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EVALUATION OF MECHANICALLY VENTILATED PATIENTS (VOLUME-CONTROL AND PRESSURE CONTROL MODES) FOR DEVELOPMENT OF VENTILATOR-INDUCED LUNG INJURY (VILI) USING NORMALIZED MECHANICAL POWER (SIMPLIFIED GATTINONI FORMULA)

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ABSTRACT
Mechanical ventilation is essential for the management of acute respiratory failure, but excessive mechanical stress and strain may contribute to ventilator induced lung injury (VILI). Mechanical power integrates multiple ventilatory variables and may provide a comprehensive measure of the energy delivered to the respiratory system. This prospective observational study evaluated the association between normalized mechanical power and VILI in mechanically ventilated adult ICU patients receiving volume control ventilation (VCV) or pressure control ventilation (PCV). One hundred patients requiring invasive mechanical ventilation for more than 24 hours were evaluated over a six month period. Demographic characteristics, clinical scores, and daily ventilator parameters were recorded, and normalized mechanical power was calculated using the simplified Gattinoni formula and predicted body weight. VILI occurred in 28% of patients and was more frequent with VCV than PCV (38% vs 18%, $p = 0.027$). Normalized mechanical power was significantly higher with VCV than PCV (0.32 ± 0.11 vs 0.27 ± 0.09 J/min/kg PBW, $p = 0.013$). Increasing normalized mechanical power was associated with progressively higher VILI incidence, with a significant trend across mechanical power categories ($p < 0.001$). In multivariate logistic regression, normalized mechanical power remained independently associated with VILI (adjusted OR 1.64, 95% CI 1.28 to 2.12; $p < 0.001$). Receiver operating characteristic analysis demonstrated good discrimination for VILI (AUC 0.82), with a cutoff of 0.31 J/min/kg PBW yielding 78.6% sensitivity and 74.2% specificity. Normalized mechanical power was associated with VILI and adverse clinical outcomes and may have potential utility for risk assessment during lung protective ventilation, although prospective multicenter studies are required for validation.

KEYWORDS: Mechanical power; Ventilator-induced lung-injury; Mechanical ventilation; Volume control ventilation; Pressure control ventilation; Lung protective ventilation

1. INTRODUCTION
Mechanical ventilation is a fundamental supportive therapy for patients with acute respiratory failure, but the forces generated during positive pressure ventilation can contribute to additional pulmonary injury. Ventilator induced lung injury (VILI) arises from excessive mechanical stress and strain imposed on the respiratory system and encompasses several interacting forms of injury, including volutrauma, barotrauma, atelectrauma, and biotrauma. Consequently, the selection and monitoring of ventilatory variables are central to lung protective ventilation, particularly in patients with acute respiratory distress syndrome (ARDS), for whom limiting excessive tidal volume and driving pressure forms an important component of established ventilatory management strategies [1]. Traditional approaches to assessing injurious ventilatory exposure have focused on individual variables such as tidal volume, airway pressure, driving pressure, respiratory rate, inspiratory flow, and positive end expiratory pressure (PEEP). Although each variable represents an important component of the mechanical load applied to the respiratory system, consideration of individual parameters does not fully describe the cumulative

