Original Article

# The accuracy of simplified calculation of mechanical power: a simulation study

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**Background:** Mechanical ventilation (MV) is an important life-saving method in the intensive care unit (ICU). A lower mechanical power (MP) is associated with a better MV strategy. However, traditional MP calculating methods are complicated, and algebraic formulas seem to be rather practical. The aim of the present study was to compare the accuracy and application of different algebraic formulas calculating MP.

**Methods:** A lung simulator, TestChest, was used to simulate pulmonary compliance variations. Using the TestChest system software, the parameters, including compliance and airway resistance, were set to simulate various acute respiratory distress syndrome (ARDS) lungs. Ventilator was also set to volume- and pressure-controlled modes with various parameter values (respiratory rate, RR, time of inspiration, $T_{insp}$, positive end-expiratory pressure, PEEP) to ventilate the simulated lung of ARDS (with various respiratory system compliance, $C_{rs}$). For the lung simulator, resistance of airway ($R_{aw}$) was fixed to 5 $cmH_2O/L/s$. $C_{rs}$ below lower inflation point (LIP) or above upper inflation point (UIP) was set to 10 $mL/cmH_2O$. The reference standard geometric method was calculated offline with a customized software. Three algebraic formulas for volume-controlled and three for pressure-controlled were used to calculate MP.

**Results:** The performances of the formulas were different, although the derived MP were significantly correlated with that derived from the reference method ($R^2$>0.80, P<0.001). Under volume-controlled ventilation, medians of MP calculated with one equation was significantly lower than that with the reference method (P<0.001). Under pressure-controlled ventilation, median of MP calculated with two equations were significantly higher (P<0.001). The maximum difference was over 70% of the MP value calculated with the reference method.

**Conclusions:** The algebraic formulas may introduce considerably large bias under the presented lung conditions, especially in moderate to severe ARDS. Cautious is required when selecting adequate algebraic formulas to calculate MP based on the formula's premises, ventilation mode, and patients' status. In clinical practice, the trend rather than the value of MP calculated by formulas should require more attention.

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## Introduction

The acute respiratory distress syndrome (ARDS) affects approximately 3 million patients annually, accounting for 10% of intensive care unit (ICU) admissions (1). Despite decades of research, treatment options for ARDS are limited, with high mortality ranging from 35% to 46% for severe patients (1). Supportive care with mechanical ventilation (MV) remains the mainstay of management to maintain respiratory function and to reduce work of breathing in ARDS patients (2). However, the mechanical forces generated during the MV by the interaction between the ventilator and the respiratory system can also damage the lung, which is called ventilator-induced lung injury (VILI) (3-5). VILI represents the unwanted result of a complex interplay among various mechanical forces that act on lung structures, which may introduce volutrauma and barotrauma. Many factors including tidal volume (Vt), driving pressure (ΔP), airflow (V'), respiratory rate (RR) and positive end-expiratory pressure (PEEP) contribute to VILI (3), especially, the driving pressure and RR (6).

Recently, the mechanical power (MP), which is the amount of energy per unit of time generated by the MV and released on the respiratory system, unifying the mechanical drivers of VILI, has been proposed as a determinant of the VILI pathogenesis (7-9). The recognition that MP represents a conjunction of parameters predisposing to VILI is an important step toward better care of critically ill patients. The reference standard method is based on an analysis of quasi-static PV curves of the respiratory system (the geometric method) (8). Unfortunately, the calculation is rather cumbersome at beside. In order to facilitate the estimation of MP, the original equation was simplified in different forms (the algebraic formulas) (10,11). However, the simplification requires a series of prerequisites that in reality could not be fulfilled. The accuracy of the algebraic formulas is remained unknown, particularly in moderated and severe ARDS. In the algebraic formulas, compliance is assumed constant throughout the entire breath, which might not be the case in moderated and severe ARDS (12).

