

Mechanical ventilation in COVID-19

Ventilación mecánica invasiva en COVID-19

Sebastián Rodríguez-Llamazares^{1,2} , Luis J. Arroyo-Hernández², Josué D. Cadeza-Aguilar^{3*}, Irene Balam-Lara³, Edith L. Nicolás-Martínez³, Jazmín G. Emeterio-Alcázar³, Gustavo Lugo-Goytia³, Iván A. Osuna-Padilla³, and Carmen Hernández Cárdenas³ 

¹Division of Respiriology and Sleep Medicine, Queen's University, Kingston, ON, Canada; ²Bronchoscopy and Endoscopy Service, Instituto Nacional de Enfermedades Respiratorias, Mexico City, Mexico; ³General Directorate, Instituto Nacional de Enfermedades Respiratorias Ismael Cosío Villegas, Mexico City, Mexico

Abstract

COVID-19 can progress to a critical condition with acute respiratory distress syndrome, characterized by alveolar collapse, exudative infiltrate with an intense inflammatory response, which can progress to biotrauma and multiple organ failure. In cases of severe respiratory failure refractory to oxygen therapy or non-invasive support, invasive mechanical ventilation is indicated based on clinical and blood gas analysis criteria. This constitutes a life-support therapy aimed at maintaining gas exchange while pulmonary recovery occurs. During the pandemic, different COVID-19 phenotypes with respiratory compromise were described, ranging from relatively preserved compliance and predominantly impaired perfusion (phenotype L) to presentations like classic acute respiratory distress syndrome with high elastance, pulmonary edema, and greater recruitment potential (phenotype H). These phenotypes can evolve dynamically, which explains the clinical heterogeneity and the variable response to interventions such as prone positioning. Initial ventilation programming should be individualized, usually using volume-controlled modes, and continuous monitoring, including static and dynamic variables; this is essential for ventilatory optimization and reducing ventilator-induced lung injury. Furthermore, alveolar recruitment and prone positioning are key strategies in moderate to severe respiratory distress syndrome, with evidence of reduced mortality when implemented early and for an extended period.

Keywords: COVID-19. ARDS. Prone positioning. Invasive mechanical ventilation.

Resumen

La COVID-19 puede evolucionar a una condición crítica con síndrome de insuficiencia respiratoria aguda caracterizada por colapso alveolar, infiltrado exudativo e intensa respuesta inflamatoria, que puede progresar a biotrauma y falla multiorgánica. En caso de insuficiencia respiratoria grave refractaria a oxigenoterapia o soporte no invasivo, considerando criterios clínicos y gasométricos, está indicada la ventilación mecánica invasiva; constituye una terapia de soporte vital, orientada a mantener el intercambio gaseoso mientras ocurre la recuperación pulmonar. Durante la pandemia se describieron distintos fenotipos de COVID-19 con compromiso respiratorio, desde formas con distensibilidad relativamente conservada y alteración predominante de la perfusión (fenotipo L), hasta cuadros similares al SIRA clásico con alta elastancia, edema pulmonar y mayor potencial de reclutamiento (fenotipo H). Estos fenotipos pueden evolucionar dinámicamente, lo que explica la heterogeneidad clínica y la respuesta variable a intervenciones como la posición prona. La programación inicial de la ventilación debe individualizarse, usualmente con modos controlados por volumen y el monitoreo continuo es fundamental, incluyendo variables estáticas y

*Correspondence:

Josué D. Cadeza-Aguilar
E-mail: jdcnm@gmail.com

Date of reception: 28-11-2025
Date of acceptance: 18-05-2026
DOI: 10.24875/NCTE.M26000035

Available online: 21-10-2026
Neumol Cir Torax (Eng). 2025;84(4):286-294
www.revistanct.org.mx

3082-0006 / © 2026 Sociedad Mexicana de Neumología y Cirugía de Tórax. Published by Permanyer. This is an open access article under the license CC BY-NC-ND (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

dinámicas, para la optimización ventilatoria y la reducción del daño inducido por el ventilador. Además, el reclutamiento alveolar y la posición prona son estrategias clave en SIRA moderado a grave, con evidencia de disminución de mortalidad cuando se aplican de forma temprana y prolongada.

