Review

Mechanical ventilation for the non-critical care trained practitioner. Part 1

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Abstract

There have been a recent shortage of both critical care physicians and respiratory therapists with training in mechanical ventilation that is accentuated by the recent COVID-19 crisis. Hospitalists and primary care physicians find themselves more often dealing with and treating critically ill patients on mechanical ventilation without specific training.

This two part review will try to explain and simplify some of the physiologic concepts of mechanical ventilation, strategies for managements of different diseases, monitoring, brief review of some of the common modes used for support and weaning during mechanical ventilation and to address some of the adverse effects associated with mechanical ventilation.

We understand the complexity of the subject and this review would not be a substitute of seeking appropriate counselling, further training, and medical knowledge about mechanical ventilation.
Further free resources are available to help clinicians who feel uncomfortable making decisions with such technology

Keywords: Mechanical ventilation, Driving pressure, Compliance, Resistance, Capnometry, Dead space, ARDS, PEEP, auto-PEEP, Plateau pressure, esophageal balloon

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Introduction

Over the last decade, there has been a shortage of critical care physicians, [1] and respiratory therapists [2] which has been markedly accentuated during the COVID-19 pandemic crisis. Hospitalists find themselves confronted by taking the lead of caring for such complex patients especially the ones suffering from respiratory failure requiring mechanical ventilatory support.

The science of mechanical ventilation has evolved significantly over the last decades with new smart modes and automatic feedback servo systems. Furthermore, the issue has been made more confusing by the different nomenclature of modes in the literature and between ventilator manufactures. [3*]

The literature is cramped by so many mechanical ventilator articles, but most are difficult to understand and read. Also, there are multiple mechanical ventilation textbooks and online materials that are great resources for those dealing with mechanical ventilatory support. The problem is lack of training, and time to get expertise in such complex technology.

This article cannot be used as a substitute for adequate training or expertise but tries to simplify the basics of mechanical ventilation. Some important references are listed with an asterisk beside them to highlight the importance of reading them.

Basic Physics

The Breath variables

Every breath can have three variables:

- Trigger: is what initiates the breath. It can be patient triggered or time (ventilator) triggered and from here came the erroneous term Assist Control (AC). It does not matter who triggers the breath, if all the breaths are similar then it is controlled breaths.

- Limit: is the target thar keeps the breath going depending on the ventilator mode or the maximum value allowed during inspiration, this could be either flow, volume or pressure.

- Cycle: is what terminates inspiration to start the expiratory phase. Depending on the ventilator mode it can be set inspiratory time as in the case of pressure-controlled mode (PCV), or flow cycle when the flow reaches a specific level as in the volume-controlled (VCV) and pressure support (PSV) modes.

Pressure/Flow/Volume

The ventilator applies force in the form of positive pressure (driving pressure DP) to the patient airways that generates a volume of gas (tidal volume V_T) to enter the lung. Different ventilator modes use one of the five different flow deliveries and depending on the different way the ventilator applies the gas (Flow $\dot{V}$), the configuration of the airway pressure, and tidal volume will vary (Figure 1). [4*]

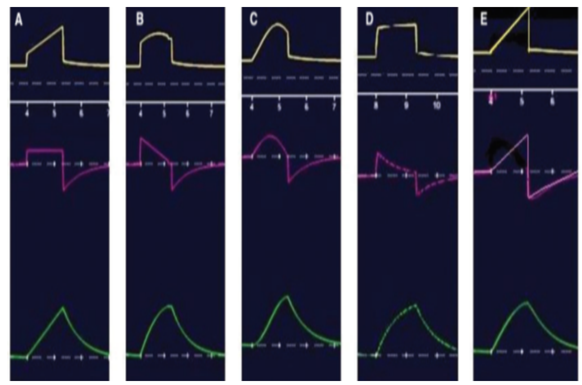

Figure 1
Typical flow waveforms used by different modes of ventilators. Upper yellow curves are the airway pressures in cmH_2O, middle pink curves are flows in L/min, and lower green curves are tidal volumes in mL (A) Constant or square flow waveform, (B) descending, (C) sinusoidal, (D) decelerating, and (E) ascending. Reproduced by permission from Canadian Journal of Respiratory Therapy.[4]

Whether the patient is actively breathing (active) or not (passive) the resultant airway pressure, flow wave forms and tidal volume might be different (Figure2)

It is important to remember that the patient (if actively breathing) and the ventilator work together and not solely the ventilator doing all the work.

The interaction between the ventilator and the patient is described by the equation of motion:

$$P\ Total = P\ vent + P\ mus = V_T/C_{RS} + R_{aw} \times \dot{V} + PEEP$$
(applied PEEP + PEEPi)

Where P Total: total pressure required to move tidal volume in cmH_2O; P vent: airway pressure in cmH_2O, P mus: patients' muscle pressure in cmH_2O; V_T: tidal volume in mL, C_{RS}: respiratory system compliance in mL/cmH_2O; R_{aw}: airway resistance in $cm\ H_2O/L/s$, $\dot{V}$: flow in L/s; PEEPi: the intrinsic PEEP in $cm\ H_2O$. Those variables are explained below.

The above equation states that both the ventilator and the patient work together (if the patient is actively breathing) or the ventilator works alone (if patient is passive) to overcome three major obstacles to deliver the breath: compliance, resistance, and auto-PEEP.

