Mechanical power and Power Compliance Index in independent lung ventilation. New insight

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Abstract

Background
Unilateral lung disease (ULD) requiring mechanical ventilation is a unique challenge due to individual and interactive lung mechanics. The distribution of volume and pressure may not be even due to inequities in compliance and resistance. Independent lung ventilation (ILV) is a strategy to manage ULD but is not commonly employed. We assessed the mechanical power (MP) between single lung ventilation (SLV) and ILV in a dual lung model with different compliances.
Methods
A passive lung model with two different compliances (30 ml/cmH_2O and 10 ml/cmH_2O) and a predicted body weight of 65 kg was used to simulated ULD and ILV. In SLV the ventilator was set with the following: tidal volume (V_T) 400 ml, PEEP 7, RR 20, I:E 1:2. In ILV, each lung was given a separate ventilator with equivalent settings to SLV: V_T 300 ml, PEEP 7, RR 20, I:E 1:2 in the more compliant lung (MCL) and V_T 100 ml, PEEP 7, RR 20, I:E 1:2 in the less compliant lung (LCL). The study was repeated with different PEEP levels and different ventilator modes, volume (VCV) and pressure control (PCV). PEEP was set according to the compliance: V_T 300 ml, PEEP 8, RR 20, I:E 1:2 in the MCL and V_T 100 ml, PEEP 10, RR 20, I:E 1:2 in the LCL. The MP in each study and compared SLV to the combined results from each lung in ILV. MP was indexed to the compliance in all the studies
Results
The MP was significantly lower in VCV compared to PCV in all studies. In VCV, the total MP in SLV was 12.61 J/min compared to 11.39 J/min in the combined lungs with the same PEEP levels (8.84 MCL and 2.55 LCL) ($P < 0.001$). The total MP in SLV was also higher when comparing to ILV with different PEEP levels 12.57 J/min (9.43 MCL and 3.01LCL) ($P < 0.001$). In PCV, the total MP was 14.25 J/min which was higher compared to 13.22 in the combined lungs with the same PEEP levels (9.88 MCL and 3.32 LCL) ($P < 0.001$) however, the MP was lower compared to 14.55 in the combined lungs with different PEEP levels (10.58 MCL and 3.92 LCL) ($P < 0.001$).The Power Compliance Index (PCI) was significantly lower in ILV with same PEEP level (0.295 MCL and0.255 LCL, compared to 0.315 in the SLV) and similar in the different PEEP levels (0.314 MCL and , 0.314 LCL, compared to 0.315 in the SLV) in VCV. The PCI was significantly lower in the ILV with the same PEEP level (0.329 MCL, 0.332 LCL compared to 0.356 in the SLV). In the different PEEP levels, the MCL was less (0.352), and higher in the LCL (0.392) compared to the SLV (0.356) in PCV.
Conclusions
ILV can be achieved with lower MP in VCV using the same or higher PEEP levels than SLV, however in PCV the MP was less using the same PEEP but higher using different PEEP levels. Indexing the MP to compliance can be more meaningful in interpreting the results than the MP alone. Further studies are needed to confirm our findings.

Keywords: Independent lung ventilation, Unilateral lung disease, Mechanical power, Power Compliance Index

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Introduction

One of the principal goals of mechanical ventilation is to reduce the incidence of ventilator induced lung injury (VILI), however this presents a unique challenge in unilateral lung pathologies. [1] Due to the heterogeneity of compliance in the lungs in unilateral disease, conventional modes of ventilation may predispose both lungs to VILI, where barotrauma, volutrauma, and biotrauma are experienced by the lung with higher compliance, and the lung with lower compliance experiences atelectasis with atelectrauma and biotrauma. [2]

In many cases, conventional modes of ventilation can be applied effectively, however the asymmetry of disease may lead to refractory respiratory failure. [1] In this scenario, independent lung ventilation (ILV) may be advantageous to individualize ventilatory parameters for each lung. The tidal volume received by each lung during single lung ventilation can be predicted if each lung compliance is known: Volume = Compliance x Pressure. Because the two lungs are connected in parallel, the compliances share the same pressure and act like resistors in series, thus the total compliance of both lungs is equal to the sum compliance of both lungs.

$$V_{tot} = V_1 + V_2$$

$$V_{tot} = PC_1 + PC_2 = P\,(C_1 + C_2) = PC_{tot}$$

$$C_{tot} = V_{tot} / P = (C_1 + C_2)$$

However, it is not possible to determine the compliance and resistance in each separate lung in single lung ventilation. ILV allows the assessment of lung mechanics separately and allows personalized protective ventilation with different tidal volumes, airway pressures, PEEP delivered to each lung, depending on its mechanics.