Palabras clave: COVID-19. SIRA. Posición prono. Ventilación mecánica invasiva.

Introduction

COVID-19 can progress to acute respiratory distress syndrome (ARDS), characterized by alveolar collapse, exudative consolidation, and pulmonary inflammation that may progress to biotrauma and multiple organ failure. In this context, mechanical ventilation is an essential supportive therapy that maintains gas exchange while allowing the lung to recover, through careful adjustment of volume and pressure to optimize ventilation and promote alveolar recruitment.

Protective ventilation, based on tidal volumes of 6-8 ml/kg of predicted body weight, aims to avoid both overdistension (volutrauma) and cyclic alveolar collapse (atelectrauma), which is particularly relevant in ARDS, where lung injury is already established.¹ This condition compels the mechanical ventilator operator to exercise extreme caution in selecting administered volumes and pressures, with the goal of neither perpetuating nor worsening the underlying lung injury. The settings used in this context are known as lung-protective parameters.

The indication for invasive mechanical ventilation (IMV) in patients with COVID-19 is established when severe respiratory failure is refractory to other therapeutic strategies, such as conventional oxygen therapy, non-invasive mechanical ventilation, or high-flow nasal cannula. In particular, IMV should be considered when one or more of the following criteria are met: a) arterial oxygen pressure (PaO_2)/inspired oxygen fraction (FiO_2) ratio < 200; b) deterioration of neurological status; c) increased work of breathing (WOB); d) tachypnea greater than 30 breaths per minute; and e) respiratory acidosis, defined as $\text{pH} < 7.35$ with $\text{PaCO}_2 > 45$ mmHg² at altitudes such as that of Mexico City at 2,240 m. To adequately understand ventilatory parameters and monitoring strategies, it is essential to be familiar with the clinical phenotypes described throughout the pandemic.

COVID-19 phenotypes

Patients with COVID-19 may present with different patterns of refractory hypoxemia, ranging from cases with preserved pulmonary compliance to more severe forms resembling classic ARDS. Some patients show

a good response to prone positioning, while others without improvement tend to have low alveolar recruitment capacity.³ Gattinoni et al.,³ in their editorial *COVID-19 pneumonia: different respiratory treatments for different phenotypes?*, hypothesize that the clinical presentation and severity of COVID-19 pneumonia depend on the interaction of multiple factors: 1) the severity of infection, the host response, physiological reserve, and comorbidities; 2) the ventilatory response to hypoxemia; and 3) the interval between symptom onset and initiation of hospital management.

Two main phenotypes have been proposed:

- Phenotype L is characterized by relatively preserved compliance, predominantly perfusion-related ventilation/perfusion mismatch, a ground-glass pattern with low lung weight, and limited recruitment response.
- Phenotype H, in contrast, presents with high elastance, increased edema and lung weight, greater intrapulmonary shunt, and high alveolar recruitment capacity. It resembles classic ARDS.³

These phenotypes can evolve from L to H due to increased ventilatory work and intrathoracic pressures, as well as progression of inflammatory injury and edema. This pathophysiological dynamic explains the clinical variability observed in severe COVID-19, including heterogeneous responses to ventilation and oxygenation.³ Figure 1 illustrates the differences between the two phenotypes.

The H and L phenotypes described by Gattinoni constitute a useful conceptual tool for understanding the pathophysiological heterogeneity of COVID-19; however, hyperinflammatory and hypoinflammatory sub-phenotypes of ARDS have since been described, making individual assessment of pulmonary mechanics, recruitability, and clinical response is of greater relevance for guiding therapeutic decisions.

