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Mean airway pressure - Minute ventilation product (mM): A simple and universal surrogate equation to calculate mechanical power in both volume and pressure controlled ventilation

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Abstract

Introduction
Mechanical power represents the energy delivered by a mechanical ventilator onto the lungs. It incorporates all the variables participating in ventilator-induced lung injury, including driving pressure, tidal volume, positive end expiratory pressure, and respiratory rate. The pitfall of mechanical power is its mathematical complexity, as the gold standard method of calculation involves deriving the inspiratory area under the pressure-volume curve of each breath. Prior studies attempted to create simplified equations, they lack clinical utility as calculations cannot be done by solely looking at ventilator settings or they require manipulation of variables. There are also different formulas depending on the type of the mode of ventilation used. This study offers a simplified, universal equation called the mean airway pressure - Minute ventilation product (mM equation) which renders mechanical power clinical application more feasible at the bedside.

Methods and Statistics
Data collection used the online SIVA simulator, which simulate mechanical ventilation and calculate the geometrical area of the inspiratory limb of the pressure-volume curve. Different combinations of passive scenarios with varying compliances (10-80 ml/cmH_2O) and resistances (5-30 cmH_2O/L/S) in each the VCV and PCV modes were accomplished by adjusting ventilator settings with respiratory rate (5-40 BPM), tidal volume (150-700 mL), DP (5-30 cmH_2O), and PEEP (0-15 cmH_2O), with different inspiratory times in PCV and different flows rates in the VCV.
A total of 2,000 values were collected in each mode. Range of Mechanical power measured by the simulator: 0.1 - 105 J/min and range of mM equation (mean airway pressure x Minute ventilation): 0.37 - 820 cmH_2O/L/min.
Pearson correlation coefficients were calculated to compare the relationship of the mM equation to the measured MP, and linear regressions were used for predicting the MP derived from the mM equation in each mode separately and when combining all data from both modes. T-test for equal variance and Bland Altmann plot were used to compare the reference MP measured (MPR) from the simulator to the one derived from the Mm formula (MPD).

Results
There was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.931$), CI (0.961, 0.967) between the mM formula and the gold-standard method of calculating mechanical power for the combined two modes. For the VCV: there was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.936$), CI (-0.963, 0.971). For the PCV: there was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.936$), CI (-0.964, 0.970).
A linear regression model predicted the MP from the mM as follows: for both modes MP = 0.13 (mM) + 3.41, for PCV MP = 0.15 (mM) + 3.79, for VCV MP = 0.13 (mM) + 2.48.
The derived mechanical power from the mM was not statistically different (P 0.498) from the calculated reference MP using two sample T-tests assuming equal variance.
The Bland-Altman plot for VCV mode showed a mean of 0.78 with 95% CI (0.34, 1.22), SD (-13.27, 14.83). In PCV, a mean of - 0.53 with 95% CI (-0.68, -0.38), SD (-6.28, 5.22). For both modes, a mean of 0, with 95% CI (-0.2, 0.2), SD (-10.06, 10.05).

Conclusion
The mM equation and its MP derived formula is a reliable method of calculating mechanical power. The simplicity and universal nature of its calculation can provide significant clinical utility at the bedside. More studies are needed to validate this method of calculation.

Keywords: Mechanical power, mean airway pressure, minute ventilation

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Introduction

Mechanical ventilation is a life-saving intervention for patients with significant respiratory compromise, but unfortunately can cause subsequent damage of the lungs, referred to as ventilator induced lung injury (VILI). Several pathways have described the pathophysiology of VILI including volutrauma, barotrauma, atelectotrauma, ergotrauma, rheotrauma, and biotrauma. [1,2] It was not until 2000 when the ARDSnet ARMA trial [3] illustrated lung-protective medical practice; the study demonstrated patients on lower tidal volume ventilation had decreased mortality rates and a shorter number of days requiring mechanical ventilation.

Many patients on mechanical ventilation have acute respiratory distress syndrome (ARDS), thus the ventilation / perfusion ($\dot{V}/Q$) is unlikely to be evenly distributed throughout lung parenchyma. [4] Because of this, other factors like driving pressure, tidal volume, flow, end expiratory positive pressure, and respiratory rate have been incorporated to develop a more precise representation of VILI.

The mechanical power (MP) concept was introduced in 1962 by Engstrom and Norlander [5] and got more recognition after 2016's Gattinoni and colleagues [6] study. Mechanical power (MP) has emerged as a surrogate representing factors contributing to the risk of VILI. Composed of pressure, volume, flow, and respiratory rate, it quantifies the work per unit of time applied by a ventilator on the respiratory system. Consideration of MP allows for the consolidation of the aforementioned ventilatory parameters, unifying them as a single variable which clinicians and researchers may consider during the management of a patient on mechanical ventilation.

Mechanical power (i.e., work per unit of time or work per breath times breath rate) has been closely associated with mortality, [7-10] and in some studies [11,12] a level greater than 17 J/min was strongly associated with worsen mortality.

The pitfall of mechanical power is its mathematical complexity, as the gold standard method of calculation is through the numerical integration of the inspiratory limb of a pressure-volume curve. [13-19] This method of calculation is not practical in the clinical setting. Hence other equations have been proposed to counteract this issue. [8,13,18-20]

When comparing the different formulas for calculating mechanical power, an important consideration is the type of ventilation mode being used, such as volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV). This is because work per breath is the integral of pressure with respect to flow and VCV has different flow waveforms compared to PCV. Therefore, for each ventilation mode there are simplified and comprehensive equations which have different accuracies and hold intrinsic biases from the gold standard. [13,21] Figure 1 includes a short list of simplified equations for calculating MP.

