Mechanical Power Correlates With Stress, Strain, and Atelectrauma Only When Normalized to Aerated Lung Size in Patients With Acute Respiratory Distress Syndrome

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OBJECTIVES: First, to investigate whether the severity of acute respiratory distress syndrome (ARDS) influences ventilator-induced lung injury (VILI) risk in ventilated patients with similar mechanical power of respiratory system (MP_{RS}). Second, to determine whether, under these circumstances, there is a relationship between transpulmonary mechanical power (MP_{Tp}) normalized to the aerated lung (specific lung mechanical power or SLMP) and VILI risk, and third, to determine whether normalizing MP_{RS} to compliance of respiratory system (CRS) can replace SLMP to bedside.

DESIGN: Prospective cohort study.

SETTING: The study was conducted in a tertiary academic ICU.

PATIENTS: The study included 18 patients with ARDS.

INTERVENTIONS: Ventilatory settings were adjusted to achieve a similar MP_{RS}.

MEASUREMENTS AND MAIN RESULTS: Mechanical power was normalized to CRS (specific mechanical power or SMP = MP_{RS}/CRS), and SLMP was calculated as the ratio between MP_{Tp} and end-expiratory lung volume (SLMP = MP_{Tp}/EELV). The strain was defined as the ratio between tidal volume and EELV (strain = V_T/EELV), stress as transpulmonary pressure at the end of inspiration, and atelectrauma as the difference between expiration and inspiration in the nonaerated lung. Although patients had been ventilated with similar MP_{RS} = 23.75 (23–24) J/min and MP_{Tp} = 11.6 (10.8–12.8) J/min, SLMP increased linearly with the fall in Pa_{O_2}/F_{IO_2} ($R = -0.83$, $p = 0.0001$). MP_{RS} only correlated positively with VILI-associated mechanisms when normalized to aerated lung size: correlations between SLMP and stress ($R = 0.9$, $R^2 = 0.84$, $p = 0.00004$), strain ($R = 0.97$, $R^2 = 0.94$, $p < 0.00001$) and atelectrauma ($R = 0.82$, $R^2 = 0.70$, $p = 0.00002$), and correlations between SMP and stress ($R = 0.86$, $R^2 = 0.75$, $p = 0.00001$), strain ($R = 0.68$, $R^2 = 0.47$, $p = 0.001$) and atelectrauma ($R = 0.67$, $R^2 = 0.46$, $p = 0.002$).

CONCLUSIONS: The results suggest that normalizing mechanical power to lung-aerated size or CRS may correlate positively with stress, strain, and atelectrauma.

KEY WORDS: acute respiratory distress syndrome; mechanical power; mechanical ventilation and respiratory failure; ventilator-induced lung injury

I n patients with acute respiratory distress syndrome (ARDS), ventilator-induced lung injury (VILI) can occur due to excessive pressure (barotrauma), alveolar overdistension (volutrauma), and insufficient positive end-expiratory pressure (PEEP) (atelectrauma) (1). The concept of mechanical power refers to the work imposed by the ventilator on the respiratory system per unit of time. It aims to provide a value (joules/minute)

KEY POINTS

Questions: Do ventilated patients with similar mechanical power have different risks of ventilator-induced lung injury (VILI) depending on the severity of acute respiratory distress syndrome (ARDS)? Is it necessary to normalize mechanical power to the size of the baby lung in patients with ARDS?

Findings: In this prospective cohort study, regional mechanical power increased linearly from mild to severe ARDS, despite all ARDS patients receiving similar global mechanical power. This increase was significantly associated with higher stress, strain, and atelectrauma.

