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A validation study of a continuous automatic measurement of the mechanical power in ARDS patients

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ABSTRACT

The mechanical power (MP) is the energy delivered into the respiratory system over time. It can be computed as a direct measurement of the inspiratory area of the airway pressure and volume loop during the respiratory cycle or calculated by "power equations". The absence of a bedside computation limited its widespread use. Recently, it has been developed an automatic monitoring system inside of a mechanical ventilator.

Purpose: Our aim was to investigate the repeatability and the accuracy of the measured MP at different PEEP values and tidal volume compared with the calculated MP.

Material and methods: MP was measured and calculated in sedated and paralyzed ARDS patients at low and high tidal volume, at 5–10–15 cmH_2O of PEEP both in volume and pressure-controlled ventilation. The same measurements were performed twice.

Results: Fifty ARDS patients were enrolled. MP was measured and calculated for a total of 300 measurements. The bias and limits of agreement were 0.38 from −1.31 to 2.0 J/min. The measured and calculated MP were similar in each ventilatory condition.

Conclusions: The mechanical power measured by a new automatic real time system implemented in a mechanical ventilator was repeatable and accurate compared with the computed one.

1. Introduction

Invasive mechanical ventilation is commonly applied to support gas exchange, to recruit the lung and to reduce the work of breathing in patients with ARDS [1,2]. However, irrespective of these beneficial effects the mechanical ventilation can be associated with the development of ventilator induce lung injury (VILI) [3]. Accordingly, to reduce as much as possible or avoid the VILI, several experimental and human studies showed the possible utility to limit the amount of tidal volume, level of PEEP and driving pressure [4-6]. In addition, also the respiratory rate and inspiratory flow have been reported to contribute to the development of VILI [7,8].

In order to combine all these elements together, Gattinoni et al. proposed the mechanical power as a unique physical variable, reflecting the interaction between the mechanical ventilatory settings and the patient's respiratory conditions [9]. The mechanical power is the amount of energy delivered into the respiratory system over time according to the applied airway pressure, tidal volume and respiratory rate [9]. Previous animal data reported that a mechanical power above 12 J/min significantly increased the lung edema and lung damage [10,11]. In addition, retrospective ARDS studies showed that the mechanical power was associated to a worse outcome [12-14].

The mechanical power can be computed as a direct measurement of the dynamic inspiratory area of the airway pressure and volume loop during the respiratory cycle (geometric method) or by using "power equations" (algebric method) [2,9]. One of the first proposed equations requires the knowledge of several variables such as tidal volume, airway resistance, respiratory rate and elastance, which precludes a bedside widespread use [9]. In order to facilitate the computation of the mechanical power, subsequently equations have been proposed (surrogate equations), which require fewer variables [2]. However, depending on the type of mechanical ventilation (pressure or volume-controlled), different equations have been suggested. Thus, in the everyday clinical practice, the absence, at bedside, of a simple computation of mechanical power significantly limited its widespread use as a tool to reduce the VILI and to promote lung protection.

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Recently a new automatic monitoring system inside of a mechanical ventilator, which is capable of directly and real-time measuring the mechanical power has been released.

Aim of this study was to investigate the repeatability of the measured MP at different PEEP levels and tidal volume and to test the accuracy of the measured MP compared with the calculated MPboth for volume and pressure controlled mechanical ventilation.

2. Methods

2.1. Study population

All consecutive mechanically ventilated patients admitted in the intensive care of ASST Santi Paolo Carlo San Paolo Hospital Milan, affected with ARDS according to Berlin definition were considered eligible from the study. The study was approved by the Institutional Review board of the Hospital (Comitato Etico Area 1 Milano 2020/ST/287) and informed consent was obtained according to Italian regulations. Patients with haemodynamic instability and barotrauma were excluded.

All patients were ventilated with a Mindray SV800 mechanical ventilator (Shenzhen Mindray Bio-Medical Electronics Co., Keji 12th Road South, High-tech Industrial Park, Nanshan, Shenzhen 518,057, P.R. China). Sedated and paralyzed patients were supported by volume-controlled ventilation with a constant inspiratory flow or pressure-controlled ventilation. Each patient was tested at two different tidal volumes (high: 8 ml/Kg of Predicted Body Weight (PBW) and low: 6 ml/Kg of PBW) and at three different PEEP levels (5, 10 and 15 cmH_2O) applied in random order. Respiratory rate was not changed throughout the study.

