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Mechanical Power Differs Between Pressure-Controlled Ventilation and Different Volume-Controlled Ventilation Modes

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OBJECTIVES: Mechanical power (MP) is a way of estimating the energy delivered by the ventilator to the patient. For both volume-controlled ventilation (VCV) and pressure-controlled ventilation (PCV) methods have been described to calculate the MP. The pressure-volume (PV) loop, from which the MP is calculated, is different for VCV compared with PCV. We aimed to compare the MP of VCV with zero pause time (VCV-0), VCV with 10% pause time (VCV-10), and PCV within patients in different patient categories based on severity of lung injury.

DESIGN: In a proof-of-concept study, we enrolled 46 mechanically ventilated patients without spontaneous breathing efforts. Baseline measurements were done in pressure-controlled mode. Subsequently, measurements were done in VCV-0 and VCV-10. Tidal volume and all other settings were kept the same.

SETTING: ICU, single university medical center.

PATIENTS: Fifty-eight cases in 46 patients on controlled ventilation modes.

INTERVENTIONS: Comparison between the MP of PCV, VCV-0, and VCV-10.

MEASUREMENT AND MAIN RESULTS: The mean MP of VCV-0, VCV-10, and PCV was 19.30, 21.80, and 20.87 J/min, respectively ($p < 0.05$ for all comparisons). The transpulmonary MP of VCV-0, VCV-10, and PCV was 6.75, 8.60, and 7.99 J/min, respectively ($p < 0.05$ for all comparisons).

CONCLUSIONS: In patients ventilated in a controlled mode, VCV without pause time had the lowest MP followed by PCV. VCV with 10% pause time had the highest MP.

KEY WORDS: mechanical power; mechanical ventilation; pressure-controlled ventilation; stress and strain of the lung; ventilator-induced lung injury; volume-controlled ventilation

Mechanical ventilation is crucial in the treatment of respiratory failure but comes with a price. Despite its benefits mechanical ventilation can also induce harm to the lung called ventilator-induced lung injury (VILI) (1). Overdistention and atelectasis are important determinators of VILI next to stress, which is equivalent to the reaction of lung tissue upon the applied pressure generated by the ventilator, and strain, which is equivalent to the change in volume of the lung upon the generated stress (2). Several other ventilatory parameters, such as driving pressure, plateau pressure, volume, flow, and respiratory rate, are thought to contribute to VILI (3). These parameters reflect the amount of energy distributed to the lung by the ventilator. Gattinoni et al (4) called the energy distribution the mechanical power (MP) and described, in volume-controlled ventilation (VCV), how MP could be measured using the pressure-volume (PV) loop. They derived a mathematical equation using the settings of the ventilator as variables for the calculation of the MP, which is an approximation and only valid for VCV (4).

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The hypothesis is that a higher MP reflects higher stress and strain and therefore a higher chance to develop VILI. Cressoni et al (5) showed in an animal study that ventilating healthy piglets with high transpulmonary MP (MP_L) led to more lung damage but only after a threshold of 12 J/min. Serpa Neto et al (6) calculated retrospectively the MP in two large Acute Respiratory Distress Syndrome Cohorts (Medical Information Mart for Intensive Care - III and eICU Collaborative research database) and found a consistent increase in mortality with larger MP after a threshold of 17 J/min.

The work of a single breath in mechanically ventilated patients is defined as the area between the inspiratory limb of the dynamic PV loop and the zero-pressure axis (4, 7). The dynamic PV loop depends, apart from resistance, compliance, and set parameters, predominantly on the flow pattern. In VCV, it is common to ventilate with constant flow leading to a characteristic pressure and volume loop (**Figs. 1–3**). Calculation of the MP of VCV has been described by Gattinoni et al (4). In pressure-controlled ventilation (PCV), the flow pattern has a decelerating character leading to a different characteristic pressure and volume loop (Figs. 1–3). Calculation of the MP of PCV has been described by van der Meijden et al (7).

The amount of energy distributed by the ventilator could be different for VCV and PCV because there is a difference between flow patterns. This could have clinical implications. However, PCV and VCV are extensively used in clinical studies, and one ventilation mode has not been found superior to the other (8).

