The effect of inspiratory rise time on mechanical power calculations in pressure control ventilation: dynamic approach

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Abstract

Background Mechanical power may serve as a valuable parameter for predicting ventilation-induced injury in mechanically ventilated patients. Over time, several equations have been developed to calculate power in both volume control ventilation (VCV) and pressure control ventilation (PCV). Among these equations, the linear model mechanical power equation (MP_{LM}) closely approximates the reference method when applied in PCV. The dynamic mechanical power equation (MP_{dyn}) computes power by utilizing the ventilatory work of breathing parameter (WOB_v), which is automatically measured by the mechanical ventilator. In our study, conducted in patients with Covid-19 Acute Respiratory Distress Syndrome (C-ARDS), we calculated mechanical power using both the MP_{LM} and MP_{dyn} equations, employing different inspiratory rise times (T_{slope}) at intervals of 5%, ranging from 5 to 20% and compared the obtained results.

Results In our analysis, we used univariate linear regression at both I:E ratios of 1:2 and 1:1, considering all T_{slope} values. These analyses revealed that the MP_{dyn} and MP_{LM} equations exhibited strong correlations, with R^2 values exceeding 0.96. Furthermore, our Bland–Altman analysis, which compared the power values derived from the MP_{dyn} and MP_{LM} equations for patient averages and all measurements, revealed a mean difference of -0.42 ± 0.41 J/min (equivalent to $2.6\% \pm 2.3\%$, $p < 0.0001$) and -0.39 ± 0.57 J/min (equivalent to $3.6\% \pm 3.5\%$, $p < 0.0001$), respectively. While there was a statistically significant difference between the equations in both absolute value and relative proportion, this difference was not considered clinically relevant. Additionally, we observed that each 5% increase in T_{slope} time corresponded to a decrease in mechanical power values by approximately 1 J/min.

Conclusions The differences between mechanical power values calculated using the MP_{dyn} and MP_{LM} equations at various T_{slope} durations were determined to lack clinical significance. Consequently, for practical and continuous mechanical power estimation in Pressure-Controlled Ventilation (PCV) mode, the MP_{dyn} equation presents itself as a viable option. It is important to note that as T_{slope} times increased, the calculated mechanical power exhibited a clinically relevant decrease.

Keywords Mechanical power, PCV, ARDS, VILI

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Introduction

Mechanical power (MP) is an emerging parameter that combines all respiratory variables contributing to ventilator-induced lung injury (VILI), enabling predictions at the bedside (1, 2). Various equations, differing in accuracy and complexity, have been introduced to compute MP during both volume control ventilation (VCV) and pressure control ventilation (PCV) (see Additional file 1:

Table S1) (2–5). However, the precision and practicality of power equations developed for PCV mode remain subjects of ongoing debate (1, 6–9). This stems from the mathematical complexity of PCV equations and the need for inspiratory resistance, a parameter not easily accessible at the bedside (10). As a result, the integration of mechanical power into clinical practice has been delayed.

To address this challenge, we introduced and published the dynamic mechanical power equation (MP_{dyn}) as one of the methods for calculating mechanical power (3). More recently, Trinkle et al. presented a simplified equation (Linear Model Mechanical Power Equation, MP_{LM}) for calculating mechanical power in PCV mode in their latest publication. When compared to the gold standard geometric method, the MP_{LM} equation demonstrated superior performance, with an 8% bias, outperforming the Becher comprehensive equation (PCV_{slope}, 10% bias) and the Van der Meijden equation (MP_{pcv}, 16.5% bias). As a result, we have chosen the MP_{LM} equation as the reference method for our study. Since T_{slope} is a key factor in this equation, our aim is to investigate the impact of varying T_{slope} values on mechanical power.

In this study, we calculate mechanical power using both the MP_{LM} and MP_{dyn} equations in patients with Covid-19-related Acute Respiratory Distress Syndrome (C-ARDS) undergoing pressure control ventilation (PCV) with Inspiration/Expiration ratios (I:E) of 1:2 and 1:1. We also assess the influence of different T_{slope} durations (5%, 10%, 15%, and 20%) on these equations. Furthermore, we performed a comprehensive comparison of all equations under two different I:E ratios and across the four T_{slope} durations.

Material and methods
Study design and data collection
This study was performed in the general intensive care unit of the University of Health Sciences, Bakırköy Dr. Sadi Konuk Training and Research Hospital, between June 10, 2022, and January 15, 2023. The study included 38 patients diagnosed with Covid-19-related Acute Respiratory Distress Syndrome (C-ARDS) who met the following criteria: deep sedation, paralysis, and mechanical ventilation in pressure control ventilation (PCV) mode. Patients with chronic obstructive pulmonary disease (COPD) and heart failure, pregnant individuals, patients with tube thoracostomy, and hemodynamically unstable patients were excluded from the study. A flowchart describing the patient selection process is provided in Additional file 1: Figure S1. Clinical data, including Sequential Organ Failure Assessment (SOFA) scores, Acute Physiology and Chronic Health Evaluation-II (APACHE II) scores, age, gender, height, predicted body weight (PBW), ideal weight, and body mass index (BMI),

were retrieved from the hospital's database using SQL queries and transferred to Microsoft Excel for analysis.

All patients were ventilated using a Maquet Servo-U ventilator (Gothenburg, Sweden) in PCV mode. Patient data were recorded on the ventilator at a scanning rate of 20 mm/s. Patients were intubated with a 7.5 mm endotracheal tube and were provided humidification using a heat and moisture exchange (HME) filter (GIBECK Humid-Vent, UK). Active humidification systems were not employed during the study.

Inspiratory pressure change (ΔP_{insp}) was adjusted to achieve a tidal volume of 4–6 ml/kg based on Predicted Body Weight (PBW). Positive end-expiratory pressure (PEEP) was set between 8 and 12 cmH$_2$O, and the Fraction of Inspired Oxygen (FiO$_2$) was adjusted to range from 40 to 80%, targeting an oxygen saturation (SpO$_2$) of 88–92%. The parameter T_{slope} was varied between 5 and 20% (5%, 10%, 15%, and 20%) under two different Inspiration/Expiration (I:E) ratios, 1:2 and 1:1, with 5% increments every 20 min. To assess the presence of intrinsic PEEP, total PEEP was measured by performing an expiratory hold maneuver at each change in T_{slope} setting.