While ILV is routinely performed for lung surgeries, it is seldom used in the critical care setting. Aside from the mechanical advantages of separating lung ventilation, ILV may also have the added benefit of separating the lungs physically to prevent contamination of the healthy lung from the inflammatory milieu of the diseased lung such as in pneumonia. [3]

There are no clear guidelines for the use of ILV, however case reports and case series have successfully utilized this strategy with asymmetric lung disease including in pneumonia, [4-7] trauma, [5,8,9,10] pulmonary edema, [11] pulmonary hemorrhage, [6] bronchopleural fistulas. [12-14] and even acute respiratory distress syndrome. [9,14]

The downsides to ILV include significant hypoxemia during pauses in ventilation which occurs at the placement of the double lumen tube and evaluation of separation. This may be problematic in patients with already low functional reserve. In addition, the double lumen tube has a low volume, high pressure cuff which may predispose to bronchial ischemia, stenosis, or rupture in patients requiring prolonged periods of intubation, as may be seen in the critical care setting. [3]

Meanwhile, mechanical power is a single variable that describes the mechanical forces experienced by lung per unit time by considering ventilatory parameters that can contribute to VILI including respiratory rate, airflow, tidal volume, tidal pressure (also known as driving pressure or inspiratory pressure), and positive end expiratory pressure (PEEP). [15,16] Higher mechanical power has been associated with increased mortality in several retrospective studies. [17,18]
We therefore assessed the mechanical power between single lung ventilation and ILV in a two lung model.

Methods

Using a dual lung simulator (TTL, Michigan Instruments, Michigan, USA), we constructed a two compartment passive lung model with an ideal body weight (IBW) 65 kg with different compliances. One lung was set at a compliance of 30 ml/cmH_2O, while the other was set at compliance of 10 ml/cmH_2O for a combined compliance of 40 ml/cmH_2O. In the single ventilator strategy, we ventilated both lungs using the settings: tidal volume 400 ml, PEEP 7 cmH_2O, RR 20, I:E 1:2. In the ILV strategy, each lung was ventilated with a different ventilator with equivalent settings: tidal volume 300 ml, PEEP 7cmH_2O , RR 20, I:E 1:2 in the more compliant lung and tidal volume 100 ml, PEEP 7cmH_2O, RR 20, I:E 1:2 in the less compliant lung. The PEEP levels were chosen using a quasi-static pressure-volume curve (P-V curve) using the low inflection point as the reference point.

We repeated the experiment with the same tidal volumes but different PEEP levels according to the compliance of each lung: tidal volume 300 ml, PEEP 8 cmH_2O, RR 20, I:E 1:2 in the more compliant lung and tidal volume 100 ml, PEEP 10 cmH_2O, RR 20, I:E 1:2 in the less compliant lung. The experiments were repeated with two different modes: volume and pressure controlled. Ventilators used were Bellavista™ 1000e Ventilators (Vyaire Medical, Illinois, USA). Figures 1 and 2 illustrate the study.

We calculated the mechanical power in each experiment and compared the single lung ventilation to the combined results from each lung in the ILV strategy. We also indexed the MP to the compliance in all the experiments. Comparisons between VCV and PCV were done using T-test. Comparison between the variables of mechanical power and power compliance index in SLV and ILV using same and different PEEP in each mode were done using analysis of variance (single factor ANOVA) with post Hoc Tukey test.

