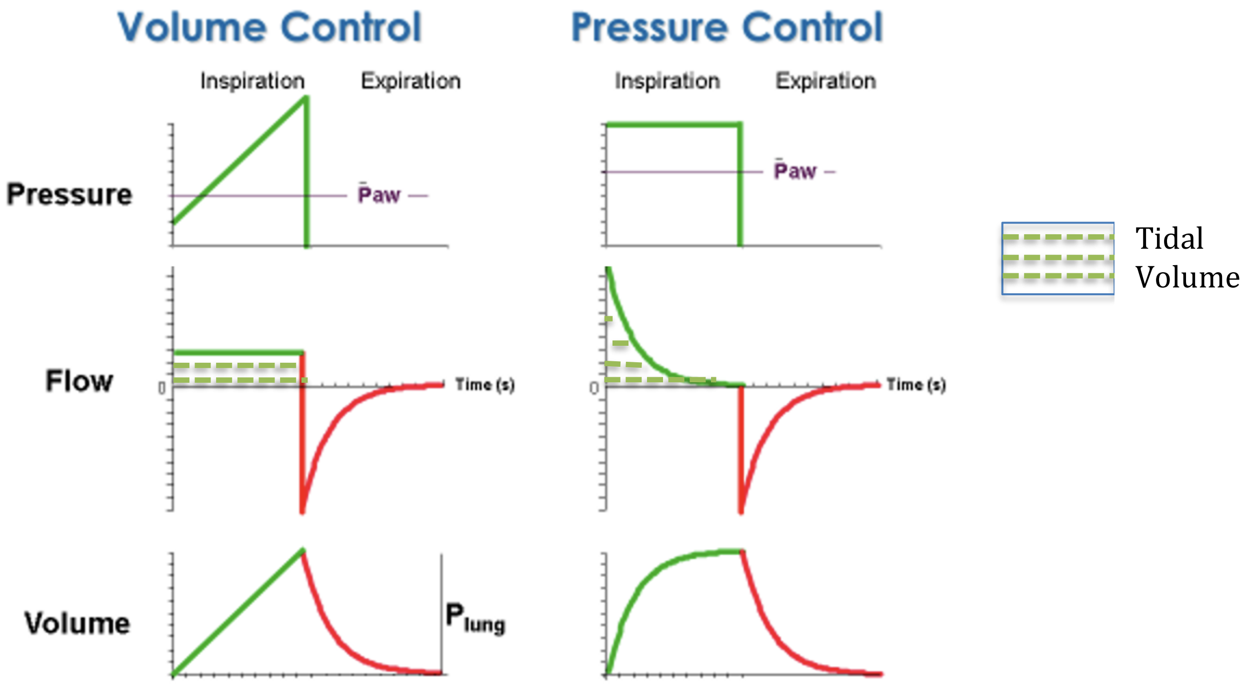
$$Paw = F \times R + V/C + PEEP$$

   b. <u>If the ventilator is set to control the volume (VC)</u>, the clinician will control the right side of the equation.
      i. As the clinician(purple), you control the tidal volume and inspiratory flow (the flow rate and shape) into the respiratory system. As in PC, you also control the set PEEP.
      ii. As a result, the pressure exerted by the ventilator is a <u>patient-dependent variable</u> (orange) and will change based on the resistance and compliance of the respiratory system.

$$Paw = F \times R + V/C + PEEP$$

   c. The curves below illustrate the two basic approaches to ventilator control.
      i. These are idealized waveforms shown on the ventilator's graphics screen (green is inspiration, red is expiration)
      Note- the VC example shows a specific example of a square-waveform (as above, you can set the inspiratory flow rate *and shape*). Just so you are aware, some ventilators require the provider to set the inspiratory time even on volume control and the flow rate is determined by the ventilator.

This is based on the relationship that the area under the flow-time curve = tidal volume.