Meaning: Mechanical power only correlated positively with VILI-associated mechanisms when normalized to the size of the aerated lung or compliance of respiratory system.

to explain all the stresses mentioned earlier (2). In this regard, Serpa Neto et al (3) suggest a relationship between the value of the mechanical power of the respiratory system (MP_{RS}) and the mortality of ARDS patients. However, the risk of VILI does not depend solely on the intensity of mechanical ventilation. Other pulmonary factors, such as aerated lung size, pulmonary homogeneity, or pulmonary vascular hypertension, can also contribute to the development of VILI (4). Based on this, we could infer that for patients ventilated with similar MP_{RS}, the risk of VILI will depend on the size of the aerated lung (ergotrauma). In this sense, Coppola et al (5) observed that MP_{RS} is related to ICU deaths only when normalized to aerated lung size or indirectly through compliance of respiratory system (CRS). The objectives of this study were first to investigate whether the severity of ARDS influences the risk of VILI in ventilated patients with similar MP_{RS}. Second, to determine under these circumstances whether there is a relationship between the mechanical power transferred to the ventilated lung (specific lung mechanical power or SLMP) and the risk of VILI, and third, to determine whether normalizing MP_{RS} to CRS (specific mechanical power or SMP) can replace SLMP at the bedside.

MATERIALS AND METHODS

Ethical Aspects

The study was approved by the medical ethics committee (Hospital El Cruce Néstor C. Kirchner), resolution: 083/2022, June 26, 2022. Original title: "Evaluation of the reliability of mechanical power calculation in ARDS to define the risk of VILI." Written consent was obtained from patients or their surrogates. Procedures were followed in accordance with the ethical standards of the responsible Medical Ethics Committee on human experimentation and with the Helsinki Declaration of 1975. ClinicalTrials.gov: NCT05410262.

Procedure

Patients with ARDS ($\geq$ 18 yr) were prospectively and consecutively included, whereas those with emphysema, asthma, pneumothorax, or severe instability such as arterial oxygen saturation (Sao_2) less than or equal to 90%, severe shock (norepinephrine $\geq$ 0.5 γ/kg/min), ventricular arrhythmia or myocardial ischemia were excluded. All patients were temporarily ventilated in the tomography room under deep sedation (Richmond Agitation Sedation Scale: –5) using volume-controlled ventilation mode with tidal volume (Vt) of 6mL/kg- predicted body weight (PBW), plateau pressure (PPlat) of 30cm H_2O, respiratory rates of 15 breaths/min, and an inspiration/expiration ratio of 35/65%. A square wave flow pattern was used, and PEEP was adjusted to achieve the target PPlat. If necessary, the Vt was decreased below 6mL/kg to maintain a PPlat of 30cm H_2O. Fio_2 was titrated based on Sao_2 (92–96%).

Evaluation of CT Images

Two complete thorax CT scans were performed (Aquilion CXL from Toshiba, Tokyo, Japan), one in expiratory pause (PEEP) and the other in inspiratory pause (PPlat). The evaluation of CT images was done by analyzing three pulmonary regions: the basal region, the middle region at the carina, and the upper region at the aortic arch level. The nonaerated lung area (100 to –100 HU) was expressed as a percentage of the total area, and atelectrauma was defined as the difference between expiration and inspiration in the nonaerated lung. End-expiratory lung volume (EELV) and end-inspiratory lung volume were measured using specific software (Lung Volume Analysis Software,

Toshiba). The strain was calculated as the relationship between Vt and EELV (strain = Vt/EELV) (6).

Evaluation of Mechanical Power and its Components

Transpulmonary pressures were measured with a specific ventilatory mechanics monitor (Flux Med GrT, Buenos Aires, Argentina). Stress was defined as the transpulmonary pressure at the end of inspiration.

The following variables were calculated: driving pressure (ΔP = PPlat – PEEP), static CRS = Vt/ΔP, and mechanical power of the respiratory system, which was calculated based on the equation of motion of gases (2):

$$MPRS = 0.098 \times RR$$
$$\times \left\{ Vt^2 \times \left[\frac{1}{2} \times Ers + RR \right. \right.$$
$$\times \frac{(1 + I:E)}{6 \times I:E} \times Raw \right]$$
$$\left. + Vt \times PEEP \right\}$$

where Ers is the elastance of the respiratory system and Raw is airway resistance.