To measure the plateau pressure in VCV, it is common to set an inspiratory pause time. A pause time of 10% is a common setting, in which the inspiratory time is shortened with 10% of the total cycle time. However, this leads to a higher flow because the tidal volume is reached in a shorter time, which leads to a different PV loop and different energy distribution.

To estimate the stress and strain of the lung instead of the total respiratory system, it is necessary to use an esophageal catheter to measure the esophageal pressure as an estimate of the pleural pressure (9). This makes it possible to assess the mechanics of the lung and chest wall separately. With an esophageal catheter, it is possible to create a transpulmonary PV loop and calculate the transpulmonary energy (5), that is, the energy distributed only to the lung. The transpulmonary power has possibly a better association with lung injury than the total MP (10).

It is possible to calculate the MP using algebraic methods for VCV and PCV (4, 7, 11, 12). The calculations are approximations of the measured or geometric method but are more convenient in daily clinical practice.

The aim of the study is to compare the measured—total MP, dynamic MP, and MP_L of PCV, VCV without a pause time (VCV-0), and VCV with a 10% pause

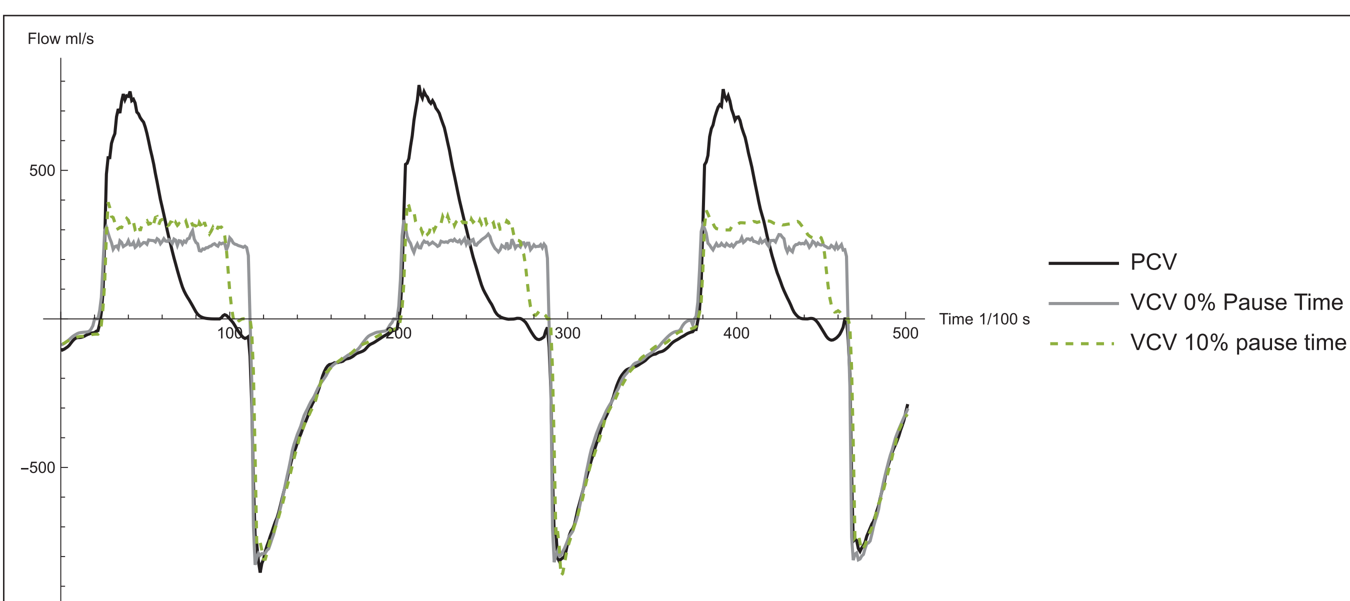

Figure 1. The flow of volume-controlled ventilation with 10% pause time (VCV-10) mode is higher than the flow of volume-controlled ventilation with 0 pause time (VCV-0) mode due to the pause time. The pressure-controlled ventilation (PCV) flow curve is completely different in nature. The flow curves are from the same patient.