The aim of the present study was to compare the accuracy and application of different formulas calculating MP. A lung simulator was used to simulate pulmonary compliance variations. We present this article in accordance with the STROBE reporting checklist (available at https://jtd.amegroups.com/article/view/10.21037/jtd-22-1409/rc).

### Highlight box

**Key findings**

- The algebraic formulas may introduce considerably large bias under the presented lung conditions. In clinical practice, the trend rather than the value of mechanical power (MP) calculated by formulas should require more attention.

**What is known and what is new?**

- Although the algebraic formulas would have different accuracy under volume- or pressure-controlled ventilation, they were reported to be accurate.
- The bias introduced by algebraic formulas could be considerably significant. And we are the first to find that in volume- and pressure-controlled ventilation, MPs calculated by algebraic formulas seem to be larger than those of the gold standard in very severe ARDS patients ($C_{rs}$ <25 mL/cm$H_2O$).

**What is the implication, and what should change now?**

- In clinical practice, the trend rather than the value of MP calculated by formulas should require more attention.

## Methods

### Study design

We performed a prospective bench study using a lung simulator (TestChest®, ORGANIS GmbH, Switzerland) to assess the accuracy of the algebraic formulas when calculating MP under different ventilation modes. The TestChest® is a full physiologic artificial lung that can simulate the human respiratory and circulatory systems' responses of the healthy and pathological adult lung (13). A male patient with the height of 175 cm, with a predicted body weight of 70 kg, and tidal volume of 6 mL/kg, was simulated.

### *MP calculation*

The amount of energy transferred from the ventilator to the patient is measured in joules (J), while power is defined as the amount of energy transferred per unit of time (J/min). The reference standard geometric method can be validated using the area enclosed by the dynamic pressure-volume loop, which was calculated offline with a customized software developed with Matlab (The MathWorks Inc., Natick, USA). In order to calculate MP from the variables measured at the bedside, a simplified equation (Eq. [1]) was proposed (7), which was derived under volume controlled (VC) mode when inspiratory flow is constant.

$$MP = 0.098 \cdot RR \cdot Vt\left[P_{peak} - \frac{1}{2}\left(P_{plat} - PEEP\right)\right] \qquad [1]$$

where 0.098 is a conversion factor to J/min, $MP$ is the mechanical power, $RR$ is the respiratory rate, $Vt$ represents the tidal volume in liter, $P_{peak}$ denotes the peak pressure, $P_{plat}$ is the plateau pressure and PEEP is positive end-expiratory pressure in $cmH_2O$. Eq. [1] can be further transformed to other forms (Eqs. [2] and [3]) (7, 11).

$$MP = 0.098 \cdot RR \cdot \left\{Vt^2\left[\frac{1}{2 \cdot C_{rs}} + RR \cdot \frac{(1+I:E)}{60 \cdot I:E} \cdot R_{aw}\right] + Vt \cdot PEEP\right\} \qquad [2]$$

$$MP = \frac{Vt \cdot RR \cdot \left(Peak\ pressure + PEEP + \frac{Inspiratory\ flow}{6}\right)}{20} \qquad [3]$$

where $C_{rs}$ is the respiratory system compliance $L/cmH_2O$, *I:E* denotes the inspiratory-to-expiratory time, $R_{aw}$ represents the airway resistance in $cmH_2O/L/s$.

When ventilated with pressure controlled (PC) mode, the algebraic formulas of MP can be calculated by the complicated equation (Eq. [4]) and the simple forms (Eqs. [5] and [6]) (10,14).

