Journal of Mechanical Ventilation

Evaluation of the mean airway pressure - Minute ventilation (mM) Equation for mechanical power during spontaneous breathing

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DOI: https://doi.org/10.53097/JMV10125

Cite: Lee PM, Morikawa K, Daoud EG. Evaluation of the mean airway pressure - minute ventilation (mM) Equation for mechanical power during spontaneous breathing. J Mech Vent 2025; 6(2):72-78.

Abstract

Background
Mechanical power (MP) is a comprehensive measure that captures the energy delivered to the lungs during mechanical ventilation. By incorporating driving pressure (DP), tidal volume (VT), positive end-expiratory pressure (PEEP), and respiratory rate (RR), MP helps quantify the risk of ventilator-induced lung injury (VILI). The minute ventilation–mean airway pressure (mM) equation has been proposed as a simplified method for estimating MP, and while it has shown good accuracy in passive patients, its validity in those with spontaneous breathing effort remains unclear. This study evaluates the accuracy and reliability of the mM equation in ventilated patients exhibiting spontaneous respiratory effort.

Methods and Statistics
This study used the online SIVA simulator to model a broad range of ventilatory scenarios, with varying respiratory compliance (10–80 mL/cmH₂O), airway resistance (5–30 cmH₂O/L/s), and key ventilator settings: RR (5–40 breaths/min), VT (150–700 mL), PEEP (0–15 cmH₂O), and DP (5–30 cmH₂O). Simulations were performed in both the volume-controlled (VCV) and pressure-controlled (PCV) modes. To simulate spontaneous breathing, inspiratory muscle pressure (Pmus) was adjusted from 1 to 20 cmH₂O.

A total of 1,500 simulations per mode were generated in each mode. The gold standard method of geometrically deriving the area under the Pressure-Volume curve was used to calculate MP with the SIVA simulator (Total, Ventilator, Muscle powers). The mM estimates were derived from corresponding minute ventilation and mean airway pressure values.

Pearson correlation coefficients were calculated to compare the relationship of the mM equation to all the measured MP, and linear regressions were used for predicting the three different MP derived from the mM equation in each mode separately. T-test for equal variance and Bland Altmann plot were used to compare the reference MP measured (MP-R) from the simulator to the ones derived from the Mm formula (MP-D).

Results
Pearson correlation showed a very strong correlation between mM and ventilator power (R 0.969), very strong correlation between mM and total power (R 0.963), and strong correlation between mM and Pmus power (R 0.771) within the pressure-controlled mode, with all demonstrating non-significant differences between the measured and estimated ones. For the volume-controlled mode, Pearson correlation showed a very strong correlation between mM and ventilator power (R 0.963) and strong correlation between mM and total power (R 0.888), but weak correlation between mM and Pmus power (R 0.339).

Conclusion
During spontaneous efforts, the new mM equation accurately predicted the total, ventilator, muscle power in the pressure-controlled mode. However, in volume-controlled ventilation, it accurately predicted the total and ventilator power only, the weak correlation between mM-derived values and patient-generated (Pmus) power suggests that spontaneous breathing may reduce its accuracy. These findings highlight the need for further research into alternative methods for calculating mechanical power in patients with active respiratory effort.

Keywords: Mechanical power, Mm Equation, mean airway pressure, minute ventilation

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Conflict of interest/Disclosures: None

Background

Mechanical ventilation is a common intervention for patients with significant respiratory compromise, and although a necessary and life-saving treatment option, oftentimes causes iatrogenic damage of the lungs, known as ventilator induced lung injury (VILI). The existing literature has described several explanations of the pathophysiology of VILI, such as volutrauma, barotrauma, atelectotrauma, ergotrauma, and biotrauma. [1,2]

In 2016, Gattinoni et al. utilized pressure, volume, flow, and respiratory rate to develop a surrogate variable to quantify the work applied over time by a ventilator onto a patients' respiratory system, termed Mechanical power (MP). [3] Creation of MP allowed several complex yet significant ventilatory parameters to be unified into a single variable, which clinicians and researchers can utilize when managing patients on mechanical ventilation.[7] Moreover, elevated MP has been demonstrated to be associated with significant morbidity and mortality, particularly in regards to developing VILI. [4,5]