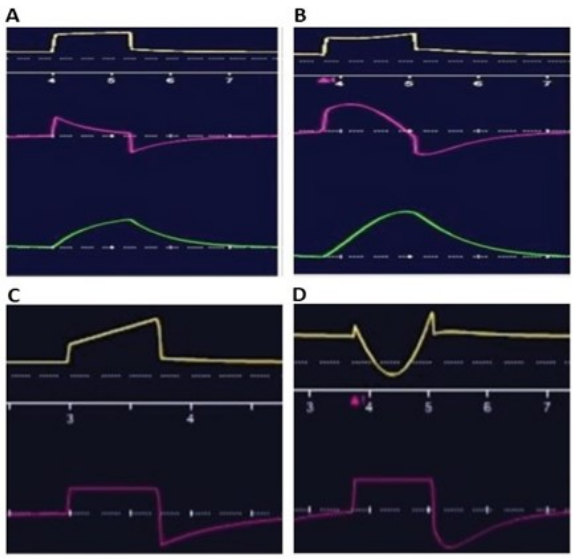

Figure 2
Effect of patients' muscle effort on pressure, volume, flow waveforms. A: passive patient on PCV (square pressure waveform, decelerating flow wave, low tidal volume), B: active patient on PCV (slight convexity on airway pressure, concave flow waveform and higher tidal volume), C: passive patient on VCV (straight triangular airway pressure, square flow waveform), D: active patient on VCV (marked convexity on airway pressure, unchanged flow waveform). Yellow: airway pressure-time waveform, Pink: flow-time waveform, Green: volume-time waveform. Reproduced by permission from Canadian Journal of Respiratory Therapy.[4]

Compliance/Resistance/Time-constant/Auto-PEEP

Knowledge of the respiratory mechanics play a crucial role in diagnosing respiratory failure, in trending progress or regress of disease during treatment and in the weaning process.

Compliance: describes how the respiratory system (lungs and chest wall) behaves in terms of the applied pressure exerted on it. It is the relationship between the tidal volume over pressure and it is the inverse of elastance. (Figure 3)

Total respiratory system compliance (C_{RS}) mL/cmH_2O =
V_T / Plateau pressure (B) – Total PEEP (C)

Low compliance as in cases of Pneumonia, pulmonary edema or ARDS require high pressures to inflate and achieve a V_T versus high compliance in cases of emphysema.

It is important to remember that the equation describes both the lungs and surrounding chest wall which can be decreased secondary to obesity, ascites, edema, etc. To differentiate and calculate each separately, an esophageal balloon is required. [5]

The compliance and resistance calculations have traditionally been done on the VCV using the constant (square) flow waveform and the patient must be passive (heavily sedated or paralyzed) to achieve accurate calculations. New generation ventilators calculate breath to breath respiratory mechanics automatically using a regression analysis of the equation of motion called the least square fitting method (LSF), but our previous work has shown those to be inaccurate in the spontaneously breathing patients. [6]

Also, worth noting that the compliance is not a linear relationship between airway pressure and tidal volume, but rather a sigmoid shaped curve. Similar to inflating a balloon, the breath starts with low concave compliance (high pressure with no much volume), then a linear good compliance (high volume for little pressure changes), followed by plateau low compliance again (not much volume gain for more pressure added) (Figure 4). The idea is to ventilate the lung on the best compliance curve.

Resistance: similar to a water flowing through a pipe, is the pressure drop from the beginning of the pipe to its end divided by how fast the water is flowing. Peak airway pressure (PIP) is the beginning point minus the end point (alveolar pressure as denoted by plateau pressure or P_{plat}) to the ratio of the airway flow ($\dot{V}$). (Figure 3)

Total airway resistance (R_{aw} cmH_2O/L/s) =
PIP (A) – P_{plat} (B) / $\dot{V}$ (D) in cmH_2O/L/s

The total resistance encompasses anatomical airways, artificial airways and frictional forces. Factors influencing resistance are most importantly radius of airways and its length per Ohm's law.

Time constant (τ): is the amount of time taken by the lung unit to fill during inhalation or empty during exhalation at a stable pressure. This parameter can is measured in seconds and is a product of compliance and resistance.[7]

$TC = C_{RS} \times R_{aw}$

It tells us about the overall respiratory characteristics. It takes 1 time constant to fill or empty 63% of lung unit, thus about 4 TC are needed to fully inflate or empty lung units (Figure 5)

Diseased lungs are markedly heterogenous, some alveolar units have fast components (low compliance, normal resistance), while others might have much slower components (high compliance and resistance). For example in a normal respiratory system with compliance of 0.1 L/cmH_2O and resistance of 1.0 cmH_2O/L/s, the TC is 0.1 second, while in ARDS with compliance of 0.3 L/cmH_2O and resistance of 10 cmH_2O/L/s, the TC is 0.3 seconds. COPD with average compliance of 0.8 L/cmH_2O and resistance of 20 cmH_2O/L/s, the TC is about 1.6 second and thus need long exhalation time to avoid hyperinflation and auto-PEEP.