$$MP = 0.098 \cdot RR \cdot Vt \cdot \left[\begin{array}{l}\left(PEEP + \Delta P_{insp}\right) \cdot Vt - \Delta P_{insp}{}^{2} \cdot C_{rs} \cdot \\ \left(0.5 - \frac{R_{aw} \cdot C_{rs}}{T_{slope}} + \left(\frac{R_{aw} \cdot C_{rs}}{T_{slope}}\right)^2 \cdot \left(1 - e^{\frac{-T_{insp}}{R_{aw} \cdot C_{rs}}}\right)\right)\end{array}\right] \qquad [4]$$

$$MP = 0.098 \cdot RR \cdot Vt \cdot \left[PEEP + \Delta P_{insp} \cdot \left(1 - e^{\frac{-T_{insp}}{R_{aw} \cdot C_{rs}}}\right)\right] \qquad [5]$$

$$MP = 0.098 \cdot RR \cdot Vt \cdot \left[PEEP + \Delta P_{insp}\right] \qquad [6]$$

where $\Delta P_{insp}$ is the inspiratory pressure in $cmH_2O$, $T_{slope}$ is the inspiratory pressure rise time in s, $T_{insp}$ is the inspiratory time in s.

### *Parameter settings*

In the study, a simulated lung was ventilated by CARESCAPE R860 (GE Healthcare, Chicago, US). Using the TestChest system software, the parameters, including compliance and airway resistance, were set to simulate various ARDS lungs. Ventilator was also set to different modes (VC and PC) with various parameters (*RR*, $T_{insp}$, *PEEP*) to ventilate the simulated lung of ARDS. *Vt* was set to 420 mL during VC and driving pressure was titrated to result in a similar *Vt* during PC. For the lung simulator, $R_{aw}$ was fixed to 5 $cmH_2O/L/s$. $C_{rs}$ below lower inflation point (LIP) or above upper inflation point (UIP) was set to 10 $mL/cmH_2O$. Other parameter settings for the lung simulator and ventilator in different scenarios were summarized in *Table 1*. The variables explained in the Eqs. [1-6] were measured in each condition. MP was calculated according the above formulas. Mean values were computed over five consecutive breaths.

### *Statistical analysis*

The data were analyzed with MATLAB (R2015a, The MathWorks Inc., Natick, USA). Lilliefors test was used to check the distribution. For non-normal distribution, data were presented as median (interquartile range). The MPs measured by the geometric method and calculated with the simplified algebraic formulae were compared using the Bland-Altman technique, Pearson's linear correlation and Wilcoxon signed rank test. A P value <0.05 was considered statistically significant.

## Results

The performances of the formulas were different, although the derived MP were significantly correlated with that derived from the reference method (Ref) ($R^2$>0.80, P<0.001). Under volume-controlled ventilation, medians of MP calculated with Eqs. [1] and [3] were similar to the geometric method. The mean difference for Eq. [1] *vs.* Ref was −0.13 J/min, with upper and lower limits of agreement 1.60 and −1.85 J/min. The mean difference for Eq. [3] *vs.* Ref. was 0.06 J/min, with upper and lower limits of agreement 1.78 and −1.66 J/min. However, MP calculated with Eq. [2] was significantly lower than that with the reference method (P<0.001). The mean difference for Eq. [2] *vs.* Ref was −1.82 J/min, with upper and lower limits of agreement −3.49 and −0.16 J/min (*Table 2*, *Figure 1*, Table S1

**Table 1** Summary of the ventilator and simulator settings

| Fixed ventilator parameters | Fixed simulator parameters | Changing parameter |
|---|---|---|
| Scenario 1 | | |
| PEEP 5 $cmH_2O$ | – | $C_{rs}$ between LIP & UIP: 10–45 with a step of 5 mL/$cmH_2O$ |
| RR 20/min | | |
| $T_{insp}$ 1 s | | |
| Scenario 2 | | |
| RR 20/min | $C_{rs}$ between LIP & UIP: 30 mL/$cmH_2O$ | PEEP: 5–15 with a step of 2 $cmH_2O$ |
| $T_{insp}$ 1 s | | |
| Scenario 3 | | |
| PEEP 5 $cmH_2O$ | $C_{rs}$ between LIP & UIP: 30 mL/$cmH_2O$ | $T_{insp}$: 0.9–1.4 with a step of 0.1 s |
| RR 20/min | | |
| Scenario 4 | | |
| PEEP 5 $cmH_2O$ | $C_{rs}$ between LIP & UIP: 30 mL/$cmH_2O$ | RR: 12 to 24 with a step of 4/min |
| $T_{insp}$ 1 s | | |