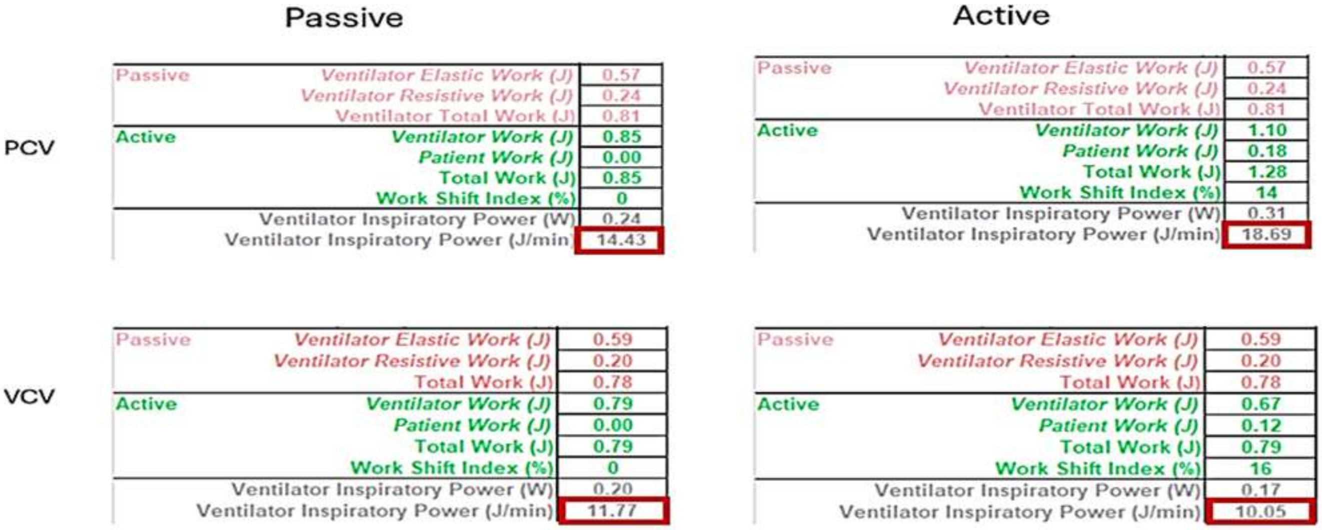
The pitfall of mechanical power is its mathematical complexity, often limiting its practicality within a clinical setting, as the gold standard method of calculation includes the numerical integration of the inspiratory limb of a pressure-volume curve. [6–8] Hence, researchers have explored alternative equations in order to provide MP more clinical utility. [3,9,10] Additionally, there are some challenges in measuring the MP in spontaneous breathing patients.

The power generated during spontaneous efforts will be the sum of both the ventilator and the patient

$$MPtotal = MPventilator + MPpatient$$

During inspiratory effort: the patient generates negative intrathoracic pressure, which might not be reflected in airway pressure measurements. Pressure-Volume Loop: The patient's work contributes to pressure-volume dynamics. Monitoring Requirements: Assessing mechanical power accurately requires measuring both ventilator-delivered and patient-generated work or power needs to be estimated using an esophageal pressure swings and volume.

In pressure-controlled ventilation (PCV), patient effort and ventilator work typically act in the same direction, increasing tidal volume with the same inspiratory and mean airway pressures. [11] In volume-controlled ventilation (VCV), patient effort may act in the opposite direction with the reduction of the peak and mean airway pressures but with the same volume. [12] The calculated mechanical power based on ventilator parameters alone will underestimate the total energy applied to the lungs especially in the VCV mode (Figure 1).



Passive

Active

PCV

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

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	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

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 1: Simulated data to calculate the total, ventilator, patient work in both the passive and active conditions with the same respiratory mechanics and ventilator variables. Top row is PCV, bottom row is VCV with passive condition on the left and active condition on the right (Pmus -5 cmH_2O)

Equations in Calculating Mechanical Power

Between all formulas calculating mechanical power, the tidal volume, respiratory rate, and minute ventilation all remain constant. However, the surrogates representing pressure are variable within each. Moreover, an important component when comparing the different formulas that calculate mechanical power is the type of ventilation mode being used, namely volume-controlled ventilation (VCV) or pressure-controlled ventilation (PCV). Since each ventilation mode is often accompanied by simplified and comprehensive equations, which have different accuracies and hold intrinsic biases from the gold standard. [9,13]

The mean airway pressure - Minute ventilation (mM) Equation

A recent study by our group offered the mean airway pressure - Minute ventilation product (mM equation) to be a mathematically simple yet accurate and reliable method in calculating MP during passive mechanical ventilation in both the volume and pressure-controlled modes. [14] The mM equation is the product of tidal volume, respiratory rate, and mean airway pressure X correction factor and demonstrated an excellent correlation with the gold standard method of measuring the geometrical area under the Pressure-Ventilation curve.