More recently, a simplified formula only including the driving pressure and respiratory rate (4DPRR) was also proposed as a surrogate for MP and equivalent in its relationship to mortality. [9] However, a follow-up study by Paul and colleagues [22] did not confirm the same findings in COVID-19 patients with respiratory failure.

Mean Airway Pressure and Mechanical Power

Mean airway pressure ($\bar{P}_{aw}$) is the average pressure measured at the airway opening during the respiratory cycle. Prior literature has demonstrated $\bar{P}_{aw}$ to have a similar correlation as plateau pressure in predicting outcomes and patient mortality. [23,24] This is hypothesized to be because $\bar{P}_{aw}$ is closely associated with mean alveolar pressure and mean trans-alveolar pressure (alveolar - pleural) that represent the stress exerted on the lung parenchyma during mechanical ventilation. [24,25] Calculating $\bar{P}_{aw}$ can be either graphical or numerical, and vary according to ventilation mode; however, all take into account variables including the peak inspiratory, inspiratory time, and total cycle time. [26] In general, PCV delivers higher $\bar{P}_{aw}$ than VCV with the constant flow due to the nature of the square airway pressure. [27,28] Most ventilators display the $\bar{P}_{aw}$ on a breath-to-breath basis or an average of several respiratory cycles.

			MECHANICAL POWER (J/MIN)					
			POWER OF INSPIRATION ($cmH_20.L/min$)					Conversion factor
			WORK OF INSPIRATION ($cmH_20.L$)				RR (BPM)	
			VOLUME X	PRESSURE (cm H_20)				
				Elastic + static component	Elastic + dynamic component	Resistive component		
VCV	Simplified equation	Gattinoni et al	ΔV	Peak pressure- (plateau pressure- PEEP) / 20			RR	0.098
	Surrogate	Giosa et al	ΔV	(Peak pressure + PEEP+F/6) /20			RR	0.1
PCV	Surrogate	Becher et al	ΔV	PEEP	Pinsp. $(1 - e^{-Tinsp/T})$		RR	0.098
	Simplified equation	Becher et al	ΔV	PEEP	Pinsp		RR	0.098

Figure 1: Example of simplified equations used for calculation of mechanical power in the VCV and PCV As seen in the Formulas above, the tidal volume and the respiratory rate (minute ventilation) are constant between all the formulas. However, the surrogates representing pressure are variable within each mode. 0.098 is a conversion factor to convert to Joules/min. Δv: tidal volume, Pinsp: Inspiratory pressure, PEEP: Positive End Expiratory Pressure, RR: Respiratory rate

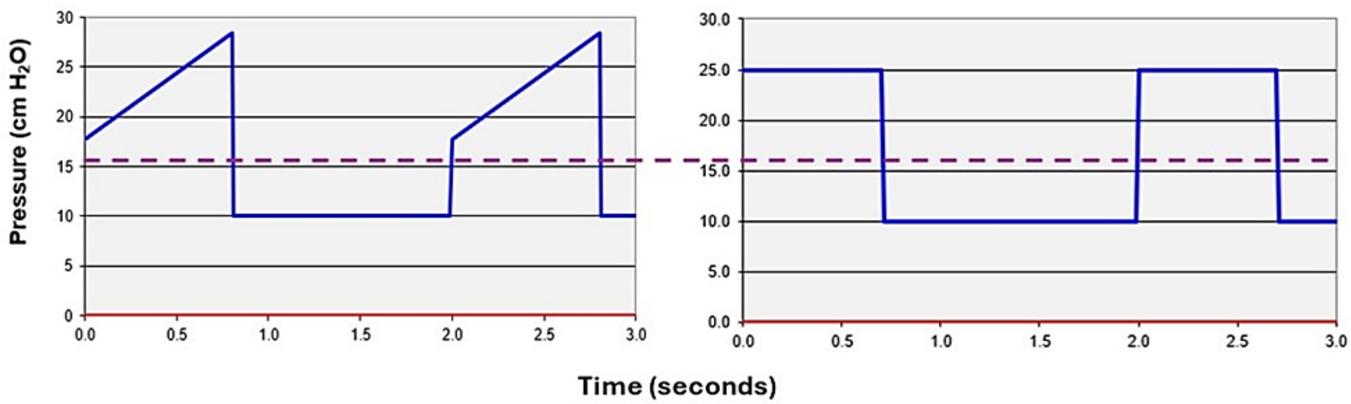

Figure 2: Airway pressure - time scale with the same $\bar{P}_{aw}$ (purple dashed line) in VCV (Left) and PCV (right). despite different peak inspiratory pressures and the same I:E.

The rationale of using mean airway pressure in estimating the mechanical power

A recent study evaluated the use of mean airway pressure instead of plateau pressure in mechanical power calculation in the VCV mode and found that the derived MP correlated well with the reference MP in patients with or without ARDS. [29]

The energy delivered to the lungs in one respiratory cycle can be approximated by the area under the pressure-volume curve. This is roughly represented as:

$$W = \int_{V_i}^{V_f} P\,dV$$

where *W* is the work done, *P* is the airway pressure, and *V* is the volume. Vf (volume final) − Vi (volume initial) is the tidal volume (VT)

Using mean airway pressure ($\bar{P}_{aw}$) simplifies this to:

$$W \approx \bar{P}_{aw} \times VT$$

Mechanical power is the work done per unit time. For a given respiratory rate (*RR*), the mechanical power can be expressed as:

$$\mathrm{MP} = W \times RR \approx \bar{P}_{aw} \times VT \times RR$$

Using the mean airway pressure as a proxy, provides a practical and simplified approach to estimate the average force exerted over the entire respiratory cycle. This is particularly useful because it encapsulates the cumulative effect of various phases of the breathing cycle (inspiration, expiration, and any pauses) in a single value, making the calculation more straightforward without losing significant accuracy.