Each scenario was adapted to VCV and PCV. PEEP, positive end-expiratory pressure; RR, respiratory rate; $C_{rs}$, respiratory system compliance; LIP, lower inflection point; UIP, upper inflection point.

**Table 2** Summary of mechanical power calculated with various algebraic formulas and the reference method

| MP | Algebraic | Median (IQR) | Ref. | P (signed rank) | $R^2$ | Δ/Ref. in % |
|---|---|---|---|---|---|---|
| VC | Eq. [1] | 12.1 (2.8) | 12.7 (1.7) | 0.38 | $0.90^§$ | 5.0 (5.0) % |
| | Eq. [2] | 10.5 (2.5) | | <0.001* | $0.89^§$ | 17.2 (6.1) % |
| | Eq. [3] | 12.3 (2.7) | | 0.72 | $0.91^§$ | 4.0 (3.4) % |
| PC | Eq. [4] | 13.6 (3.3) | 13.3 (2.1) | 0.44 | $0.94^§$ | 4.9 (2.6) % |
| | Eq. [5] | 19.3 (4.1) | | <0.001* | $0.82^§$ | 36.0 (14.7) % |
| | Eq. [6] | 19.3 (4.1) | | <0.001* | $0.82^§$ | 36.1 (14.8) % |

*, significantly different compared to the MP calculated with the reference method; $^§$, two methods were significantly correlated. MP, mechanical power; VC, volume controlled; PC, pressure controlled; Eq., equation; IQR, interquartile range; Ref., reference method; R, linear correlation coefficient; Δ/Ref., the differences of MP calculated with algebraic formulas and the reference method divided by reference MP.

and Table S2). Under pressure-controlled ventilation, median of MP calculated with Eq. [4] was similar to the geometric method. The mean difference for Eq. [4] *vs.* Ref was 0.26 J/min, with upper and lower limits of agreement −1.77 and 2.29 J/min. However, MPs calculated with Eqs. [5] and [6] were significantly higher than that with the reference method (P<0.001). The mean difference for Eq. [5] *vs.* Ref was 5.41 J/min, with upper and lower limits of agreement 9.58 and 1.24 J/min. The mean difference for Eq. [6] *vs.* Ref was basically the same with that of Eq. [5] (*Table 2*, *Figure 2*, Tables S3,S4).

## Discussion

In this study, some of the explored algebraic formulas delivered satisfactory MP values compared to the reference method (Eqs. [1], [3] and [4]). However, the others have significant differences compared to the reference method. The maximum difference was over 70% of the MP value calculated with the reference method. To our best knowledge, this is the first simulation study investigating the algebraic formulas under various conditions.