Although the mM equation demonstrated a very strong correlation with MP in passive ventilation, there remains significant gaps in the mM equations' utility in patients with partial or full spontaneous breathing. Therefore, the goal of this study is to assess if spontaneous breathing affected the accuracy and reliability of the mM equation in calculating MP. Given the mM equation only considers the tidal volume, respiratory rate, and mean airway pressure, we intended to do new equations for the estimation of MP during spontaneous efforts and hypothesized that the formulas described will be altered when considering pressure generated by spontaneous respiratory effort.

Methods

This study utilized the online SIVA simulator (Chatburn RL. Simulator Interface for Ventilatory Analysis (https://societymechanicalventilation.org/simulators/) to create different ventilation scenarios with various combinations of compliances (10-80 mL/cmH_2O) and resistances (5-30 cmH_2O/L/s), with various inspiratory flow and volume rates in VCV and inspiratory times in PCV modes. Ventilator variables were manipulated to stimulate different ventilatory scenarios, including respiratory rate (5 - 40 BPM), tidal volume (150 - 700 mL), PEEP (0 - 15 cmH_2O), and DP (5 - 30 cmH_2O). The variable Pmus was manipulated to demonstrate changes in spontaneous breathing (2-20 cmH_2O).

Over 30 different combinations of resistances and compliances with 100 different ventilatory settings were created, creating a total of 1,500 values in each mode. The mM equation calculated from correspondent values of the mean airway pressure and minute ventilation using the SIVA simulator (range 0.37 - 820 cmH_2O/L/min) and the gold standard method of geometrically deriving the area under the Pressure-Volume curve was used to calculate reference MP (MP-R) with the SIVA simulator (range 0.1 - 105 J/min).

Linear regression models were used to predict the derived MP from the mM equation (MP-D). T-tests for equal variance and Bland Altmann plot were used to compare the reference MP (MP-R) to that derived by the linear regression equation from mM (MP-D). Pearson correlation coefficients were used to compare the relationship of these equations to the measured reference MP (MP-R).

Results

Pressure-Controlled Ventilation

A total of 1,500 data points were collected on the PCV mode. Pearson correlation showed a very strong correlation between mM and ventilator power (R 0.969), total power (R 0.963), and strong correlation with Pmus power (R 0.771).

Regression analysis

Estimated Ventilator power = 0.142 (mM) + 3.011, Bland-Altman Plot (mean - 0.01, SE 0.43, - 0.44, SD 14.53, -14.55), T-test showed non-significant difference P 0.497.

For the Total power = 0.18 (mM) + 5.427, Bland-Altman Plot (mean 0.08, SE 0.69, - 0.53, SD 20.53, -20.37), T-test showed non-significant difference P 0.480.

For Pmus power = 0.037 (mM) + 2.415, Bland-Altman Plot (mean 0.0, SE 0.37, - 0.38, SD 12.57, -12.57), T-test showed non-significant difference P 0.496.

Figure 1 illustrates the correlation, and Bland-Altman curves of mM and Total Power, Ventilator Power, and Pmus Power in pressure-controlled ventilation respectively.