Mechanical ventilator and respiratory parameters of all patients were recorded with 'ImdSoft-Metavision/Qlin-ICU Clinical Decision Support System (Israel). Data from mechanical ventilators, including end-inspiratory pressure (P_{peak}), ΔP_{insp}, PEEP, mean airway pressure (P_{mean}), respiratory rate (RR), expiratory tidal volume (TVe), inspiratory time (T_{insp}), compliance (C, calculated automatically by the ventilator: ΔV / P_{peak}—PEEP), work of breathing ventilator (WOBv), I:E ratio, end-tidal carbon dioxide (etCO$_2$), SpO$_2$, and arterial blood gas values at admission (pH, PaO$_2$, HCO$_3$, PaCO$_2$, BE), were extracted from the data pool using SQL queries. Statistical analyses were performed after calculating patient averages using Microsoft Excel.

If the end expiratory flow (V_{ee}) is close to zero, it is considered that there is no intrinsic PEEP (11). V_{ee} flow values of 6080 min (38×4x20=3040 min for each I:E ratio) obtained in I:E 1:2 and I:E 1:1 ratios of 38 patients included in the study were measured close to zero (0.012 vs 0.035 L/s, respectively). See supplementary data for mean, confidence interval and P values of V_{ee} flow values measured at T_{slope} 5%, 10%, 15% and 20% (Additional file 1: Table S4). In addition, there was no clinically significant difference between the total PEEP obtained with the expiratory hold maneuver performed at the beginning of each 5% T_{slope} (5%-20%) change and the PEEP values set for all measurements (9.07 vs 9.22 cmH$_2$O). Therefore, it was assumed that the patients included in the study did not have intrinsic PEEP.

Respiratory mechanics were obtained for each patient for a total of 80 min (80 min for I:E = 1:2 and 80 min for

1:1) with measurements of 20 min at each T_{slope} time, (Respiratory rate (RR), PEEP, expiratory tidal volume (TVe), ΔP_{insp}, T_{slope}, WOBv, expiratory velocity (Vee), FiO_2, SpO_2 and End-tidal carbon dioxide ($EtCO_2$)). No adverse events observed requiring changes in these parameters (ΔP_{insp}, PEEP, RR, and FiO_2) during the study. ΔP_{insp}, PEEP, RR, and FiO_2 settings were constant throughout the study period in each patient. SPO_2, $etCO_2$ and all hemodynamic parameters and other vital signs of the patients were monitored at the bedside.

Diagnosis of C-ARDS

The diagnosis of COVID-19 in all 38 patients was confirmed through a combination of chest computed tomography (CT) imaging and nasal swab sample with Polymerase Chain Reaction (PCR) testing using the Bio-Speedy Covid-19 RT-qPCR detection Kit (Bioeksen, Turkey). Furthermore, the diagnosis of Acute Respiratory Distress Syndrome (ARDS) was established following the criteria outlined in the Berlin definition (12). Among the 38 patients included in the study, three patients were classified as having mild ARDS, 20 had moderate ARDS, and 15 were diagnosed with severe ARDS.

Calculation of the dynamic mechanical power (MP$_{dyn}$)

WOBv is the amount of energy spent to ventilate one liter of gas and is expressed as J/L (16, 17). In this study, WOBv values were obtained from mechanical ventilators (Maquet Servo-U, Sweden), which is calculated as described Cabello and Mancebo (16) using following quation:

$$WOB = \int Pressure \times Volume$$

Then, WOBv values were dived by the tidal volume (17), which is calculated by mechanical ventilator, expressed as J/L.

To calculate mechanical power (MP$_{dyn}$), we multiplied the minute volume (MVe) by the WOBv values (3), assuming expiratory valve is inactive.

$$MP_{dyn} = WOB_v \times MV_e$$

With the contribution of PEEP, ($0.098 \times RR$ x TVe x PEEP) (2) the equation is formulated as follows:

$$MP_{dyn} = MV_e \times [(WOBv) + (PEEP \times 0.098)]$$

MVe is the expiratory minute volume (L/min), WOBv is the Work of Breathing ventilator (J/L), PEEP is the Positive End Expiratory Pressure (cmH_2O), and 0.098 is the transformation factor.

Calculation of the linear model mechanical power (MP$_{LM}$)

Mechanical power calculation was performed using the Linear Model mechanical power equation (MP$_{LM}$) by Trinkle et al.

$$MP_{LM} = 0.098 \times RR \times \Big[TVe \times \left(PEEP + \Delta P_{insp} \right) - 0.15 \times \Delta P_{insp}^2 \times T_{slope}/Ri \Big]$$

RR is the Respiratory rate, ΔP_{insp} is the Inspiratory airway pressure change (cmH_2O), PEEP is the Positive End Expiratory Pressure (cmH_2O), TVe is the Expiratory tidal volume (L), Ri is the Inspiratory resistance ($cmH_2O/L/s$), T_{slope} is the Inspiratory rise time (sc), and 0.098 is the transformation factor.

In PCV mode, inspiratory resistance (Ri) used in mechanical power calculation with MP$_{LM}$ and MP$_{slope}$ equations can only be measured with the least square fit method (LSF) in mechanical ventilators. Since a fixed T_{pause} time is set in volume control ventilation, the inspiratory resistance is continuously measured automatically by the mechanical ventilator. In ARDS patients, the median inspiratory resistance value in VCV mode is considered to be 10 cmH_2O s/L (4, 15, 16). In this way, practical alternatives to the complex VCV equation have been developed (4, 17). This approach in VCV mode can also be applied to PCV mode.

Arnal JM et al. calculated the median inspiratory resistance value with LSF as 15 cmH_2O s/L in ARDS patients ventilated in PCV mode (the same value is valid for adult non-ARDS patients without COPD) (10, 18).

