

Mechanical Power; definition, calculation, and measurement

1. Definition

The mechanical power as coined by Gattinoni and coworkers (1) is the summation of the work done during inflation by the ventilator to the respiratory system of all breaths in one minute. The respiratory system is not only the lungs and thorax of the patient but also the conducting airways, the endotracheal tube and other tubing connecting the ventilator to the patient. The work done during exhalation is discarded.

This is sensible if, and only if, the patient has no respiratory muscle activity whatsoever. It is thereby assumed that passive exhalation does not contribute to VILI. In that case the amount of energy is obtained which the ventilator needs to ventilate the patient, which is assumed to be an important determinant of VILI.

Work is defined as Force (\vec{F}) times displacement (\vec{s}) in the direction of the force and is expressed in Nm or Joules (equation (eq) 1). When the force is variable equation 2 is the governing equation.

$$W = \vec{F} \cdot \vec{s} \quad (1)$$

$$W = \int_{x1}^{x2} F_x dx \quad (2)$$

Power is defined as work per unit time (eq 3) and is expressed in J/s or Watt, but a different timeframe can be chosen as has been done in the current literature about mechanical power (J/min).

$$P = \frac{\Delta W}{\Delta t} \quad (3)$$

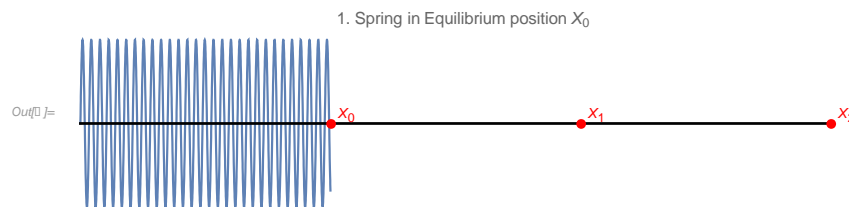
Mechanical ventilation is a thermodynamic process. In that case the applied force is distributed over an area, which is the definition of pressure which is expressed in Pascals (Pa). If the area on which the force is applied is displaced, there is an increase in volume. The work done in a thermodynamic process is described by the following equation (eq 4).

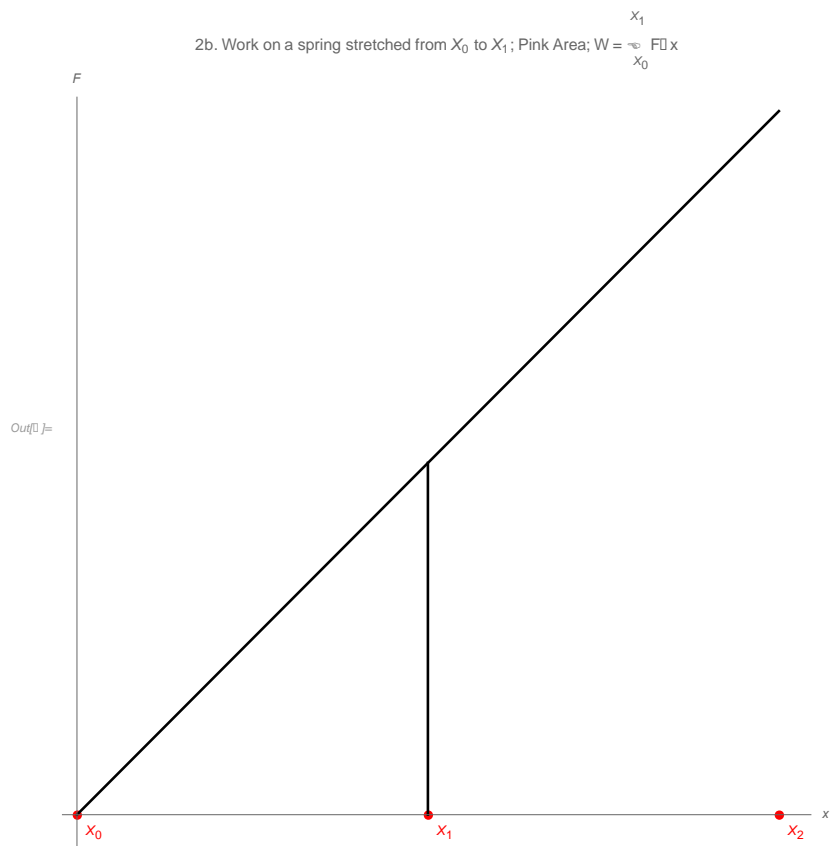
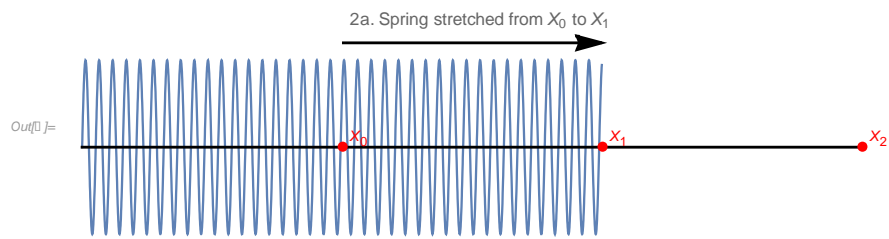
$$W = \int_{v_1}^{v_2} p \, dV \quad (4)$$