The algebraic formulas were derived under various

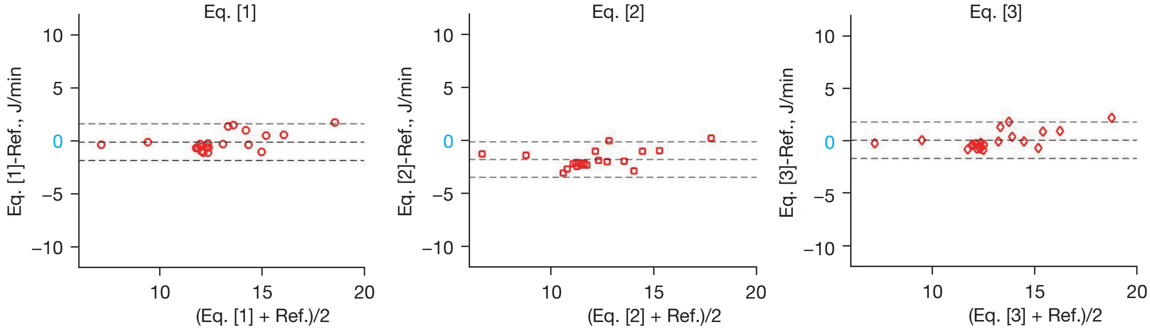

**Figure 1** Bland-Altman plots comparing the mechanical power calculated with algebraic formulas (Eqs. [1-3]) and the reference method under volume controlled ventilation. The dashed line at the middle depicts the mean value of the whole data set. The other two dashed lines represent mean ± 1.96 × standard deviation. Blue highlights zero difference between two methods. Eq., equation; Ref., reference method.

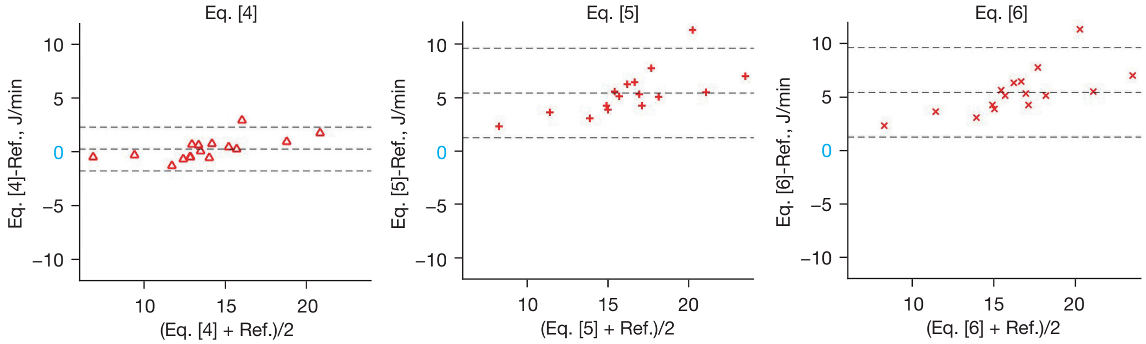

**Figure 2** Bland-Altman plots comparing the mechanical power calculated with algebraic formulas (Eqs. [4-6]) and the reference method under pressure controlled ventilation. The dashed line at the middle depicts the mean value of the whole data set. The other two dashed lines represent mean ± 1.96 × standard deviation. Blue highlights zero difference between two methods. Eq., equation; Ref., reference method.

assumptions, as discussed in their original studies (7,14). Applications without clarifying the perquisites may lead to significant errors. One of the most common mistakes of applying the algebraic formulas is to mix up pressure- and volume-controlled ventilation. Inspiratory flow during volume-controlled ventilation is approximately constant, which is not the case during pressure-controlled. The corresponding error introduced to MP calculation is unneglectable (6,15,16). Another point that acquires attention is the units of the parameters in the formulas. Typically, the parameter values read from ventilator need to be converted before MP calculation (e.g., tidal volume in milliliter to liter, compliance in mL/cm$H_2O$ to L/cm$H_2O$). Failed to convert the units may lead to incorrect results (8). In Eqs. [4] and [5], time constant is required. A previous study claimed to have $C_{rs}$ in mL/cm$H_2O$ and $R_{aw}$ in cm$H_2O$·s·$L^{-1}$ (17), which would not have a correct result *per se*.