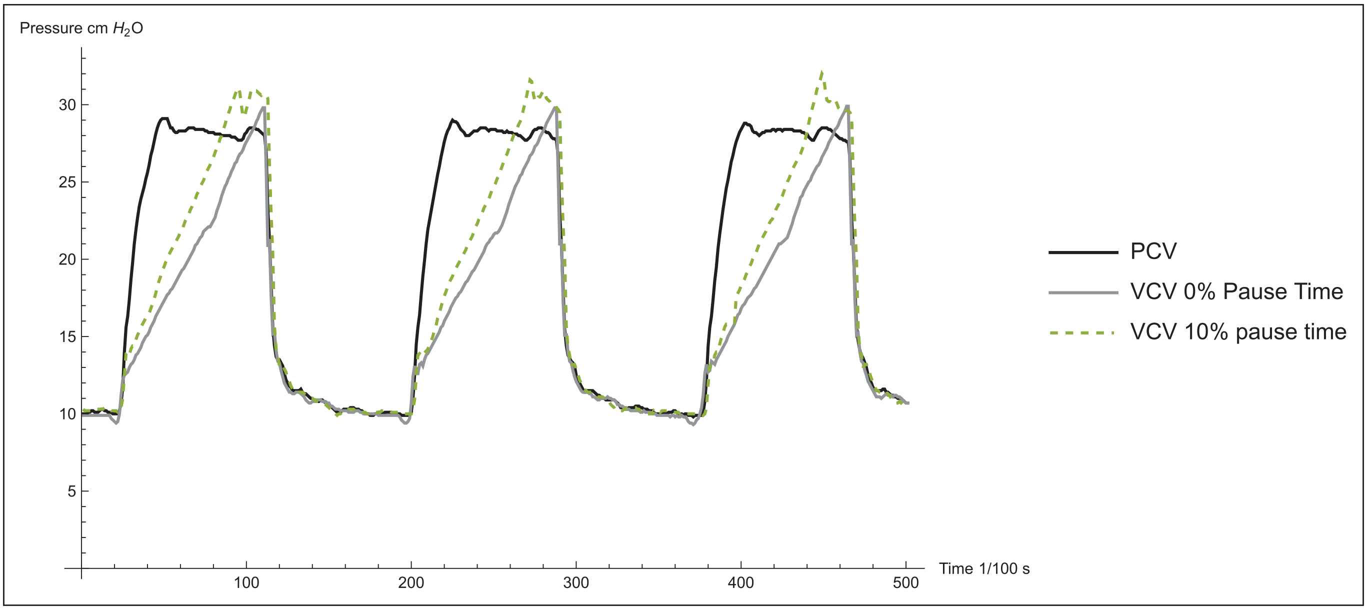

Figure 2. The peak pressure of volume-controlled ventilation with 10% pause time (VCV-10) mode is higher than the peak pressure of volume-controlled ventilation with 0 pause time (VCV-0) mode. Pressurization in pressure-controlled ventilation (PCV) is completely different in nature. The pressure curves are from the same patient.