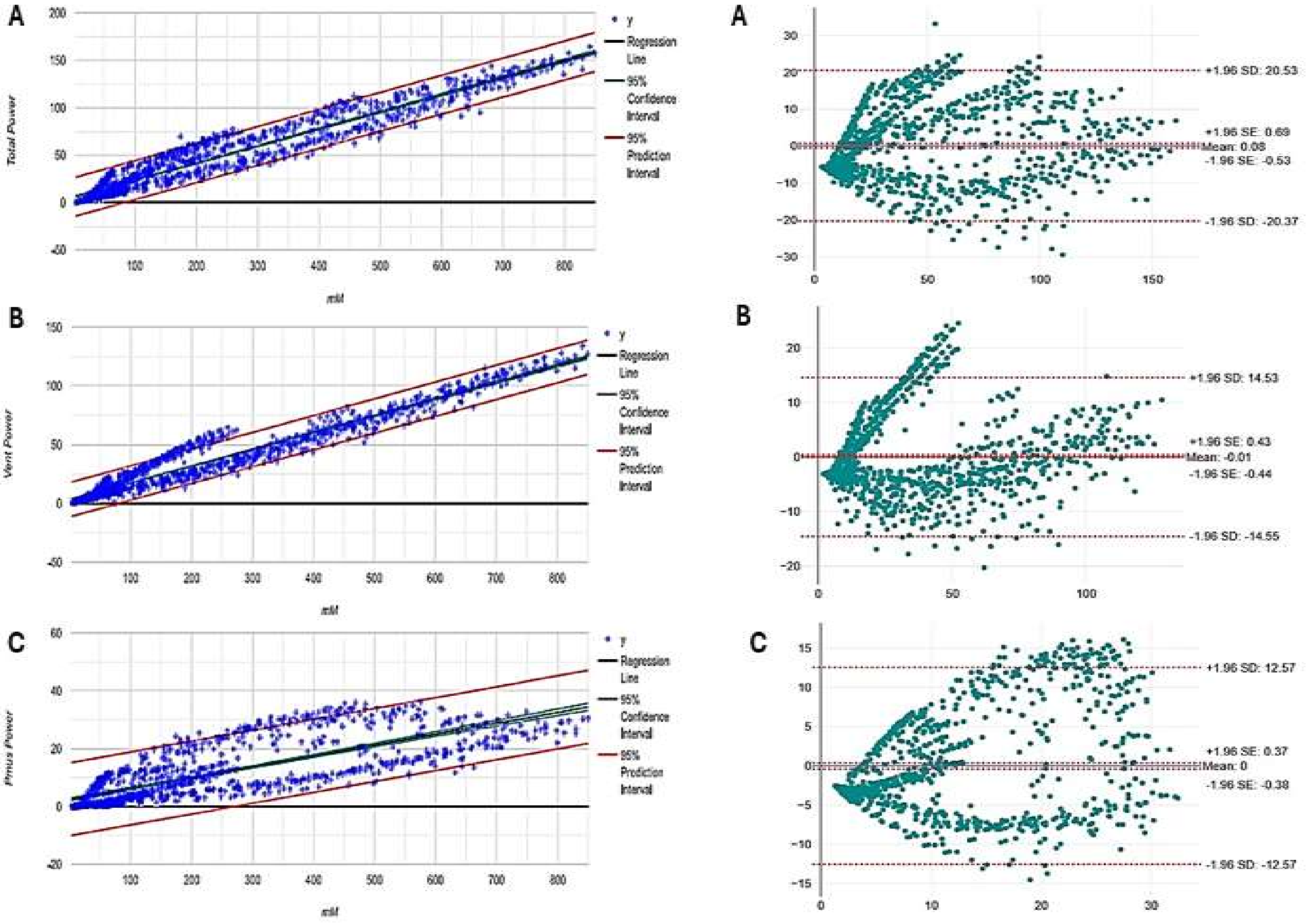


Figure 2: Correlation and Bland-Altman plot between A: Total power and mM, B: Ventilator power and mM, C: Pmus power and mM in the pressure-controlled mode

Volume-Controlled Ventilation

A total of 1,500 data points were collected on the VCV mode. Within VCV, Pearson correlation showed a very strong correlation between mM and ventilator power (R 0.963) and total power (R 0.888), but weak correlation between mM and Pmus power (R 0.339).

Regression analysis
Estimated Total power = 0.167 (mM) + 7.38, Bland-Altman Plot (mean 0.0, SE 0.51, - 0.52, SD 14.59, - 14.59). T-test showed non-significant difference P 0.499.

Ventilator power = 0.148 (mM) + 3.10), Bland-Altman Plot (mean 0.02, SE 0.12, - 0.13, SD 7.03, - 6.99), T-test showed non-significant difference P 0.486.

Pmus power = 0.018 (mM) + 4.284, Bland-Altman Plot (mean 0.01, SE 0.29, - 0.27, SD 8.81, -8.8), T-test showed non-significant difference P 0.48.

Figure 2 illustrates the correlation, and Bland-Altman curves of mM and Total Power, Ventilator Power, and Pmus Power in the volume-controlled ventilation respectively.