### *Volume-controlled ventilation*

During volume-controlled ventilation, Eq. [2] delivered MPs that were in average 17.2% different from the reference values (*Table 2*) (7). Compared to Eqs. [1] and [3], Eq. [2] has the term of $C_{rs}$ and $R_{aw}$, which are non-linear in the present study. On the one hand, $C_{rs}$ was overestimated below LIP and beyond UIP, and at the same time, the $C_{rs}$ of TestChest also changed dynamically near the set value with the ventilation setting, but Eq. [2] only used the set value for calculation. On the other hand, $R_{aw}$ was directly derived from the set value of TestChest, it was $R_{aw}$ =5 cm$H_2O$/L/s, but the actual $R_{aw}$ changes dynamically. Therefore, using $R_{aw}$ and $C_{rs}$ that are not precise to calculate MP that makes the calculation process of Eq. [2] more complicated, and the calculation result contains larger errors. It can be seen that the calculation result of Eq. [2] is smaller than that of Eq. [1], which may be that the actual $R_{aw}$ is smaller than the set value and/or the actual Crs is larger than the set value. In the original validation, over 50% of the ARDS patients were mild ARDS ($PaO_2/FiO_2$, 244±135 mmHg) and a short ICU stay (3.8±5.9 days). The application of MP in such patient group is less important compared to moderated and severe ARDS (7,17). But in this study, we simulated different ARDS lungs varied from mild to severe ARDS. The computed results varied depending on PEEP levels, which may also be explained by non-linear $C_{rs}$ within tidal breathing when recruitment and overdistension were presented in different PEEP levels. In actual operation, it is recommended to directly select Eq. [1] to calculate the MP during volume-controlled ventilation (VCV), which can effectively save calculation steps and reduce errors. Eq. [3] is a simplification of Eq. [1] and does not require to measure plateau pressure (Pplat). If the patient does not have a valid Plat measurement, MP can be calculated using this formula.

### *Pressure-controlled ventilation*

During pressure-controlled ventilation (PCV), since the *Paw* dose not rise in a linear way, applying the formulas derived from VCV will cause obvious calculation errors. Hence, several formulas are proposed to calculate MP during PCV. Under the assumption of an ideal "square wave" Paw during inspiration, thus pressure rise time (Tslope) =0, the simplified formula, Eq. [6] is brought out. Eq. [5], proposed by van der Meijden *et al.*, which is simpler than Becher's approach and maybe match the physiology of PCV better (14,18). However, since $1-e^{\frac{-T_{insp}}{R_{aw}\cdot C_{rs}}} \approx 0$, Eq. [5] can be roughly the same as Eq. [6]. However, in our study, during PCV, Tslopes varied from 0.63 to 1 s. The assumption that Tslope =0 would significantly ascend the value of MP. Therefore, MPs calculated with Eqs. [5] and [6] introduced significant biases. According to Becher *et al.* (10), Eq. [4] would be the most suitable one when the inspiratory pressure rise time is unneglectable, which is the case in the present study. Taken together, based on our study, we recommend using Eq. [4] for the calculation of MP during PCV.

### *Respiratory system compliance, PEEP, and RR*

We also found that the change of $C_{rs}$ will influence the accuracy of the algebraic formulas under VCV (Table S1). As we kept $C_{rs}$ below LIP and beyond UIP constant, increasing $C_{rs}$ between LIP and UIP will increase the error using single $C_{rs}$ to represent the whole breath (18). Moreover, when changing Crs, it is actually simulating different degrees of ARDS. The lower the Crs is, the higher the degree of ARDS. When reviewing our research data, it can be found that the lower the $C_{rs}$ during VCV or PCV, the MPs calculated by equations are higher than the gold standard. When $C_{rs}$ ≥25 mL/cm$H_2O$, the MPs calculated by equations are close to the gold standard (Table S1 and Table S3). Although the dominant method for grouping ARDS is based on the oxygenation index, we have also found a method, the Murray Lung Injury Score, that based on $C_{rs,}$ alveolar consolidation, hypoxemia, and PEEP (19). According to this Score, $C_{rs}$ bellowing 39 mL/cm$H_2O$ should be severe lung injury, which means in our study, most of our settings, setting $C_{rs}$ at 30 mL/cm$H_2O$, should be simulating severe ARDS. Exceptions occur in Scenario 1, that we have settings of $C_{rs}$ =40 mL/cm$H_2O$ and $C_{rs}$ =45 mL/cm$H_2O$, which maybe represent mild to moderate ARDS, and the calculating results of equations for these models are very similar to gold standard. However, we have also simulated the $C_{rs}$ from 10 to 20 mL/cm$H_2O$, these models may represent very severe ARDS. On these cases, the calculating results of equations are larger than that of gold standard. Changing PEEP may influence the recruitment and overdistension, which again influence the volume-dependent $C_{rs}$ (20). The dominate factor for the errors with Eqs. [5] and [6] was mainly the $T_{slope}$, therefore, the change of PEEP or RR did not influence the error in MP calculation.