5. The form of the equation above applies to patients who are **not** making any spontaneous effort (for example, patients who are paralyzed). In patients who are not paralyzed, an advanced form of the equation applies which takes into account physical interactions between the patient (effort from inspiratory muscles) and the ventilator (P_{mus}).

$$P_{mus} + P_{aw} = F \times R + V/C + PEEP_{total}$$

6. Please note that PEEP refers to $PEEP_{total}$ which may be different than the PEEP that you have set. This occurs when autoPEEP has developed.
   a. Total PEEP = set PEEP + autoPEEP
      i. This is the pressure above the set PEEP (which to this point we have been using as our reference point) that is associated with trapped gas.
      ii. Also known as air trapping or dynamic hyperinflation
      iii. Gas trapping occurs when the expiratory time is too short for expiratory flow to naturally decay to zero before the next inspiration begins.

Mechanics and Terminology

Key Terminology:

- **Mode:** predetermined pattern of patient-ventilator interaction.
- **Assisted Breath:** ventilator does some work of breathing during breath sequence
- **Trigger:** to *start* inspiration
- **Cycle:** to *end* inspiration
- **Spontaneous breath:** inspiration is both triggered AND cycled by patient
- **Mandatory Breath:** inspiration is triggered OR cycled (or both) by machine
- **Control Variable:** independent variable that the ventilator manipulates to deliver a breath (pressure or volume)

- Volume control means <u>tidal volume</u> and <u>inspiratory flow</u> are set.
- Pressure control means <u>inspiratory pressure</u> is set.

Modes of Ventilation:

1. Two basic types of modes, based on the "control variable": Pressure Control or Volume Control
2. There are 2 types of mandatory breaths within these modes: Controlled or Assisted
    a. <u>Controlled</u> means that the machine triggers (initiates inspiration) and cycles (completes inspiration) the breath.
    b. <u>Assisted</u> means that patient initiates their own breath (triggers the vent), but the ventilator assists them with the remainder of inspiration and determines breath cycling (completion of inspiration).
        - When a patient initiates a breath, the ventilator generally detects this by noting a change either in the bias flow or a decrease in pressure within the ventilator circuit.
3. Pressure Control
    a. Pressure Assist Control Mode **(AC-PC)**. The goal is safety of the patient.

        You set:
        1. The driving pressure (i.e., the increase in pressure above the set PEEP)
        2. Inspiratory time
        3. Minimum frequency (respiratory rate).
        4. PEEP (set)
        5. FiO2

        Tidal volume and flow rate are the <u>patient-dependent</u> variables.

    b. Pressure Support Mode (PS). The goal is comfort of the patient or liberation from the ventilator.

        You set:
        1. The driving pressure (i.e., the increase in pressure above the set PEEP)
        2. The cycling parameter – breaths cycle (terminate) at a preset % of the peak flow – usually ~25%. This allows a patient to cycle the ventilator on their own as opposed to waiting for a preset inspiratory time to elapse (as in AC-PC)
        3. PEEP (set)
        4. FiO2

        All factors above are the same as Pressure A/C except for 2 things:
        -patients must trigger all breaths (there is no preset respiratory rate). This <u>cannot</u> be used in patients who are paralyzed or lack a drive to breathe.)
        -the inspiratory time is not fixed – cycling occurs when peak flow drops below a % of the peak inspiratory flow.

        Tidal volume and flow rate are the patient-dependent variables (same as AC-PC)

    c. SIMV + PS – mandates a prespecified number of pressure-controlled breaths (set by you). Note: SIMV can function in pressure control or volume control mode for the mandatory breaths.
        - Additional breaths are initiated by the patient and once initiated can either be pressure supported (in PS mode) or spontaneous (unsupported).
        - If the patient is apneic, they will only receive the specified number of mandatory controlled breaths set by you.

    a. CPAP- this is just PEEP

b. BiPAP- this is essentially PS mode, but non-invasive. The nomenclature for determining inspiratory and expiratory pressures differs though. Bipap 10/5 = PS 5/5.

4. Volume Control:
    a. Volume Assist Control Mode **(AC-VC).** The goal is safety of patient.
        i. You set:
            1. Tidal volume
            2. Inspiratory flow rate
            3. Two types of inspiratory flow patterns (square wave, decelerating)
            4. Minimum frequency (respiratory rate).
                a. Additional breaths allowed above the minimum frequency, but once triggered, the breath cycle is the same as machine triggered breaths (volume, flow, length of inspiration)
            5. PEEP (set)
            6. FiO2
        ii. Pressure is the patient-dependent variable
5. Synchronized Intermittent Mandatory Ventilation (VC-IMVs or PC-IMVs)
        i. Patients can initiate breaths beyond the set minimum frequency, but for these breaths do not receive the mandatory assist (these breaths are spontaneous, not mandatory). The delivered volume of the spontaneous breaths varies based on patient strength, neural drives and whether or not pressure support is provided.