At each PEEP level, tidal volume, peak inspiratory pressure and respiratory rate were collected; the plateau pressure and PEEP were measured during an end-inspiratory and expiratory pause, respectively. Each measurement was performed twice.

2.2. Data computation

2.2.1. Mechanical power measured by the mechanical ventilator

The mechanical power was measured by the ventilator as the area of the airway pressure and volume during the inspiration at each breath multiplied by the respiratory rate [9]. The mechanical ventilator continuously shows the mechanical power expressed as J/L; mechanical power is averaged using the latest 16 breaths and the value is refreshed every breath.

We performed the same measurements in same conditions twice in order to investigate the repeatability of the measured mechanical power.

2.2.2. Mechanical power computed by power equation

The mechanical power was computed using the equation proposed by Gattinoni et al. [9] for volume-controlled ventilation:

$$MP = 0.098 \times RR \times TV \times \left[Peak\ Pressure - \frac{(Plateau\ Pressure - PEEP)}{2}\right]$$

where 0.098 is a conversion factor from $cmH_2O\ L/min^{-1}$ to J/min, RR is the respiratory rate in breaths per minute, TV is the tidal volume in Liters, Peak Pressure is the peak airway inspiratory pressure in cmH_2O and Plateau Pressure is the airway pressure during an end inspiratory pause in cmH_2O,

while using the surrogate formula proposed Becher et al. [15] for pressure-controlled ventilation:

$$MP = 0.098 \times RR \times TV \times \left[PEEP + \Delta P_{insp}\right]$$

where ΔPinsp is the pressure above PEEP in cmH_2O during pressure-controlled ventilation.

2.3. Statistical analysis

Data are reported as mean (standard deviation) or median [interquartile range], as appropriate. The repeatability between two time points was investigated using the Analysis of Variance (ANOVA) for repeated measures at three different PEEP levels within the low and high tidal volume. Univariable logistic regression was performed in order to assess the association between the measured and the calculated mechanical power. The agreement between measured and calculated mechanical power was assessed by Bland–Altman analysis [16]. The statistical significance cut off will be considered as a P value < 0.05. The statistical analysis was performed using RStudio (R Foundation for Statistical Computing, Vienna, Austria.).

3. Results

Fifty patients with ARDS were enrolled. The baseline clinical characteristics are shown in Table 1. The mechanical power was measured and calculated at high and low tidal volume for each PEEP level, resulting in a total of 300 measurements. The measured mechanical power values, carried out twice under the same ventilatory conditions, were similar for each PEEP level both at high and low tidal volume. (Fig. 1 and Table S1).

Thirty-one and nineteen patients were ventilated in volume controlled and in pressure controlled, respectively. The mechanical power directly measured by the mechanical ventilator and the one calculated by the power equation of the whole population considering all the different combinations of ventilatory variables were 17.7 [13.1–24.3] and 18.6 [13.4–24.5] J/min, respectively. The linear regression between the measured mechanical power and the calculated mechanical power is shown in Fig. 1 (left panel). The measured mechanical power was strictly correlated with the calculated mechanical power (mechanical power measured = −0.58 + 1.01 • mechanical power calculated; R^2 0.98, $p < 0.001$). The correspondent Bland-Altmann analysis is reported in the Fig. 1 (right panel). The bias, or mean difference, was 0.38 J/min (95% CI 0.29 to 0.48 J/min), the upper limit of agreement was 2.0 J/min (95% CI 1.91 to 2.25 J/min) and the lower limit of agreement was −1.31 J/min (95% CI -1.48 to −1.14 J/min).

Table 1
Baseline characteristics of the study population. BMI: Body Mass Index; PBW: Predicted Body Weight; PEEP: Positive End-Expiratory Pressure.