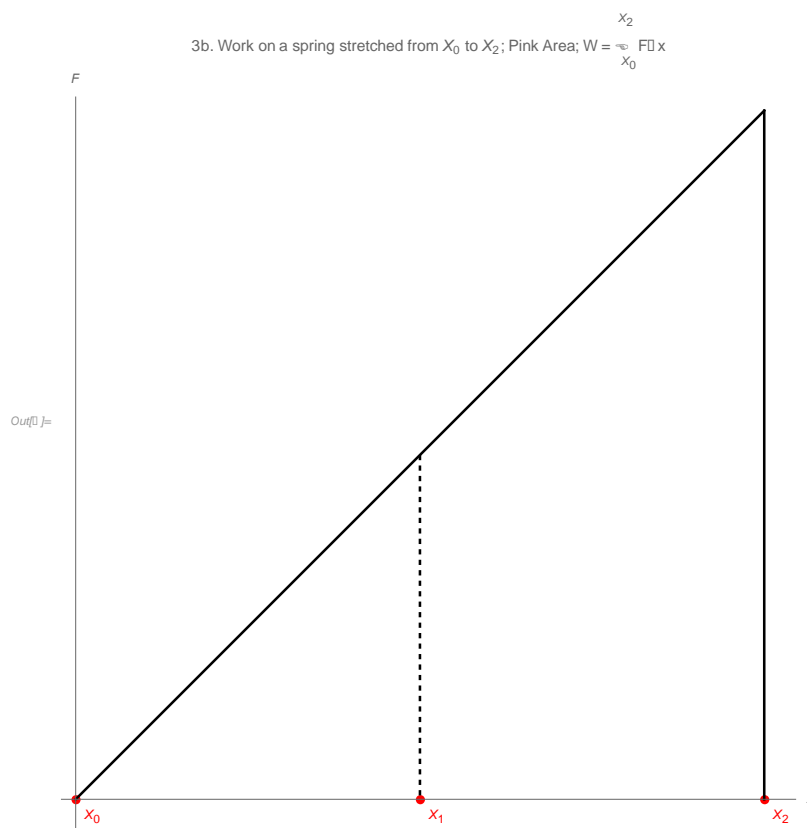
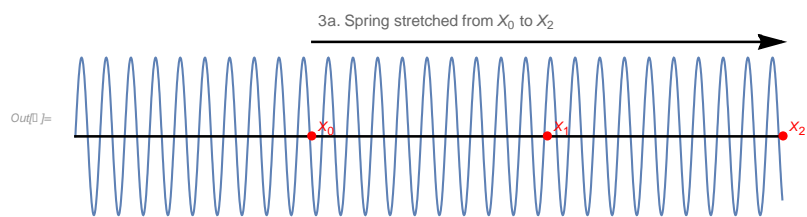
Equation 4 states that work is the area of the pressure volume diagram. It is very important to remark that work is dependent on the PV path (see measurements and calculations).