The goal of this study is to offer a simple and universal equation called the mean airway pressure - Minute ventilation product (mM equation) while demonstrating its accuracy, in order to make the MP's clinical application more feasible at the bedside.

We hypothesized that a formula based on the $\bar{P}_{aw}$ x MV product will strongly correlate with the mechanical power derived from the pressure-volume curve (reference value) and that derived from the mM equation (derived value).

Figure 3: Example of automated display of Inspiratory (yellow circle), Tidal (green circle) and total (blue circle) mechanical power on a Bellavista 1000 e ventilator.

Methods and Statistical Analyses

Using the online SIVA simulator (Chatburn RL. Simulator Interface for Ventilatory Analysis (https://societymechanicalventilation.org/simulators/) that uses equations for passive ventilation. [30] Different passive scenarios of different compliances (10-80 ml/cmH_2O) and resistances (5-30 cmH_2O/L/s) combinations in each the volume and the pressure-controlled modes by adjusting different ventilator settings: respiratory rate 5-40 BPM, tidal volume 150-700 ml, DP 5-30 cmH_2O, PEEP 0-15 cmH_2O with different inspiratory times in PCV and different flows rates (constant or square flow pattern) in the VCV.

20 different combinations of resistances and compliances were created with 100 different ventilator settings in each for a total of 2,000 values that were collected in each mode. Mechanical power (ranged from 0.1 - 105 J/min) was measured via the current gold standard of geometrically deriving the area under the Pressure-Volume curve using the SIVA simulator. mM (ranged from 0.37 - 820 cmH_2O/L/min) was calculated from the correspondent values of the mean airway pressure and minute ventilation from the same simulator.

Statistical Analysis
Pearson correlation was used to compare the relationship of these equations to the measured reference MP (MP-R), and linear regression was used for predicting the derived MP from the mM equation (MP-D). T-test for equal variance and Bland Altmann plot were used to compare the reference MP from the one derived by the linear regression equation (MP-D) .

Results

There was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.931$), CI (0.961, 0.967) between the mM formula and the gold-standard method of calculating mechanical power for the combined two modes. For the VCV: there was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.936$), CI (-0.963, 0.971). For the PCV: there was a statistically significant linear relationship ($P < 0.001$) and strong correlation of determination ($R^2 = 0.936$), CI (-0.964, 0.970).

A linear regression model predicted the MP from the mM as follows:

For both modes MP = 0.13 (mM) + 3.41
For PCV MP = 0.15 (mM) + 3.79
For VCV MP = 0.13 (mM) + 2.48

The derived mechanical power (MP-D) from the mM was not statistically different (P 0.498) from the measured MP-R (reference) using two sample T-test assuming equal variance.

The Bland-Altman plot for VCV mode showed a mean of 0.78 with 95% CI (0.34, 1.22), SD (-13.27, 14.83). In PCV, a mean of -0.53 with 95% CI (-0.68, -0.38), SD (-6.28, 5.22). For both modes, a mean of 0, with 95% CI (-0.2, 0.2), SD (-10.06, 10.05).

The results are summarized in figures 4, 5, 6.

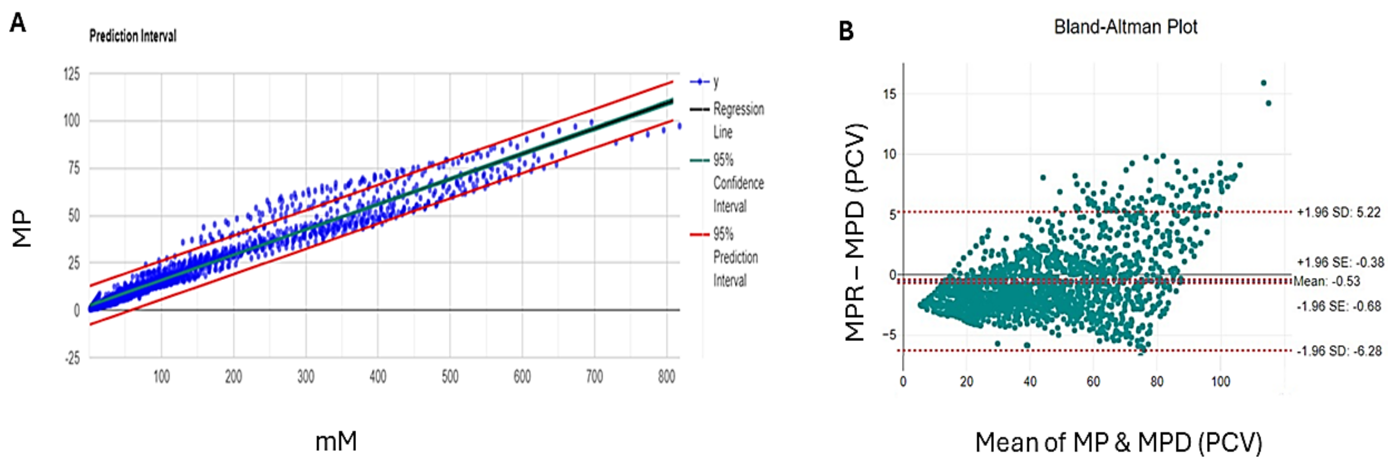

Figure 4A (left): Correlation between measured mechanical power (MPR) by simulator and the mM equation in PCV.
Figure 4B (right): Bland-Altman plot comparing the measured mechanical power (MPR) by simulator to the MP derived (MPD) from the mM equation in the PCV.