Figure 1: Two ventilators and simulator used in the study

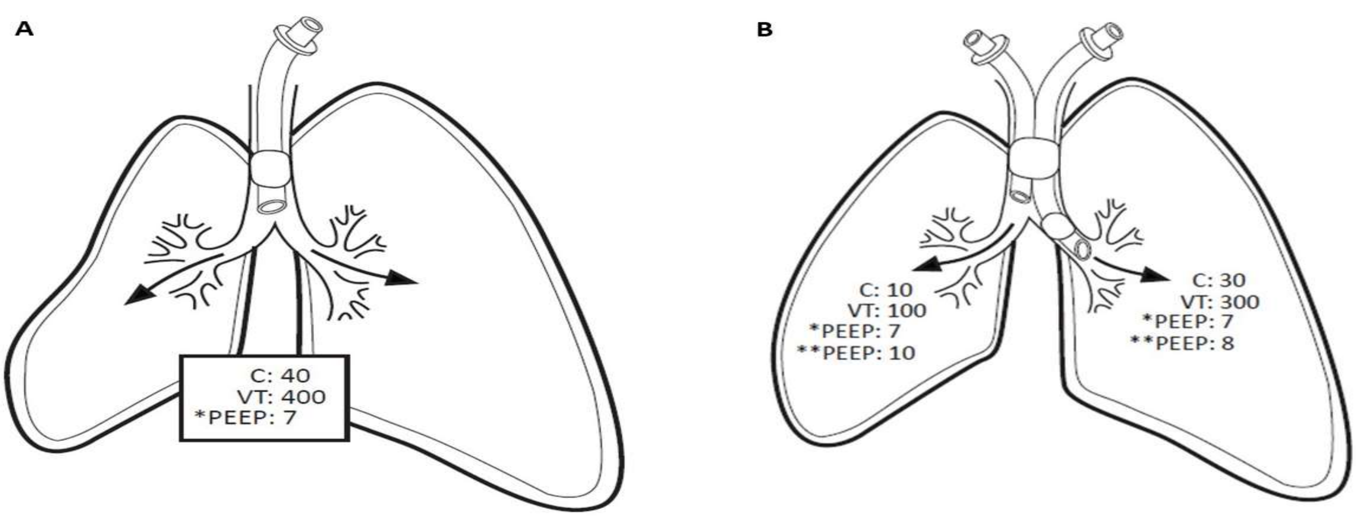

Figure 2: Illustration of the study. A: Single lung ventilation. B: ILV. * Same PEEP level of 7, ** Different PEEP levels of 8 and 10 cmH_2O. C: Compliance, V_T: tidal volume. Illustration by Robert Cabbat

Results

Results are summarized in Tables 1, 2, 3, 4 and Figure 3. The mechanical power was significantly lower in the volume-controlled mode compared to the pressure-controlled mode in all experiments. In the volume-controlled mode, the total mechanical power in single lung ventilation was 12.61 J/min which was statistically significantly higher compared to 11.39 in the combined lungs under ILV with equivalent PEEP levels (8.84 in the more compliant and 2.55 in the less compliant) and was statistically significantly higher compared to compared to 12.57 in the combined lungs under ILV with different PEEP levels (9.43 in the more compliant and 3.01 in the less compliant). In the pressure-controlled mode, the total mechanical power was 14.25 J/min which was statistically significantly higher compared to 13.22 in the combined lungs with the same PEEP levels (9.88 in the more compliant and 3.32 in the less compliant) and was statistically significantly lower compared to compared to 14.55 in the combined lungs with different (10.58 in the more compliant and 3.92 in the less compliant).

In VCV, the Power Compliance Index (PCI) was significantly lower in the independent lung ventilation with same PEEP level (0.295 in the more compliant lung, 0.255 in the less compliant lung compared to 0.315 in the single lung ventilation) but not significantly different in the different PEEP levels (0.314 in the more compliant lung, 0.314 in the less compliant lung compared to 0.315 in the single lung ventilation). In the pressure-controlled mode, the Power Compliance Index was significantly lower in the ILV with same PEEP level (0.329 in the more compliant lung, 0.332 in the less compliant lung compared to 0.356 in the single lung ventilation), and in the different PEEP levels, the more compliant lung was less (0.352), and higher in the less compliant lung (0.392) compared to the single lung ventilation (0.356).

	VCV	**PCV**	**P value**
SLV	12.61 ± 0.01	14.25 ± 0.01	< 0.001
ILV same PEEP	11.39 ± 0.05	13.22 ± 0.06	< 0.001
ILV different PEEP	12.57 ± 0.06	14.52 ± 0.08	< 0.001

Table 1: T-Test comparing mechanical power during single lung ventilation and independent lung ventilation between volume-controlled mode (VCV) to pressure-controlled mode (PCV). SLV: single lung ventilation, ILV: independent lung ventilation

	Single Lung 40	**Independent Lung 30 Independent Lung 10**	**P value CI**
VCV Same PEEP	12.61 ± 0.01	11.39 ± 0.05 (8.84 + 2.55)	< 0.001 (-1.22 -1.21)
VCV Different PEEP	12.61 ± 0.01	12.57 ± 0.06 (9.43 + 3.01)	< 0.001 (-0.05 -0.034)
PCV Same PEEP	14.25 ± 0.08	13.22 ± 0.06 (9.88 + 3.32)	< 0.001 (1.02 - 1.03)
PCV Different PEEP	14.25 ± 0.01	14.52 ± 0.08 (10.58 + 3.92)	< 0.001 (-0.31 -0.23)