Different components of mechanical power were calculated from the following equations:

1. $\text{Elastance-related component} = \dfrac{\left(Vt^2 \times Ers \times \frac{1}{2} \right)}{RR \times 0.098}$

2. $\text{Resistance-related component} = \dfrac{(Vt \times Raw \times Flow)}{\times RR \times 0.098}$

3. $\text{PEEP-related component} = \dfrac{(Vt \times PEEP)}{\times RR \times 0.098}$

Global variables were replaced by their transpulmonary equivalents to assess the transpulmonary mechanical power (MP_{Tp}). SLMP was calculated as the ratio between MP_{Tp} and the aerated lung volume (EELV).

$$SLMP = \frac{MPTp}{EELV}$$

SMP resulted from normalizing MP_{RS} with CRS.

$$SMP = \frac{MPRS}{CRS}$$

Statistical Analysis

Data are reported as median and interquartile range. Pearson's coefficient was used to estimate the correlation, and the Wilcoxon-Mann-Whitney test was used to compare quantitative variables. Statistical significance was defined as $p < 0.05$.

RESULTS

The study included 18 patients with an age range of 34 (24–47) years and a gender distribution of 4 women and 14 men. The Acute Physiology and Chronic Health Evaluation II score was 20.5 (19–22) points and the mortality rate on day 28 was 27.8%. **Table 1** provides a summary of the data on ventilatory parameters.

SLMP increased linearly from mild to severe cases (**Fig. 1**), possibly due to the positive relationship between baby lung size (EELV) and Pa_{O_2}/F_{IO_2} ($R = 0.75$, $R^2 = 0.57$, $p = 0.0003$).

MP_{RS} only correlate positively with VILI-associated mechanisms when normalized to aerated lung size or CRS:

1. Correlations between SLMP and stress ($R = 0.9$, $R^2 = 0.84$, $p = 0.00004$), strain ($R = 0.97$, $R^2 = 0.94$, $p < 0.00001$), and atelectrauma ($R = 0.82$, $R^2 = 0.70$, $p = 0.00002$) were observed.
2. Correlations between SMP and stress ($R = 0.86$, $R^2 = 0.75$, $p = 0.00001$), strain ($R = 0.68$, $R^2 = 0.47$, $p = 0.001$), and atelectrauma ($R = 0.67$, $R^2 = 0.46$, $p = 0.002$) were observed.

Although the MP_{RS} and MP_{Tp} were similar for all ARDS, their relative composition varied depending on the mean CRS. In patients with higher CRS (≥ 24 mL/cm H_2O), the PEEP-related component prevailed over the elastance-related component (42 [41–48%] vs 35 [31–37%], $p = 0.01$), whereas the opposite occurred in ARDS with low CRS (31 [30–33%] vs 49 [46–50%], $p = 0.01$).

DISCUSSION

Patients ventilated with similar MP_{RS} have different consequences at the lung level depending on the severity of ARDS. The regional ventilator load (SLMP) increases as the Pa_{O_2}/F_{IO_2} ratio decreases, which, in turn, is associated with higher stress, strain, and atelectrauma. Normalizing MP_{RS} with the CRS, an indirect surrogate for baby lung size, appropriately links with these injury mechanisms.

Conceptually, VILI development depends on several factors, such as the intensity and speed of the load delivery to the aerated lung above basal pressure (PEEP),

TABLE 1.
Ventilatory Parameters

Variables	Results
Murray score (points)	3 (2.75–3.5)
Pao_2/Fio_2	158 (123.9–201.2)
V_T (mL/kg/predicted body weight)	6 (6–6.2)
V_T (mL)	385 (350–420)
Positive end-expiratory pressure (cm H_2O)	14 (12–16)
Respiratory rate (cycles/min)	15
Fio_2 (%)	50 (42–75)
Plateau pressure (cm H_2O)	30
Driving pressure (cm H_2O)	16 (14–18)
Flow (L/min)	16.8 (15.2–18.5)
Inspiratory time (s)	1.38 (1.37–1.39)
Inspiration:expiration (%)	35/65
Mechanical power of the respiratory system (J/min)	23.75 (23–24)
Transpulmonary mechanical power (J/min)	11.6 (10.8–12.8)
Specific mechanical power (J/min/mL/cm H_2O)	0.98 (0.84–1.1)
Specific lung mechanical power (J/min/L)	7.5 (4.75–11)
Static compliance of the respiratory system (mL/cm H_2O)	24 (21.25–26.75)
E_{RS} (cm H_2O/L)	26.7 (23.3–29)
E_L (cm H_2O/L)	18.25 (14.2–21.9)
E_L/E_{RS} (%)	0.65 (0.60–0.76)
End-expiratory lung volume (L)	1.5 (1.2–2.2)
End-inspiratory lung volume (L)	1.8 (1.6–2.6)
Nonaerated lung (%)	63 (41.6–70.3)
Transpulmonary pressure at the end of inspiration (cm H_2O)	15.7 (13.9–18.1)
Transpulmonary pressure at the end of expiration (cm H_2O)	5 (4.3–6)
Strain (%)	25 (17–34)
Atelectrauma (%)	3.7 (1.5–18)