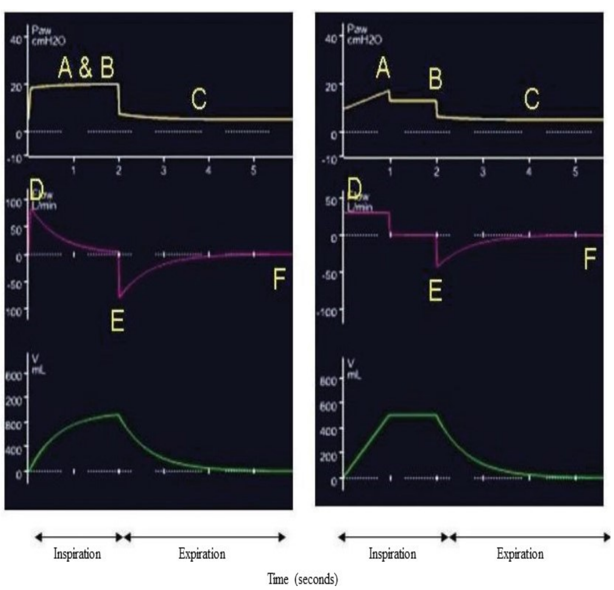

Figure 3
Basic waveform for PCV mode and VCV mode. The left figure is an example of PCV mode using decelerating inspiratory flow wave. The right figure is an example of VCV mode using a constant (square) inspiratory flow with an inspiratory pause. Top yellow curve is airway pressure in cmH_2O, middle pink curve is flow in L/min, bottom green is tidal volume in mL. A is peak inspiratory pressure (PIP), B is plateau pressure (P plat) after inspiratory pause in VCV (notice that PIP and P plat are almost the same in PCV), C is expiratory pressure (PEEP), D is peak inspiratory flow (PIF) (i.e., the maximum positive flow during inspiration), E is peak expiratory flow (PEF) (i.e., the maximum negative flow). A & B, and D to E are the inspiratory time (I time), C, and E to F are expiratory time (E time). Reproduced by permission from Canadian Journal of Respiratory Therapy.[4]

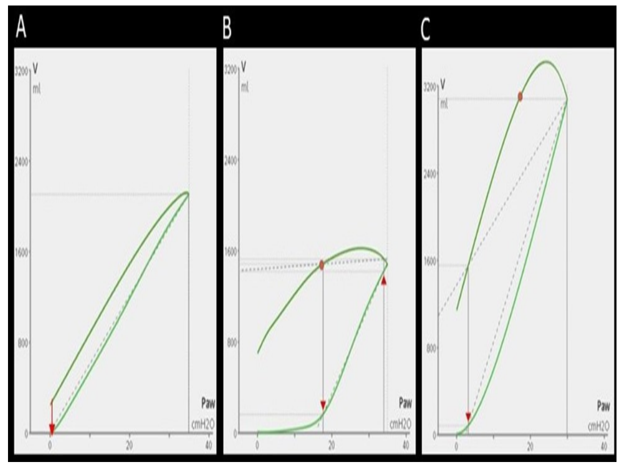

Figure 4
Pressure-Volume curves, Airway pressure on x-axis and Volume on the y-axis. A: normal lung notice the narrow hysteresis (the area between the inspiratory and expiratory limbs)between inspiration and expiration, and the semi-linear inspiratory and expiratory limbs, B: ARDS lung, notice the wide hysteresis and the high pressure required to open the lung, C: COPD lung, notice the wide hysteresis but the low pressure required to open the lung and the very high tidal volume at the end of the pressure maneuver.
Red arrow indicates the beginning of the linear portion or the beginning of the best compliance of the inspiratory limb (low inflection point or LIP). The red circle indicates the de-recruitment of the lung during exhalation, named the point of maximum curvature (PMC)

Auto-PEEP: this describes the additional positive pressure to the applied PEEP remaining in the alveoli before the next breath. It can be recognized visually in the flow-time curve when the expiratory flow does not return to the baseline before the next breath. An expiratory pause maneuver is needed to calculate the total PEEP. For example, if total PEEP is 12 cmH_2O and applied PEEP is 5 cmH_2O, then auto-PEEP is 7 cmH_2O (Figure 6).

It usually occurs as a result of severe bronchoconstriction, extremely high V_T or short E-time. Numerous hemodynamic and respiratory adverse effects can occur secondary to auto-PEEP including hypotension, reduced cardiac output, shock, baro-trauma, pneumothorax, worsening patient work of breathing (WOB), patient-ventilator asynchronies and weakness with failure to wean and prolonged mechanical ventilation. [8]

Recognizing this phenomenon is extremely important. Reversal of the above factors is usually effective. Decreasing the respiratory rate, V_T, bronchodilators, and sometimes matching 70-80% of auto-PEEP with applied PEEP can help. Some physicians tend to disconnect the patient from the ventilator, which is discouraged and should be last effort in extreme cases especially in ARDS patients.

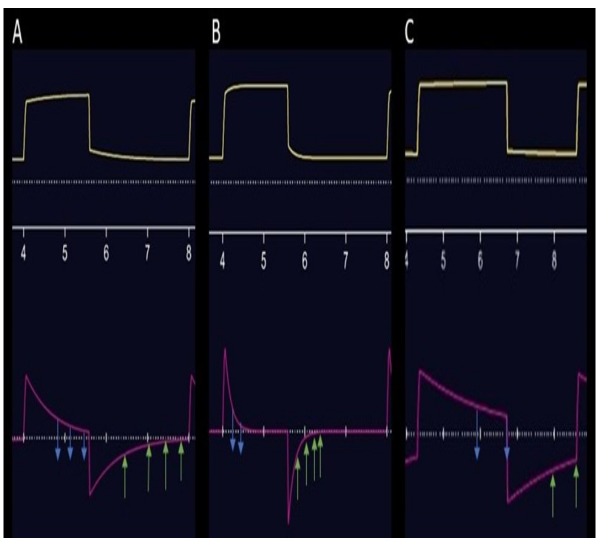

Figure 5
Time constant in the PCV mode. A: Normal lung, inspiration terminates slightly after the 3rd TC and expiration after the 4th TC. B: ARDS lung, the flow is higher and opens and closes quick. C: COPD lung, shows extremely high TC with short inspiration only 2 TC, similarly expiration only lasts 2 TC so not emptying fully resulting in auto-PEEP (next breath starting before flow reaching baseline zero). The blue arrows are the inspiratory TC, the green ones are the expiratory limb.