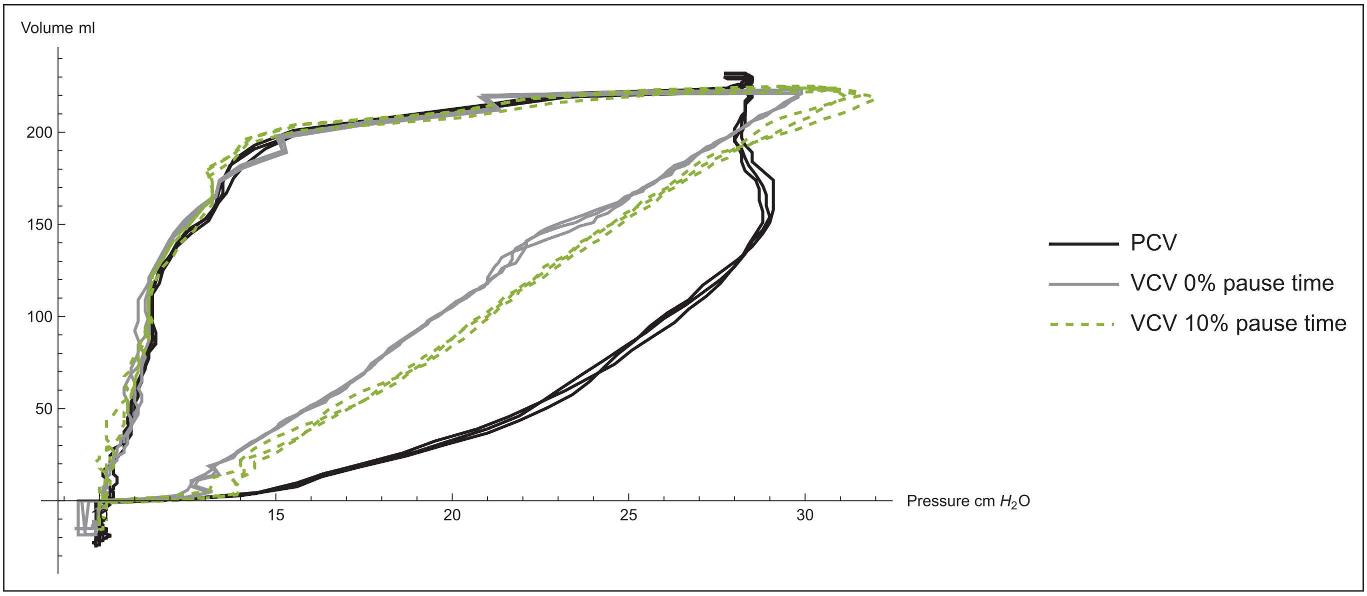

Figure 3. The area between the inspiratory limb of the pressure-volume (PV) loop and the zero-pressure axis is equivalent to the energy of a breath. The PV area of volume-controlled ventilation with 10% pause time (VCV-10) is larger than that of volume-controlled ventilation with 0 pause time (VCV-0). The PV area of the pressure-controlled ventilation (PCV) completely different in nature. The PV loops are from the same patient.

time (VCV-10), in patients with a different severity of lung injury.

METHODS

Study Population

All patients on mechanical ventilation who were admitted to the ICU of the Leiden University Medical Center from January 2021 to May 2021 were eligible for the study. Patients could be included if they were 18 years or older, were mechanically ventilated in a controlled mode, had no spontaneous breathing activity, and if consent was given to use their data by the patient or next of kin. Patients were excluded if they had any spontaneous breathing activity, showed patient-ventilator interactions like reverse triggering, or denied the use of their data.

Measurements

The MP was calculated from the recorded dynamic PV loop data from the mechanical ventilator (Hamilton-C6; Hamilton Medical AG, Bonaduz, Switzerland). Flow, volume, and airway pressure were recorded on a dedicated data acquisition system (Hamilton Medical AG). Before recording an inspiratory and expiratory hold maneuver was done to obtain the plateau pressure and total positive end-expiratory pressure (PEEP) for compliance/elastance calculations. Data recordings in each patient started in PCV mode. The duration of the recording was at least 5 minutes. After that, the mode was switched to VCV mode with 0% pause time and subsequently to VCV mode with 10% pause time. The tidal volume goal of the VCV modes was the tidal volume reached in PCV mode so that in all three recorded modes, the tidal volumes were the same. PEEP, respiratory rate, inspiratory time, and FIO_2 were kept the same for all modes. A patient could be measured multiple times but only if a large change in the clinical situation of the patient had occurred, like the necessity for controlled ventilation after a period of spontaneous ventilation because of a deteriorating clinical situation. MP was calculated from the measured data using MATLAB (Version 2020 b, Natick, MA) and Mathematica (Version 13.0.1; Wolfram Research, Champaign, IL); figures were made with Mathematica.

We calculated the MP according to the methods described by Gattinoni et al (4). The work of a single breath is the area between the inspiratory limb of the dynamic PV loop and the zero-pressure axis. The MP is the work of a single breath times the respiratory rate per minute. This geometric method is valid for both VCV and PCV measurements (4, 7). More information about the measurement and calculation of the MP can be found in **Supplement 1** (http://links.lww.com/CCX/B34).

If a patient had an esophageal balloon (Cooper Surgical, Trumbull, CT), we calculated MP_L. The MP_L is the energy distributed by the ventilator to the lungs. This is defined as the area of the transpulmonary PV loop.