energy transferred from the ventilator to the respiratory system during repeated respiratory cycles. Mechanical power was proposed as an integrative parameter that combines several determinants of ventilator related mechanical load into a measure of energy transfer per unit time. The mechanical power framework incorporates tidal volume, driving pressure, respiratory rate, inspiratory flow, airway resistance, and PEEP, thereby providing a physical representation of the overall intensity of ventilator energy delivery. Experimental and physiological analyses have demonstrated that changes in these variables contribute differently to mechanical power, supporting its use as a composite descriptor of ventilatory exposure [2].
The clinical relevance of mechanical power has subsequently been investigated in critically ill populations. In large observational cohorts, higher mechanical power has been associated with mortality and other adverse clinical outcomes among patients receiving invasive mechanical ventilation, including associations that persisted in analyses considering tidal volume. In patients with ARDS, mechanical power has also been associated with mortality after adjustment for other ventilatory variables, although analyses comparing its prognostic contribution with individual parameters indicate that simpler combinations of driving pressure and respiratory rate may provide comparable predictive information. These findings support the biological and clinical relevance of the total mechanical energy delivered during ventilation while also indicating that mechanical power should not be interpreted as an isolated determinant of outcome [3].
Practical application of mechanical power requires an appropriate method for its calculation. The original mechanical power formulation is based on the pressure volume relationship of the respiratory system and incorporates the principal components of the equation of motion. Simplified algebraic approaches have subsequently been developed to facilitate bedside estimation using ventilator variables that are routinely available in the intensive care unit. Importantly, the calculation of mechanical power is influenced by the mode of mechanical ventilation. During Volume control ventilation (VCV), commonly used equations can incorporate measured airway pressures, tidal volume, respiratory rate, and PEEP. PCV presents a different flow and pressure profile, requiring calculation approaches specifically adapted to pressure controlled breaths. Comparative evaluation of bedside methods has demonstrated that simplified approaches can approximate reference measurements during both volume control and PCV, supporting their potential clinical application [4]. Normalization of mechanical power to predicted body weight (PBW) provides an additional approach for accounting for differences in expected lung size between patients. Because absolute mechanical power does not account for body size, normalization may facilitate comparison of ventilatory energy exposure across individuals and may provide a more patient specific representation of the mechanical load relative to predicted lung size. This consideration is particularly relevant when evaluating heterogeneous ICU populations in which body size and respiratory system characteristics vary substantially. The use of normalized mechanical power has therefore emerged in clinical investigations examining the relationship between ventilatory energy delivery and outcomes [5].
Despite increasing evidence linking mechanical power with clinically important outcomes, uncertainty remains regarding its application across different controlled ventilation modes and its usefulness for identifying patients at increased risk of VILI. Existing literature has established the physiological basis of mechanical power and its association with mortality, while studies of bedside calculation have demonstrated the feasibility of estimating the parameter during both volume control and PCV. However, assessment of normalized mechanical power in relation to VILI across these two commonly used ventilation modes may provide clinically relevant information regarding the relationship between cumulative ventilator energy exposure and lung injury. The present study therefore evaluated mechanically ventilated adult ICU patients receiving volume control or PCV, with the objective of examining the association between normalized mechanical power calculated using the simplified Gattinoni formula and the development of VILI. The study also evaluated the relationship of normalized mechanical power with selected clinical outcomes and its ability to discriminate patients who developed VILI.

2. MATERIALS AND METHODS

2.1. Study Design and Setting

A prospective observational study was conducted among mechanically ventilated adult patients admitted to the intensive care unit of a tertiary care hospital from 6th July 2024 to 5th January 2025. The study evaluated patients receiving either VCV or PCV and examined the relationship between normalized mechanical power and the development of VILI [6].

2.2. Study Population

Adult patients requiring invasive mechanical ventilation for more than 24 hours were considered for inclusion. Patients receiving either VCV or PCV with complete ventilator data were included in the analysis. Patients younger than 18 years, those with incomplete ventilator records, and those with severe pre-existing chronic lung disease were excluded.
The final study population comprised 100 patients, including 50 patients receiving VCV and 50 receiving PCV, according to the group data presented in the study tables [7].

2.3. Clinical and Ventilatory Data Collection

Demographic characteristics, clinical severity scores, and ventilator parameters were recorded during the study period. The collected clinical variables included age, sex, predicted body weight (PBW), primary clinical condition, Acute Physiology and Chronic Health Evaluation II (APACHE II) score, and Sequential Organ Failure Assessment (SOFA) score. Ventilator variables included tidal volume, respiratory rate, PEEP, peak airway pressure, plateau pressure, and driving pressure. Mechanical power was calculated from the recorded ventilatory parameters [8].

2.4. Calculation of Normalized Mechanical Power

The simplified Gattinoni mechanical-power equation used for volume-controlled ventilation was:
Mechanical power (J/min) = 0.098 × RR × VT × [Ppeak − ½(ΔP)]
where RR is respiratory rate (breaths/min), VT is tidal volume (L), Ppeak is peak airway pressure (cmH_2O), and ΔP is driving pressure (cmH_2O). Normalized mechanical power was calculated as:
Normalized mechanical power (J/min/kg PBW) = Mechanical power (J/min) ÷ PBW (kg)
This normalization was used to account for differences in predicted body size when evaluating ventilator delivered mechanical energy among patients. The study evaluated normalized mechanical power in patients receiving both VCV and PCV [4,9].