Initial ventilator settings in mechanical ventilation

Initial mechanical ventilation programming should be individualized according to the patient's clinical characteristics, with emphasis on lung protection, oxygenation,

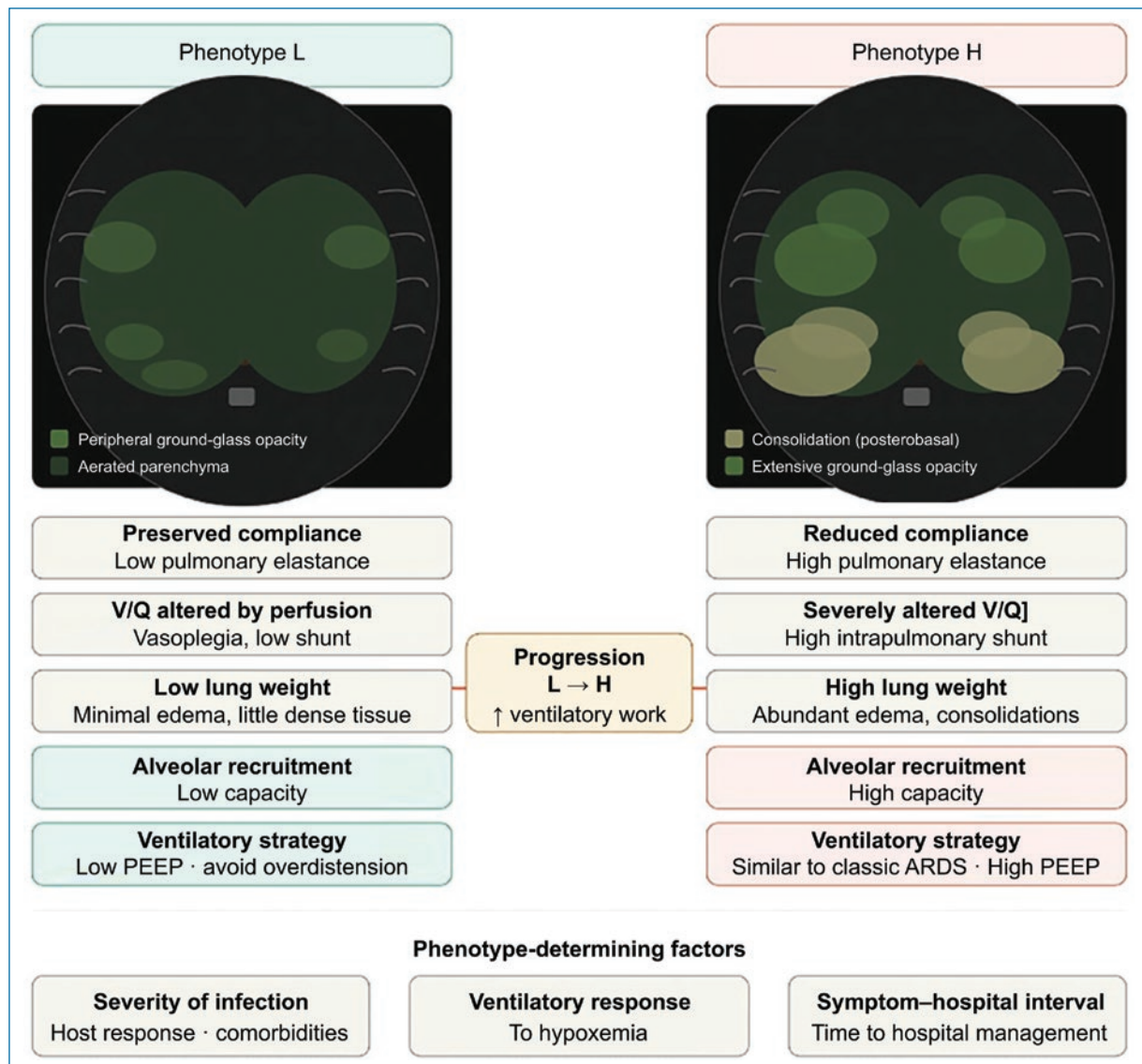


Figure 1. Phenotypes of severe COVID-19 pneumonia. Schematic axial cross-sections illustrate the characteristic computed tomography findings of each phenotype. Phenotype L (left panel) shows peripheral and sparse ground-glass opacities, with predominantly aerated pulmonary parenchyma and low lung weight. Phenotype H (right panel) presents extensive posterobasal consolidations and diffuse ground-glass opacities, reflecting abundant pulmonary edema and increased lung weight. Physiologically, phenotype L is characterized by preserved compliance, predominantly vascular ventilation/perfusion mismatch, and low recruitment capacity; phenotype H, in contrast, resembles classic ARDS, with high elastance, elevated intrapulmonary shunt, and high alveolar recruitment capacity. Both phenotypes may coexist or progress from L to H due to increased ventilatory work and progression of inflammatory injury. The images are schematic representations; they do not correspond to real patient computed tomography scans. *Adapted from Gattinoni et al.³*. PEEP: positive end-expiratory pressure; ARDS: acute respiratory distress syndrome; V/Q: ventilation/perfusion ratio.

and ventilator synchrony. No single ventilatory mode is superior, so the choice depends on clinical experience. However, it is frequently recommended to begin with volume-controlled ventilation to ensure a protective tidal volume (VT) (4-8 ml/kg of predicted body weight, ideally 6-8 ml/kg), with a respiratory rate of 12-18 breaths/min

and adjustments that may require increments according to the patient's condition.⁴

Other initial parameters include an inspiratory flow of 40-60 l/min, an inspiratory-to-expiratory ratio (I:E) of 1:2 to 1:3, an initial positive end-expiratory pressure (PEEP) ≥ 5 cmH₂O, and a sensitivity of 1.5 to 2 l/min