Table 2: T-Test comparing mechanical power between single lung ventilation and independent lung ventilation using same and different PEEP levels during volume-controlled mode (VCV) to pressure-controlled mode (PCV)

VCV same PEEP	Single Lung 40 0.315	Independent Lung 30 0.295	Independent Lung 10 0.255
Single Lung 40		P 0.02 (0.02 – 0.02)	P 0.05 (0.05 – 0.06)
Independent Lung 30			P 0.04 (0.04 – 0.02)
VCV different PEEP	**Single Lung 40** 0.315	**Independent Lung 30** 0.314	**Independent Lung 10** 0.314
Single Lung 40		P 0.09 (0.01 – 0.01)	P 0.15 (0.01 – 0.01)
Independent Lung 30			P 0.97 (0.01 – 0.01)

Table 3: Power Compliance Index in VCV. ANOVA same PEEP (P 0.01), different PEEP (P 0.068)

PCV same PEEP	Single Lung 40 0.356	Independent Lung 30 0.329	Independent Lung 10 0.332
Single Lung 40		P 0.03 (0.03 – 0.03)	P 0.02 (0.02 – 0.02)
Independent Lung 30			P 0.01 (0.01 – 0.01)
PCV different PEEP	**Single Lung 40** 0.356	**Independent Lung 30** 0.351	**Independent Lung 10** 0.392
Single Lung 40		P 0.01 (0.01 – 0.01)	P 0.01 (0.03 – 0.03)
Independent Lung 30			P 0.04 (0.04 – 0.01)

Table 4: Power Compliance Index in PCV. ANOVA same PEEP (P 0.01), different PEEP (P 0.01)

Figure 3: Bar histogram of Mechanical power (J/min) in VCV (left) and PCV (right) between SLV, ILV with same PEEP levels and ILV with different PEEP

Discussion

This study showed that independent lung ventilation contributes less mechanical power compared with single lung ventilation when volume-controlled ventilation is used with equivalent tidal volumes and PEEP levels and even higher PEEP levels than single lung ventilation. On the other hand, although independent lung ventilation by pressure-controlled ventilation contributes to less mechanical power with equivalent tidal volumes and PEEP to single lung ventilation, it contributes higher power with higher PEEP levels compared to single lung ventilation. It also showed that VCV with constant inspiratory flow, provides less power compared to PCV with equivalent tidal volumes and PEEP in both SLV and ILV.

Mechanical power can be calculated using the geometric method which measures the dynamic inspiratory area in the airway pressure and volume curve during the respiratory cycle. [19] In volume-controlled ventilation (VCV) there is a linear increase in airway pressure during inspiration [20] and inspiratory flow remains constant. While in pressure-controlled ventilation (PCV) the flow decelerates, while the pressure in the airways remains constant. This generates variation in inspiratory pressure (ΔP_{insp}) which is dependent on the resistance and the compliance of the respiratory system. [20] The different shapes of the pressure-volume curve under VCV and PCV explains the lower mechanical power in VCV compared to PCV despite the same tidal volume, inspiratory time, and PEEP levels (Figure 4). Given these findings, we concluded that volume-controlled ventilation would be the preferred setting when independent lung ventilation is utilized.