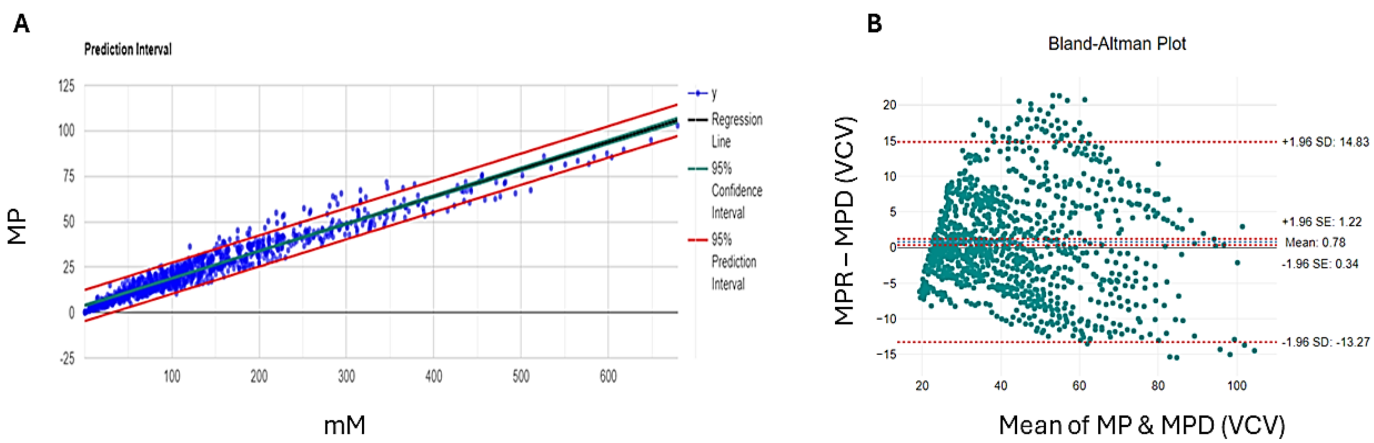

Figure 5A (left): Correlation between measured mechanical power (MPR) by simulator and the mM equation in VCV.
Figure 5B (right): Bland-Altman plot comparing the measured mechanical power (MPR) by simulator to the MP derived (MPD) from the mM equation in the VCV.

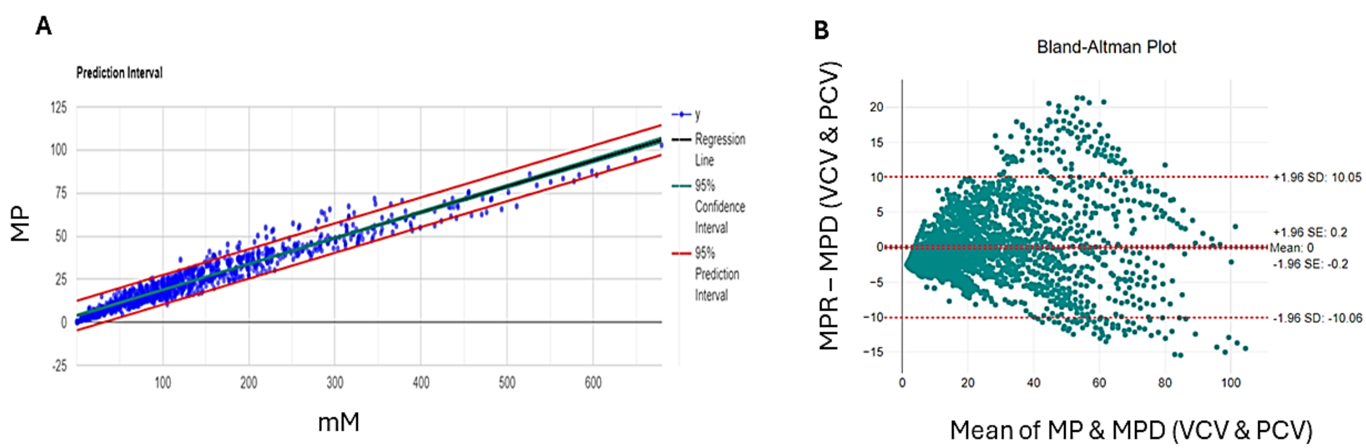

Figure 6A (left): Correlation between measured mechanical power (MPR) by simulator and the mM equation in the combined VCV and PCV.
Figure 4B (right): Bland-Altman plot comparing the measured mechanical power (MPR) by simulator to the MP derived (MPD) from the mM equation in the combined VCV and PCV.

mM	MP
710	100
672	95
636	90
600	85
562	80
528	75
488	70
452	65
415	60
378	55
342	50
305	45
268	40
235	35
195	30
158	25
120	20
85	15
48	10
11	5