2.5. Operational Definition and Diagnostic Criteria for VILI

The study operationally defined clinically suspected VILI as new or worsening pulmonary injury developing after initiation of invasive mechanical ventilation, with no alternative predominant explanation.

1. New or worsening bilateral pulmonary infiltrates on chest radiography or CT after initiation of mechanical ventilation, not adequately explained by another diagnosis.
2. Worsening oxygenation, defined as a ≥20% decrease in the PaO_2/FiO_2 ratio from baseline, or a new/increased FiO_2 or PEEP requirement to maintain the predefined oxygenation target.
3. Worsening respiratory-system mechanics, defined as an increase in driving pressure (ΔP) of ≥3–5 cmH_2O from baseline and/or progressive reduction in respiratory-system compliance.
4. Absence of another predominant cause better explaining deterioration, particularly pneumonia, aspiration, cardiogenic pulmonary edema/heart failure, atelectasis, pulmonary embolism, pneumothorax, or progression of the underlying lung disease.

A patient was classified as having clinically suspected VILI when at least two of the above criteria were present after initiation of mechanical ventilation. Baseline was the earliest standardized ventilator assessment after initiation of invasive ventilation and before the observed deterioration. Serial assessments were performed during invasive ventilation. Final classification was based on the predefined criteria and clinical adjudication. Mechanical power was treated as the exposure/predictor and was not used as a diagnostic criterion for VILI [6].

2.6. Statistical Analysis

Data were analyzed using SPSS/R software. Comparative statistical analyses were performed to evaluate differences between the VCV and PCV groups. Correlation analysis was used to assess relationships among relevant study variables. Logistic regression analysis was performed to evaluate factors associated with VILI, including multivariable assessment of normalized mechanical power and other ventilatory and clinical variables. Receiver operating characteristic (ROC) curve analysis was performed to assess the discriminatory performance of normalized mechanical power for identifying patients who developed VILI. Statistical significance was assessed using the reported p values, with the study results presented using effect estimates and 95% confidence intervals where applicable [10].

2.7. Outcome Measures

The primary outcome was the association between normalized mechanical power and development of VILI. Secondary outcomes included duration of mechanical ventilation, ICU length of stay, and ICU mortality. The study also evaluated differences in normalized mechanical power and VILI occurrence between VCV and PCV and assessed the predictive performance of normalized mechanical power using ROC curve analysis [11].

3. RESULTS

3.1. Baseline Characteristics

A total of 100 mechanically ventilated adult ICU patients were included in the study, with 50 patients receiving VCV and 50 receiving PCV. The mean age of the study population was 56.1 ± 14.2 years, and 62 patients (62%) were male. The mean predicted body weight was 61.3 ± 9.4 kg. The most frequent underlying conditions were pneumonia in 32 patients (32%), ARDS in 28 patients (28%), and nonpulmonary sepsis in 20 patients (20%). The mean APACHE II and SOFA scores were 18.7 ±
6.1 and 7.6 ± 2.7, respectively. No statistically significant differences were observed between the VCV and PCV groups for age, sex, predicted body weight, underlying clinical condition, APACHE II score, or SOFA score (all $p > 0.05$). (Table 1)

Table 1: Baseline characteristics of the study population (N=100)

Variable	Total	VCV	PCV	p
Age, mean ± SD (years)	56.1 ± 14.2	55.4 ± 13.8	56.8 ± 14.6	0.63
Male, n (%)	62 (62%)	32 (64%)	30 (60%)	0.67
PBW, mean ± SD (kg)	61.3 ± 9.4	60.8 ± 9.1	61.8 ± 9.7	0.61
Pneumonia	32 (32%)	17 (34%)	15 (30%)	0.78
ARDS	28 (28%)	15 (30%)	13 (26%)	0.64
Sepsis, nonpulmonary	20 (20%)	9 (18%)	11 (22%)	0.59
Post-operative	12 (12%)	6 (12%)	6 (12%)	1.00
Other	8 (8%)	3 (6%)	5 (10%)	0.44
APACHE II score, mean ± SD	18.7 ± 6.1	18.4 ± 6.0	19.0 ± 6.3	0.62
SOFA score, mean ± SD	7.6 ± 2.7	7.5 ± 2.6	7.7 ± 2.8	0.74