(or, in pressure-triggered mode, between -1 and -3 cmH_2O). The central objective is to maintain a plateau pressure (P_{plat}) < 30 cmH_2O and to avoid ventilator-induced lung injury (VILI) by simultaneously adjusting rate and flow to prevent auto-PEEP. Minute volume must be adapted to metabolic demands and dead space. In some cases, permissive hypercapnia may be accepted as a protective strategy.²

Pressure-controlled mode is a valid alternative, but it requires knowledge of its programming differences depending on the ventilator. In this mode, VT is variable and depends on the patient's pulmonary mechanics and the applied pressure gradient, such that thoracopulmonary impedance directly influences effective ventilation; with greater impedance, peak inspiratory pressure is reached more rapidly, resulting in a lower delivered VT. From an operational standpoint, the pressure difference (ΔP) between the baseline (PEEP plus auto-PEEP) and peak inspiratory pressure (PIP) is the primary determinant of the administered VT. This relationship is influenced by both the mechanical properties of the lung and the patient's respiratory effort.⁴ Other relevant considerations include the use of a preferentially decelerating flow waveform, programming a minimum respiratory rate, appropriate adjustment of the I:E ratio, and trigger sensitivity. Inspiratory pressure should be titrated progressively to achieve the target tidal volume within a safe range, in accordance with the principles of lung protection.⁴

Concept of recruitment

Pulmonary recruitment, described by Lachmann in 1992, consists of the reopening of collapsed alveolar units to restore them to ventilation. This process is achieved through the transient application of elevated inspiratory pressures (positive inspiratory pressure) and their maintenance with adequate PEEP levels, in order to prevent end-expiratory collapse and promote more homogeneous and protective ventilation.⁵ Alveolar recruitment maneuvers aim to increase transpulmonary pressure in a controlled manner to reopen collapsed or partially ventilated alveoli. In the context of ARDS, they represent a relevant strategy in the management of refractory hypoxemia. However, the available evidence, particularly in COVID-19, is limited and of low quality, so their use is not recommended systematically. When employed, they may include the application of elevated pressures over brief periods, always under close clinical monitoring.⁶⁻⁹