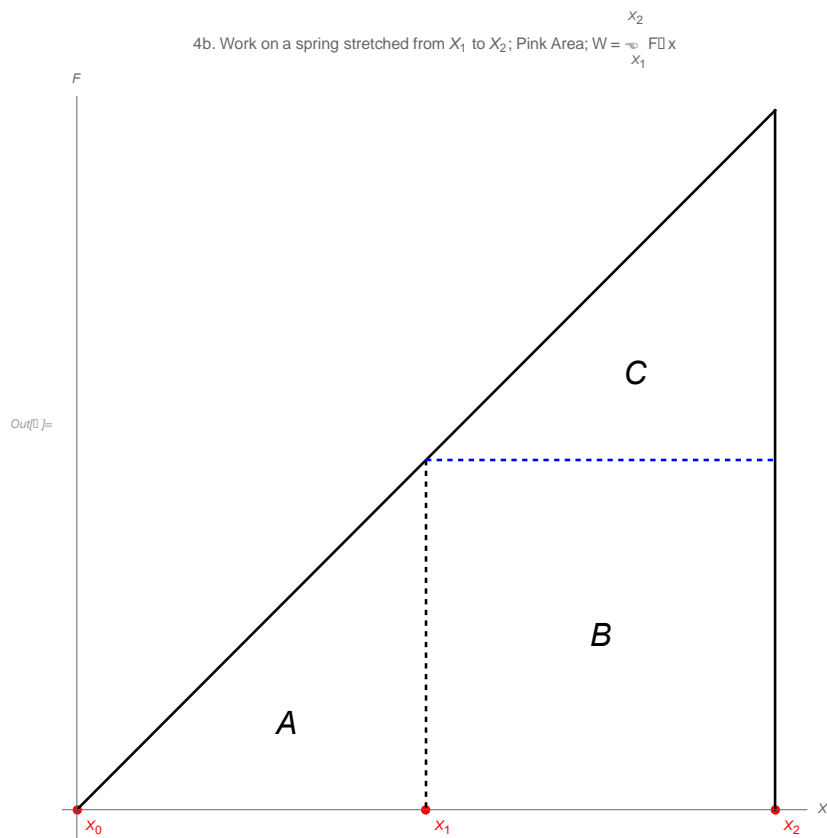
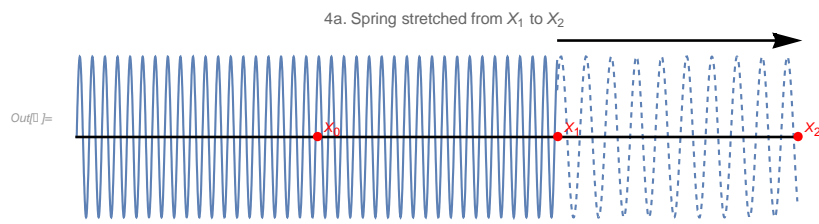
The respiratory system is an elastic system, it is therefore comparable to a spring with a spring constant. Figure 1. Shows the spring in Equilibrium position X_0 . If the spring is stretched from X_0 to X_1 a force is needed that increases linearly with the displacement of the spring. Work on the spring is the pink shaded area (figure 2). The larger the stretch of the springer the more force you need, equivalently the more you inflate the lung the more pressure you need. More stretch on the spring will result in more work, more volume in the lung will also result in more work. This is shown in figure 3a, where the spring is stretched from X_0 to X_2 . Work done on the spring is the larger pink shaded area (fig 3b).

In mechanically ventilated patients PEEP is often applied. This means that the spring is already stretched, and equivalently, that there is already volume in the respiratory system above FRC. This has consequences for the calculation of work. Even though the displacement is the same from x_0 to x_1 as from x_1 to x_2 the area under the displacement curve is larger. This is shown in figure 4b (work is the pink shaded area). The work done on the spring in figure 4b is larger than in figure 2b.









The distance the spring is stretched is the same as in figure 2. The Work however is much larger because the string was already stretched. Area A is as large as area C which is the same area as the pink shaded area in figure 2. Because the spring was already stretched to X_1 .

2. Calculation (algebraic)

The Work done on the respiratory system, in volume-controlled mode, can be represented by using the geometric representation in figure 5. The mechanical power consists of three components. The elastic static, the elastic dynamic, and the resistive component. The elastic static occurs when PEEP is set and is equivalent to the volume in the respiratory system times PEEP. It occurs only when PEEP is set or changed and is therefore discarded.

The Elastic dynamic part is the work done on the respiratory system without the resistive part. It is comparable with the spring stretched from PEEP to P_{plat} . The size of the square part of the elastic dynamic part (blue) is the energy due to the PEEP set and the tidal volume given. The resistive part (green) is the energy due to the total resistance i.e., not only the resistance of the airways and the viscoelastic resistance of the respiratory system but also that of the endo tracheal tube and other tubing between the ventilator and the patient. The blue dashed area approximates the PV loop. The work of one breath is the sum of the Elastic Dynamic part (blue) and the Resistive part (Green). The mechanical power is sum of the work of all breaths in one minute.