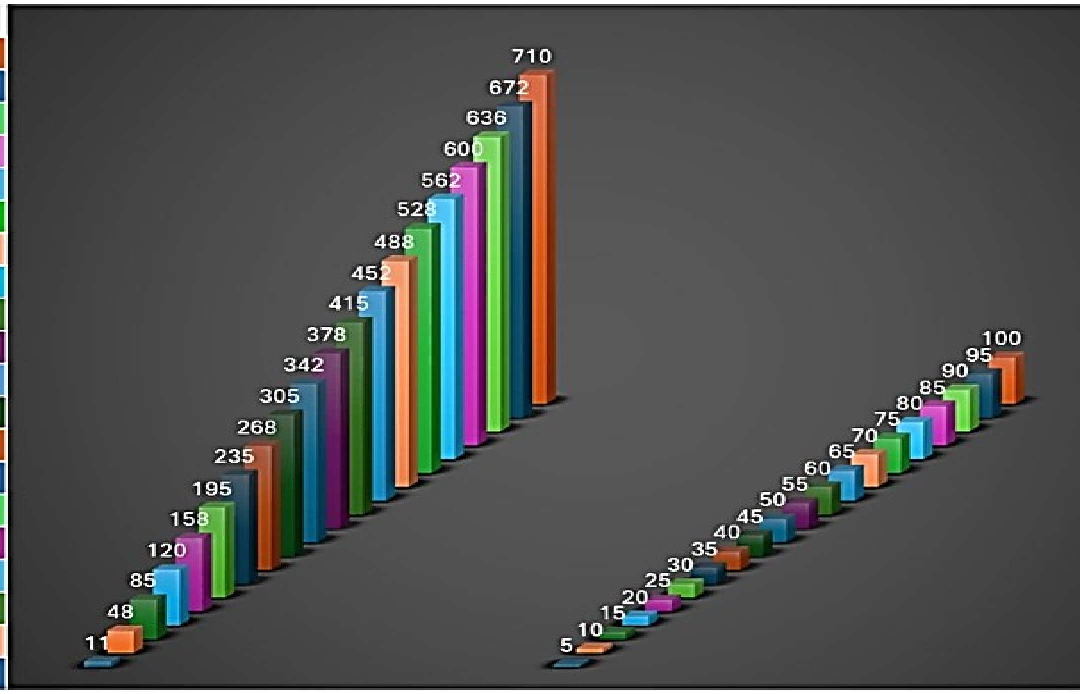

Figure 7: Graphical colored table and bar displays of the mM values with their correspondent MP values in increments of 5.

Discussion

Our results show an excellent correlation between the simplified mM formula and the gold standard of measuring the MPR using the geometrical area under the curve of the Inspiratory P-V curve. Additionally, when comparing the derived MP (MP-D) from the regression analysis to the reference value from the simulator, they were not significantly different. Furthermore, the mean differences and 1.93 SE (95% CI) were very narrow in the Bland-Altmann curves, further supporting that the MP-D from the mM formula is accurate.

The regression equations for the PCV: MP = 0.15 (mM) + 3.79, for VCV: MP = 0.13 (mM) + 2.48, and for both modes: MP = 0.13 (mM) +3.41. The MP in PCV is usually higher than VCV with the constant flow attributing to the shape of the P-V curve, our study confirms those findings. [31,32] The use of the combined formula might overestimate the MP in VCV and underestimate it in PCV.

It is important to note that the mM equation is not the MP but rather a simplified estimate. The formula can be expressed as $cmH_2O/L/min$ as it is a form of pressure multiplied by volume (work) per unit time. We didn't include the conversion factor of 0.098 (to convert to J/min) to further simplify the calculation. However, the MP-D is in J/min as it is derived from the reference measured MP.

In figure 7, we illustrate a visual graph and table for the average MP in increments of 5 with their corresponding mM, for example if the mM is below 85 then the MP is ≈ below 15, if between 85-120 then MP is ≈ between 15 - 20 so clinicians can quickly realize that they are reaching a MP level that is deemed too high or unsafe. [12] This might be an oversimplification and does not replace the actual calculation.

Mean airway pressure represents the overall effect of the different components of pressures exerted on the respiratory system (Peak, Plateau, PEEP) during the whole respiratory cycle. It has been correlated with mean alveolar pressure, hemodynamics, and mortality. [25] Thus its validity to calculate the ventilator work or energy is justified.

Mean airway pressure reflects the mean alveolar pressure consistently when the inspiratory and expiratory resistances are similar, however in conditions where the expiratory resistance is higher than the inspiratory and especially with high respiratory rate and intrinsic PEEP, mean airway pressures can seriously underestimate mean alveolar pressures.

$$\text{mean Palv} = \text{Paw} + (\dot{V}_E/60) \times (R_E - R_I)$$

where $\dot{V}_E$ is the expiratory flow, R_E is expiratory resistance, R_I is inspiratory resistance. [24,25]

In our calculations, we included cases of intrinsic PEEP (especially in the high compliance, high resistance, high respiratory rate) which could have slightly changed the results compared to no intrinsic PEEP.

Using mean airway pressure in calculating mechanical power is not novel, Chi and colleagues [29] used the mean airway pressure to derive a simplified formula during VCV with constant flow with no inspiratory pause and showed a good correlation with the formula proposed by Gattinoni [6] that uses an inspiratory pause to measure the plateau pressure. Our formula has the advantage of extra simplicity and the ability to utilize it in both the VCV with constant flow and the PCV with decelerating flow.