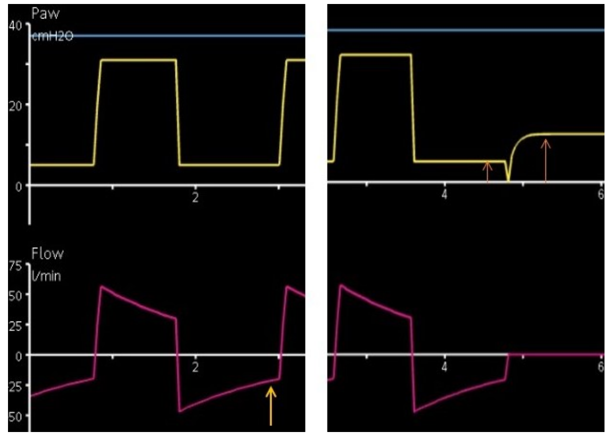

Figure 6
Left figure showing flow-time curve (pink) not returning to baseline before the next breath (yellow arrow). Right figure showing expiratory maneuver showing the increase pressure after the maneuver. The difference between the second arrow (total PEEP) and first arrow (applied PEEP) is the auto-PEEP.

Ventilator setting

Most modes of ventilation require specific settings by the clinicians. Ventilator modes will be detailed in Part 2 of this review. Though not required for each mode, most common settings required are: tidal volume or driving pressure or minute ventilation, respiratory rate, FiO_2, PEEP, inspiratory time or I:E ratio, and expiratory sensitivity, inspiratory ramp or rise time.

PEEP (Positive End Expiratory Pressure)

Perhaps the most difficult, yet one of the most important settings of mechanical ventilation is setting the appropriate PEEP level. Despite thousands of research articles over the last 4 decades, there has been no agreement on how to set the ideal PEEP appropriately. The hemodynamic effects of PEEP and the heart-lung interactions can be especially important in setting PEEP. We will mention some of the most common ways to set PEEP, but detailed description of all methods is beyond this article. [9*]

Given the multitude of illness differences, the heterogenicity of our respiratory system, and the fact that not all ARDS lungs behave similarly or responds to PEEP similarly, we believe that PEEP should be set individually to patients' needs, not a one hat fit all strategy. Multiple studies have examined that issue concluding that there are no outcome differences between higher or lower PEEP levels in ARDS.[10] To be noted most of those studies, did not consider the fact that ARDS of different etiologies are not the same, and not all ARDS lungs are recruitable.

A) PEEP-FiO_2 tables (Figure 7)
Perhaps the easiest and most widely used method of setting PEEP is the famous PEEP-FiO_2 tables. There are low and high PEEP tables. Its advantages are that it is extremely easy and need no clinical experience. Disadvantages are, it is not physiologically tailored to the condition of the respiratory system and whether the lung is recruitable or not or whether the patient would benefit from increasing PEEP or not, and the side effects of high PEEP especially if clinically not necessary.

Lower PEEP/F_{IO_2} Combination*

F_{IO_2}	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1.0
PEEP, cm H_2O	5	5	8	8	10	10	10	12	14	14	14	16	18	18–24

Higher PEEP/F_{IO_2} Combination†

F_{IO_2}	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.7	0.8	0.8	0.9	1.0
PEEP, cm H_2O	12	14	14	16	16	18	20	20	20	20	22	22	22–24

Figure 7
ARDS network low and high PEEP-FiO_2 tables

B) Pressure-Volume curve (P-V curve) (Figure 4)
As mentioned above, the curve describes the compliance of the respiratory system. Despite its availability on most new generation ventilators, its widely underused. There remains wide debate on its usefulness and interpretations. [11]

Most authors suggest setting the PEEP above the low inflection point (LIP) on the inspiratory limb of the curve (the beginning of the steep uprise portion of the curve), while others have suggested to set the PEEP according to the point of maximal curvature (PMC) of the expiratory limb of the curve (the point where the curve starts to sharply declines), and others have suggested to set it according to the hysteresis (the area between the inspiratory and expiratory limbs) of the curve (the widest area between both curves has the best compliance).
Advantages are that it is more physiologic to the individual patient. Disadvantages are, it needs a passive patient to perform (no respiratory effort whether heavily sedated or paralyzed) , must be done with the VCV mode with extremely low flow rate (3-7 Lit/min to avoid the effect of airway resistance), and finally the disagreements mentioned above on its usefulness.

C) Stress index (Figure 8)
Analogous to the P-V curve, this can be examined on the pressure-time curve in the VCV mode with a constant (square) flow wave form, and patient must be passive with no effort. Ideally an index of 1 (straight line curve) indicate an adequate PEEP, If the index < 1 that symbolizes tidal recruitment and the need to increase PEEP, but if index > 1 that means overinflation and the need to decrease the PEEP. [12]

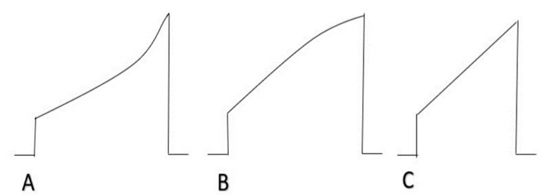

Figure 8
Pressure-time curve in volume-controlled mode. A: Stress index > 1 convex line indicating overdistention and too high PEEP setting, B: Stress index < 1 concave line indicating the continues recruitment during inhalation and the need to increase the PEEP, C: Stress index of 1 straight line indicating adequate PEEP.