In our study, mechanical power was calculated at T_{slope} 5%, 10%, 15% and 20% with I:E ratios 1:2 and 1:1 by using the median Ri value of 15 cmH_2O s/L instead of inspiratory resistance used in MP$_{LM}$ equation. Among the mechanical power equations developed for PCV mode, the MP$_{LM}$ equation was preferred as the reference equation in this study because it calculates the closest values (bias 8%) to the geometric method, which is accepted as the gold standard method in power calculations (1). With a median value of 15 cmH_2O s/L of inspiratory resistance, both MP$_{LM}$ and MP$_{dyn}$ equations were compared with each other in T_{slope} of 5%, 10%, 15% and 20%.

Statistical methodology

To compare the mechanical power values obtained from different equations, univariate linear regression was employed to analyze pairs of equations. Bland–Altman analysis, with a subsequent simple t-test for post hoc analysis, was utilized to further assess the similarity or divergence between these methods. Multiple comparisons of respiratory mechanics, including mechanical power, obtained at T_{slope} values of 5%, 10%,

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15%, and 20%, were conducted using a repeated measures Multivariate Analysis of Variance (MANOVA) approach. Post hoc analyses were performed using the Tukel test. All statistical analyses were carried out using GraphPad Prism version 9.3.1.471 (Serial Number: GPS-2345356-TCTS-A6818).

Measurements were made for 160 min for each patient and 6080 min for a total of 38 patients. Data were saved in ImdSoftMetavision/QlinICU Clinical Decision Support Software. Statistical analyzes were performed on the basis of patient averages and data (in minutes). Subgroup analyses were performed based on both Inspiration/Expiration (I:E) ratios and T_{slope}. To establish the required sample size, a preliminary study was conducted involving 5 patients. The primary outcome measure was the difference between the MP_{dyn} and MP_{LM} equations. The mean difference between the equations was approximately 0.35 J/min, with a standard deviation of approximately 0.5 J/min. Power analysis was then conducted, considering an 85% power difference with a standard error of 0.05. Based on these parameters, the sample size for the study was determined to be 38 patients when the maximum mean difference and standard deviation of the difference between methods were approximately 0.5 ± 1.0 J/min, as calculated using G*power version 3.

Results

The characteristics of 38 ARDS patients, including mean and standard deviation values for demographic data, scores, arterial blood gases and respiratory mechanics, providing a comprehensive review of these parameters are displayed in Table 1.

Mechanical power was calculated for four different T_{slope} values (5%, 10%, 15%, and 20%) under two different Inspiration/Expiration (I:E) ratios (1:2 and 1:1) using both the MP_{LM} equation and the dynamic mechanical power equation (MP_{dyn}) in the cohort of 38 patients with Covid-19-related Acute Respiratory Distress Syndrome (C-ARDS). These calculations were then subjected to analysis through univariate linear regression and Bland–Altman analysis to elucidate the relationships and differences between the two equations.

Univariate linear regression and Bland–Altman analysis

In the univariate linear regression analysis was performed on the mean power values of all 38 patients, encompassing 6080 min of data, both the MP_{dyn} and MP_{LM} equations displayed significant correlations ($y = 1.0 \pm 0.018$, $R^2 = 0.99$, and $y = 1.0 \pm 0.002$, $R^2 = 0.98$, respectively, $P < 0.0001$, Fig. 1A and C).

Bland–Altman analysis based on the mean power values of all patients and all measurements revealed mean differences and standard deviations of bias

Table 1 Patient characteristics

Patients characteristics (n:38)	Means and sd
Gender, female (%)	16 (42%)
Height (m)	1,71 ± 0,08
Weight (kg)	81,9 ± 11,7
Body mass index (kg/m^2)	28,2 ± 3,7
Predicted body weight (kg)	64,4 ± 9,6
Age (years)	60,7 ± 17,1
pH	7,29 ± 0,13
PaCO$_2$ (mmHg)	56 ± 16
PaO$_2$ (mmHg)	92 ± 24
PaO$_2$/FiO$_2$ (mmHg/%)	152 ± 52
FiO$_2$ (%)	64 ± 15
HCO$_3$ (meq/dL)	22,9 ± 4,9
BE (meq/dL)	−1,9 ± 6,2
ΔP$_{insp}$ (cmH$_2$O)	16,1 ± 3,0
PEEP (cmH$_2$O)	9,7 ± 2,0
TV$_e$/PBW (ml/kg)	7,2 ± 1,4
P$_{peak}$ (cmH$_2$O)	25,8 ± 3,0
Minute volume (L/minute)	6,9 ± 1,6
Compliance (ml/cmH$_2$O)	29,0 ± 7,0
WOBv (J/L)	1,3 ± 0,23
Vee (ml/s)	0,024 ± 0,016
APACHE II score first and last	23 ± 9 and 26 ± 11
Expected mortality (%)	48 ± 25
ICU mortality	22 (58%)
SOFA score first and last	10 ± 4 and 12 ± 6
Length of stay in ICU (days)	16,8 ± 8,2
Invasive mechanical ventilation time (day)	15,0 ± 7,4

values as −0.42 ± 0.41 J/min (2.6% ± 2.3%, $P < 0.0001$) and −0.39 ± 0.57 J/min (3.6% ± 3.5%, $P < 0.0001$), respectively, indicating statistical significance (Fig. 1B and D).

Patient mean power values calculated with MP_{dyn} and MP_{LM} equations at T_{slope} 5%, 10%, 15%, and 20% for an Inspiration/Expiration (I:E) ratio of 1:2 were correlated in univariate linear regression analysis ($y = 1.0 \pm 0.015$, $R^2 = 0.99$; $y = 1.0 \pm 0.018$, $R^2 = 0.99$; $y = 1.0 \pm 0.035$, $R^2 = 0.96$; $y = 1.0 \pm 0.027$, $R^2 = 0.98$,   respectively; $P < 0.0001$, see Additional file 1: Figure S3A, B, C, D).

In T_{slope} 5%, 10%, and 15% Bland–Altman analysis, mean differences and standard deviations of bias values were calculated as −0.75 ± 0.39 J/min (4.2% ± 1.9%, $P < 0.0001$), −0.54 ± 0.39 J/min (3.3% ± 2.1%, $P < 0.0001$), −0.31 ± 0.48 J/min (1.9% ± 2.8%, $P = 0.0004$), respectively, all of which were statistically significant (Fig. 2A, B, C). The mean difference and standard deviation of bias values for T_{slope} 20% were calculated as −0.01 ± 0.55 J/min (0.2% ± 3.8%) and were not statistically significant ($P = 0.91$, Fig. 2D).

