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Alveolar mechanics at the bedside

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Abstract

Mechanical power has recently emerged as an important indicator of ventilator lung injury, and mortality. Most studies have focused on the whole respiratory system mechanical power, and few have studied the trans-pulmonary mechanical power.

A newer calculation highlighted the concept of alveolar mechanics and mechanical power. In this brief review, we illustrate the various types and different calculations of the respiratory system, lung, and alveolar mechanical power.

Keywords: Mechanical power, trans-pulmonary mechanical power, alveolar mechanical power

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Introduction

Ventilatory management is a common and essential practice in critical care medicine. Clinicians must be aware of potential risks, including ventilator-induced lung injury (VILI), which is primarily comprised of volutrauma, barotrauma, atelectrauma, ergotrauma, rheotrauma, myotrauma, and biotrauma. [1] Previously, driving pressure and tidal volume have been viewed as markers of mortality; however new studies are now exploring mechanical power as a marker for VILI and a prognostic tool. [2-6]

Mechanical power is the amount of energy per unit of time that is transferred from the ventilator to the patient. Based on previous work, clinicians can use known values to calculate compliance, elastance, and mechanical power.

Below is an example based on the ventilator settings of a patient admitted to the critical care unit with acute hypoxia with ARDS on the pressure-controlled ventilation mode.

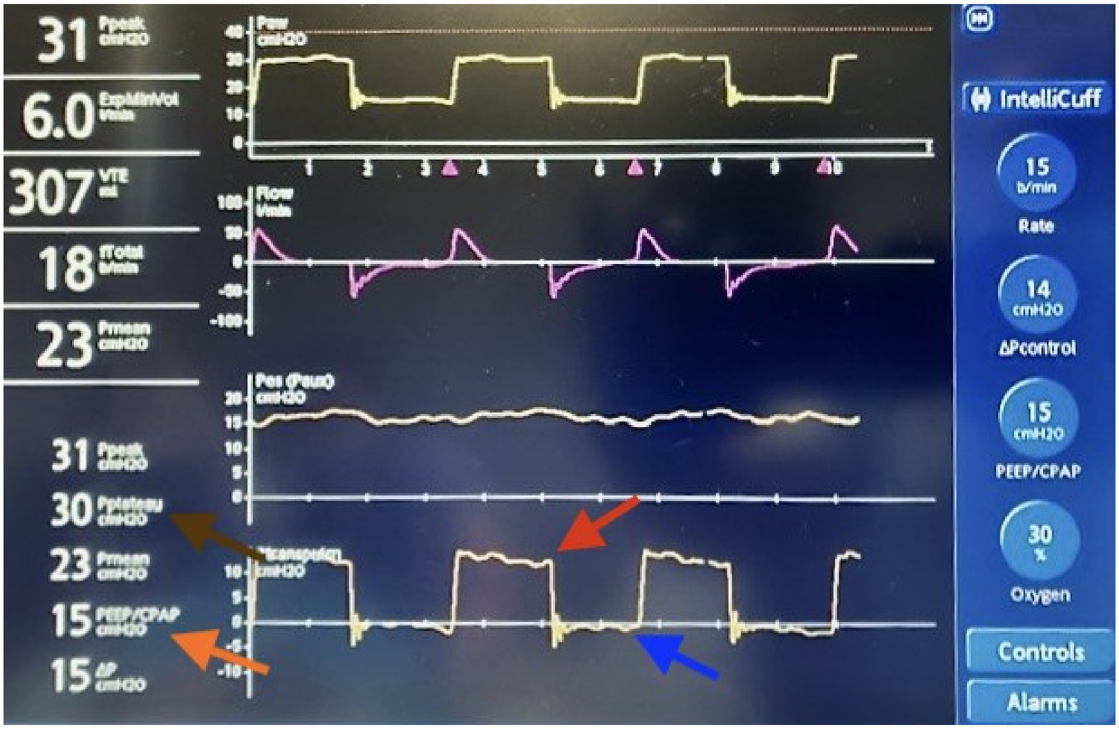
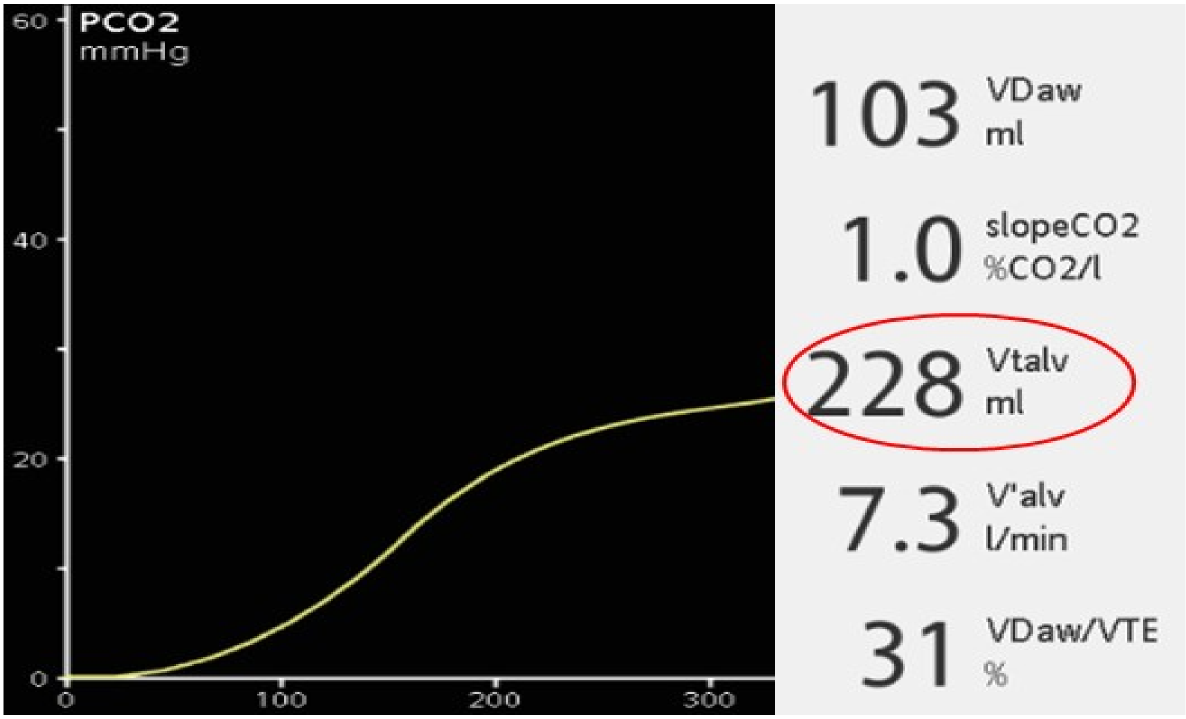


