Ventilator-related causes of lung injury: the mechanical power.

Electronic supplement

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E-1. Mechanical power and positive end-expiratory pressure

For many years, the literature on the respiratory work referred to the end-expiratory pressure point as a “zero” point on the x-axis. Each movement from this ideal zero (i.e. ΔP), once multiplied by the corresponding variation in volume (i.e. ΔV), actually represents the change in energy/work. The classical literature, however, refers to ZEEP conditions, where the P=0 point equals the atmospheric pressure. For analogy, the papers referring to PEEP just translated the zero point to the PEEP level. This approach may lead to a common belief that PEEP does not contribute to the mechanical energy, or power, if we express the energy per unit of time.

However, as the lung roughly behaves as a spring, the force at any given “position” (i.e. at any given level of lung distension) is function of the position itself. In fact, in a spring F=k*x (as first approximation) so the position matters, as the force is not constant, but is a function of the position x.

If we want to expand (or compress) a spring for a length of 4L starting from the resting position in, say, four equal steps, we need four different amounts of energy (where A is the energy of the first step):

- step 1, from 0 to L = k*L*L*0.5 (1 A)
- step 2, from L to 2L = k*4*L*L*0.5 - k*L*L*0.5 (3 A)
- step 3, from 2L to 3L = k*9*L*L*0.5 - k*4*L*L*0.5 (5 A)
- step 4, from 3L to 4L = k*16*L*L*0.5 - k*9*L*L*0.5 (7 A)

Summing all up, we obtain k*16*L*L*0.5, thus the total energy to reach 4L is \(0.5*k *x^2\) → \(0.5*k*16*L^2\).

PEEP behaves like a rest on one of the intermediate steps (say on step 2, having used 3A+1A energy to reach this point from the start at 0). Then, to go forward from there (say up to step
4) we need \((5 \ A + 7 \ A = 12 \ A)\) energy to reach the end point. So the total energy at the end is 16 A, the energy used to reach PEEP is 4 A but energy used to reach the end from PEEP is 12 A. In the figure below, we represent graphically the above equations.

As shown in the figure, the amount of energy required to reach level 2 is 4A, while the energy required to reach level 4 starting from level 2 (i.e. the same \(\Delta V\) change) is 12A. This, as stated above, happens because the force is proportional to the distance, which is exactly as to say that the pressure is proportional to the volume. Therefore, to expand the system of 2 units of volume starting from ZEEP requires 4A of energy, while to expand the system of 2 units of volume starting from PEEP requires 12A of energy.
E-2. Simplification of the main equation

We chose to present the mechanical power as we did in the equation 6 of the main manuscript, as its meaning may be easier understood as its components reflect the common ventilator’s settings. However, the equation 6 maybe easily simplified as shown here below.

Knowing that Raw=(P\text{peak}−P\text{plat})/F and F=ΔV/\text{T}\text{insp}, the equation 3 in the main manuscript can be rewritten as follows:

\[ E_{\text{breath}} = \Delta V^2 \cdot E_{Lrs} \cdot \frac{1}{2} + \Delta V \cdot (P_{\text{peak}} - P_{\text{plat}}) + \Delta V \cdot \text{PEEP} \] (I)

Knowing that EL\text{rs}=\Delta P_{aw}/\Delta V, the equation (I) can be rewritten as follows:

\[ E_{\text{breath}} = \Delta V \cdot \left( \frac{1}{2} \cdot \Delta P_{aw} + P_{\text{peak}} - P_{\text{plat}} + \text{PEEP} \right) \] (II)

Where ΔP_{aw}=P_{plat}−\text{PEEP}. Accordingly:

\[ E_{\text{breath}} = \Delta V \cdot \left[ P_{\text{peak}} - \frac{1}{2} \cdot (P_{\text{plat}} - \text{PEEP}) \right] \] (III)

Or:

\[ E_{\text{breath}} = \Delta V \cdot \left( P_{\text{peak}} - \frac{1}{2} \cdot \Delta P_{aw} \right) \] (IV)

So:

\[ \text{Power}_{rs} = 0.098 \cdot RR \cdot \Delta V \cdot \left( P_{\text{peak}} - \frac{1}{2} \cdot \Delta P_{aw} \right) \] (V)
E-3. Computation of the mechanical power to the lung

The mechanical power delivered to the lung implies the use of the transpulmonary pressure \( P_L \) instead of the airway pressure at \( P_{plat} \) and at PEEP. The relationship between \( P_L \) and \( P_{aw} \) (either \( P_{plat} \) or PEEP) is expressed by \( P_L = P_{aw} \cdot (\frac{E_L}{E_{rs}}) \), where \( E_L \) is the elastance of the lung.

Therefore, substituting in the equation 6 of the main manuscript:

\[
\text{Power}_L = 0.098 \cdot RR \cdot \left\{ \Delta V^2 \cdot \left[ \frac{1}{2} \cdot E_L + RR \cdot \frac{(1+F_E)}{60+IE} \cdot R_{aw} \right] + \Delta V \cdot \text{PEEP} \cdot \frac{E_L}{E_{rs}} \right\}
\]

Where \( \text{Power}_L \) is the mechanical power delivered to the lung.

From the above formula, it is possible to calculate the effects of changing whatever variable (tidal volume, driving pressure, respiratory rate, resistance) on the mechanical power applied to the lung.