It is important to stress that the mechanical power here is the work done during inflation only. On top of that, the patient must exhibit no breathing activity whatsoever.

Figure 5.

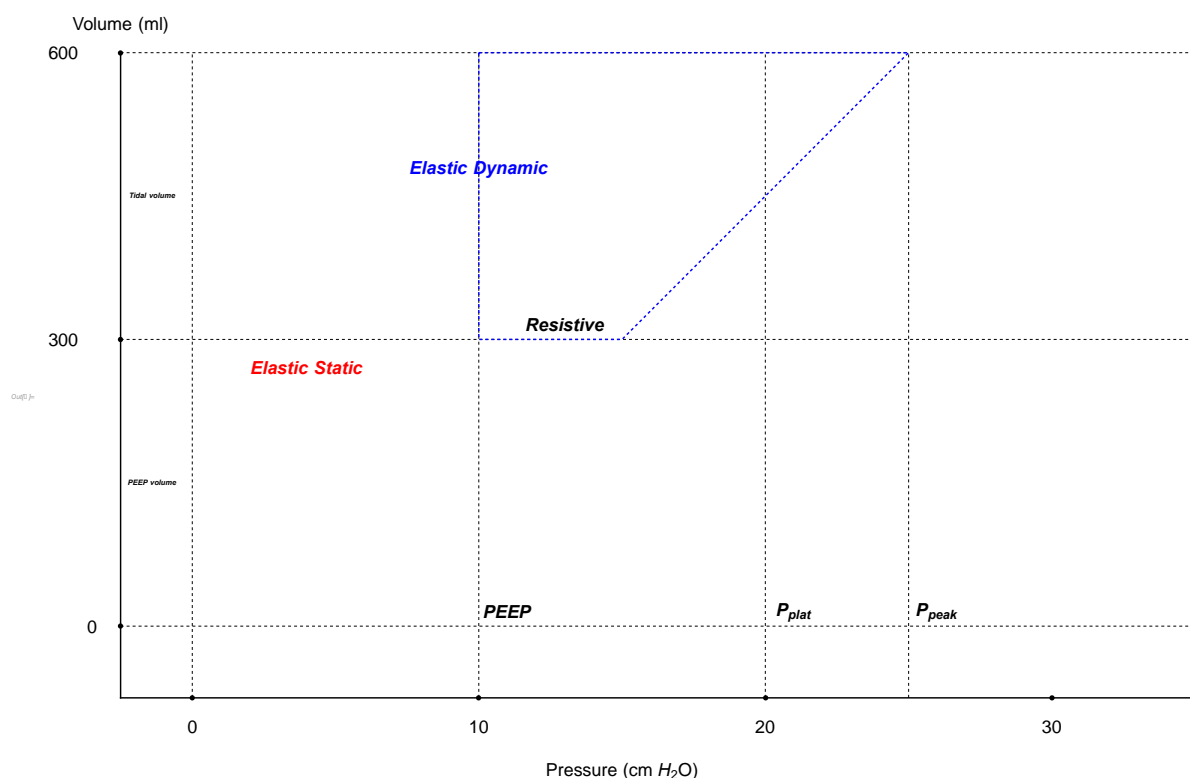
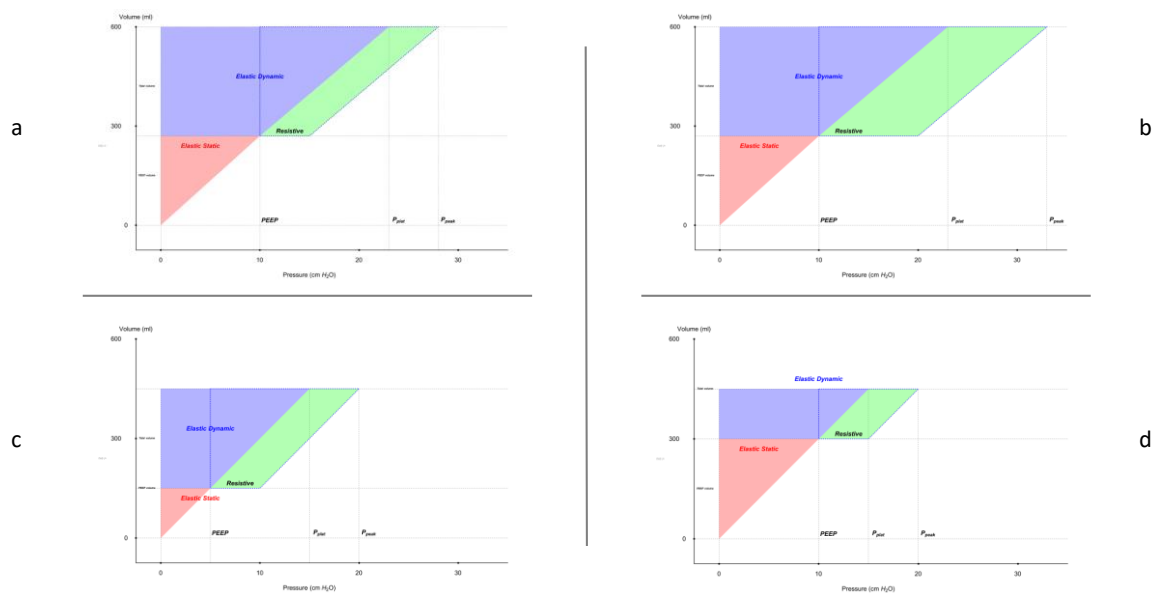