Figure 1 A: Ventilator settings of interest in the patient with both transesophageal balloon (third line down), calculated transpulmonary pressure (fourth line down). Note: tidal volume (VT, 307ml), respiratory rate (18), plateau pressure (brown arrow: 30cmH_2O), PEEP (orange arrow: 15cmH_2O), transpulmonary end inspiratory pressure (red arrow: 13 cmH_2O), and transpulmonary end expiratory pressure (blue arrow: - 1.4 cmH_2O).



103 VDaw ml

1.0 slopeCO2 %CO2/l

228 Vtalv ml

7.3 V'alv l/min

31 VDaw/VTE %

Figure 1 B: Volumetric capnometry curve in the left side (tidal volume on x-axis), exhaled pressure of CO_2 ($PeCO_2$) on y-axis. Alveolar tidal volume V_{Talv}: 228 ml (red circle)

Calculation

In order to calculate mechanical power, the clinician must first compute tidal volume, driving pressure and compliance.

Compliance

Compliance describes the relationship between tidal volume and pressure and is the inverse of the term elastance (E).

Respiratory system compliance is calculated as: [7]

V_T / (Plateau pressure - Total PEEP)

Lung and alveolar compliance require the placement of an esophageal balloon, which is used as a surrogate for pleural pressure and can be used to calculate the trans-pulmonary and trans-alveolar driving pressures, the theory of which is described elsewhere. [7,8]

Driving (Tidal) pressure for each of the three systems is described as:

Trans-respiratory pressure (P_{TR})

Airway pressure - Body surface pressure
(End-inspiratory plateau pressure – Total PEEP)

Trans-pulmonary pressure (P_{TP})

Airway pressure - Pleural pressure
(End-inspiratory plateau pressure - End-inspiratory pleural pressure)

Trans-alveolar pressure (P_{TA})

Alveolar pressure - Pleural pressure
(End-inspiratory trans-alveolar pressure - End-expiratory trans-alveolar pressure)

Of note: the trans-pulmonary is equal the trans-alveolar pressure in static conditions.