The dynamical power was calculated using the dynamic PV loop and was defined as the area between the inspiratory limb of the PV loop and the PEEP axis.

Calculations

We calculated the MP using algebraic equations for VCV and PCV (4, 7, 11, 12). We used an extensive (4, 7) and a surrogate equation (11, 12) for VCV and PCV, respectively. The equations are given in Supplement 1 (http://links.lww.com/CCX/B34).

Statistical Analysis

Data were checked for normality with Quantile-Quantile - plot and the Shapiro-Wilk normality test. Continuous data are presented as mean (SD), and categorical data as n (%). Differences between the MP of different modes were estimated with the Student t test with equal variance under the null hypothesis that there was no difference. The difference of the mean is reported (SE), p values of less than 0.05 were considered statistically significant. The analysis was done using R (Version 4.0.1.; R Core Team, Vienna, Austria) with the aid of R studio (Version 1.3.1073; RStudio, Boston, MA).

Ethics

The study was approved by the local monitoring board Medisch Etische Toetsingscommissie - Leiden Delft Den Haag protocol nr N20.029, approval date July 17, 2020. Informed consent to use data of the patient was obtained from the patients or the next of kin. The study was conducted in compliance with the declaration of Helsinki (Version 2013) and according to Good Clinical Practice standards.

RESULTS

MP was measured in 58 cases in 46 patients; 44 patients had COVID-19 as admission diagnosis, one patient was diagnosed with sepsis, and one patient was admitted for postoperative care after cardiac surgery. We did not meet our goal to include a wider variation of patients with a larger difference of severity of lung injury. In **Table 1**, patient characteristics and basic measurements are shown. In 35 cases, an esophageal balloon catheter was in situ allowing measurement of MP_L.

The peak pressure of PCV mode was significantly lower than that of the volume-controlled modes (26.43 vs 28.93 vs 31.09 cm H_2O; $p < 0.0001$), the peak pressure of VCV-0 mode was significantly lower than that of VCV-10 mode ($p < 0.0001$). The plateau pressure of

TABLE 1.
Patient Characteristics and Basic Measurements

Characteristic	*n* = 58
Female	18 (31.0)
Age (yr)	62.89 (9.97)
Height (cm)	175.69 (9.81)
Weight (kg)	95.09 (21.41)
Body mass index (kg/m^2)	30.88 (7.17)
Ideal body weight (kg)	69.90 (9.99)
Sequential Organ Failure Assessment score	8.55 (2.39)
Respiratory rate (min^{-}1)	22.10 (4.42)
T insp (s)	1.03 (0.23)
Positive end-expiratory pressure (cm H_2O)	12.28 (2.97)
Compliance	36.89 (12.59)
PCV_Vti	404.31 (88.56)
VCV-0_Vti	404.31 (88.76)
VCV-10_Vti	404.66 (88.46)
PCV_resistance	11.25 (2.53)
VCV-0_resistance	7.37 (2.67)
VCV-10_resistance	10.22 (2.67)
PCV_Ppeak (cm H_2O)	26.43 (3.67)
VCV-0_Ppeak (cm H_2O)	28.93 (4.03)
VCV-10_Ppeak (cm H_2O)	31.09 (4.55)
PCV_Pplat (cm H_2O)	23.90 (3.59)
VCV-0_Pplat (cm H_2O)	24.50 (3.72)
VCV-10_Pplat (cm H_2O)	24.26 (3.76)
PCV_flow (L/min)	42.27 (6.81)[a]
VCV_0_flow (L/min)	30.22 (9.17)
VCV-10_flow (L/min)	36.72 (9.98)
PCV_driving pressure (cm H_2O)	11.62 (2.54)
VCV-0_driving pressure (cm H_2O)	12.22 (3.13)
VCV-10_driving pressure (cm H_2O)	11.57 (4.59)
PCV_$P_L$ei (cm H_2O)	10.96 (4.07)
VCV-0_$P_L$ei (cm H_2O)	11.11 (4.12)
VCV-10_$P_L$ei (cm H_2O)	11.17 (3.77)
PCV_$P_L$ee (cm H_2O)	1.69 (4.13)
VCV-0_$P_L$ee (cm H_2O)	1.94 (3.79)
VCV-0_$P_L$ee (cm H_2O)	1.97 (3.87)

PCV = pressure-controlled ventilation, $P_L$ee = transpulmonary end-expiratory pressure, $P_L$ei = transpulmonary end-inspiratory pressure, Ppeak = peak pressure, Pplat = plateau pressure, T insp = inspiration time, VCV-0 = volume-controlled ventilation with 0 pause time, VCV-10 = volume-controlled ventilation with 10% pause time, Vti = inspiratory tidal volume.