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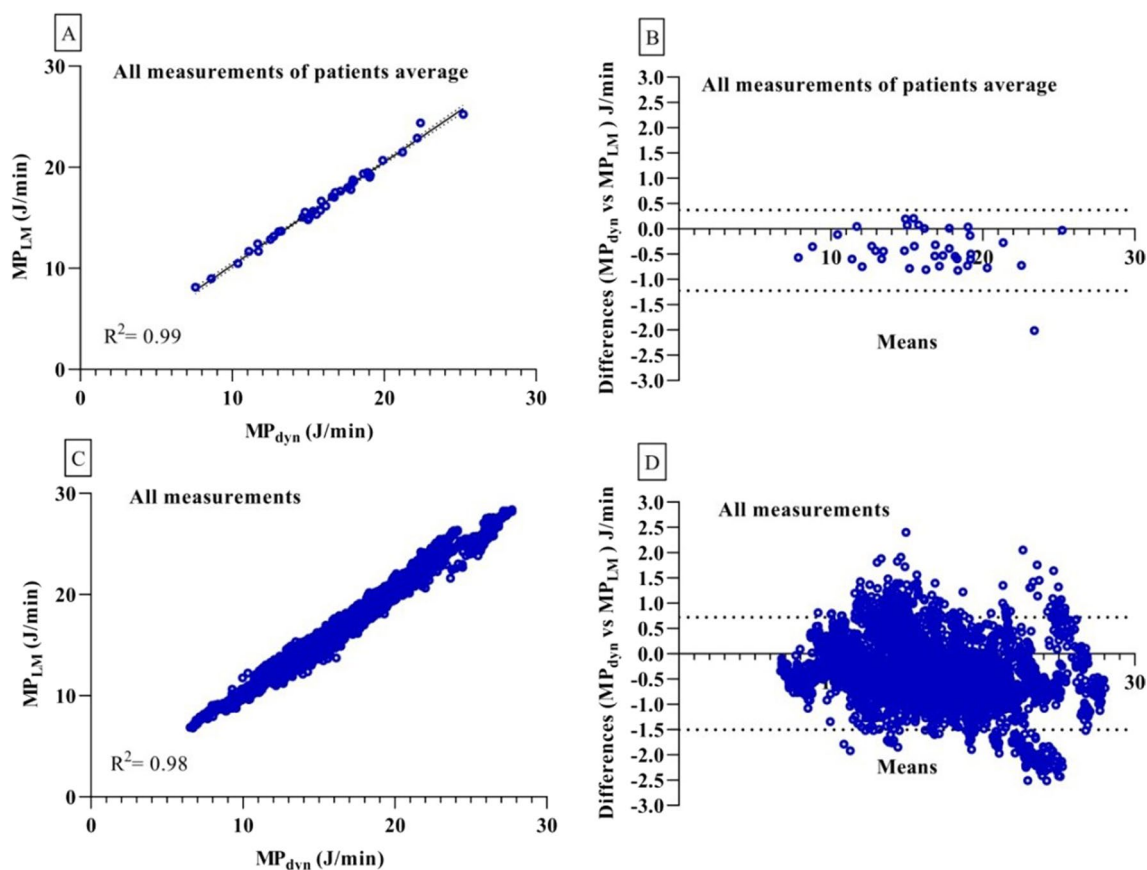
Fig. 1 Univariate lineer regression and Bland–Altman based analyses on mechanical power of all patients average and all measurements. **A**. MP_{LM} (y-axis)—is plotted as function of the MP_{dyn} equation (x-axis), **B**. MP_{dyn}- MP_{LM} corresponding Bland–Altman plots. C. MP_{LM} (y-axis)—is plotted as function of the MP_{dyn} equation (x-axis), D. MP_{dyn}- MP_{LM} corresponding Bland–Altman plots

Patient mean power values calculated with MP_{dyn} and MP_{LM} equations at T_{slope} 5%, 10%, 15%, and 20% for an I:E ratio of 1:1 were correlated in univariate linear regression analysis ($y = 1.0 \pm 0.015$, $R^2 = 0.99$; $y = 1.0 \pm 0.014$, $R^2 = 0.99$; $y = 1.0 \pm 0.020$, $R^2 = 0.99$; $y = 0.99 \pm 0.026$, $R^2 = 0.98$, respectively; $P < 0.0001$, see Additional file 1: Figure S4A, B, C, D).

In T_{slope} 5%, 10%, and 15% Bland–Altman analysis, mean differences and standard deviations of bias values were calculated as -0.81 ± 0.37 J/min ($4.5\% \pm 2.0\%$, $P < 0.0001$), -0.59 ± 0.35 J/min ($3.5\% \pm 2.1\%$, $P < 0.0001$), -0.38 ± 0.47 J/min ($2.3\% \pm 2.6\%$, $P < 0.0001$), respectively, all of which were statistically significant (Fig. 3A, B, C). The mean difference and standard deviation of bias values for T_{slope} 20% were calculated as -0.02 ± 0.60 J/min ($0.2\% \pm 3.8\%$) and were not statistically significant ($P = 0.81$, Fig. 3D).

The effect of 5% increase in T_{slope} on the mechanical power values calculated with MP_{LM} and MP_{dyn} are represented in Additional file 1: Table S2.

Additional file 1: Table S3 displays a comparison of respiratory mechanics, encompassing ΔP_{insp}, PEEP, MVe, and WOBv, for T_{slope} values of 5%, 10%, 15%, and 20% between MP_{LM} and MP_{dyn}. Additionally, Additional file 1: Table S4 presents patient averages of RR, TVe, C, T_{insp}, end-expiratory velocity (Vee), FiO_2, SpO_2, and $etCO_2$ at T_{slope} 5%, 10%, 15%, and 20% for I:E ratios of 1:2 and 1:1.