Figure 6 shows what happens if certain settings of the ventilator are changed. Figure 6a is the same as figure 5. In figure 6b the resistance is increased, or the flow is increased, both leading to a higher pressure, an increase in work, and a larger resistive area (green). In figure 6c the PEEP is set at 5 cm H₂O leading to a smaller Elastic Static part, because there is less volume stretching the respiratory system. More important, also the Elastic Dynamic part has become smaller as has the work done. This is because the square area of the Elastic Dynamic part has decreased. In figure 6d the set volume is smaller which leads to an overall reduction of the Elastic Dynamic part of the work done.

Figure 6.



From this we can conclude that Volume, Pressure, flow, resistance, and frequency are important determinants of mechanical power. Resistance is not only the resistance of the fixed tubing but also that of the semi-fixed airways and tissue resistance.

Volume controlled

Calculation of the mechanical power using an equation is possible for both modes. The equation must describe the area between the inspiratory limb and the zero-pressure axis. In volume-controlled ventilation the flow is constant, which makes the algebraic derivation more straightforward. Two methods to calculate the mechanical power for volume-controlled ventilation have been described, one by Gattinoni and coworkers (eq 5) (1) and one by Giosa and coworkers (eq 6) (2); for the exact derivation we refer to the original paper. The original equation described by Gattinoni looks complex but is mathematically equivalent to the equation given here. The equation described by Giosa et al is a surrogate equation, it approximates the more exact equation published by Gattinoni but has as an advantage that the input variables are more readily available.

$$MP = 0.098 \cdot RR \cdot \Delta V \cdot \left(P_{peak} - \frac{(P_{plat} - PEEP)}{2} \right) \quad (5)$$

$$MP = 0.1 \cdot RR \cdot \Delta V \cdot \left(\frac{P_{peak} + PEEP + \frac{F}{6}}{2} \right) \quad (6)$$

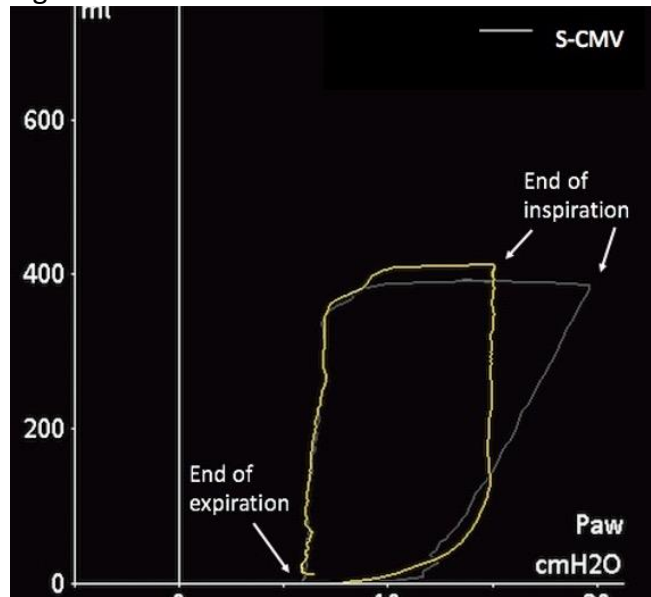
Where MP is Mechanical power; RR is respiratory frequency, ΔV is tidal volume, P_{peak} is peak pressure, P_{plat} the plateau pressure and F is flow.