It is already recognized that mean airway pressure is extremely important in mechanical ventilation, as has been demonstrated in a study carried out on patients with ARDS and SARS-CoV-2 in subjects undergoing pressure-controlled ventilation, in which mean airway pressure proved to be a variable which can interfere with mortality. [32]

That's being said, it might have been more accurate to base our formula according to the mean inspiratory pressure instead of the mean airway pressure as we are calculating the inspiratory power. However, the mean inspiratory pressure is not an available measurement at the bedside in contrast to the mean airway pressure which would have made our equation rather impractical.

As seen in figure 1, there are different variations calculating MP from the reference value. Prior to adoption of new and improved equations, Gattinoni's linear equation was commonly used to calculate MP for VCV with constant flow. [6] However, it is limited as it can only calculate inspiratory MP. [33] Becher et al. then presented two equations for the PCV power estimation issue. [18] Their simplified equation removed rise time and represented pressure during inspiration as a square wave, which although provides mathematical simplicity, leads to decreased accuracy when rise time is not equal to zero. Although their comprehensive equation addresses this issue by accounting for rise time, it's calculation may be challenging for providers to perform at bedside, thus limiting its practicality. Van der Meijden and colleagues [34] attempted to simplify the equation for greater clinical application; however, subsequent studies tested this formula's validity on a larger sample size and demonstrated it yielded a lower accuracy compared to both Becher's comprehensive and simplified equations. [18]

The proposed mM equation addresses each of these issues. First, mM is an easy and practical method for calculating MP at bedside as it follows a simple slope - intercept formatting. Furthermore, it maintains versatility by being applicable for both PCV and VCV modes. Finally, since its derivative is the gold standard method of geometrically deriving the area under a pressure-volume curve, its high accuracy provides a reliable means for attaining reliable MP values, this is supported by amounts of data points attained through its reproducibility.

Other concerns have been raised for mechanical power calculations including the calculation of the inspiratory work or power and ignoring the expiratory limb or the hysteresis of the P-V curve. Indeed, there are expiratory energy transfer during exhalation in the opposite direction with different compliance and resistance than the inspiratory limb. [35] Our proposed formula uses the mean airway pressure which represents the airway pressure during inspiration and expiration which could make the calculations different from the inspiratory limb calculations used in current practice.

Additionally, concerns have been raised using PEEP in the calculation of mechanical power as PEEP is a static component of the mechanical power and it is probably the dynamic components that correlate with the VILI. This issue is still a subject of debate in the literature. [36] If indeed PEEP is deemed unreasonable to be included in the calculations, we could alternatively use the mean inspiratory tidal or driving pressure. This issue can be resolved by compartmentalizing the mechanical power into static (PEEP) and dynamic (Tidal) elastic, resistive compartments and comparing them in studies to evaluate which one is related to lung injury.

Effect of spontaneous breathing and auto-PEEP

In our study we had variable auto-PEEP developing especially in the high resistance, high compliance, high respiratory rate scenarios. Auto-PEEP increased the elastic work per breath and thus increased the whole MP, however the mM still moved in the same direction as the tidal volume changed in the PCV and PIP changed in the VCV. [37]

We conducted our calculation under passive conditions, where there were no inspiratory efforts. During active breathing, the airway pressure, flow, and esophageal pressure are affected simultaneously and counter-directionally, due to the overlapping actions of both the ventilator and the respiratory muscles. [38] It is intuitive to think that the spontaneous patient effort will exert different conditions on the P-V curve and thus the MP calculation. With the settings unchanged, we assume that the MP will be higher in PCV with spontaneous effort compared to the passive condition as the tidal volume will increase. On the other hand, the MP would decrease or stay the same in VCV with the spontaneous effort. Figure 8 shows an example from the SIVA simulator.

PCV — Passive

Passive	Ventilator Elastic Work (J)	0.57
	Ventilator Resistive Work (J)	0.24
	Ventilator Total Work (J)	0.81
Active	Ventilator Work (J)	0.85
	Patient Work (J)	0.00
	Total Work (J)	0.85
	Work Shift Index (%)	0
	Ventilator Inspiratory Power (W)	0.24
	Ventilator Inspiratory Power (J/min)	14.43

PCV — Active

Passive	Ventilator Elastic Work (J)	0.57
	Ventilator Resistive Work (J)	0.24
	Ventilator Total Work (J)	0.81
Active	Ventilator Work (J)	1.10
	Patient Work (J)	0.18
	Total Work (J)	1.28
	Work Shift Index (%)	14
	Ventilator Inspiratory Power (W)	0.31
	Ventilator Inspiratory Power (J/min)	18.69

VCV — Passive

Passive	Ventilator Elastic Work (J)	0.59
	Ventilator Resistive Work (J)	0.20
	Total Work (J)	0.78
Active	Ventilator Work (J)	0.79
	Patient Work (J)	0.00
	Total Work (J)	0.79
	Work Shift Index (%)	0
	Ventilator Inspiratory Power (W)	0.20
	Ventilator Inspiratory Power (J/min)	11.77

VCV — Active

Passive	Ventilator Elastic Work (J)	0.59
	Ventilator Resistive Work (J)	0.20
	Total Work (J)	0.78
Active	Ventilator Work (J)	0.67
	Patient Work (J)	0.12
	Total Work (J)	0.79
	Work Shift Index (%)	16
	Ventilator Inspiratory Power (W)	0.17
	Ventilator Inspiratory Power (J/min)	10.05

Figure 8: Top row is PCV, bottom row is VCV with passive condition on the left and active condition on the right (Pmus -5 cmH_2O) with resultants patient, ventilator and total work and power (red square)

Limitations

There were some limitations to this study. Notably, all the data points were collected from the online SIVA simulator which utilizes a single compartment lung model with fixed resistance and compliances. Because of this, the stimulator can mimic breathing mechanics but is unable to re-create hemodynamics or gas exchange or changing patient - ventilator interactions, it also lacks the ability to recreate advanced ventilator modes.