Scenarios/Application:

Scenario 1: Asthma Exacerbation.

Scenario: A 24-year-old man with history of poorly controlled asthma presents with acute onset dyspnea and chest tightness. The patient was emergently intubated in emergency department due to increased work of breathing.

Initial ventilator settings:

- Mode = AC-VC
- V_T = 500mL
- Set resp rate = 12 (pt breathing at 20)
- Flow Rate = 60 L/min
- FiO_2 = 1.0
- PEEP = 5 cm H_2O

Initial alarm settings: P_{peak} 50 cmH_2O

Your monitor reads elevated peak pressures.

Goal #1- Identify the difference between Peak and Plateau pressures

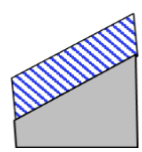
$$\Delta P = F \times R$$
$$Paw - Palv = F \times R$$
$$Paw = F \times R + Palv$$

$$C = \Delta V / \Delta P$$
$$C = V/Palv - PEEP_{Total}$$
$$Palv - PEEP_{Total} = V/C$$
$$Palv = V/C + PEEP_{Total}$$

$$Paw = F \times R + Palv$$
$$Paw = F \times R + \underbrace{V/C + PEEP_{Total}}_{Palv}$$

- The differential for elevated peak pressures *without* an increase in Ppl: an issue with F or R.
  - Cough
  - Dyssynchrony
  - Bronchospasm
  - Bronchial obstruction (foreign body, mucous, blood)
  - Biting the tube
  - ET tube kinked
- The differential for elevated peak pressures *and* elevated Ppl: high V_T, low respiratory system compliance, or high PEEP (including autoPEEP)

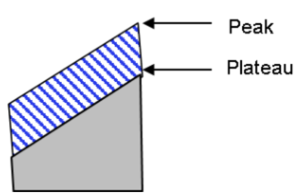
- Patient is being ventilated using a square flow waveform. Using the equation of motion, how does this flow setting affect the pressure waveform?
  - At beginning of breath, there is an immediate increase in pressure from resistive component of equation of motion. (hatched lines below)
  - As lung volume increases, the resistive component remains constant, but the pressure from the elastic component (gray area below) increases.



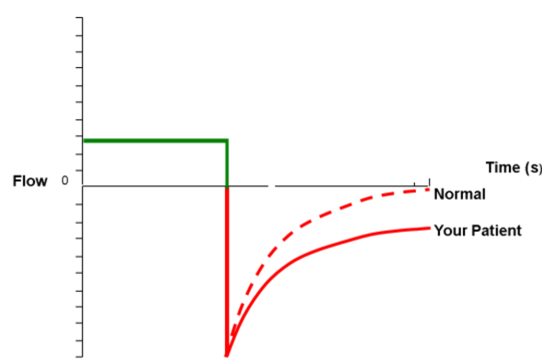
Pressure Waveform

Flow Waveform

-
- Identify difference between Peak and Plateau pressure
  - Because the plateau pressure is measured during a period of zero flow, it does not include the resistive pressures generated on inspiration. It only accounts for the "$V/C + PEEP_{total}$" component of the equation of motion. Therefore, it may be normal despite elevated peak pressures. Understanding the components of peak pressure (resistive and elastic pressure) and the differences between peak and plateau pressure are necessary to determine what changes to the vent are required, if any.



30 minutes later: Patient is now becoming hypotensive. Monitor shows that expiratory flow does not reach 0 prior to next breath.



Goal #2- Identify and manage Auto-PEEP

- Differential diagnosis for hypotension in this setting:
    - Tension pneumothorax
    - AutoPEEP
    - Other shock states (less likely)
- Performing an **expiratory hold** (by pushing a button on the ventilator) is one way to identify auto-PEEP. One may suspect it if the expiratory flow waveform repeatedly does not approach zero (see above figure) prior to the next inspiration.
    - Management options for auto-PEEP
        - Acutely, relieve pressure overload by transiently disconnecting the circuit and pushing down on the patient's chest.
        - Then, prevent the air trapping from reoccurring with one or more of the following:
            - Decrease respiratory rate (most effective)
                - Note: you may need to increase the V_T in order to preserve the minute ventilation. In certain situations this is okay, despite what we are taught about the benefits of low V_T ventilation in general.
            - Increase inspiratory flow rate (least effective)
                - $F_{inspiration}$ = volume / $time_{inspiration}$
                    - If you increase the inspiratory flow rate (F) without changing the volume, inspiratory time decreases. If your inspiratory time decreases, this proportionally increases the expiratory time.
            - Bronchodilate!