Discussion

Monitoring mechanical power (MP), a parameter that combines key variables involved in ventilator-induced lung injury (VILI), holds promise as a valuable tool in guiding lung-protective ventilation for critically ill patients (19). However, the practical implementation of MP calculations, particularly in pressure control ventilation (PCV), has presented challenges (10). In this study, the dynamic mechanical power (MP_{dyn}) equation, which calculates MP in PCV mode without the need for inspiratory resistance measurement, was compared with the Linear Model mechanical power equation (MP_{LM}) (1) in
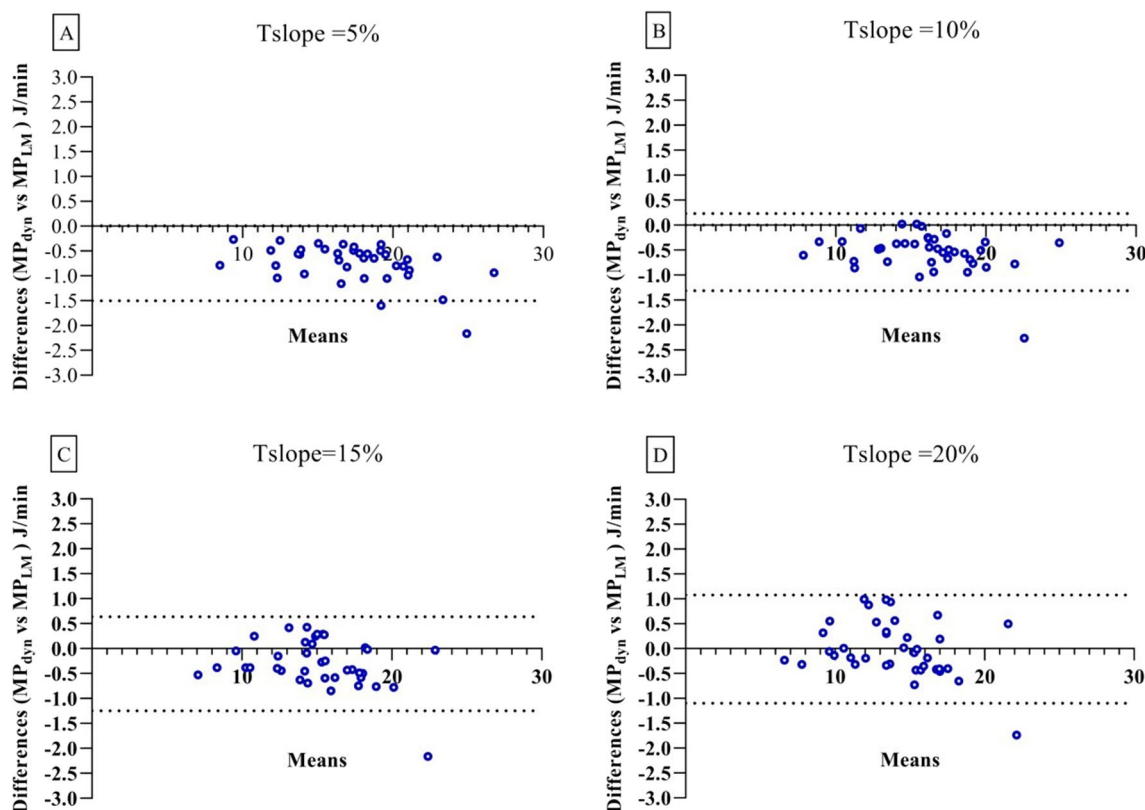
Fig. 2 Bland–Altman based analyses on mechanical power of all patients average. For I:E 1:2 T$_{slope}$ 5%: **A** MP$_{dyn}$- MP$_{LM}$ corresponding Bland–Altman plots. For I:E 1:2 T$_{slope}$ 10%: 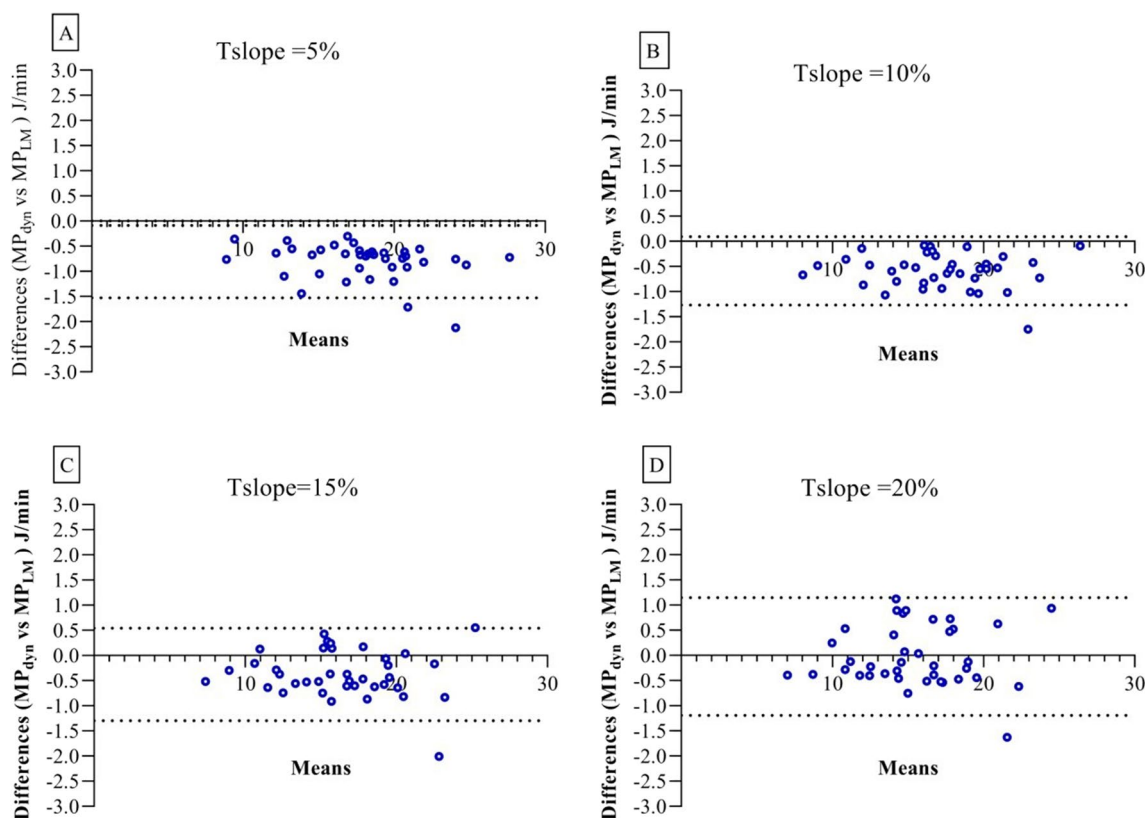**B** MP$_{dyn}$- MP$_{LM}$ corresponding Bland–Altman plots. For I:E 1:2 T$_{slope}$ 15%: **C** MP$_{dyn}$- MP$_{LM}$ corresponding Bland–Altman plots. For I:E 1:2 T$_{slope}$ 20%: **D** MP$_{dyn}$- MP$_{LM}$ corresponding Bland–Altman plots