Pulmonary monitoring

The interpretation of pulmonary mechanics variables is fundamental to understanding the functional state of the lung and guiding mechanical ventilation adjustments. It is necessary to measure, analyze, and interpret the forces applied during insufflation – particularly transpulmonary pressure (stress) and the resulting deformation of pulmonary tissue (strain) – without losing sight of the central objective of maintaining open and functional alveolar units for adequate gas exchange. From the perspective of the ventilation/perfusion (V/Q) relationship, ventilation can be understood as the response of the respiratory system to the mechanical impulse of insufflation and its subsequent return to the resting position. This process is divided into three components: 1) the dynamic phase, in which the resistive forces of the respiratory system (lung, thoracic cage, and abdomen) are overcome; 2) the static phase, corresponding to the distribution of gas within pulmonary compartments; and 3) the elastic recoil phase of the lung. Identifying the variables that represent each of these phases is essential for adequate monitoring and for titrating a protective ventilatory strategy.⁶⁻⁹

Monitoring under static conditions

In volume-controlled mechanical ventilation, assessment under zero-flow conditions allows the elastic properties of the respiratory system to be analyzed with greater precision. During the inspiratory pause – after closure of the inspiratory valve and before opening of the expiratory valve – flow ceases, and the administered volume redistributes homogeneously. At this point, the plateau pressure (P_{plat}) is measured, which reflects the elastic recoil pressure of the respiratory system and, in equilibrium, approximates alveolar pressure.⁸

Additionally, intrinsic PEEP (PEEP_i) is measured through an end-expiratory pause, also under zero-flow conditions, allowing the identification of air trapping and dynamic hyperinflation. PEEP_i may occur in different scenarios: 1) without pulmonary overdistension, associated with active expiration and increased end-expiratory alveolar pressure; 2) due to increased ventilatory demands (elevated respiratory rate or tidal volume) with insufficient expiratory time, leading to incomplete alveolar emptying; and 3) in the presence of airflow limitation, where dynamic airway collapse during expiration promotes air trapping and increased alveolar pressure without improvement in expiratory flow.¹⁰ Correct interpretation