[a]PCV_flow has an exponential decelerating flow pattern. Here the peak flow is given. It cannot be compared easily with VCV-0 and VCV-10 modes, which have a continuous flow pattern.

Data are presented as mean (SD) for continuous variables and *n* (%) for categorical variables.

PCV was lower than that of VCV-0 (23.9 vs 24.5; p = 0.002), although the absolute difference was small and probably falls within the error margins of the ventilator. Inspiratory tidal volume differed only little between different modes; this difference was not statistically significant. There was no statistically significant difference between the end-inspiratory transpulmonary pressures of the different modes. The flow of VCV-0 was significantly lower compared with VCV-10 (30.22 vs 36.72 L/min; $p < 0.00001$). The flow of PCV ventilation has an exponential decelerating character. The flow in Table 1 is the peak flow and not the average flow, which is difficult to estimate. It can therefore not be compared with the flows of both volume-controlled modes.

The mean MP of VCV-0 was significantly lower than the MP of PCV with an absolute difference of 1.26 J/min (SE, 0.14 J/min; $p < 0.00001$). MP of VCV-0 was also significantly lower than the MP of VCV-10 with an absolute difference of 2.18 J/min (SE, 0.28 J/min; $p < 0.00001$). The MP of PCV was significantly lower than the MP of VCV-10 with an absolute difference of 1.12 J/min (SE, 0.25 J/min; p = 0.0005) (**Table 2**). The same pattern could be seen with the dynamical MP, in which only the dynamical PV loop contributes to the distributed energy. The relative difference, however, is larger.

The MP_L was the lowest in VCV-0 mode followed by PCV and VCV-10 mode (6.75, 7.99, and 8.60 J/min, respectively). The differences between modes were all statistically significant. Because of the low values of the MP_L, the relative difference was substantial (Table 2).

The same pattern as described above was seen with the calculated MP (extended and surrogate [**Supplement 2**, http://links.lww.com/CCX/B35]). The mean MP differed between the geometric method and the calculated method (Table 2). Bland-Altman analysis showed that the bias was large for the surrogate method, according to Becher et al (12) and the difference between the measured and calculated methods became larger as MP increased (Supplement 2, http://links.lww.com/CCX/B35). For all the calculated methods, the limits of agreement were between ± 2 and ± 3 J/min.

DISCUSSION

We found that the MP was significantly different between ventilation modes in the same patient with the same mechanical characteristics. The lowest MP was seen with VCV with no pause time followed by PCV. The highest MP was measured consequently in VCV mode with 10% pause time. This was true for the MP, the dynamic MP, and the MP_L.

The lower MP for VCV-0 compared with PCV is due to the different flow pattern and, as a result, a different pressurization of the ventilator leading to different PV loops (Figs. 1–3). The difference between VCV-0 and VCV-10 can be explained by looking more closely at the mechanism of the pause time. With 10% pause time, 10% of the total duration of breath cycle is subtracted from the total inspiration time and used as a pause, during which no flow is given. The same volume must be inflated in a shorter time leading to a higher constant flow. Higher flow will lead to a higher pressure-difference to overcome the resistance of the endotracheal tube, conducting airways, and tissue resistance. This will always lead to a different PV loop with a higher peak pressure and therefore a higher amount of work per breath in comparison with VCV with no pause time.

The absolute difference was in the order of 1 to 2 J/min and was statistically significant. It is not known if this is clinically important. The present study was not designed to give an answer to that question.