Covid-19-related Acute Respiratory Distress Syndrome (C-ARDS) patients. The study assessed the impact of different inspiratory rise times (T$_{slope}$) on MP values.

The results of this study revealed that MP values calculated using the MP$_{dyn}$ and MP$_{LM}$ equations were highly correlated, indicating that both equations can provide consistent estimations of MP. The most significant differences between the two equations were observed at T$_{slope}$ 5%, with MP$_{dyn}$ consistently showing lower values compared to MP$_{LM}$. However, these differences diminished as T$_{slope}$ increased, and no statistically significant difference was found at T$_{slope}$ 20%. Interestingly, while the differences between the two equations were statistically significant at T$_{slope}$ 5%, these differences were not considered clinically relevant. This finding suggests that despite the statistical variance, both equations produce MP values that are practically equivalent for clinical decision-making. We also observed that increasing T$_{slope}$ resulted in a decrease in MP values calculated by both equations. This decrease in MP with longer T$_{slope}$ times can be explained by the fact that slower inspiratory gas flow at the beginning of inspiration applies less energy to the respiratory system. Importantly, this decrease in MP

may be beneficial, as high energy levels have been linked to lung damage in both experimental and clinical studies. It is known that MP values exceeding certain threshold values (12 J/min for ARDS and 17 J/min for non-ARDS patients) can lead to significant lung injury. Thus, reducing MP, especially in ARDS patients, is desirable to minimize the risk of VILI.

The study's findings are consistent with the notion that flow patterns and rates are crucial in ARDS patients. In PCV, MP is concentrated at the beginning of inspiration, which can be problematic, whereas in volume control ventilation (VCV), MP is distributed more evenly throughout inspiration. Increasing T$_{slope}$ to slow the gas flow at the beginning of inspiration can reduce the concentration of power and minimize the risk of damage to the lungs.

In conclusion, this study underscores the practicality and clinical relevance of calculating MP using both the MP$_{dyn}$ and MP$_{LM}$ equations in PCV mode. While differences in MP values were observed at lower T$_{slope}$ settings, these differences were not considered clinically significant. The study also highlights the potential benefits of adjusting T$_{slope}$ to lower MP values, thereby reducing

Fig. 3 Bland–Altman based analyses on mechanical power of all patients average. For I:E 1:1 T_{slope} 5%: **A** MP_{dyn}- MP_{LM} corresponding Bland–Altman plots. For I:E 1:1 T_{slope} 10%: **B** MP_{dyn}- MP_{LM} corresponding Bland–Altman plots. For I:E 1:1 T_{slope} 15%: **C** MP_{dyn}- MP_{LM} corresponding Bland–Altman plots. For I:E 1:1 T_{slope} 20%: **D** MP_{dyn}- MP_{LM} corresponding Bland–Altman plots

the risk of VILI. Additionally, the MP_{dyn} equation offers a convenient option for continuously and in real time calculating MP in PCV mode without the need for inspiratory resistance measurements, which could prove valuable in clinical practice.

However, without altering the fundamental respiratory parameters (ΔP_{insp}, RR, and PEEP) that constitute mechanical power, each 5% increase in T_{slope} led to an approximate 1 J/min reduction in the mechanical power values calculated using both the MP_{LM} and MP_{dyn} equations. Consequently, an approximate 3 J/min difference was observed between the power values at T_{slope} 5% and 20%. Since all the respiratory mechanics contributing to power remained constant (no difference in MV_e at I:E 1:1, and a clinically insignificant decrease at I:E 1:2), no changes were expected in the static and dynamic elastic components of power (PEEP and driving pressure). The reason behind the decrease in mechanical power was attributed to the constriction of the area forming the resistive component of the P–V loop as T_{slope} increased (refer to Fig. 4 for I:E 1.2 and Additional file 1: Figure S2 for 1:1).

Trinkle et al. (1) reported that mechanical power decreases as T_{slope} increases, and our study is in agreement with them. In ARDS patients with reduced lung volume and inhomogeneity, reducing flow amplitude by increasing T_{slope} and providing a low peak flow may be advantageous (20). Importantly, it was observed that prolonging T_{slope} up to 20% did not induce intrinsic PEEP in this patient population. Additionally, a minimal increase in carbon dioxide, which was not clinically significant, was deemed acceptable. Each 5% increase in T_{slope} resulted in a minimal end-tidal carbon dioxide increase of approximately 1 mmHg and a decrease in tidal volume of approximately 10 ml, which was not clinically relevant (see Additional file 1: Table S4). Longer T_{slope} times resulted in less energy being applied to the respiratory system. High energy levels have been linked to significant lung damage in experimental and clinical studies (over 12 and 17 J/min for ARDS and non-ARDS, respectively) (19, 21–23). It has been suggested that damage increases exponentially as mechanical power exceeds these threshold values due to factors such as gradual breaking of carrier microstructure elements, decreased ventilated areas

Fig. 4 Dynamic pressure–volume loop (P–V), pressure- time, flow- time and volume- time graphics of I:E 1:2 and T_{slope} 5%, 10%, 15% and 20% in PCV mode (obtained with screen shots of the Servo-U mechanical ventilator)

(baby lungs), increased load on the remaining structures, and the catalytic effect of stress increasers (22).