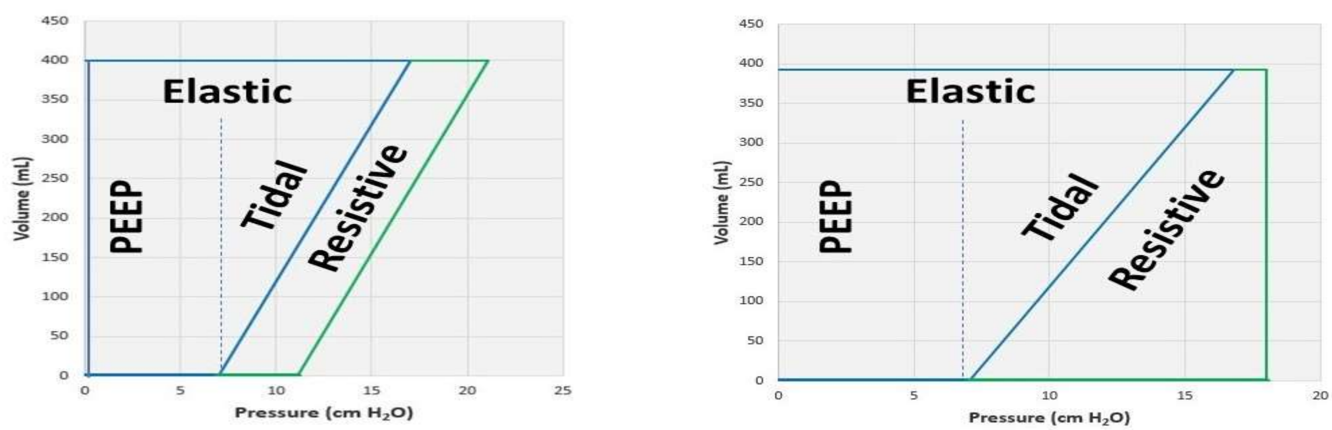

Figure 4: Components of total work in VCV (left) and PCV (right) using the geometrical volume-pressure curve. Total work equals the Elastic work (PEEP + Tidal work) plus the Resistive work.

As mentioned before, the mechanical power has been linked to mortality during mechanical ventilation [17, 18]. However, like previous studies in driving pressure, the ratio indexing the tidal volume and the compliance, has an association with increased survival in patients with acute respiratory distress syndrome. Normalizing or indexing the mechanical power to the compliance of the lung (Trans-pulmonary mechanical power) or the amount of aerated lung might be more meaningful than mechanical power alone, as it represents the amount of energy delivered to a specific injured unit. [21,22]

Theoretically, a well aerated lung with better compliance will require less mechanical power i.e. a lower Power Compliance Index or higher Power Elastance Index, versus a non-aerated lung with poorer compliance which requires a higher mechanical power i.e. higher Power Compliance Index or lower Power Elastance index to achieve targets of ventilation. Some authors suggested that a well aerated compliant lung might be less vulnerable to develop VILI in response to mechanical power, [23] on the other hand some suggested that a healthy lung might be more vulnerable to injury versus an already injured lung. [24]

To our knowledge, our study is only the second study to index the mechanical power to the compliance. In a retrospective study of ARDS, Coppola and colleagues found that the mechanical power alone did not correlate with mortality, however, the mechanical power and trans-pulmonary mechanical power indexed to the compliance and inflated lung tissue did correlate with mortality. [22] We coin the term Power Compliance Index. This allows us to compare the power exerted to different compliances between single lung ventilation and in independent lung ventilation. It also helps us understand the effect of mechanical power in the context of the severity of the diseased lungs.

Our results should be reviewed in the context of some limitations. Firstly, the study was performed to simulate a passive patient only due to difficulty in calculating or measuring the mechanical power in an active patient. To accurately calculate the mechanical power in an active patient would require the knowledge of muscle pressure and muscle work using an esophageal balloon or other methods not commonly used in clinical practice. [25] Additionally, it is not yet clear how the active patients' work would contribute to the mechanical power in the different modes. For example, it might be additive in pressure control with increased total power, which may reduce the ventilator contribution to power with unchanged total power in the volume-controlled mode. Secondly, the use of a lung simulator doesn't allow us to examine other important measures such as oxygenation and ventilation. Third, the tidal volumes and PEEP levels in our study were based on the respiratory mechanics chosen, however there are an infinite combination of respiratory mechanics and compliance. Despite this, we believe that experiments involving different respiratory mechanics or compliances would parallel our results. Lastly, although our analyses showed a statistically significant difference, some of the differences between the mechanical power or the PCI are small and may not have clinical significance.

In conclusion, in the setting of unilateral lung disease, the independent lung ventilation delivered less mechanical power compared with single lung ventilation especially with utilization of volume-controlled ventilation. Power compliance index would be more meaningful than the mechanical power alone. More studies are needed to confirm our findings.

References

1. Thomas AR, Bryce TL. Ventilation in the patient with unilateral lung disease. Crit Care Clin 1998. 14(4): 743-773.

2. Dreyfuss D. Saumon G. Ventilator-induced lung injury: lessons from experimental studies. Am J Respir Crit Care Med1998; 157(1):294-323.

3. Berg S, Bittner EA, Berra L, et al. Independent lung ventilation: Implementation strategies and review of literature. World J Crit Care Med 2019; 8(4):49-58.