	$N = 50$
Age, *years*	66 [56–80]
Male sex, *% (n)*	70 (35)
Weight, *kg*	70 [60–80]
BMI, kg/m^2	24 [22–28]
Ventilation time before study, *days*	2 [1–4]
Cause of ARDS, *% (n)*	
Pneumonia	74 (37)
Sepsis	20 (10)
Other	6 (3)
Arterial pH	7.40 ± 0.08
PaO_2, *mmHg*	87 [71–117]
$PaCO_2$, *mmHg*	44 [39–54]
FiO_2	0.5 [0.4–0.7]
PaO_2/FiO_2	157 [123–218]
Tidal volume, *mL*	480 [422–508]
Tidal volume per PBW, *mL/kg*	7.4 [6.8–7.8]
Respiratory rate, *breath per minute*	16 ± 3
Minute ventilation, *L/min*	7.5 ± 1.8
Plateau pressure, cmH_2O	20.6 ± 4.9
PEEP, cmH_2O	10 [6–10]
Mean airway pressure, cmH_2O	13 ± 3
Driving pressure, cmH_2O	11 [9–13]
Mechanical power, *J/min*	16.9 [11.2–19.7]

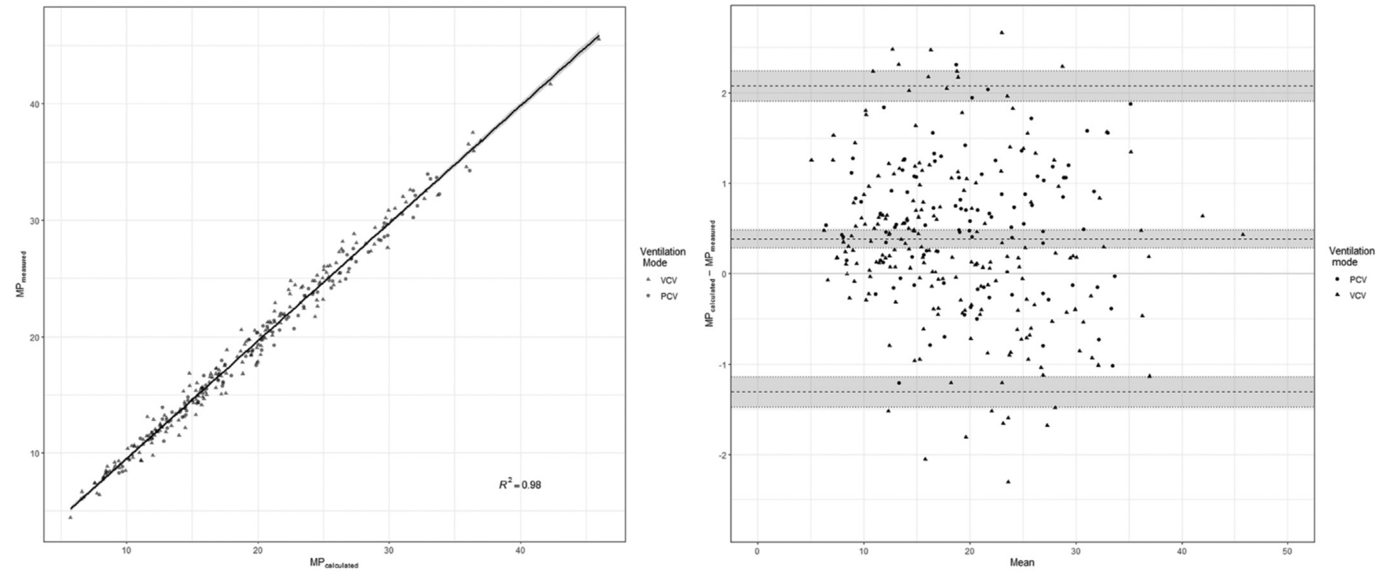

Fig. 1. Relationship between the mechanical power measured by the ventilator and the computed mechanical power, assumed as the reference method, in 50 ARDS patients mechanically ventilated in volume or pressure-controlled ventilation both with high and low tidal volume and at three different PEEP levels. Left panel shows the linear regression plot ($MP_{measured} = -0.58 + 1.01 \cdot MP_{calculated}$, $p < 0.001$; $R^2 = 0.98$); right panel shows the Bland-Altman plot (bias: 0.38 cmH_2O [95% C.I.: 0.29 to 0.48]; L-LOA: −1.31 cmH_2O [95% C.I.: −1.48 to −1.14]; U-LOA: 2.08 cmH_2O [95% C.I.: 1.91 to 2.25]).