D) Incremental-Decremental titration
Incremental titrating the PEEP up by 1-2 cmH_2O to achieve the best compliance. Decremental PEEP is setting a high PEEP level 20-25 cmH_2O and decrease down by 1-2 cmH2O till best compliance is achieved. On doing the decremental PEEP, initially the V_T may start increasing indicating hyperinflation, once the V_T start to decrease with further dropping the PEEP, that indicate de-recruitment and previous level before the drop is the best PEEP. The decremental PEEP is the preferred method. [13]

E) Esophageal balloon manometry and trans-pulmonary pressures (P_L) (Figure 9)
This old concept has been used in research since 1970. Measuring the esophageal pressure with a special catheter equates to the pleural pressure (P_{pl}) which is the other force acting on the alveoli from outside.

Probably the most physiologic way to set the pressures applied during inspiration (driving pressure) is to measure the inspiratory trans-pulmonary pressure (P_{plat} – end-inspiratory P_{pl}). Similarly, to set expiratory pressure (PEEP) is to measure the expiratory trans-pulmonary pressure (PEEP – end expiratory P_{pl}) trans-pulmonary pressures to reduce the stress and strain on lung units. [14*] The concept is to keep end-inspiratory $P_L < 20$ cmH_2O and end-expiratory P_L above zero cmH_2O (Figure 10). Such strategy has shown improved oxygenation and compliance in ARDS. [15]
Despite the multiple benefits obtained from the esophageal balloon, unfortunately it remains underused and not available on all commercially available ventilators.

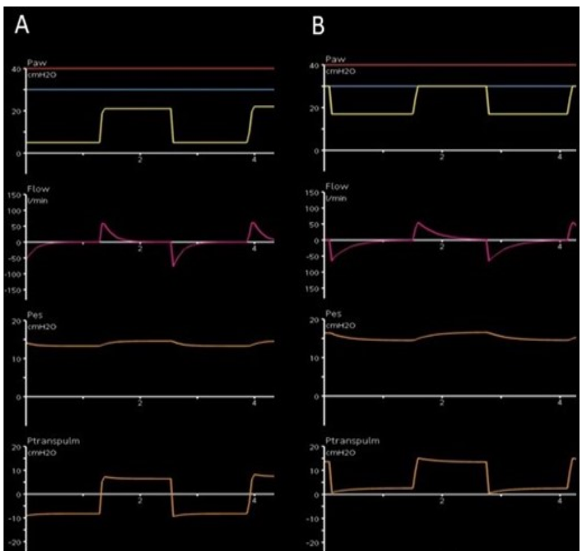

Figure 9
PCV showing pressure-time curve on top (yellow), flow-time curve 2nd (pink), Esophageal-time curve 3rd (orange), transpulmonary pressure-time curve on bottom (orange). A: Pplat 22 cmH2O, PEEP 5 cmH2O, end-inspiratory Ppl 15 cmH_2O resulting in inspiratory PL of 7 and expiratory PL of -8 cmH_2O. B: PEEP increased to 17, Airway pressure now 31 cmH_2O, Ppl 15 cmH2O resulting in end expiratory PL of 1 cmH_2O

F) Impedance tomography (EIT)
This relatively new imaging technology is non-invasive lung imaging that shows regional distribution of ventilation and the effect of PEEP on over and under inflation of lung units directly. [16] This technology is starting to make its way to be incorporated to the bedside and into the new ventilators.

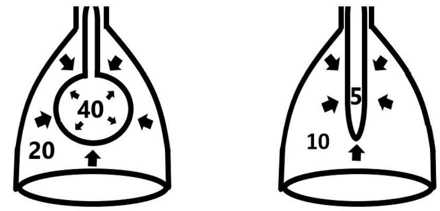

Figure 10
Left side: end inspiration with plateau pressure (alveolar pressure) of 40 cmH_2O and Pleural pressure 20 cmH_2O resulting in inspiratory trans-pulmonary pressure of 20 cmH_2O. in this case, despite a high plateau pressure, the transpulmonary pressure is within a safe margin.
Right side: end expiratory pressure (PEEP) of 5 cmH_2O and Pleural pressure of 10 cmH_2O, resulting in expiratory trans-pulmonary pressure of -5 cmH_2O and alveolar collapse. In this case the PEEP needs to be increased to above 10 cmH_2O.