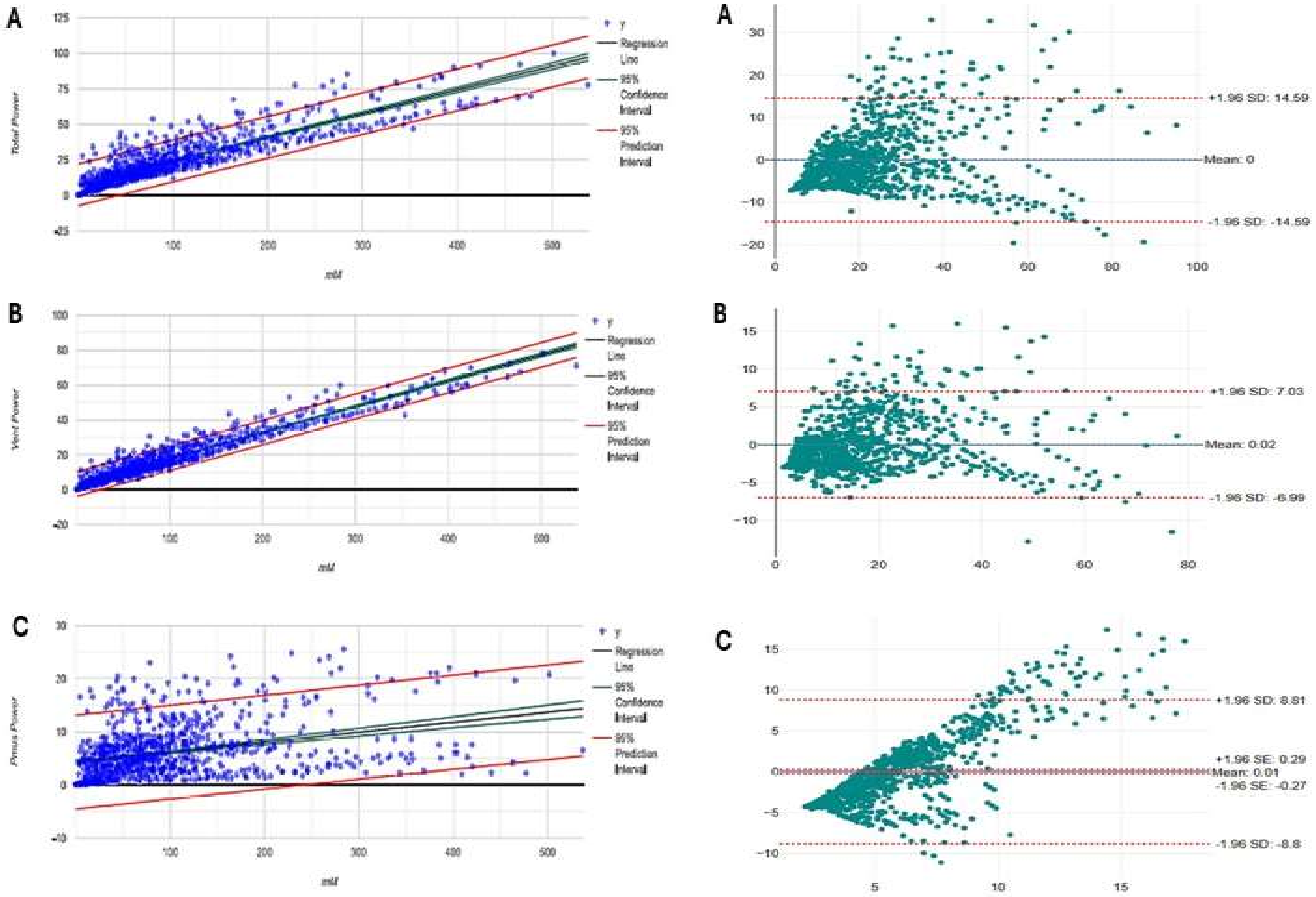


Figure 3: Correlation and Bland-Altman plot between A: Total power and mM, B: Ventilator power and mM, C: Pmus power and mM in the volume-controlled mode

Discussion

Our results demonstrate that the mM equation remains accurate in PCV even during spontaneous effort, likely due to the alignment of patient and ventilator forces. In contrast, in VCV, where patient effort may reduce airway pressure, the mM equation underestimates total mechanical power.

Pearson correlation coefficients from this analysis demonstrated strong correlation between mM and ventilator power (R 0.969), total power (R 0.963), and Pmus power (R 0.771) in the PCV mode. When evaluating VCV mode, mM was strongly associated with ventilator power (R 0.963) and total power (R 0.888) but demonstrated a weak correlation with the Pmus power (R 0.339), suggesting that spontaneous breathing significantly affects parameters used for calculating MP.