3.1.1. Volume-controlled ventilation

The mechanical power measured by the mechanical ventilator and the one calculated for volume-controlled ventilation was 17.0 [12.7–24.0] and 16.8 [12.3–24.2] J/min, respectively. The applied tidal volume corresponding to 6 and 8 mL of PBW was 419 ± 68 mL and 554 ± 85 mL, respectively. The mechanical power measured and calculated both considering high and low tidal volume and all three PEEP levels were closely correlated (R^2 0.98, $p < 0.001$), with a bias of 0.29 J/min (95% CI 0.16 to 0.42 J/min), with limits of agreements from −1.52 J/min (95% CI −1.74 to −1.3 J/min) to 2.1 J/min (95% CI 1.89 to 2.33 J/min) (Fig. 2). The linear regression and Bland Altman plots for the measured mechanical power against the calculated mechanical power in volume-controlled ventilation within each PEEP level are shown in Figs. S1–S2–S3.

3.1.2. Pressure-controlled ventilation

The mechanical power measured by the mechanical ventilator and calculated for pressure- controlled ventilation were 19.0 [14.0–24.8] and 19.9 [14.6–25.7] J/min, respectively. The inspiratory pressure above PEEP delivered to guarantee 6 and 8 mL/Kg of PBW was 12 ± 3 and 17 ± 3 cmH_2O, respectively. As shown in Fig. 3, the measured mechanical power had a good correlation with the computed one in pressure-controlled ventilation considering high and low tidal volume and all the three level of PEEP (R^2 0.98, $P < 0.001$). The Bland Altman