3.2. Ventilator Parameters and Normalized Mechanical Power

During the first 24 hours of mechanical ventilation, the mean tidal volume was significantly higher in the VCV group than in the PCV group (470.2 ± 71.3 vs 436.5 ± 68.9 mL, $p = 0.015$). Respiratory rate, PEEP, peak airway pressure, plateau pressure, and driving pressure did not differ significantly between the two ventilation groups. The mean mechanical power was 17.8 ± 4.6 J/min in the VCV group and 16.3 ± 4.1 J/min in the PCV group ($p = 0.10$). In contrast, normalized mechanical power was significantly higher in patients receiving VCV than in those receiving PCV (0.32 ± 0.11 vs 0.27 ± 0.09 J/min/kg PBW, $p = 0.013$). (Table 2)

Table 2: Ventilator Parameters and Normalized Mechanical Power (First 24 hr)

Parameter	VCV (n=50)	PCV (n=50)	p
Tidal volume (mL)	**470.2 ± 71.3**	**436.5 ± 68.9**	**0.015**
Respiratory rate (/min)	20.1 ± 3.6	19.6 ± 3.4	0.48
PEEP (cmH_2O)	8.6 ± 2.3	8.2 ± 2.1	0.37
Peak pressure (cmH_2O)	26.8 ± 5.1	25.9 ± 4.7	0.35
Plateau pressure (cmH_2O)	22.4 ± 4.2	21.3 ± 4.1	0.20
Driving pressure (cmH_2O)	13.8 ± 3.3	13.1 ± 3.1	0.26

Mechanical power (J/min)	17.8 ± 4.6	16.3 ± 4.1	0.10
Normalized mechanical power (J/min/kg PBW)	**0.32 ± 0.11**	**0.27 ± 0.09**	**0.013**

3.3. Development of VILI and Clinical Outcomes

VILI developed in 28 patients (28%) overall. The incidence of VILI was higher among patients receiving VCV than among those receiving PCV, occurring in 19 patients (38%) and 9 patients (18%), respectively ($p = 0.027$). ICU mortality was observed in 24 patients (24%), with mortality rates of 32% in the VCV group and 16% in the PCV group ($p = 0.048$). The median duration of mechanical ventilation was 7 days (IQR, 4 to 11 days) overall, compared with 8 days (IQR, 5 to 12 days) in the VCV group and 6 days (IQR, 4 to 9 days) in the PCV group ($p = 0.033$). The median ICU length of stay was 10 days (IQR, 6 to 16 days) overall, with 11 days (IQR, 7 to 17 days) in the VCV group and 8 days (IQR, 6 to 14 days) in the PCV group ($p = 0.041$). (Table 3)

Table 3: Development of VILI and Clinical Outcomes

Outcome	Total	VCV	PCV	p
VILI, n (%)	**28 (28%)**	**19 (38%)**	**9 (18%)**	**0.027**
ICU mortality, n (%)	24 (24%)	16 (32%)	8 (16%)	0.048
Ventilator days, median (IQR)	7 (4–11)	8 (5–12)	6 (4–9)	0.033
ICU length of stay, median (IQR), days	10 (6–16)	11 (7–17)	8 (6–14)	0.041

3.4. Relationship Between Normalized Mechanical Power and VILI

The incidence of VILI increased across progressively higher categories of normalized mechanical power. VILI occurred in 6.3% of patients with normalized mechanical power below 0.20 J/min/kg PBW, 17.6% of patients with values between 0.20 and 0.30 J/min/kg PBW, 39.1% of patients with values between 0.31 and 0.40 J/min/kg PBW, and 61.1% of patients with values above 0.40 J/min/kg PBW. The trend across these categories was statistically significant (p for trend < 0.001). (Figure 1)