A notable finding is that WOBv decreased significantly as T_{slope} increased. It is known that WOB decreases when the inspiratory gas flow is reduced in PCV mode, while in VCV mode, increasing gas flow by 20% results in a 37% increase in mechanical power (2, 24, 25). The gas flow profile and high gas flow amplitude have been associated with increased VILI, highlighting the importance of flow pattern and rate in ARDS patients (26–28). Similar findings have been demonstrated in animal models of lung injury (29, 30). Notably, in PCV, mechanical power is concentrated at the beginning of inspiration, while in VCV, it is evenly distributed throughout inspiration (31). This study indicates that increasing T_{slope} and slowing gas flow during the initial phase of inspiration can lead to lower mechanical power applied to the lung and reduced

power concentration at the start of inspiration (approximately 1 J/min for every 5% increase).

A recent in-silico study in single and multi-compartment lung models highlighted the importance of flow profile and amplitude in determining strain and strain-related power distribution (32). These findings support the idea that setting longer T_{slope} times to reach the target pressure (ΔP_{insp}) in pressure control ventilation can provide slower inspiratory gas flow to the lungs during early inspiration, resulting in safer lung ventilation (i.e., less power) (20).

The debate over whether rapid transmission of per-cycle energy to the lungs during early inspiration may increase damage in ARDS patients is ongoing. It is suggested that the decelerating flow pattern may put PCV mode at a disadvantage in this context (33). However, with extended T_{slope} periods in which inspiratory time is adjusted to achieve the target tidal volume (4–6 ml/

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kg), this concern is alleviated, and lower mechanical power is applied to the lungs. For existing mechanical ventilator brands that display parameters such as work of breathing (WOB) and work of breathing ventilatory (WOBv), the MP_{dyn} equation can be considered as an alternative method for continuously and in real-time calculating mechanical power in control ventilation (PCV) modes without the need for inspiratory resistance measurements.

Limitations

The results of this study cannot be extrapolated to patients with COPD, who typically exhibit higher median inspiratory resistance values, as our calculations were based on a constant inspiratory resistance value of 15 cmH_2O s/L. Furthermore, in patients with a stiff chest wall, such as those who are obese or kyphotic, the utilization of WOB and WOB_v parameters to estimate the force applied to the lung may introduce a higher margin of error (16). It's worth noting that this limitation applies to all power equations that rely on respiratory parameters obtained from mechanical ventilators. The predictive accuracy of the MP_{dyn} equation might be less apparent to the user for prospective estimation because the equation relies on WOBv calculated by the ventilator and does not incorporate user-controlled variables such as ΔP_{insp} (change in inspiratory pressure) and TVe (tidal volume). Unfortunately, due to the unavailability of the necessary equipment, we were unable to compare the mechanical power values calculated with all the equations against the geometric method, which is widely regarded as the gold standard for power calculation.

Conclusion

The disparity between mechanical power values computed using the MP_{dyn} and MP_{LM} equations at varying T_{slope} durations did not yield clinically significant differences. We recommend for the use of the MP_{dyn} equation as a practical and continuous alternative for calculating mechanical power in PCV mode. Notably, a substantial reduction in mechanical power was observed with longer T_{slope} durations. Specifically, each 5% increment in T_{slope} corresponded to a decrease in mechanical power by approximately 1 J/min.

In the quest for safer ventilation strategies, inspiratory rise time should be considered as a variable that exerts a clinically significant impact on mechanical power.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40635-023-00584-6.

Additional file 1: Table S1. Mechanical power equations in PCV,VCV, and PCV: Pressure Control Ventilation; MP_{pcv}: alternative pressure control power equation, $MP_{pcv(m-simpl)}$: modified pressure control simplified power equation, $MP_{pcv(simpl)}$: simplified pressure control power equation, $MP_{pcv(slope)}$: comprehensive pressure control simplified power equation, VCV: Volume Control Ventilation; MP_{std}: standart volume control power equation $MP_{vcv-simpl}$: Gattinoni simplified equation $MP_{vcv-surr}$: volume control surrogate power equation, MP_{dyn}: dynamic power equation, MP_{pmean}: mean airway pressure (P_{mean}) derived power equation, CF: conversion factor. **Figure S1.** Flow chart C-ARDS, Covid-19 related acute respiratory distress syndrome; CHF, congestive heart failure; COPD, Chronic obstructive pulmonary disease; IMV, invasive mechanical ventilation; ECMO, extracorporeal membrane oxygenation; ICU, intensive care unit; LOS, length of stay. **Figure S2.** Dynamic pressure–volume loop (P–V), pressure—time, flow—time and volume—time graphs of IE 1:1 and T_{slope} 5%, 10%, 15% and 20% times of the patient ventilated in passive pressure control mode (obtained with screen shots of the Servo-U mechanical ventilator). **Figure S3.** In univariable logistic regression analyses on mechanical power of all patients average. For IE 1:2 and T-slope 5%: A. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:2 and T-slope 10%: B. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:2 and T_{slope} 15%: C. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:2 and T_{slope} 20%: D. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). **Figure S4.** In univariable logistic regression analyses on mechanical power of all patients average. For IE 1:1 and T-slope 5%: A. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:1 and T_{slope} 10%: B. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:1 and T_{slope} 15%: C. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). For IE 1:1 and T-slope 20%: D. MP_{LM} (y-axis) is plotted as function of the MP_{dyn} equation (x-axis). **Table S2.** The patient averages of mechanical power values calculated with MP_{LM} and MP_{dyn} equations at I:E 1:2 and 1:1 ratios at T_{slope} 5%, 10%, 15%, 20% times were compared with the repeated measures MANOVA method. Tukey's multiple comparisons test was used to detect significant difference between groups. **Table S3.** The patient averages of T_{slope} 5%, 10%, 15%, and 20% P_{insp}, PEEP, MVe and WOBv parameters were compared with the repeated MANOVA method. Tukey's multiple comparisons test was used to detect significant difference between groups. **Table S4.** The patient averages of T_{slope} 5%, 10%, 15%, and 20% RR, TVe, T_{insp}, Vee, FiO_2, SpO_2 and $etCO_2$ parameters were compared with the repeated MANOVA method. Tukey's multiple comparisons test was used to detect significant difference between groups.