E_{RS} = elastance of the respiratory system, E_L = lung elastance, V_T = tidal volume.
Murray scores were calculated at 24 hr. Data are presented as median (interquartile range).
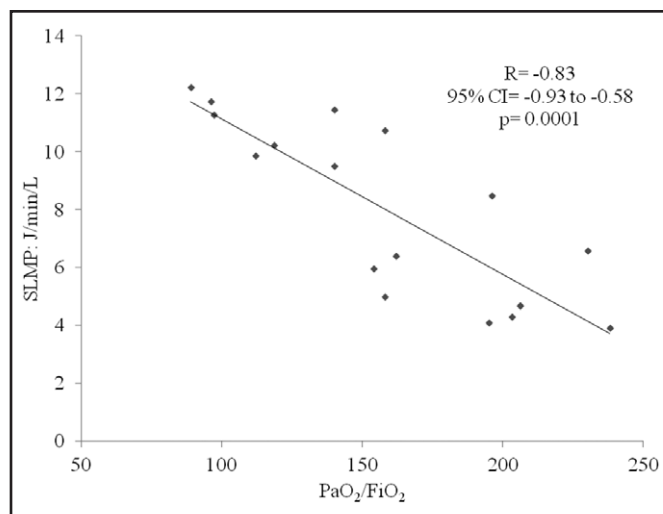
Figure 1. Correlation was positive between specific lung mechanical power (SLMP) and Pao_2/Fio_2. SLMP linearly increased from mild to severe acute respiratory distress syndrome. SMP = specific mechanical power.

ARDS patients do not closely correlate with PBW due to the heterogeneous distribution of lung disease. The size, location, and heterogeneity of the aerated portion of the lung can vary widely not only among ARDS patients but also within the same patient, depending on the disease progression, decubitus change, or after a recruitment maneuver. If the V_T does not change, the energy delivered by mechanical ventilation affects a smaller number of alveoli, and the stress per unit volume increases (7). Based on our study's findings, MP_{RS}'s seemingly innocent value could even triple its relative value at the regional level, depending on the severity of ARDS. In this sense, calculating SMP could be an adequate tool to estimate the risk of VILI at the patient's bedside.

The study has several limitations. First, the number of included patients was small, and the methodology used, including the mechanical power calculation has its restrictions (2, 8). Second, the relationship between lung elastance and total respiratory system elastance was consistent across all patients, indicating that the energy transferred to the lung by mechanical ventilation (MP_{Tp}) was approximately equal (Table 1). However, it is worth noting that MP_{RS} may overestimate the risk of VILI in obese patients or those with intra-abdominal hypertension. Third, the MP_{Tp} has been normalized to EELV rather than functional residual capacity, and the results may vary depending on the alveolar recruitment capacity. Fourth, different combinations of ventilatory variables, such as V_T, driving pressure, flow, or

frequency, duration, and the lung's capacity to tolerate it. Although V_T is typically set at the ideal or predicted lung volume based on body weight, lung volumes in

PEEP, could influence the risk of VILI regardless of the MP_{RS} value (9).

Finally, it is worth noting that experimental studies suggest that kinetic energy poses a greater risk than potential energy for the same MP_{RS} (9, 10). In this study, the patients were subjected to a similar total load, but the type of energy delivered to the lungs varied depending on the CRS. Adjusting the PEEP to achieve a PPlat of 30 cm H_2O resulted in static distension in patients with higher CRS. On the other hand, the fixed value of V_T (6 mL/kg/PBW) promoted dynamic distension in severe cases of ARDS. These qualitative differences prevent definitive conclusions about the SMP and SLMP.

In conclusion, normalizing MP_{RS} to aerated lung size or CRS was directly related to higher stress, strain, and atelectrauma.

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