G) Dead space
Adjusting PEEP for the best dead space fraction is an easy, available method of adjusting PEEP. [17]

Dead space refers to the wasted V_T not engaged in gas exchange. It consists of the airway volume (anatomical) and alveolar volume (physiological) not perfused by capillaries. Normal dead space is about 25-30% of V_T or almost the IBW in ml (150 ml for 150 pounds person). New monitors can measure the dead space and further quantifies the alveolar tidal volume. Measuring dead space and alveolar V_T are not important only in obstructive airway disease where it is significantly increased but also in setting appropriate PEEP and have shown important correlation with mortality in ARDS. [18]

Capnography is the measurement and graphical display of CO_2 concentration within the expired gas and can be plotted against time or tidal volume (Figure 10). Monitoring the waveforms not only the end tidal number ($PetCO_2$) has many advantages not restricted to only during intubation or cardio-pulmonary resuscitation. Capnometry can aid in measurements of dead-space ventilation fraction (V_D/V_T), adjustment of PEEP, and early warnings of hemodynamic compromise, and early detection of pulmonary embolisms. Additionally, cardiac output can be measured non-invasively using this technology. Nutritional support can be adjusted according to carbon dioxide production (VCO_2) as an indirect measure of energy expenditure. [19*]

H) Radiologically
Multiple clinical studies have used lung ultrasound and computerized tomography to set PEEP at the bedside. [20] This requires clinical experience with ultrasound technology and the difficulty of obtaining multiple CT scans for unstable patients especially, if they have to transfer to radiology suites.

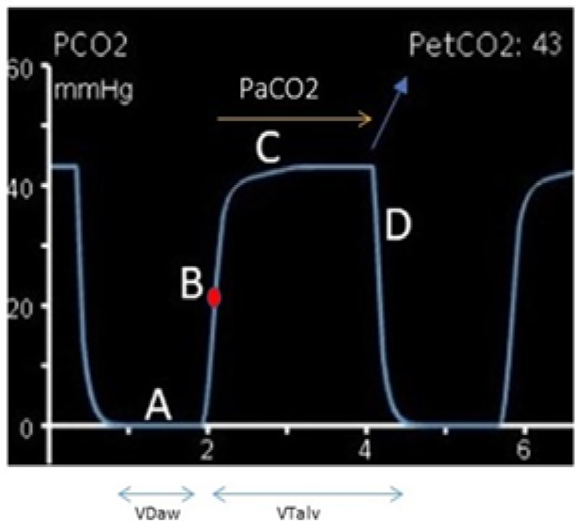

Figure 11
End tidal capnography waveform versus time. 4 phases identified (3 during exhalation and one during inspiration). A: Anatomical dead space, B: Mixing wave (gas mixed from alveoli and airways, important in perfusion and cardiac output), C: alveolar phase, D: Inspiration. Blue arrow indicates end tidal CO_2 ($PetCO_2$), yellow arrow indicates its relationship to $PaCO_2$. Red dot: is mean airway–alveolar interface that separates the airway dead space (VDaw) from the alveolar compartment (VTalv)

Tidal Volume (V_T)

Perhaps the most well recognized setting in mechanical ventilation is the V_T. The landmark ARDS network ARMA trial [21] in the beginning of this century emphasized the role of the relatively lower V_T 6 ml/kg IBW compared to the much higher 12 ml/kg to limit the plateau pressure. This strategy has been adopted universally even outside of the settings of ARDS. This strategy can be achieved by any mode of mechanical ventilation not necessarily the VCV mode used in that study. The concerns of this strategy are the resultant air hunger, flow starvation and increased sedation, along with the possible auto-PEEP resulting from increased respiratory rate to control the hypercarbia usually associated with the low V_T. Another concern is that strategy only limits the plateau pressure but does not consider the trans-pulmonary pressure (the other side of the coin in lung injury).

Worth noting that the ventilators does not measure tidal volumes directly but rather from integration of the flow curve over time: $VT = \dot{V} / \text{I-time}$

Flow ($\dot{V}$)

As explained above in figure 1, the ventilator can deliver the gas in five different flow aspects.
In the PCV modes, the flow is variable and depends on the respiratory mechanics and patients' efforts, it does not set by the clinician. In the traditional VCV mode, the clinician sets the inspiratory flow usually empirically at 4-5 times the minute ventilation (MV) e.g. MV 10 L/min, then flow set at 40-50 L/min. The expiratory flow is usually a passive phenomenon where the lung returns to the functional residual capacity FRC.

The flow-volume loop gives information on the relationship between those two parameters which are especially helpful in obstructive lung diseases in assessing resistance, auto-PEEP and the response to bronchodilators.

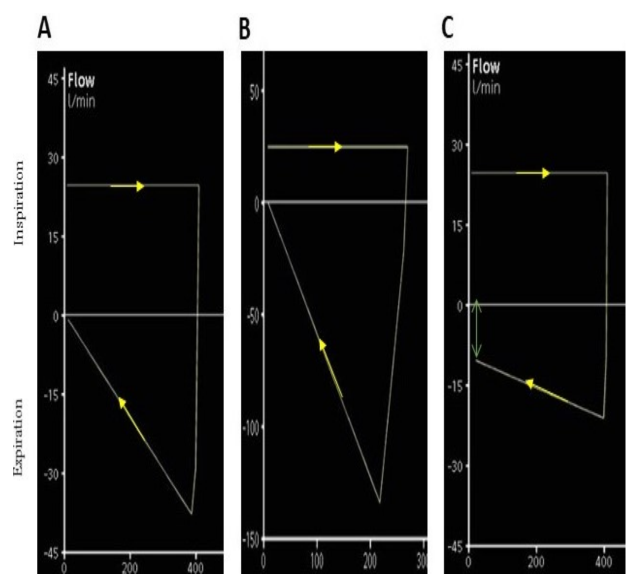

Figure 12
Flow-volume loops in VCV using the constant square flow curve.
Flow on x-axis and Volume on y-axis. Top positive numbers indicate inspiration, bottom negative numbers indicate expiration. Yellow arrows indicate direction of the breath.
A: normal compliance and resistance, B: ARDS with low compliance and normal resistance (note the very high expiratory peak flow), C: COPD with very high resistance and compliance (note the low peak expiratory flow and expiratory flow not reaching zero before next breath indicating auto-PEEP (green arrow)