The method of Giosa has been compared with the method of Gattinoni and was fairly equivalent (2).

Pressure controlled

Figure 7 (and figure 3 in the manuscript) shows the difference of the PV loop between VCV and PCV. This means that the path is different for volume controlled in comparison with pressure-controlled ventilation. This also implies that the work for a single breath is different between VCV and PCV ventilation.

Figure 7.



In pressure-controlled ventilation the flow is not constant, but the pressure is constant. Because of that the flow has a decelerating nature and therefore the volume change per time interval is not constant. Three equations have been derived for PCV, two by Becher et al. (3) and one by van der Meijden et al. (eq 7) (4). Becher derived a very complex equation considering not only the decelerating flow pattern but also the pressure rise time. We will not discuss this equation here but refer to the original paper. They also derived a surrogate formula which is an approximation with the advantage that the parameters are readily available (eq 8).

$$MP = 0.098 \cdot RR \cdot \Delta V \cdot \left(PEEP + P_{insp} \cdot \left(1 - e^{-\frac{T_{insp}}{R \cdot C}} \right) \right) \quad (7)$$

$$MP = 0.098 \cdot RR \cdot \Delta V \cdot (PEEP + P_{insp}) \quad (8)$$

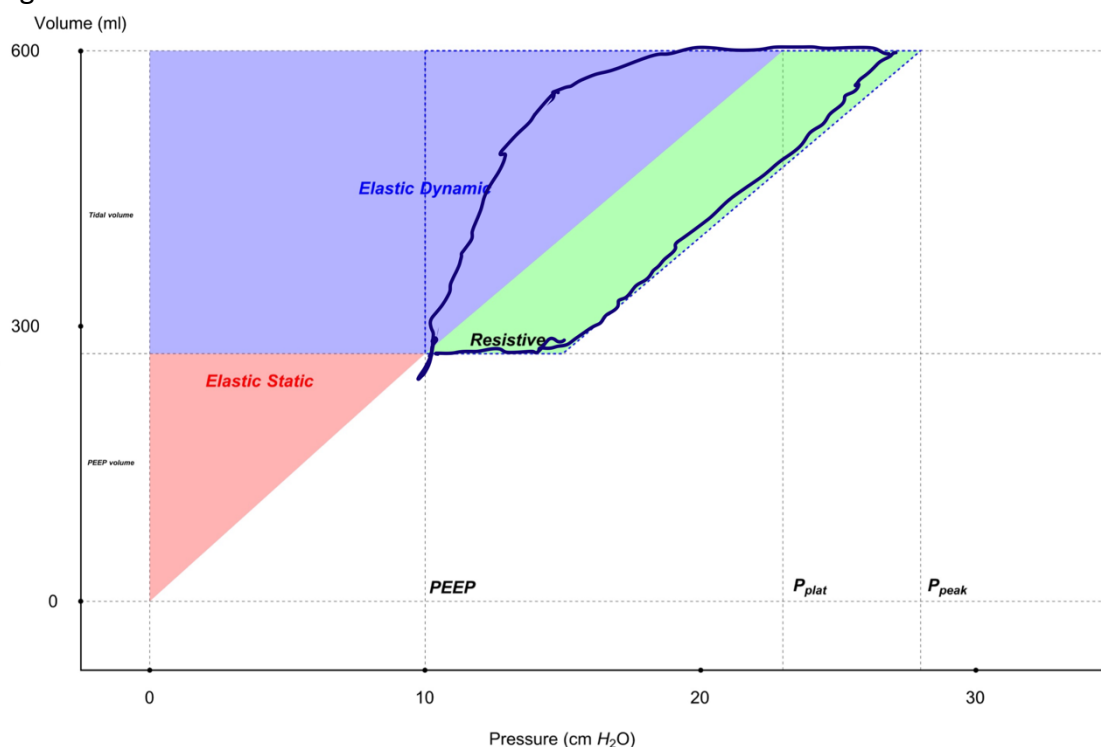
Where MP is mechanical power; RR is respiratory frequency; ΔV is tidal volume, P_{insp} is the peak pressure – peep, R is resistance, C is compliance and T_{insp} is the inspiratory time.