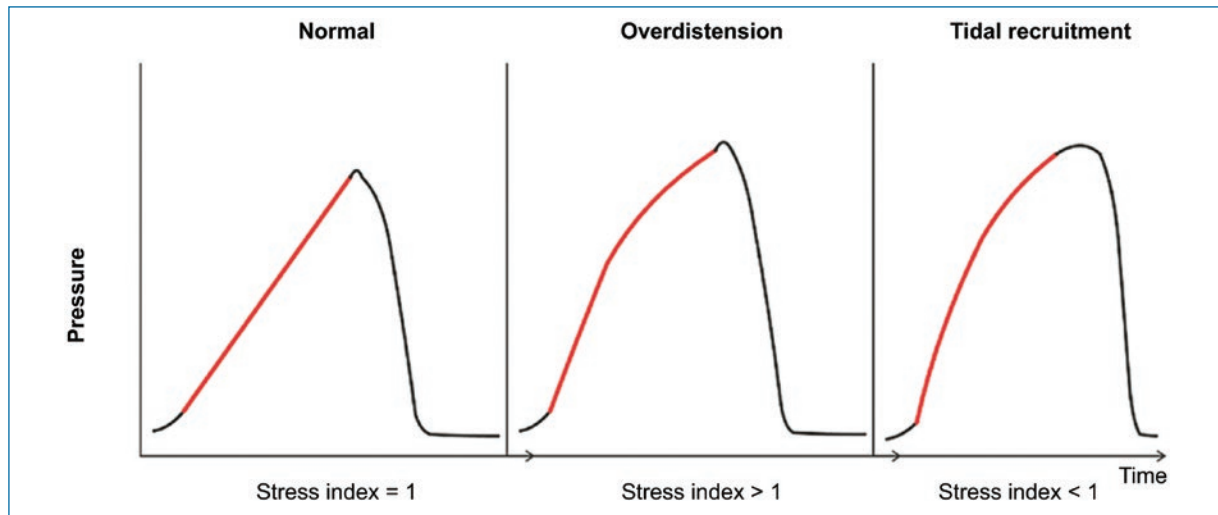


Figure 2. Monitoring of the stress index on the pressure curve (y-axis) and time (x-axis) during invasive mechanical ventilation. The red segment marks the inspiratory portion in each case: Normal ($= 1$): pressure rises linearly during inspiration; Overdistension (> 1): the curve accelerates (upward concavity), indicating alveolar overdistension; Tidal recruitment (< 1): the curve decelerates (downward concavity), indicating cyclic recruitment with each breath.

of these variables is essential for optimizing ventilation and minimizing the risk of ventilator-induced lung injury.

Compliance (C) describes the relationship between the change in lung volume and the pressure required to generate it ($C = V/P$, ml/cmH₂O). In patients under IMV, static compliance is estimated from the tidal volume (VT) divided by the difference between Pplat and PEEP ($C = VT/(P_{plat} - PEEP)$). As a reference, normal values are approximately 100 ml/cmH₂O under general conditions, approximately 75 ml/cmH₂O in the supine position, and approximately 50 ml/cmH₂O in patients with ARDS, reflecting the loss of pulmonary elasticity in this context.¹¹

Driving pressure is defined as the difference between Pplat and PEEP and is ideally evaluated in the absence of spontaneous respiratory effort. This parameter reflects the relationship between tidal volume and respiratory system compliance, serving as an indirect indicator of functional lung size. Clinical evidence has demonstrated that elevated driving pressure is associated with higher mortality in patients with ARDS; therefore, it is recommended to maintain it below 15 cmH₂O. Furthermore, monitoring this parameter is useful for adjusting PEEP within a protective ventilation strategy aimed at optimizing oxygenation and minimizing lung injury.¹²

Monitoring under dynamic conditions

Dynamic monitoring allows evaluation of the interaction between flow, pressure, and volume during the

respiratory cycle, integrating both the elastic and resistive properties of the respiratory system.

Airway resistance is defined as the relationship between the pressure gradient (from the proximal airway to the alveoli) and airflow ($R = P/F$, cmH₂O/L/s). This parameter varies as a function of lung volume: the greater the volume, the lower the airway resistance, and vice versa.¹³ Its assessment is useful for identifying airflow obstruction or changes in the mechanical conditions of the respiratory system.

Dynamic compliance is calculated as the ratio between VT and the difference between peak pressure and PEEP ($C_{dyn} = VT/(P_{peak} - PEEP)$). Unlike static compliance, this parameter integrates the combined effect of airway resistance, the thoracic cage, and the pulmonary parenchyma. Its values are typically 10-20% lower than those of static compliance and may be influenced by factors such as the patient's age and weight.¹³

Monitoring of pulmonary parenchymal deformation

Pulmonary stress is defined as the distending pressure applied to the fibro-skeleton of the lung during ventilation. Based on this concept, Grasso et al.¹⁴ developed the stress index, a useful tool for optimizing PEEP titration and reducing the risk of VILI. This index is evaluated through the morphology of the pressure-time curve (Fig. 2). A downward-concave curve (index < 1)

indicates increased compliance and suggests potential alveolar recruitment, such that increasing PEEP to achieve a more linear tracing might be considered. In contrast, an upward-concave curve (index > 1) suggests alveolar overdistension, indicating the need to reduce PEEP. A linear profile is associated with more homogeneous ventilation and, therefore, with a lower risk of lung injury.