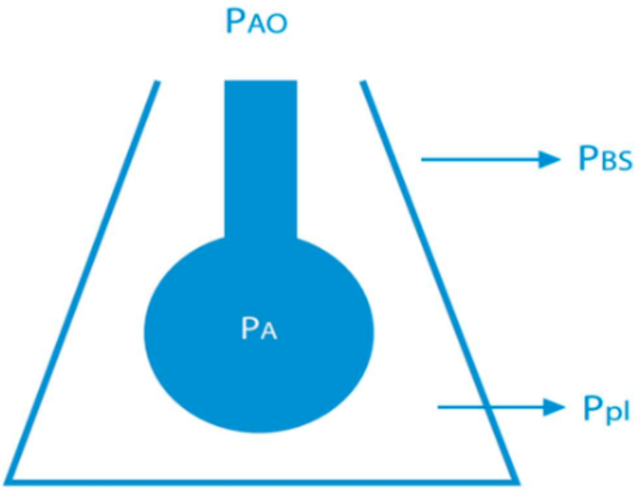


Figure 2: Schema showing the concept of different pressure gradients, including airway pressure (P_{AO}), body surface (atmospheric) pressure (P_{BS}), alveolar pressure (P_A), and pleural pressure (P_{PL}). [7]

Volumetric capnography is needed in order to obtain the alveolar tidal volume (Expiratory tidal volume - Anatomical dead space).

The equation for alveolar compliance is as follows:

$$V_{TAlv} \text{ / Trans-alveolar Driving Pressure}$$

Using the above equations and the example in figure 1, total respiratory system, lung, and alveolar compliance can be calculated as follows:

Respiratory system compliance (C_{RS})

$$V_T \text{ / DP (DP} = P_{plat} - \text{Total PEEP)}$$
$$0.307 / (31 - 15) = 0.019 \text{ L/cmH}_2\text{O}$$

Lung compliance (C_{Lung})

$$V_T \text{ / trans-pulmonary DP}$$
$$0.307 / (13 - (- 1.4) = 0.021 \text{ L/cmH}_2\text{O}$$

Alveolar compliance (C_{Alv})

$$V_{TAlv} \text{ / trans-alveolar DP}$$
$$0.228 / (13 - (- 1.4) = 0.016 \text{ L/cmH}_2\text{O}$$

Mechanical power

The expanded equation for mechanical power is:

$$0.098 \times RR \times \{2\ V_T \times (½\ E + RR\ [(1+I{:}E)/(60 \times I{:}E)]) + V_T \times PEEP\}$$

Where 0.098 is the conversion factor of L/cmH$_2$O to Joules (J); RR is respiratory rate; V_T is tidal volume; E is elastance; I:E is inspiratory:expiratory time ratio; and PEEP is positive end expiratory pressure. [9] Note, compliance is inversely proportional to elastance (E = 1/C).

As calculated by Daoud et al. [7] This equation may also be simplified to:

$$0.098 \times RR \times \{\ 2\ V_T \times ½\ E + [V_T \times PEEP]\ \}$$

Using the elements from above, the mechanical power of the respective systems (respiratory, lung, and alveolar), can be calculated as below:

Respiratory system mechanical power (MP_{RS})

$$0.098 \times 18\ (RR)\ \{\ 0.614\ \times (½ \times 52.632\ (E) + [0.307\ (V_T) \times 15\ (PEEP)\ ]\ )\ \}$$
$$36.626 \text{ J/Min}$$

Lung mechanical power (MP_{lung})

$$0.098 \times 18\ (RR)\ \{\ 0.614\ \times (½ \times 47.619\ (E) + [0.307\ (V_T) \times 15\ (PEEP)\ ]\ )\ \}$$
$$33.911 \text{ J/Min}$$

Alveolar mechanical power (MP_{alv})

$$0.098 \times 18\ (RR)\ \{\ 0.456\ \times (½ \times 62.5\ (E) + [0.228\ (V_{TAlv}) \times 15\ (PEEP)\ ]\ )\ \}$$
$$31.170 \text{ J/Min}$$

Discussion

Mechanical power is the concept in ventilatory mechanics of describing the amount of energy transferred from the ventilator to patient in units of time. The equation employs multiple aspects of ventilation including tidal volume, rate of delivery, pressure, and flow. [6] A well-cited benefit is the integration of multiple variables of respiration; nonetheless the individuality of each aspect underscores its inherent complexity. Utilizing this, prior studies have already associated increased mechanical power with mortality in critically-ill patients, even moreso when normalized to lung size based on predicted body weight, compliance, or amount of aerated lung. [4-5,10] However to date, most references calculate power based on the total respiratory system, with few taking into account isolated trans-pulmonary power, which is hypothesized to be a better reflection of deliberate power. [7]