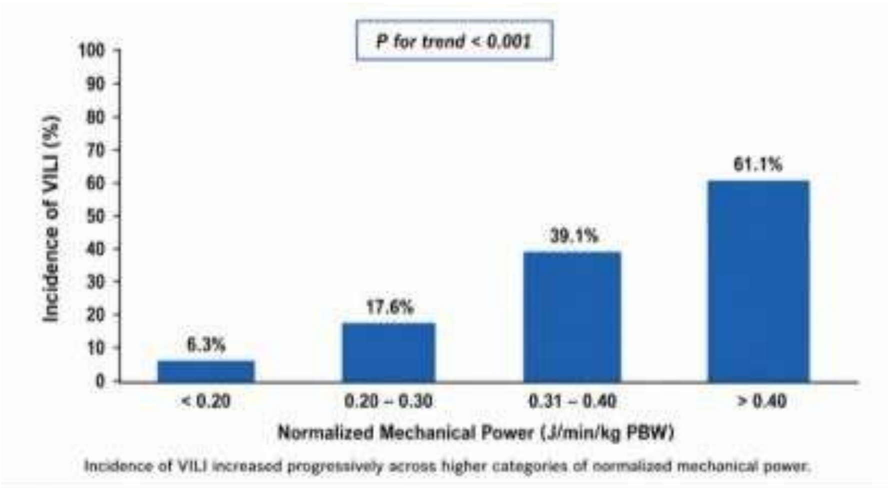

Figure 1. Incidence of VILI across categories of normalized mechanical power.

3.5. Multivariable Analysis

Multivariable logistic regression identified normalized mechanical power as an independent factor associated with VILI. For each 0.1 J/min/kg PBW increase in normalized mechanical power, the adjusted odds of VILI increased by 64% (adjusted OR, 1.64; 95% CI, 1.28 to 2.12; $p < 0.001$). Driving pressure was also independently associated with VILI (adjusted OR, 1.18 per cmH_2O increase; 95% CI, 1.05 to 1.33; $p = 0.006$). APACHE II score was independently associated with VILI (adjusted OR, 1.06 per point increase; 95% CI, 1.02 to 1.11; $p = 0.003$).

PEEP was not significantly associated with VILI (adjusted OR, 1.07 per cmH_2O increase; 95% CI, 0.95 to 1.20; $p = 0.28$). Ventilation mode, expressed as PCV relative to VCV, was also not independently associated with VILI after adjustment (adjusted OR, 1.32; 95% CI, 0.61 to 2.86; $p = 0.47$). (Table 4)

Table 4: Multivariate logistic regression for predictors of VILI

Predictor	**Adjusted OR (95% CI)**	**p**
Normalized mechanical power, per 0.1 J/min/kg incr	**ease1.64 (1.28–2.12)**	**<0.001**
Driving pressure, per cmH_2O increase	1.18 (1.05–1.33)	0.006
PEEP, per cmH_2O increase	1.07 (0.95–1.20)	0.28
Ventilation mode, PCV vs VCV	1.32 (0.61–2.86)	0.47
APACHE II score, per point increase	1.06 (1.02–1.11)	0.003

3.6. Predictive Performance of Normalized Mechanical Power

ROC analysis demonstrated an area under the curve of 0.82 (95% CI, 0.73 to 0.91) for normalized mechanical power in discriminating patients who developed VILI. A threshold of 0.31 J/min/kg PBW provided a sensitivity of 78.6% and specificity of 74.2%. (Figure 2)