The simulator graphics are perfect lines where pressure and flow have zero rise time, which is not the case in real life mechanical ventilation. In practice, rise time is > 0 because it takes time for the ventilator to pressurize the circuit and airway albeit very short in new generation ventilators. Additionally, oscillations can happen from secretions or water condensations or air leaks.

The Bland-Altman plots showed some level of disagreement (plots above the upper limits of standard deviation) especially when the MP is elevated above 40 J/min (proportional bias). Those points represent 5% (outside the upper 95% CI). In current practice especially in the era of low tidal volume and DP, it is rare to have such an extreme levels of elevated MP.

Another limitation to the mM equation is that mean airway pressure cannot discriminate the different components of mechanical power. Mechanical power can be fragmented into different components including resistive, static (PEEP) and dynamic elastic (Tidal), and inspiratory power (Figure 3). [20,25,37] Rocco and colleagues found in an experimental ARDS animal model that the total power, rather than the driving power or resistive power alone, correlated well with VILI indicators. [38] Vassalli and colleagues in an experimental model with different components of the mechanical power but kept the sum value the same “iso-power” led to similar anatomical lung injury. [39]

We did not compare our equation with other established published equations for MP as this was not the aim of our study in hand.

Future Direction

The mM equation can be pursued in multiple directions. Conceptually, the same formula can be used for estimating trans-pulmonary MP from the mean trans-pulmonary pressures. The trans-pulmonary pressure corresponds to the stress exerted to the lungs only and the trans-pulmonary MP might be more relevant than the whole mechanical power in inducing VILI. [40,41] However, because of the irregularity of the pleural pressures and the heart artifacts might make it less precise to calculate the mean pressure.

The formula can be also used in other modes, even non-conventional modes like APRV [42] or HFOV. [43]

Another consideration is the automation of calculating MP. [44] For example, as with many scoring systems within medicine we may consider creating an online calculator where clinicians can input variables accessed through the ventilator home screen.

Another example may include incorporating MP calculations using this formula within modern ventilators. This would facilitate access to MP more readily. Until that establishment, the mM equation may serve as a tool for clinicians to use with any mechanical ventilator.

Conclusion

The mM equation and its MP derived formula is a novel, reliable method of estimating and calculating mechanical power that is a simpler method when compared to gold standard equations. The simplicity and universal nature of its calculation provides significant clinical utility that allows for the increased use of mechanical power at the bedside. Clinicians may consider using this equation in medical management of patients to minimize VILI.

References

1. AK AK, Anjum F. Ventilator-Induced Lung Injury (VILI). 2023 Apr 27. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan

2. Katira BH. Ventilator-Induced Lung Injury: Classic and Novel Concepts. Respir Care 2019; 64(6):629-637.

3. Acute Respiratory Distress Syndrome Network; Brower RG, Matthay MA, Morris A, et al. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000; 342(18):1301-1308.

4. Chiumello D, Carlesso E, Cadringher P, et. al. Lung stress and strain during mechanical ventilation for acute respiratory distress syndrome. Am J Respir Crit Care Med 2008; 178(4):346-355.

5. Engstrom CG, Norlander OP. A new method for analysis of respiratory work by measurements of the actual power as a function of gas flow, pressure and time. A preliminary report. Acta Anaesthesiol Scand 1962; 6:49-55.

6. 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.

7. Azizi BA, Munoz-Acuna R, Suleiman A. et al. Mechanical power and 30-day mortality in mechanically ventilated, critically ill patients with and without Coronavirus Disease-2019: a hospital registrystudy. J Intensive care 2023; 11:14.

8. Serpa Neto A, Deliberato RO, Johnson AEW, et al. Mechanical power of ventilation is associated with mortality in critically ill patients: an analysis of patients in two observational cohorts. Intensive Care Med 2018; 44:1914–1922.

9. Costa ELV, Slutsky AS, Brochard LJ, et al. Ventilatory variables and mechanical power in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2021; 204:303–311.

10. Kallet R. Bedside estimate of mechanical power (Part 4): Power intensity thresholds and mortality risk in ARDS. Resp Care 2023; 68(Suppl 10):3934776.

11. Schuijt MTU, Schultz MJ, Paulus F, et al. PRoVENT–COVID Collaborative Group Association of intensity of ventilation with 28-day mortality in COVID-19 patients with acute respiratory failure: insights from the PRoVENT-COVID study. Crit Care 2021; 25:283.

12. González-Castro A, Cuenca Fito E, Fernandez-Rodriguez A, et al. Mechanical power greater than 17 joules/min in patients with respiratory failure secondary to SARS-CoV-2 infection. Med Intensiva (Engl Ed). 2023; 47(2):115-117.

13. Trinkle CA, Broaddus RN, Sturgill JL, et al. Simple, accurate calculation of mechanical power in pressure controlled ventilation (PCV). Intensive Care Med Exp 2022; 10(1):22.

14. Paudel R, Trinkle CA, Waters CM, et al. Mechanical power: A new concept in mechanical ventilation. Am J Med Sci 2021; 362(6):537-545.

15. Caironi P, Langer T, Carlesso E, et al. Time to generate ventilator-induced lung injury among mammals with healthy lungs: a unifying hypothesis. Intensive Care Med 2011; 37(12):1913-1920.