Driving pressure (DP, ΔP)

It is a function of the respiratory compliance and V_T ($\Delta P = V_T/C_{RS}$). Is the inspiratory pressure above PEEP. It is set directly by the clinician in the PCV and PSV modes, but could be variable in adaptive modes that target tidal volume and automatically adjusts that pressure. In the VCV mode, the DP (Plateau pressure-PEEP) is variable according to the tidal volume and respiratory compliance. Limiting this pressure as much as possible has shown improved survival and an important factor affecting mortality more than tidal volume and PEEP in ARDS. [22]

Inspiratory time (I-Time) and Expiratory time (E-Time)

Setting I-time is important and should not be ignored. Too short or too long a time can result in asynchronies (Part 2 of this series), agitation and require higher sedation. Additionally, short I-time can cause worsening mean airway pressure (mP_{aw}) which is an important factor in oxygenation. Higher I-time can be used in severe hypoxia to the point of inverse ratio (2:1 or 3:1) named IRV. [23]

mP_{aw} = (Inspiratory time x Frequency) / 60) x (PIP – PEEP) + PEEP

In PCV, the I-time can be set directly or by adjusting the I:E ratio and respiratory rate. In VCV the I-time can be adjusted by altering the flow rate i.e. decreasing the flow rate will increase I-time and vice versa, or with adding an inspiratory pause. Some new ventilators have the option of setting I-time directly or I:E ratio parallel to PCV.

FiO_2

Setting the fraction of inspired oxygen perhaps is the easiest. Safest to start at 100% and wean down per pulse oximetry (SPO2) or partial pressure of oxygen in the arterial blood gas (PaO_2). Avoiding hyperoxia is crucial given its negative implications. [24]

Rise time

Sometimes also referred to as pressure ramp or slope, it refers to how fast the driving pressure is delivered to the patient (Figure 13). Too fast or too slow can cause patient-ventilator asynchrony.

Expiratory sensitivity

Only set on spontaneous modes like pressure support modes. It refers to cycling the breath from inspiration to expiration. It is set as a percentage of the peak inspiratory flow (PIF) and usually defaulted at 25%. For example, if the PIF is 60L/min, then expiration will start as soon as the inspiratory flow decays to 15 L/min. Decreasing the percentage will prolong the inspiratory time and vice versa (Figure 14). It should be set to match the patients' respiratory effort to avoid asynchronies (Those will be discussed in Part two of this series).

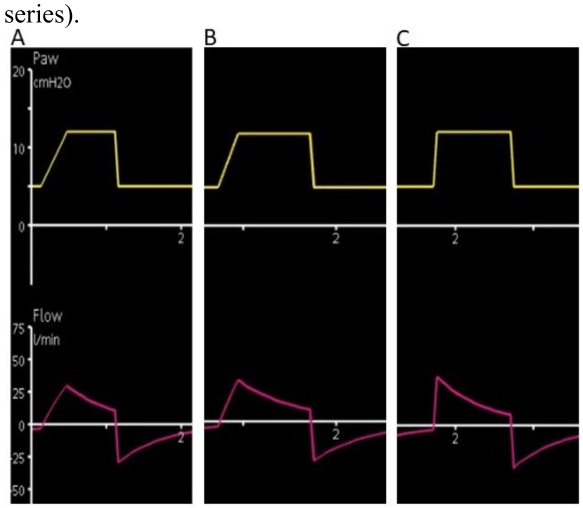

Figure 13
Airway pressure-time curves in yellow showing different rise times and their effect on the flow curves in pink. A: slow rise time of 300 msec, B: intermediate rise time of 100 msec, C: fast rise time of zero msec

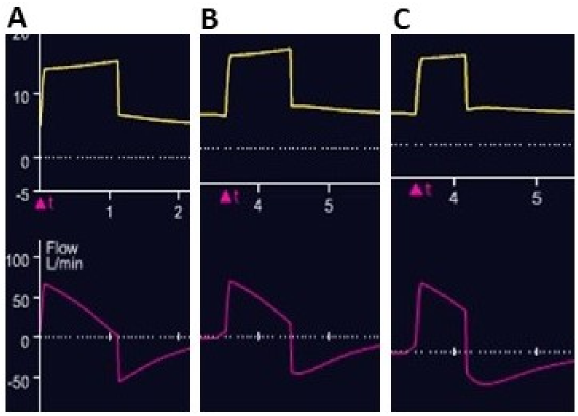

Figure 14
Different expiratory sensitivities in PSV mode. PIF of 60 L/min A: Set at 5% resulting in termination of breath at 3 L/min and inspiratory time of 1 sec. B: sensitivity set at 25% resulting in termination of breath at 15 L/min and inspiratory time of 0.7 sec, C: set at 50% resulting in termination of breath at 30 L/min and inspiratory time of 0.5 sec

Monitoring in mechanical ventilation

Monitoring of airway pressures, V_T, SPO_2 and hemodynamics are routine during ICU stay on mechanical ventilation. However, those are inadequate in such a sick population. Monitoring of respiratory mechanics including compliance, resistance, auto-PEEP are of paramount importance as described above. Monitoring the pleural pressure using an esophageal balloon manometer is also extremely important as described above. One parameter that is tremendously important yet not used consistently in ICUs is the exhaled carbon dioxide ($PeCO_2$) or end-tidal capnography.