Declarations

Ethics approval and consent to participate
This study was approved by the University of Health Sciences, Bakırköy Dr. Sadi Konuk Training and Research Hospital Clinical Research Ethics Committee with the decision number 2022/11-02 dated 06.06.2022. During the admission of the patients to the intensive care unit, the relatives of the patients were

References

1. Trinkle CA et al (2022) Simple, accurate calculation of mechanical power in pressure controlled ventilation (PCV). Intensive Care Med Exp 10(1):1–12
2. Gattinoni L, Tonetti T, Cressoni M, Cadringher P, Herrmann P, Moerer O et al (2016) Ventilator-related causes of lung injury: the mechanical power. Intensive Care Med 42:1567–1575
3. Aşar S et al (2020) Bedside dynamic calculation of mechanical power: a validation study. J Crit Care 56:167–170
4. Giosa L et al (2019) Mechanical power at a glance: a simple surrogate for volume-controlled ventilation. Intensive care Med Exp 7(1):1–13
5. Chi Yi, He H, Long Y (2021) A simple method of mechanical power calculation: using mean airway pressure to replace plateau pressure. J Clin Monit Comput 35(5):1139–1147
6. Becher T, van der Staay M, Schädler D, Frerichs I, Weiler N (2019) Calculation of mechanical power for pressure-controlled ventilation. Intensive Care Med 45(1321–3):6
7. van der Meijden S, Molenaar M, Somhorst P, Schoe A (2019) Calculating mechanical power for pressure-controlled ventilation. Intensive Care Med 45(1495–7):7
8. Becher T, van der Staay M (2019) Calculation of mechanical power for pressure-controlled ventilation: author's reply. Intensive Care Med 45:1498–1499
9. Aşar S et al (2022) Simplified calculation of mechanical power for pressure controlled ventilation in Covid-19 ARDS patients. Min Anestesiol 88(1–2):42–50
10. Iotti GA et al (1995) Respiratory mechanics by least squares fitting in mechanically ventilated patients: applications during paralysis and during pressure support ventilation. Intensive Care Med 21(5):406–413
11. Marini JJ, Crooke PS, Tawfk P, Chatburn RL, Dries DJ, Gattinoni L (2021) Intracycle power and ventilation mode as potential contributors to ventilator-induced lung injury. Intensive Care Med Exp 9:55. https://doi.org/10.1186/s40635-021-00420-9
12. Marini JJ, Crooke PS, Gattinoni L (2021) Intra-cycle power: is the flow profile a neglected component of lung protection? Intensive Care Med 47(5):609–611
13. Maeda Y et al (2004) Effects of peak inspiratory flow on development of ventilator-induced lung injury in rabbits. J Am Soc Anesthesiol 101(3):722–728
14. Rich Preston B et al (2000) Effect of rate and inspiratory flow on ventilator-induced lung injury. J Trauma Acute Care Surg 49(5):903–911
15. ARDS Definition Task Force, Ranieri VM, Rubenfeld GD, Thompson BT, Ferguson ND, Caldwell E, Fan E, Camporota L, Slutsky AS (2012) Acute respiratory distress syndrome: the Berlin definition. JAMA 307(23):2526–33
16. Cabello B, Mancebo J (2006) Work of breathing. Intensive Care Med 32(9):1311–1314
17. Marini JJ, Rodriguez RM, Lamb V (1986) Bedside estimation of the inspiratory work of breathing during mechanical ventilation. Chest 89(1):56–63
18. Ashworth L, Norisue Y, Koster M, Anderson J, Takada J, Ebisu H (2018) Clinical management of pressure control ventilation: an algorithmic method of patient ventilatory management to address "forgotten but important variables." J Crit Care 43:169–182
19. Guglielminotti J, Desmonts JM, Dureuil B (1998) Effects of tracheal suctioning on respiratory resistances in mechanically ventilated patients. Chest 113:1335–1338
20. Bernasconi M et al (1988) Respiratory compliance and resistance in mechanically ventilated patients with acute respiratory failure. Intensive Care Med 14(5):547–553
21. Chiumello Davide et al (2020) Bedside calculation of mechanical power during volume-and pressure-controlled mechanical ventilation. Crit Care 24(1):1–8
22. Arnal JM, Garnero A, Saoli M, Chatburn RL (2018) Parameters for simulation of adult subjects during mechanical ventilation. Respir Care 63(2):158–168
23. Neto Serpa, Ary, et al (2018) Mechanical power of ventilation is associated with mortality in critically ill patients: an analysis of patients in two observational cohorts. Intensive Care Med 44(11):1914–1922
24. Cressoni M et al (2016) Mechanical power and development of ventilator-induced lung injury. Anesthesiology 124(5):1100–1108
25. Marini JJ (2019) Evolving concepts for safer ventilation. Crit Care 23(1):114
26. Battaglini D et al (2021) Ten golden rules for individualized mechanical ventilation in acute respiratory distress syndrome. J Intensive Med 1(1):42–51
27. Silva PL, Rocco PRM, Pelosi P (2022) Personalized mechanical ventilation settings: slower is better!. Annual update in intensive care and emergency medicine 2022. Springer, Cham, pp 113–127
28. Al-Saady N, Bennett ED (1985) Decelerating inspiratory flow waveform improves lung mechanics and gas exchange in patients on intermittent positive-pressure ventilation. Intensive Care Med 11(2):68–75
29. Gattinoni L, Marini JJ, Collino F, Maiolo G, Rapetti F, Tonetti T et al (2017) The future of mechanical ventilation: lessons from the present and the past. Crit Care 21(1):1–11
30. Tschumperlin DJ, Oswari J, Margulies ASS (2000) Deformation-induced injury of alveolar epithelial cells: effect of frequency, duration, and amplitude. Am J Respir Crit Care Med 62(2):357–362
31. Beitler JR, Malhotra A, Thompson BT (2016) Ventilator-induced lung injury. Clin Chest Med 37(4):633–646
32. Gattinoni L, Collino F, Camporota L (2023) Mechanical power: meaning, uses and limitations. Intensive Care Med 49:465–467. https://doi.org/10.1007/s00134-023-06991-3
33. Crooke PS et al (2022) Intracycle power distribution in a heterogeneous multi-compartmental mathematical model: possible links to strain and VILI. Intensive Care Med Exp 10(1):1–14

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