Scenario 2: – Severe ARDS

Scenario: A 40 year-old woman with septic shock and ARDS was admitted last night with severe hypoxemia requiring intubation. The team is rounding on her in the morning.

Current ventilator settings:

- Mode = AC-VC
- V_T = 360 mL (6mL/kg IBW)
- Resp rate =24/min
- Inspiratory flow rate = 60 L/min
- F_iO_2 = 1.0
- PEEP = 10 cm H_2O

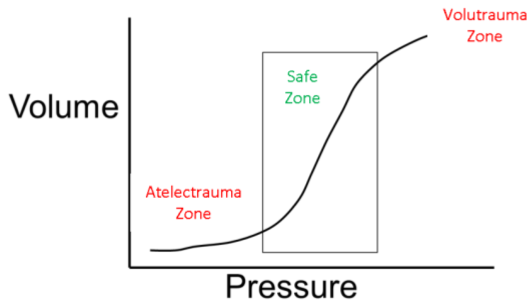
Vent pressures: Peak pressure 35 cm H_20, Plateau pressure 33 cm H_2O

Vital signs: HR 105 bpm, blood pressure 90/65 (on norepinephrine), RR 26, SpO_2 85%

Physical Examination: Intubated, sedated (RASS -2), crackles bilaterally

Goal #1 – Describe strategies to manage hypoxemia in ARDS.

- Increase FiO_2
- Increase PEEP



- PEEP decreases atelectasis, improves compliance, increases FRC, and decreases shunt to improve V/Q mismatch. PEEP keeps *end expiratory* volume out of the atelectotrauma zone.
- The optimal PEEP is to get on the steep ("safe zone") portion of the PV curve (lowest driving pressure)
- In volume control modes, very high PEEP may put *end inspiratory* volume into the volutrauma zone, lead to ARDS, pneumothorax, worsened RV filling or increased dead space

- Heavily Sedate or Paralyze – Evidence supports using paralysis in severe ARDS within the 1st 48 hours when necessary to oxygenate and ventilate the patient using low tidal volume strategy.
- Prone – Evidence supports using this in severe ARDS with P:F < 150 and FiO_2 >0.6 until P:F >150.
- High Frequency Oscillator Ventilation/ Inhaled Nitric Oxide or prostacyclin (no proven benefit, possible harm with HFOV)
- APRV – No evidence to support improved outcomes, may increase risk of atelectotrauma
- ECMO as a salvage in centers with this capability

Goal #2 – Safety: Avoiding Ventilator Induced Lung Injury (VILI) in ARDS

- Current evidence supports tidal volume goals of 6 ml/kg predicted body weight (lower is better!)
- Maintain plateau pressure < 30 cm H_2O (again, lower is better)
  - Ppl is impacted by:
    - Compliance of lung tissue
      - non-compliant lung usually due to alveolar filling process, interstitial process, or over-distended lung.
    - Compliance of Chest wall.
      - important in kyphosis, burn victims, obesity
  - There is no good way to determine which compliance is predominant (without esophageal pressure monitoring) so clinical judgment is important
  - Maintain a driving pressure (Plateau – total PEEP) <15. This should be a target even when your plateau is less than 30cm H2O. Lower driving pressures are associated with a mortality benefit.
- Trade-offs of low V_T ventilation
  - Higher dead space and PCO_2 (permissive hypercapnia)
  - Potential patient discomfort (dyspnea, air hunger)
    - In conventional volume control mode, increased patient effort shifts work from ventilator to patient, exacerbating problem and posing risk of flash pulmonary edema or diaphragmatic injury
    - In pressure control modes, work shifting from high effort can lead to high tidal volumes – worst case scenario
      - Need to monitor this according to ARDS guidelines.

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