### *Limitations*

Several limitations of the study have to be acknowledged. This is a simulation study with a lung simulator, TestChest. The advantage was that the lung mechanics were adjustable. Unfortunately, the lung physiology could not be 100% simulated. According to the manufacturer, the design of TestChest is based on our known lung physiological parameters and respiratory mechanics equations, but is far less complex than real human lungs. The compliance,

$SPO_2$ and FRC of TestChest can be changed automatically with clinical treatment changes, but other parameters are set fixed values, and the real human lung is that all physiological parameters can be changed with clinical treatment. Another example is respiratory system resistance. TestChest simulates a total resistance, while real human lung resistance is divided into elastic resistance and static resistance. In clinical treatment, there are more factors that affect the resistance due to the connection of the ventilator. Although the TestChest is the most intelligent and advanced lung simulator, all parameters are realized through the cooperation of various sensors, but there are still many gaps compared with the real human lung. As we simulate ARDS lungs, compared with the human lung, the lung's "Heterogeneity" is difficult to achieve on the TestChest. Therefore, the response to ventilator settings may not represent the response of real patients. Furthermore, only a few data points were collected in each scenario and therefore, the statistical analysis might be underpowered.

### *Clinical practice*

As we have discussed above, algebraic formulas may introduce bias during different circumstances. However, we think that in clinical practice, the most important thing for the MP is not only the "true" value but the trend. As we have observed and previous literature has reported, the trend of MP, calculated by the same algebraic formula for the same patient, is relatively credible. We use this trend to predict VILI and find it rather practical (21,22). Moreover, surrogate formulas are easier to be undertaken. According to the literature, ARDS patients with an MP more than 18 J/min would have higher mortality (17), and moderate and severe ARDS patients would have an increased risk of mortality with higher MP (23). In our daily practice, we usually use Eq. [3] as we have mentioned above. We start prone position ventilation in those patients with an MP over 17 J/min. If 2 to 3 J/min of the decrease cannot be achieved, we will start venous-venous extracorporeal membrane oxygenation (ECMO), often combining prone position ventilation. In the future, on the one hand, more clinical practice should be introduced to improve MP calculation by formulas. On the other hand, with the increasing computing power of ventilators, geometric methods should be integrated into ventilators to achieve more precise MP calculation.

## Conclusions

The algebraic formulas may introduce considerably large bias under the presented lung conditions, especially in moderate to severe ARDS. Cautious is required when selecting adequate algebraic formulas to calculate MP based on the formula's premises, ventilation mode, and patients' status. In clinical practice, the trend rather than the value of MP calculated by formulas should require more attention.

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## Footnote

*Reporting Checklist:* The authors have completed the STROBE reporting checklist. Available at https://jtd.amegroups.com/article/view/10.21037/jtd-22-1409/rc

*Data Sharing Statement:* Available at https://jtd.amegroups.com/article/view/10.21037/jtd-22-1409/dss

*Conflicts of Interest:* All authors have completed the ICMJE uniform disclosure form (available at https://jtd.amegroups.com/article/view/10.21037/jtd-22-1409/coif). The authors have no conflicts of interest to declare.

*Ethical Statement:* The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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