Management strategies:

Acute respiratory failure has many etiologies and major patho-physiologic differences; hence a ventilation strategy need be tailored to the patient and the specific etiology of his respiratory failure.

We will discuss some of the major etiologies and their broad major strategies that should be kept in mind while managing their ventilator.

Restrictive respiratory failure

The classic example of this group is ARDS with low compliance and high shunt fraction (venous blood not being oxygenated passing around collapsed alveoli) thus severe hypoxemia result. Though the ARDS network [17] put forth a frame for management of this syndrome.

The strategy in restrictive diseases are to use low VT strategy, along adequate PEEP as outlined above. Increasing the mean airway pressure (with PEEP and long I-time) prove to be helpful. Additionally, tolerating mild-moderate hypercapnia and respiratory acidemia (permissive hypercapnia) as long as PH > 7.15-7.2 have shown to be safe in these situations. The low tidal volume sometimes necessitates a higher respiratory rate which might cause asynchronies and auto-PEEP so special attention is needed in such cases.

There have been two schools of thought in ARDS. The low tidal volume-moderate PEEP strategy outlined above "baby lung". The other approach taken by others is the "open lung approach" i.e. to use recruitment maneuvers (discussed below) and high, using different non-conventional ventilatory modes namely airway pressure release ventilation (APRV) and high frequency oscillatory ventilation (HFOV). Those will be discussed in part two of this series.

Other strategies like prone positioning, or other pharmacological options (pulmonary vasodilators, glucocorticoids, neuro-muscular blockers) might be used as adjunct therapy.

In summary, a lower V_T, tailored PEEP to the respiratory mechanics, avoiding auto-PEEP, and tolerating permissive hypercapnia should be the main consideration.

Recruitment maneuvers (RM): is a transient increase in transpulmonary pressure applied to reaerate the collapsed lung. There are different ways to apply a RM, usually a sustained inflation pressure of 40 cmH_2O for 40 seconds (40x40), or using P-V curves, or step up PEEP titration. Of note, those maneuvers have shown improvements in oxygenation but no mortality benefits. It is important to set the appropriate PEEP after the maneuver if the lung is PEEP responsive. Caution must be taken using those maneuvers as can cause hemodynamic compromise. [25*]

Obstructive respiratory failure

The classic examples of this category are Asthma and COPD exacerbation. The major problem is high resistance with high dead space and low ventilation-perfusion ratio (V/Q) resulting in hypercapnia more than hypoxemia.

The goals of ventilator management of such cases are to avoid hyperinflation and auto-PEEP. This can be managed by low respiratory rate settings sometimes requiring heavy sedation or even paralytics, low V_T (6-8 ml/Kg IBW) to avoid additional auto-PEEP, and judicious use of PEEP. Similarly, tolerating hypercapnia as long as PH not detrimental should be tolerated.

Neurological respiratory failure

Many patients with severe neurological disorders can have concomitant respiratory failure to their neurological insult.

For patients with intracranial hypertension, PEEP can theoretically decrease the venous return from the brain resulting in worsening ICP and brain perfusion. However, some studies suggested that moderate amounts of PEEP 10-12 cmH_2O might be ok. [26] The other issue is that hypercapnia and hypoxia must be avoided for the same reason. Further management of V_T and DP follows same concepts of other conditions.

Obesity

Mechanical ventilation in obesity might pose a significant challenge. Increased abdominal pressures and worsening compliance of dorsal lung units and atelectasis are the major factors. Higher PEEP has shown to improve the extra abdominal wall compliance, and oxygenation with no deterioration of hemodynamics. [27] The V_T settings should be calculated according to IBW not actual body weight.

Weaning/Liberation

Weaning refers to the gradual reducing the support from mechanical ventilation, while liberation implies the removal of the artificial airway. [28] This important area has been a subject of extensive research and guidelines. [29*] Despite this progress, extubation failure remains around 10-15%.

Multiple indices, and formulas have been developed to predict the success of weaning. Most famously the rapid shallow breathing index (RSBI), airway pressure at 100 milliseconds ($P_{0.1}$), unfortunately most of those predictors have poor power.[30*]

Once the etiology of the respiratory failure starts to improve and hemodynamics stabilizes with improved mentation, the process starts with a spontaneous breathing trial (SBT) using low levels of pressure support (PSV) usually 5-7 cmH2O , continuous positive airway pressure (CPAP) or T-piece (only oxygen through the artificial airway). If the patient tolerates 30-120 minutes (similar outcome), a determination of extubation will depend on other factors like mental status, muscle strength, ability to cough and clear secretions, cuff leak if indicated.

There are variety of reasons for failed extubation (within 48 hours). Mainly volume overload, acid-base disturbances, renal failure, uncontrolled active lung disease, upper airway edema, COPD, delirium, muscle weakness and sepsis. Those must be corrected before re-attempting, as failure of extubation have shown to be a predictor of worsening mortality. [31]

Extubation directly to noninvasive positive pressure ventilation (NIPPV) or high flow nasal cannula (HFNC) have shown reduction in the failure rates of extubation especially in COPD, cardiogenic pulmonary edema, and post-operative cases.

Innovation in mechanical ventilation have produced new “smart modes” that might make the process leisurelier for clinicians. Additionally, respiratory therapists driven protocols for weaning and extubation have shown to accelerate the weaning process and its success. [32]

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