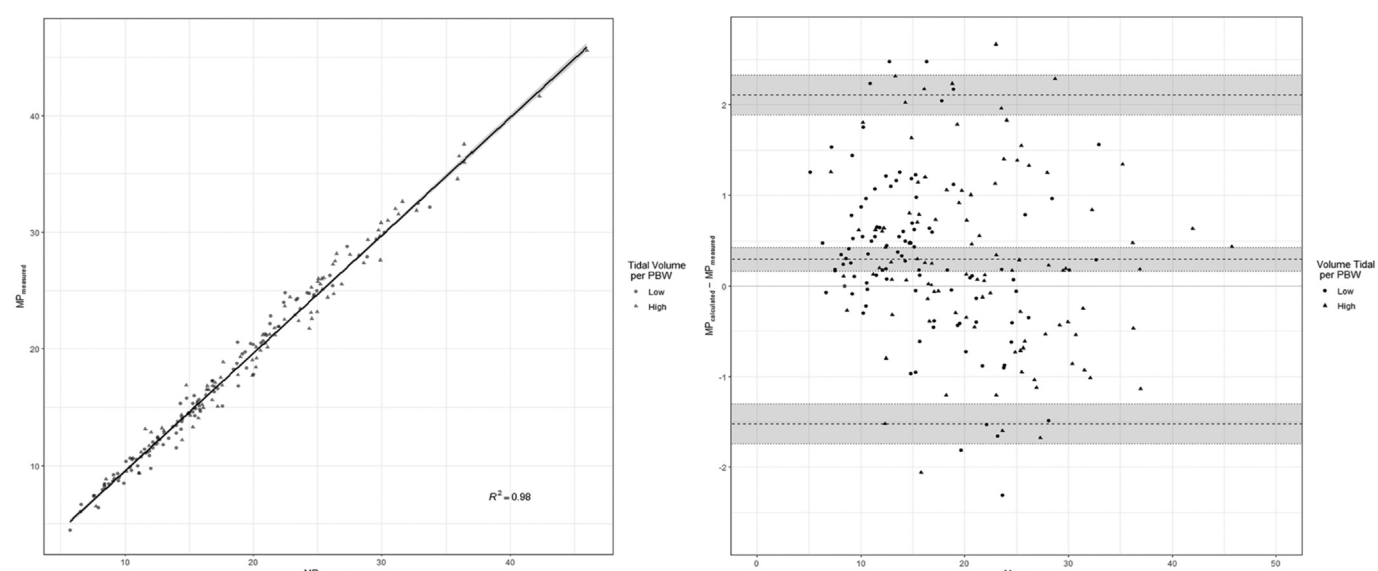

Fig. 2. Relationship between the mechanical power measured by the ventilator and the computed mechanical power, assumed as the reference method, in 31 patients ventilated in volume control both with high and low tidal volume and at three different PEEP levels. Left panel shows the linear regression plot ($MP_{measured} = -0.65 + 1.02 \cdot MP_{calculated}$, $p < 0.001$; $R^2 = 0.98$). The right panel shows the Bland-Altman plot (bias: 0.29 cmH_2O [95% C.I.: 0.16 to 0.42]; L-LOA: −1.52 cmH_2O [95% C.I.: −1.74 to −1.30]; U-LOA: 2.11 cmH_2O [95% C.I.: 1.89 to 2.33]).

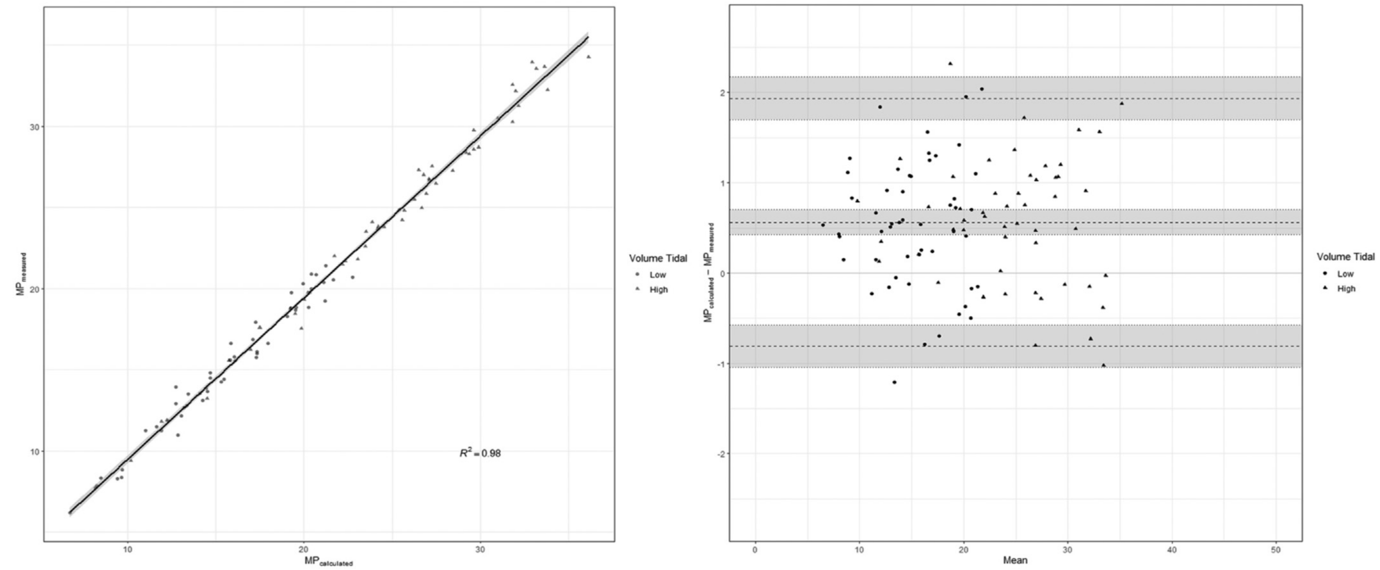

Fig. 3. Relationship between the mechanical power measured by the ventilator and the computed mechanical power, assumed as the reference method, in 19 patients ventilated in pressure control both with high and low tidal volume and at three different PEEP levels. Left panel shows the linear regression plot ($MP_{measured} = -0.48 + 1.00 \cdot MP_{calculated}$, $p < 0.001$; $R^2 = 0.98$); right panel shows the Bland-Altman plot (bias: 0.56 cmH_2O [95% C.I.: 0.42 to 0.70]; L-LOA: –0.81 cmH_2O [95% C.I.: −1.05 to −0.58]; U-LOA: 1.93 cmH_2O [95% C.I.: 1.70 to 2.17]).