Strain represents the deformation of the pulmonary fibroskeleton in response to mechanical ventilation and constitutes a key parameter in the genesis of VILI. Its assessment allows estimation of the degree of mechanical stress applied to the lung and guides protective ventilation strategies. Among the available tools, electrical impedance tomography stands out as a non-invasive, radiation-free, and low-cost method that allows real-time analysis of the regional distribution of ventilation, contributing to optimization of ventilatory parameters and reduction of VILI risk.¹⁴

Ventilator titration and lung protection

Mechanical ventilation titration is directed toward three fundamental objectives: avoiding alveolar overdistension, optimizing alveolar recruitment (preventing cyclic collapse and reopening), and adjusting ventilation to the characteristics of the “injured lung,” in accordance with oxygenation and ventilation targets.¹⁵

Establishing a VT based on predicted body weight constitutes the cornerstone of protective ventilation. Evidence has demonstrated that the use of low VT (≈ 6 ml/kg) is associated with lower mortality compared with higher volumes (≈ 12 ml/kg), primarily due to its impact on reducing plateau pressure.^{16,17} Nevertheless, in patients with COVID-19 phenotype L, characterized by greater compliance, the use of slightly higher volumes (up to 8 ml/kg of predicted body weight) may be considered, provided that plateau pressure remains below 30 cmH₂O.¹⁸

Maintaining a plateau pressure < 30 cmH₂O is a key objective, as this parameter correlates with alveolar distension and, under normal conditions, acts as a surrogate for transpulmonary pressure.¹⁴ However, its interpretation must be adjusted in the presence of alterations in thoracic or abdominal elastance, where it may lose precision and require more direct measurements, such as esophageal pressure. Elevated plateau pressure values are associated with a greater risk of alveolar edema and lung injury.²

Driving pressure (ΔP = plateau pressure–PEEP) reflects the available functional lung volume and the

degree of recruitable lung in each respiratory cycle. This parameter integrates both the ventilator configuration and the patient's mechanical properties, and it is recommended to maintain it below 15 cmH₂O as part of a protective ventilation strategy.^{13,16}

Importance of PEEP titration in patients with COVID-19

Adequate PEEP titration is a key component of the protective ventilation strategy, particularly in patients with ARDS secondary to COVID-19. A meta-analysis that included the ALVEOLI, LOVS, and EXPRESS studies evaluated the impact of high versus low PEEP strategies.¹⁹ In the overall analyzed population, no significant differences in mortality were observed between the two groups (relative risk [RR]: 0.94; 95% confidence interval [95% CI]: 0.86-1.04; $p = 0.25$). However, in the subgroup of patients with ARDS, the use of higher PEEP levels was associated with a modest but significant reduction in mortality (adjusted RR: 0.90; 95% CI: 0.81-1.0; $p = 0.049$). These findings suggest that the benefit of elevated PEEP depends on the severity of the syndrome. In particular, patients with moderate to severe ARDS may benefit from higher PEEP levels, likely due to greater alveolar recruitment potential. In contrast, in patients with mild ARDS, the use of elevated PEEP not only lacks clear benefit but could also be associated with adverse effects, including alveolar overdistension and hemodynamic compromise. Therefore, PEEP titration must be individualized, considering the clinical response, pulmonary mechanics, and the recruitment potential of each patient.²⁰

Prone positioning

In ARDS, areas of alveolar collapse and consolidation predominate in the dependent regions of the lung. In the supine position, these correspond primarily to the dorsobasal regions, promoting ventilation-perfusion imbalance. Ventilation in the prone position redistributes these areas, shifting the collapse toward anterior regions and promoting more homogeneous ventilation of the pulmonary parenchyma.²¹