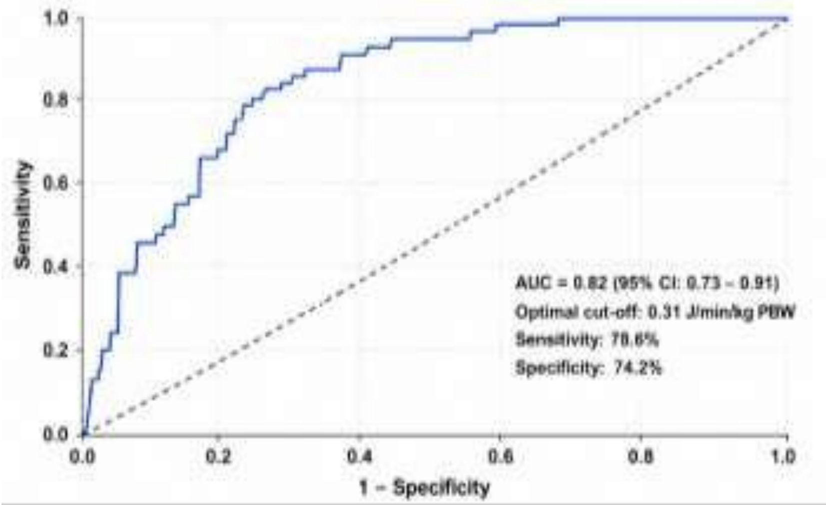

Figure 2. ROC curve of normalized mechanical power for prediction of VILI.

3.7. Study Workflow

Figure 3 summarizes the overall study workflow, including patient enrolment, ventilation-mode allocation, timing of the first-24-hour ventilator assessment used to calculate mechanical power, and the schedule of serial VILI assessment and outcome ascertainment during invasive mechanical ventilation.

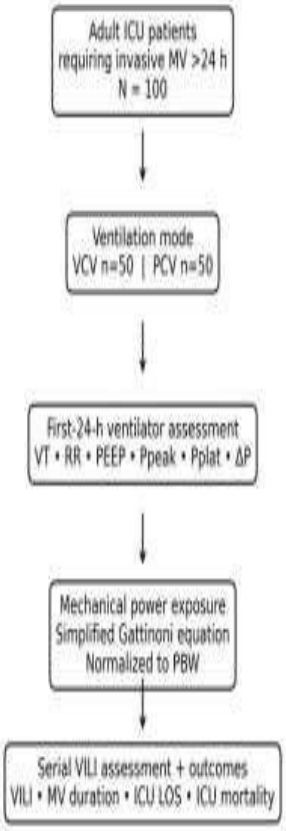

Figure 3. Study workflow and timing of mechanical-power exposure and VILI assessment.

4. DISCUSSION

The present study evaluated the association between normalized mechanical power and VILI in mechanically ventilated adult ICU patients receiving VCV or PCV. The findings indicate that normalized mechanical power was associated with VILI and that increasing mechanical power corresponded to progressively higher VILI incidence. Normalized mechanical power also remained independently associated with VILI after multivariable adjustment. These findings support the potential value of normalized mechanical power as an integrated measure of ventilatory exposure in mechanically ventilated patients, while the observational study design does not permit causal inference [12]. Mechanical power integrates several components of mechanical ventilation, including tidal volume, respiratory rate, airway pressure, and PEEP, into an estimate of the energy delivered to the respiratory system per unit time. This provides a broader assessment of ventilatory exposure than consideration of an individual ventilator variable alone. Gattinoni et al. established the mechanical power concept as a framework for evaluating the cumulative mechanical energy imposed on the respiratory system during mechanical ventilation. Subsequent clinical studies have examined its relationship with outcomes in critically ill patients and have reported associations between higher mechanical power and mortality [13].

In this study, normalized mechanical power was significantly higher in patients receiving VCV than in those receiving PCV. The corresponding values were 0.32 ± 0.11 and 0.27 ± 0.09 J/min/kg PBW, respectively. Tidal volume was also significantly higher in the VCV group, whereas respiratory rate, PEEP, peak pressure, plateau pressure, and driving pressure did not differ significantly between the two groups. The observed difference in normalized mechanical power therefore occurred alongside differences in tidal volume. However, the available observational data do not establish whether the difference in mechanical power was independently attributable to ventilation mode or to the individual ventilatory parameters used