4. Fujita M, Tsuruta R, Oda Y, et al. Severe Legionella pneumonia successfully treated by independent lung ventilation with intrapulmonary percussive ventilation. Respirology 2008; 13(3):475-477.

5. Yamakawa K, Nakamori Y, Fujimi Set al. A novel technique of differential lung ventilation in the critical care setting. BMC Res Notes 2011; 4:134.

6. Graciano AL, Barton P, Luckett PM, et al. Feasibility of asynchronous independent lung high-frequency oscillatory ventilation in the management of acute hypoxemic respiratory failure: a case report. Crit Care Med 2000; 28(8):3075-3077.

7. Plötz FB, Hassing MB, Sibarani-Ponsen RD, et al. Differentiated HFO and CMV for independent lung ventilation in a pediatric patient. Intensive Care Med 2003; 29(10):1855.

8. Achar SK, Chaudhuri S, Krishna H, et al. Re-expansion pulmonary oedema - differential lung ventilation comes to the rescue. Indian J Anaesth 2014; 8(3):330-333.

9. Siegel JH, Stoklosa JC, Borg U, et al. Quantification of asymmetric lung pathophysiology as a guide to the use of simultaneous independent lung ventilation in posttraumatic and septic adult respiratory distress syndrome. Ann Surg 1985; 202(4):425-439.

10. Rico FR, Cheng JD, Gestring ML, et al. Mechanical ventilation strategies in massive chest trauma. Crit Care Clin 2007; 23(2):299-315.

11. Badesch DB, Zamora MR, Jones S, et al. Independent ventilation and ECMO for severe unilateral pulmonary edema after SLT for primary pulmonary hypertension. Chest 1995; 107(6):1766-7170.

12. Grotberg JC, Hyzy RC, De Cardenas J, et al. Bronchopleural fistula in the mechanically ventilated

patient: A Concise Review. Crit Care Med 2021; 49(2):292-301.

13. Parish JM, Gracey DR, Southorn PA, et al. Differential mechanical ventilation in respiratory failure due to severe unilateral lung disease. Mayo Clin Proc 1984; 59(12):822-888.

14. Minhas JS, Halligan K, Dargin JM. Independent lung ventilation in the management of ARDS and bronchopleural fistula. Heart Lung 2016; 45(3):258-260.

15. Cruz FF, Ball L, Rocco PRM, et al. Ventilator-induced lung injury during controlled ventilation in patients with acute respiratory distress syndrome: less is probably better. Expert Rev Respir Med 201; 12(5):403-414.

16. Gattinoni L, Tonetti T, Cressoni M, et al. Ventilator-related causes of lung injury: the mechanical power. Intensive Care Med. 2016; 42(10):1567-1575.

17. Botta M, Tsonas AM, Pillay J, et al; PRoVENT-COVID Collaborative Group. Ventilation management and clinical outcomes in invasively ventilated patients with COVID-19 (PRoVENT-COVID): a national, multicentre, observational cohort study. Lancet Respir Med 2021; 9(2):139-148.

18. Hong Y, Chen L, Pan Q, et al. Individualized mechanical power-based ventilation strategy for acute respiratory failure formalized by finite mixture modeling and dynamic treatment regimen. EClinicalMedicine 2021; 36:100898.

19. Chiumello D, Gotti M, Guanziroli M, et al. Bedside calculation of mechanical power during volume- and pressure-controlled mechanical ventilation. Crit Care 2020; 24(1):417.

20. Becher T, van der Staay M, Schädler D, Frerichs I, Weiler N. Calculation of mechanical power for pressure-controlled ventilation. Intensive Care Med 2019; 45(9):1321-1323.

21. Amato MB, Meade MO, Slutsky AS, et al. Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med 2015; 372(8):747-755.

22. Coppola S, Caccioppola A, Froio S, et al. Effect of mechanical power on intensive care mortality in ARDS patients. Crit Care 2020; 24(1):246.

23. Silva PL, Ball L, Rocco PRM, et al. Power to mechanical power to minimize ventilator-induced lung injury? Intensive Care Med Exp 2019; 7(Suppl 1):38.

24. Marini JJ. How I optimize power to avoid VILI. Critical Care 2019; 23(1): 326.

25. Hamahata NT, S.R., Yamasaki K, et al., Estimating actual inspiratory muscle pressure from airway occlusion pressure at 100 msec. Journal of Mechanical Ventilation 2020; 1(1):8-13.