3 Measurement of work; the geometric method

The algebraic are very useful for retrospective research and estimation of the mechanical power at the bedside. However, they are approximations of reality only. This is because mechanical ventilation is a thermodynamic process. The work done by a thermodynamic system depends not only on the initial and final states, but also on the intermediate states – that is, on the Pressure-Volume path. This means that the inspiratory limb of the PV loop, which describes the intermediate states of the system, must be obtained for the exact calculation of the work done during inflation (1). Measurement of work using the inspiratory limb of the PV loop is often called the geometric method because one uses numerical integration to calculate the area between the inspiratory limb of the PV-loop and the zero-pressure axis, often by means of a trapezoid function. We will call the geometric method also the measured work in contrast to the work calculated with above mentioned equations.

In figure 8 a PV loop is plotted on the geometric representation of the work of a volume-controlled breath. The inspiratory limb of the PV Loop follows the geometric representation. The descending loop doesn't but is not used in calculation of the mechanical power

Figure 8.

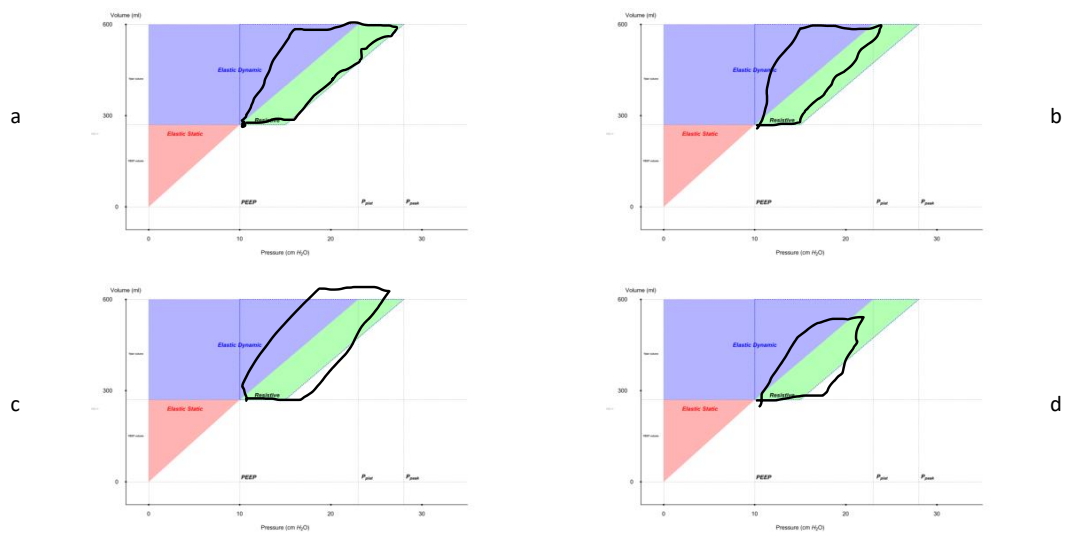


The algebraic and measured work can deviate as has been shown by Gattinoni et al. In the patient group with ARDS ventilated with a PEEP of 15 cm H₂O the calculated mechanical

power overestimated the measured mechanical power in the regions where the mechanical power was high. This is from a clinical standpoint the most interesting region. This problem is less or non-existent in patient with no or less severe lung injury or people ventilated with low PEEP (1) (5).

Figure 9 shows that different PV loops from the same patient do not always follow the idealized loop of the geometric representation. This can average out leading to concordance between calculation and measurement, but it can also lead to over or underestimation of the mechanical power when only using algebraic methods.