plot showed a bias of 0.56 J/min (95% CI 0.42 to 0.70 J/min), with limits of agreements from −0.81 J/min (95% CI −1.05 to −0.58 J/min) to 1.93 J/min (95% CI 1.70 to 2.17 J/min). The linear regression and Bland Altman plots for the measured mechanical power against the calculated mechanical power in pressure-controlled ventilation within each PEEP level are shown in Figs. S4–S5–S6.

4. Discussion

This study showed that in sedated and paralyzed ARDS patients during volume and pressure-controlled ventilation, the mechanical power measured by a new automatic real time system implemented in a mechanical ventilator was well correlated to the mechanical power calculated by standard equations. Several studies showed that a mechanical ventilation using lower tidal volume and driving pressure significantly improved the outcome [4,5]. On the contrary, the role of higher PEEP and respiratory rate is still not clear [17]. At the present time, the contribution of each of these components to modulate the VILI is not known [3]. A new unified possible theory could be to assess the mechanical power, which includes all these factors [9]. The mechanical power is defined as the amount of energy spent to move a given volume into the respiratory system during each breath (including the maintenance of the PEEP). Previous animal data found that different levels of mechanical power were significantly associated to the development of the VILI [10]. Furthermore, both in ARDS and not ARDS patients the increase of the mechanical power was independently associated to the intensive care and hospital mortality [12-14]. Thus, the reduction of mechanical power could minimize the VILI. In addition, the advantage of the mechanical power is that it combines the effects of every ventilatory variable (PEEP, flow, tidal volume, respiratory rate).

At the present time, the mechanical power can be measured as the area of the airway pressure and volume during the inspiration multiplied by the respiratory rate (geometric method) or calculated by power equations; both methods require well sedated patients with or without paralysis [2]. The use of the equations to calculate the mechanical power requires firstly the acquisition of several static variables during an end-inspiratory and end-expiratory pause and secondly the application of a dedicated equation. In addition, two different power equations should be used for volume-controlled and pressure-controlled ventilation [2]. These equations previously showed a good correlation with the geometric method [2,9]. However, the use of these equations takes time, trained medical personnel, additional manual workload which precludes a wide use in clinical practice. In the present study we aimed to evaluate the accuracy of a new automatic monitoring system implemented into a mechanical ventilator, which computes the mechanical power using the geometric method, comparing it to the algebric method. To mimic different clinical conditions, this automatic system was tested at three levels of PEEP and two tidal volumes. Irrespectively from the type of mechanical ventilation and ventilatory setting, the mechanical power measured by the mechanical ventilator was well related to the mechanical power calculated by the power equations in the same clinical conditions. A practical advantage of this system is that it offers an easy way to directly evaluate the effect of the changes of each ventilatory variables on the mechanical power without any interruption of the ventilation and any requirements of equations. Thus, the possibility to have an automatic real time system incorporated into a mechanical ventilator should increase the measurement and the application of the mechanical power in ARDS patients as an important index of the risk of VILI.

4.1. Limitations

Possible limitations of this study are: firstly, the used of only one type mechanical ventilator, secondly only the total mechanical power and not the lung mechanical power computed on the transpulmonary pressure, which could be even better related to the VILI, has been evaluated and thirdly the mechanical power calculated with the power equantion were compared to those from the mechanical ventilation because it was not recorded the airway pressure and airflow.

5. Conclusions

The possibility to have a continuous real time automatic measurement of the mechanical power at bedside should reduce the impact of the VILI in mechanically ventilated patients due to a better personalized mechanical ventilation.

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Declaration of competing interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jcrc.2021.09.009.

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