16. Brunner JX, Wysocki M. Is there an optimal breath pattern to minimize stress and strain during mechanical ventilation? Intensive Care Med 2009; 35(8):1479-1483.

17. Valenza F, Guglielmi M, Irace M, et al. Positive end-expiratory pressure delays the progression of lung injury during ventilator strategies involving high airway pressure and lung overdistention. Crit Care Med 2003; 31(7):1993-1998.

18. Becher T, van der Staay M. Calculation of mechanical power for pressure-controlled ventilation: author's reply. Intensive Care Med 2019; 45(10):1498-1499.

19. Giosa L, Busana M, Pasticci I, et. al.: Mechanical power at a glance: a simple surrogate for volume-controlled ventilation. Int Care Med Exp 2019; 7(1):61.

20. van der Staay M, Chatburn RL. Advanced modes of mechanical ventilation and optimal targeting schemes. Intensive Care Med Exp 2018; 6(1):30.

21. Zheng H, Xu Z, Zhou J, et al. The accuracy of simplified calculation of mechanical power: a simulation study. J Thorac Dis 2023; 15(6):3237-3244.

22. Paul G, Krishna MR, Gautam PL. 4DPRR- Index for predicting mortality in COVID-19 ARDS. J Mech Vent 2022; 3(2):56-61.

23. Sahetya SK, Wu TD, Morgan B, et al INTENSIVOS Cohort Study. Mean airway pressure as a predictor of 90-day mortality in mechanically ventilated patients. Crit Care Med 2020; 48(5):688-695.

24. Su L, Pan P, Liu D, et al. Mean airway pressure has the potential to become the core pressure indicator of mechanical ventilation: Raising to the front from behind the clinical scenes. J Intensive Med 2021; 1(2):96-98.

25. Marini JJ, Ravenscraft SA. Mean airway pressure: physiologic determinants and clinical importance-Part 2: Clinical implications. Crit Care Med 1992; 20(11):1604-1616.

26. Hess DR. Respiratory mechanics in mechanically ventilated patients. Respir Care 2014; 59(11):1773-1794.

27. Garnero AJ, Abbona H, Gordo-Vidal F, et al. Grupo de Insuficiencia Respiratoria Aguda de SEMICYUC. Pressure versus volume controlled modes in invasive mechanical ventilation. Med Intensiva 2013; 37(4):292-298.

28. Shah P, Yeo J, Techasatian W, et al. Mechanical power in AVM-2 versus conventional ventilation modes in a normal lung model: A bench study. J Mech Vent 2022; 3(2):45-54.

29. Chi Y, He H, Long Y. A simple method of mechanical power calculation: using mean airway pressure to replace plateau pressure. J Clin Monit Comput 2021; 35:1139–1147.

30. El-Khatib MF, Zeinelddine SM, HajAli TH, et al. Effect of ventilator settings on mechanical power during simulated mechanical ventilation of patientswith ARDS. Respir Care 2024; 69(4):449-462.

31. Yeo J, Shah P, Koichi K, et al. Mechanical power in AVM-2 versus conventional ventilation modes in various ARDS lung models: A bench study. J Mech Vent 2022; 3(3):110-122.

32. Franck CL, Franck GM, Daoud EG. Correlations of mechanical power and its components with age and its interference in the outcome of SARS-CoV-2 in subjects undergoing pressure-controlled ventilation. J Mech Vent 2022; 3(4):159-168.

33. Wu SH, Kor CT, Mao IC, et al. Accuracy of calculating mechanical power of ventilation by one commonly used equation. J Clin Monit Comput 2022; 36(6):1753-1759.

34. van der Meijden S, Molenaar M, Somhorst P, Schoe A. Calculating mechanical power for pressure-controlled ventilation. Intensive Care Med. 2019 Oct;45(10):1495-1497.

35. Vasques F, Duscio E, Pasticci I, et al. Is the mechanical power the final word on ventilator-induced lung injury? we are not sure. Ann Transl Med 2018;6(19):395.

36. Huhle R, Serpa Neto A, Schultz MJ, et al. Is mechanical power the final word on ventilator-induced lung injury? no. Ann Transl Med 2018; 6(19):394.

37. Takaoka K, Toma S, Lee P, et al. A comparative analysis of mechanical power and Its components in pressure-controlled ventilation mode and AVM-2 mode. J Mech Vent 2023; 4(4):130-140.

38. Rocco PRM, Silva PL, Samary CS, et al. Elastic power but not driving power is the key promoter of ventilator-induced lung injury in experimental acute respiratory distress syndrome. Crit Care 2020; 24(1): 284.

39.Vassalli F, Pasticci I, Romitti F, et al. Does iso-mechanical power lead to iso-lung damage?: an experimental study in a porcine model. Anesthesiology 2020;132(5):1126-1137.

40. Pistillo N, Castelluccio P, Suzuki I, et al. Mechanical power correlates with stress, strain, and atelectrauma only when normalized to aerated lung size in patients with acute respiratory distress syndrome. Crit Care Explor 2023; 5(10):e0982.

41. 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

42. Daoud EG. Airway pressure release ventilation. Ann Thorac Med 2007; 2(4):176-179.

43. Mechanical power: https://societymechanicalventilation.org/blog/mechanical-power/. Accessed May 2024.

44. Swinkels D, Weijland R, Hoekstra S, et al. Mechanical power in children mechanically ventilated with high-frequency oscillation ventilation. https://essay.utwente.nl/81513/. Accessed May 2024.

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