Trans-pulmonary (TP) pressure is a relatively new theory analyzing the pressure gradient of the lungs (stress). The placement of an esophageal balloon is necessary as a surrogate for pleural pressure, which is then used to calculate the driving pressure gradient between lungs and chest wall (see figure 2). [7] In 2008, a single-center randomized control by Talmor and colleagues compared PEEP settings according to the traditional ARDS Network PEEP-FiO_2, to PEEP levels set to achieve end expiratory TP pressure 0-10 cmH_2O. Measurements at 72 hours found significantly improved oxygenation and compliance in the intervention arm, and the study was stopped early due to overwhelming effect. [11] Knowing this, it can be reasonably theorized that atelectrauma may be prevented with close monitoring of TP driving pressure to prevent repeated alveolar collapse, an established component of VILI. This will likely prove more useful than airway driving pressure in patients with decreased chest wall compliance, as seen in obesity, fibrosis, or other interstitial lung disease. [12]

Using trans-pulmonary pressure one can calculate trans-pulmonary mechanical power, the value of mechanical power isolated to the lungs. In various pathologies common to the critical care setting the lungs can become heterogenous, with differing regions of aerations, and trans-pulmonary pressures may be stressed up to twofold normal value. [13]

Although there have been scant studies looking into this effect, a retrospective analysis of a population of 222 ARDS patients found an association between trans-pulmonary mechanical power and mortality when normalized to either the amount of well-aerated tissue, as calculated by imaging, or compliance; however further studies are needed to confirm these links. [14] A recent term coined Power Compliance Index (PCI) has been investigated in bench studies. [15]

Incorporating the technology of volumetric capnography, which compares the exhaled partial pressure of carbon dioxide to exhaled tidal volume adds more to our understating of the physiology and pathology of respiratory failure. [16] Estimates of dead space have been correlated to mortality in ARDS. [17] Its use in calculating alveolar tidal volume is based on Fowler's concept, which initially looked at nitrogen wash-out in relation to tidal volume. The plotted graph is divided into three phases, based on measured gas from the anatomic, anatomic/alveolar transition, and pure alveolar gas compartment, which is then used to determine alveolar tidal volume as described in figure 3. [7,16,18].

Alveolar volume (effective alveolar volume + alveolar dead space) can then be used to calculate alveolar mechanical power, and as demonstrated in the above example can vary from other components of the respiratory system.

Conclusion

Future direction will need to investigate lung and alveolar mechanical power specifically as a more precise marker of lung injury, mortality, and if more focus is needed for prevention of VILI.

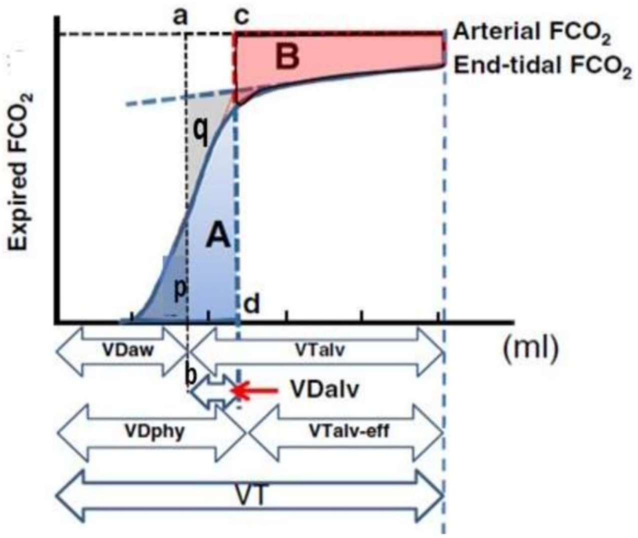


Figure 3: Volumetric capnometry waveform used to calculate alveolar tidal volume (V_{Talv}), alveolar dead space (VD_{alv}), physiological dead space (VDphy), and anatomical dead space (VD_{aw}). The line *a-b* divides phase II so that the area of *p* and *q* are equal. The area to the left describes anatomical dead space, while to the right describes alveolar tidal volume. The line *c-d* delineates phase II from phase III as so *A* and *B* are equal. The distance from b to d defines alveolar dead space, V_{Talv} – VD_{alv} = Effective alveolar tidal volume (V_{Ealv}). [7]

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