A better parameter reflecting the energy on the lung is probably the MP_L. (5). The MP_L is defined as the area between the inspiratory limb of the transpulmonary PV loop and axis defined by the end-expiratory transpulmonary pressure. The MP_L is a dynamic power because it is difficult to determine the zero-pressure axis. In our study, the difference between MP of different ventilation modes were around 1–2 J/min. However, these are relatively large differences because the MP_L of VCV-0 mode was only 6.75 J/min. If this is clinically relevant cannot be determined by this study. Future studies investigating the association between MP and lung damage should take the MP_L into account.

The calculated MP could also be used to calculate the difference between the different ventilation modes. However, there was a difference between the calculated and geometric methods and the limits of agreement were between ± 2 and ± 3 J/min. Our findings differ somewhat from Chiumello et al (13), possibly because our population included patients with more severe lung disease.

TABLE 2.
Mean Mechanical Power per Mode and Differences Between Modes

Mean MP					
Mode	MP (SD)	Dynamic MP (SD)	Transpulmonary MP (SD)	Calculated MP; Extensive Equation	Calculated MP; Surrogate Equation
PCV	20.87 (6.32)	10.23 (3.79)	7.99 (2.84)	21.85 (6.28)	23.06 (6.89)
VCV-0	19.30 (6.03)	8.85 (3.57)	6.75 (2.64)	19.96 (6.20)	20.63 (6.32)
VCV-10	21.80 (7.52)	11.13 (5.01)	8.60 (3.96)	21.87 (7.15)	22.20 (7.06)

Differences (Measured)				
Modes	*n*	Absolute (J/min) (SE)	Relative (%)	*p*
PCV vs VCV-0	51	1.26 (0.14)	6.0	< 0.00001
PCV vs VCV-10	50	−1.12 (0.25)	5.8	0.00005
VCV-0 vs VCV-10	48	−2.18 (0.28)	11.3	< 0.00001
PCV vs VCV-0 dynamic	51	1.25 (0.14)	12.2	< 0.00001
PCV vs VCV-10 dynamic	50	−1.10 (0.25)	10.8	0.00005
VCV-0 vs VCV-10 dynamic	48	−2.16 (0.28)	24.4	< 0.00001
PCV vs VCV-0 transpulmonary	30	1.24 (0.12)	15.5	< 0.00001
PCV vs VCV-10 transpulmonary	29	−0.71 (0.31)	6.9	0.031
VCV-0 vs VCV-10 transpulmonary	30	−1.77 (0,32)	26.2	0.00006
Differences (Measured vs Calculated)				
PCV vs calculated PCV according to an extensive equation	55	−0.96 (0.19)	4.7	< 0.00001
PCV vs calculated PCV according to a simplified, surrogate equation	55	−2.19 (0.14)	10.5	< 0.00001
VCV-0 vs calculated VCV-0 according to an extensive equation	53	−0.41 (0.12)	3.4	0.0017
VCV-0 vs calculated VCV-0 according to a simplified, surrogate equation	53	−1.06 (0.16)	6.7	< 0.00001
VCV-10 vs calculated VCV-10 according to an extensive equation	51	−0.38 (0.16)	0.3	0.02
VCV-10 vs calculated VCV-10 according to a simplified, surrogate equation	52	−0.48 (0.19)	1.8	0.01

MP = mechanical power, PCV = pressure-controlled ventilation, VCV-0 = volume-controlled ventilation with a constant flow without pause time, VCV-10 = volume-controlled ventilation with constant flow and a inspiratory pause time of 10% of the total cycle.
The difference of the mean from the *t* test differs because of missing values (see *Text*).
The difference of the mean is calculated by subtracting the latter mode from the first mode in the first column.
The relative difference is calculated by dividing the difference of the mean by the mean MP of the first mode.

One of the limitations of the study is that we failed to compare the MP between different modes in a heterogeneous patient population. Due to the COVID-19 pandemic, the great majority of patients admitted to the ICU had COVID-19 pneumonia. Further study is needed to show if our findings also hold for other patient categories.

CONCLUSIONS

In COVID-19 patients, mechanical ventilation with VCV with 0% pause time has the lowest MP in comparison with PCV. Both ventilation modes had a lower MP than VCV with 10% pause time. This held for the total MP, the dynamic MP, and the MP_L.

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The authors have disclosed that they do not have any potential conflicts of interest.

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