during each mode [14].
A progressive increase in VILI incidence was observed across increasing normalized mechanical power categories. VILI occurred in 6.3% of patients with normalized mechanical power below 0.20 J/min/kg PBW and increased to 61.1% among patients with values above 0.40 J/min/kg PBW, with a significant trend across categories. This pattern is consistent with the concept that greater ventilator delivered mechanical energy is associated with greater risk of lung injury. However, the observed relationship should not be interpreted as evidence that increasing mechanical power directly causes VILI, because the study design cannot establish causality [15].
Multivariable logistic regression further demonstrated an independent association between normalized mechanical power and VILI. For every 0.1 J/min/kg PBW increase, the adjusted odds ratio for VILI was 1.64. Driving pressure and APACHE II score were also independently associated with VILI, whereas PEEP and ventilation mode were not independently associated after adjustment. These findings indicate that normalized mechanical power retained an association with VILI after consideration of selected clinical and ventilatory variables. Nevertheless, residual confounding remains possible [16].
The findings are consistent with previous reports describing associations between mechanical power and clinically relevant outcomes. Serpa Neto et al. reported an association between mechanical power of ventilation and mortality among critically ill patients. Costa et al. also evaluated mechanical power and ventilatory variables in patients with ARDS and reported an association between mechanical power and mortality. These observations provide clinical context for the present findings, although mortality and VILI represent different outcomes and should not be considered interchangeable [17].
The practical calculation of mechanical power is relevant to its potential clinical application. The simplified Gattinoni approach permits estimation of mechanical power using routinely available ventilatory variables. Studies have also evaluated calculation methods during both volume control and PCV, supporting the feasibility of bedside assessment across ventilation modes. Normalization to predicted body weight provides an approach for expressing mechanical power relative to predicted patient size, which was used in the present study [18].
The ROC analysis produced an AUC of 0.82 for normalized mechanical power, with a cutoff of 0.31 J/min/kg PBW providing 78.6% sensitivity and 74.2% specificity. These findings indicate discriminatory performance within the studied population. However, this cutoff should not be considered a universally established clinical threshold. External validation in larger and multicenter populations is required before a specific normalized mechanical power value can be used as a standardized target for ventilator management [19].
The study has several limitations. Its single center observational design limits generalizability and prevents determination of causality. The moderate sample size may reduce statistical power and increase susceptibility to selection bias. Potential confounding factors and dynamic ventilator variables may also have influenced the observed associations despite multivariable adjustment. Larger multicenter prospective studies are therefore required to validate the observed associations and determine whether mechanical power guided ventilation can improve clinical outcomes. Overall, the study supports an association between normalized mechanical power and VILI in mechanically ventilated ICU patients. Its potential role as a monitoring and risk assessment parameter warrants further prospective evaluation [20].

5. STRENGTHS

- Prospective observational design with standardized collection of ventilator and clinical variables.
- Direct comparison of VCV and PCV in a defined cohort.
- Normalization of mechanical power to PBW to account for differences in predicted body size.
- Use of multivariable logistic regression to adjust for selected clinical and ventilatory factors.
- ROC analysis to quantify discriminatory performance.
- Separation of mechanical power exposure from the operational VILI endpoint.

6. LIMITATIONS

- Single-center design and relatively small sample size (N=100) limit generalizability.
- Observational design precludes causal inference and permits residual confounding.
- Ventilator variables can change dynamically; first-24-hour summary measurements may not capture cumulative exposure over the entire period of ventilation.

7. CONCLUSION

Normalized mechanical power was significantly associated with clinically suspected VILI in mechanically ventilated adult ICU patients receiving VCV or PCV. Higher normalized mechanical power was accompanied by a progressive increase in VILI incidence and remained independently associated with VILI after multivariable adjustment. Normalized mechanical power also showed good discrimination for VILI (AUC 0.82), with a study-specific cutoff of 0.31 J/min/kg PBW yielding 78.6% sensitivity and 74.2% specificity. The findings support normalized mechanical power as a potential monitoring and risk-assessment parameter, but the identified threshold should not be adopted as a universal clinical target without external validation. Larger multicenter prospective studies using standardized VILI adjudication are required.

Funding: Not available for this study

Ethical Declaration: Not Applicable

Conflicts of Interest: The authors declare no conflicts of interest.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. Requests for access to the data will be evaluated in accordance with applicable ethical, institutional, and confidentiality requirements.

Disclosure Statement: The authors declare that they have no conflicts of interest or financial relationships that could have influenced the design, conduct, analysis, or reporting of this study.

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