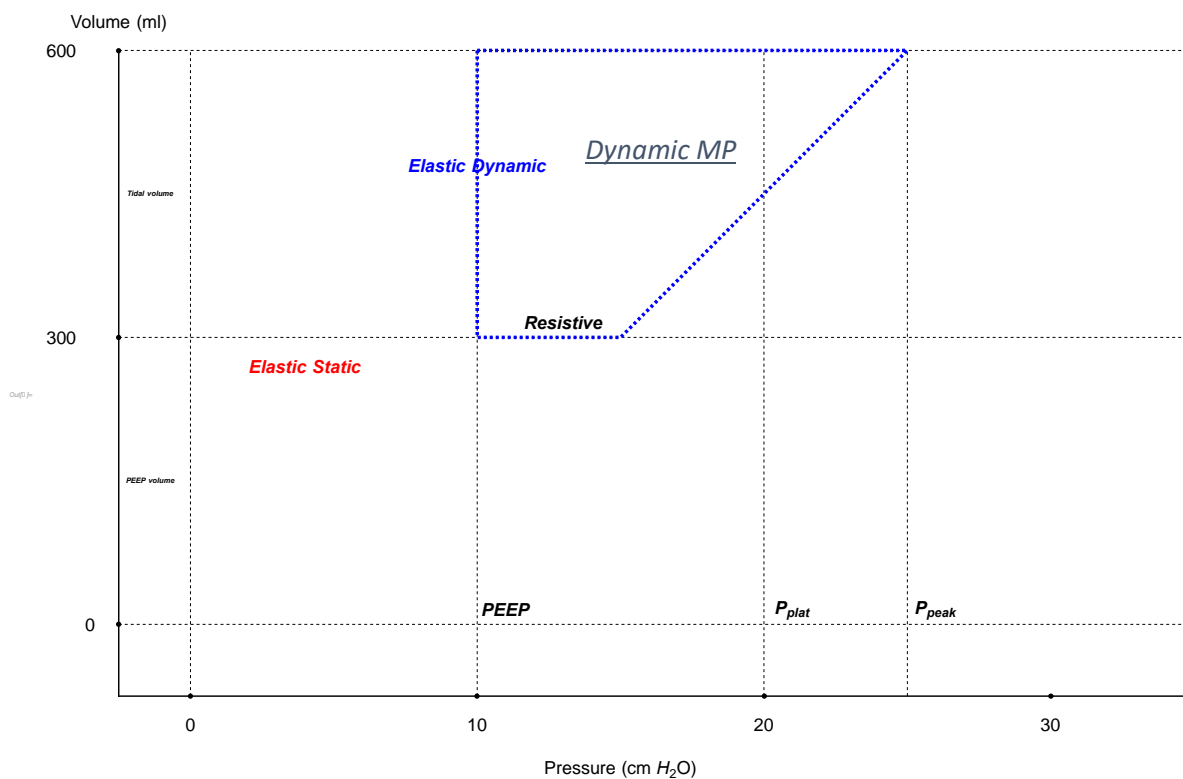
Figure 9



4. Dynamic and Transpulmonary mechanical power

A higher Mechanical power is associated with VILI and mortality (6) (7). And patients with a high mechanical power are more likely to receive vv-ECMO therapy for respiratory failure (8). A higher PEEP leads to a higher mechanical power, but a higher PEEP can also be beneficial for the right patients with severe ARDS (9) (10) (11). It is proposed by a few authors not to use the mechanical power as a whole but to use parts of the mechanical power (12) (13). Different methods have been proposed. We use as dynamic MP (work of a breath times frequency) the area between the inspiratory limb of the PV-loop and the PEEP axis, which is the area between the blue dashed polygon in figure 10. This is what Rocco et al. call the driving power plus the resistive component (12). It is still under discussion if you can just split up the mechanical power in its different components and how they relate to VILI and mortality. We need more studies to answer these questions. However, it should be stressed that the dynamic work or dynamic MP, as we or other authors describe it, from a physics point is not work nor power.

Figure 10.



The mechanical power describes, as said, only the work done during inflation during a minute of the total respiratory system, i.e., lung and chest wall. Clearly, we are mainly interested in the energy expenditure to the lung. This means that it is probable that the transpulmonary mechanical power is more important than the mechanical power per se. It is, however, difficult to establish the transpulmonary zero-pressure axis, i.e., the transpulmonary pressure of the FRC. Therefore, we use only the dynamic part of the

transpulmonary MP, which is the area between the inspiratory limb of the transpulmonary PV-loop and the transpulmonary pressure axis at the start of the inspiration.

Conclusion

The mechanical power is defined as the sum of the work done by the ventilator on the respiratory system (tubes included) during inflation in one minute. The work of a single breath (inflation) is defined as the area between the inspiratory limb of the PV loop and the zero-pressure axis. For exact measurement of the mechanical power the PV loop is needed. The mechanical power can be approximated with equations.

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