Unlike PCV, VCV delivers a fixed volume regardless of patient effort. If the patient contributes inspiratory effort, airway pressure may fall, leading to an underestimation of MP by the mM equation, which relies heavily on mean airway pressure as a surrogate for elastic and resistive work.

When intubated, patients can either depend on the ventilator fully for work of breathing, or initiate/partially participate in breathing, which is known as spontaneous work of breathing. This distinction significantly alters patient management in the ICU, as spontaneous breathing from the patient's own respiratory drive will contribute towards the overall generation of pressure, inspiratory flow and volume, subsequently influencing ventilator-derived calculations.[15]

If well controlled, spontaneous breathing may actually be protective on the lungs as it reduces the need for persistently elevated pressures, facilitate early weaning from sedatives/paralytics, and reduce diaphragm atrophy. However, the literature also demonstrates that spontaneous effort may detrimentally affect the pulmonary system by increasing the overall energy delivered onto the lungs during mechanical ventilation, as its spontaneous generation is not accounted for by the ventilator settings. [4] Strong inspiratory efforts can increase the tidal volume and transpulmonary pressure, increasing the strain placed on alveoli and subsequently increasing the risk of VILI. [16] This is particularly true in ventilated patients with strong, uncoordinated respiratory efforts, such as critically ill septic or ARDS patients beginning to be weaned off paralytics, who already present with significant morbidity and mortality, with further strain significantly compromising physiologic stability. [17,18] In other words, there is a narrow therapeutic index that depends on factors such as magnitude of effort, pressures delivered from the ventilator, and synchrony; therefore, these patients should have these parameters closely measured to maximize management and improve clinical outcomes.

Because of spontaneous breathing, calculations of mechanical power in the VCV mode with standard formulas become less accurate as many are dependent on passive and controlled ventilation and do not account for the patient's muscular effort and negative pleural pressures. [10,19] Therefore, accurate equations must consider the power generated from both the patient's muscular effort as well as the ventilator in order to accurately and reliably calculate mechanical power.

Prior literature has evaluated equations for MP, limited by inability to consider spontaneous work of breathing. For example, Pearson-Lemme and colleagues created a simplified method specifically for calculating MP in preterm lungs, and although the equation had a strong linear relationship (R = 0.98) and high intraclass correlation coefficient (ICC = 0.99, 95% CI = 0.98–0.99), the authors acknowledged that a major limitation to the equation was the intention suppression of spontaneous breathing, which would have significantly altered the accuracy of their results.

Asar and colleagues aimed to develop and validate a simplified equation for calculating dynamic MP at the bedside utilizing the Work of Breathing ventilator (WOBv) parameter. [20] The equation is as follows: MP_dyn = WOBv × Minute Volume

The study analyzed MP_dyn across various ventilatory settings, and demonstrated a high correlation between MP_dyn ($R \geq 0.98$) and no statistically significant differences with Bland-Altman tests, suggesting the MP_dyn equation was a reliable method in calculating dynamic MP during VCV. However, the MP_dyn equation was compared only in the VCV mode and to another equation by Gattinoni et al., rather than the gold standard method of calculating the area under the pressure-volume curve. [3]

Yan and colleagues reported using an equation called the mechanical power density (mechanical power normalized to respiratory compliance), patients on higher MP were significantly more likely to fail weaning off mechanical ventilation. [21] This is likely due to the fact MP serves as an indicator of the workload placed on respiratory muscles, with greater MP signifying more difficult transition off mechanical ventilation.

Ghianai and colleagues evaluated a similar variable of mechanical power density serving as a surrogate for the energy applied per unit of ventilated lung volume. [22] Similarly to Yan et al., the study found higher MPD values were significantly associated with prolonged weaning failure, indicating that patients with elevated MPD faced greater challenges in discontinuing mechanical ventilation. The significance of MPD as surrogates of outcomes in critically ill patients provide immense utility, as incorporating into clinical practice could enhance the assessment of weaning readiness in mechanically ventilated patients and minimize associated VILI.

Accordingly, measuring transpulmonary mechanical power may be more predictive of lung injury than total respiratory mechanical power, as it better reflects the mechanical energy transmitted directly to the lung parenchyma. This approach accounts for the combined effects of ventilator support and patient effort on lung tissue stress and strain. [23]

Conclusion

Incorporating patient-derived work of breathing into mechanical power estimation remains a clinical and research priority. Although the mM equation shows promise in PCV, further refinement or alternative methods are needed for reliable MP estimation in active, volume-controlled ventilation.

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