This change improves the ventilation/perfusion ratio, reduces intrapulmonary shunt, and decreases both alveolar overdistension and dead space, thereby helping to limit VILI.²¹ The benefits are most evident in patients with moderate to severe ARDS, in whom a significant reduction in mortality has been demonstrated, as evidenced by the PROSEVA study.²² **Table 1**

Table 1. Methodological aspects of studies that have implemented prone positioning ventilation in patients with ARDS

Characteristic	Classic ARDS	COVID-19 ARDS
Study	Guérin et al. ²² PROSEVA trial	Observational studies and meta-analyses (2020-2024)
Study design	Multicenter randomized clinical trial	Predominantly observational (cohort, retrospective, meta-analyses)
Level of evidence	High	Moderate-low
Population	Severe ARDS ($\text{PaO}_2/\text{FiO}_2 < 150$)	Moderate-severe ARDS, heterogeneous population
Pathophysiology	"Typical" ARDS	Initially variable phenotypes; currently managed as typical ARDS
Onset of prone	Early (< 36 hours)	Variable; often delayed at the start of the pandemic
Duration of prone	≥ 16 hours per session	≥ 16 hours; frequently prolonged (> 24 hours)
Number of sessions	Repeated cycles	Variable according to clinical response
Ventilatory strategy	Strict protective ventilation	Variable adherence to protective ventilation
Effect on oxygenation	Significant and consistent improvement in $\text{PaO}_2/\text{FiO}_2$	Consistent improvement, with variable magnitude
Effect on mortality	Significant reduction (28 days: 16% versus 32.8%)	Inconclusive; possible benefit suggested
Complications	Pressure ulcers, airway events (without significant increase)	Similar profile; manageable in experienced centers
Reproducibility	High (protocolized intervention)	Variable (resource- and experience-dependent)
Clinical recommendation	Strong recommendation	Strong recommendation (based on extrapolation and physiological benefit)

ARDS: acute respiratory distress syndrome.

presents some characteristics of the studies that have employed this therapeutic strategy.

In the context of COVID-19, although distinct phenotypes were initially proposed, current evidence supports that ventilatory management (including prone positioning) should follow the principles of classic ARDS. In these patients, especially those with severe hypoxemia ($\text{PaO}_2/\text{FiO}_2 < 150$, $\text{FiO}_2 > 60\%$, and $\text{PEEP} \geq 5$ -10 cmH_2O), prone positioning consistently improves oxygenation and is associated with better outcomes when applied early and for prolonged periods. To maximize its benefits, it is recommended to maintain the prone position for > 12 hours per day,²³ ideally during the exudative phase of ARDS and under adequate sedation. More recent evidence suggests that extending sessions beyond 24 hours may be associated with greater benefits in terms of oxygenation and clinical outcomes;²⁴ however, this approach must be balanced against the risk of complications, most notably pressure ulcers and other injuries associated with prolonged immobility.^{25,26} Discontinuation of this strategy should be considered when sustained improvement in oxygenation is achieved ($\text{PaO}_2/\text{FiO}_2 > 150$, $\text{FiO}_2 < 60\%$, and $\text{PEEP} < 10$ cmH_2O), with stability verified after returning to the

supine position. In the event of deterioration, resumption of prone positioning should be reassessed.²⁷

Contraindications include significant hemodynamic instability or conditions that make its implementation difficult, such as recent abdominal surgery or cranioencephalic trauma. Its application likewise requires a trained multidisciplinary team, given the level of complexity and resources required.²⁸ Currently, the evidence supports its use as a standard intervention in the management of ARDS, regardless of the cause, including COVID-19.²³

Prone positioning constitutes a fundamental strategy in the management of intubated patients with COVID-19 and severe ARDS. Its timely and appropriate implementation, particularly in intensive care units, has proven to be a key intervention for improving oxygenation and clinical outcomes, as shown in figure 3.

Conclusion

Taken together, current evidence confirms that ventilatory management of ARDS – including that associated with COVID-19 – should be grounded in a comprehensive protective ventilation strategy, based

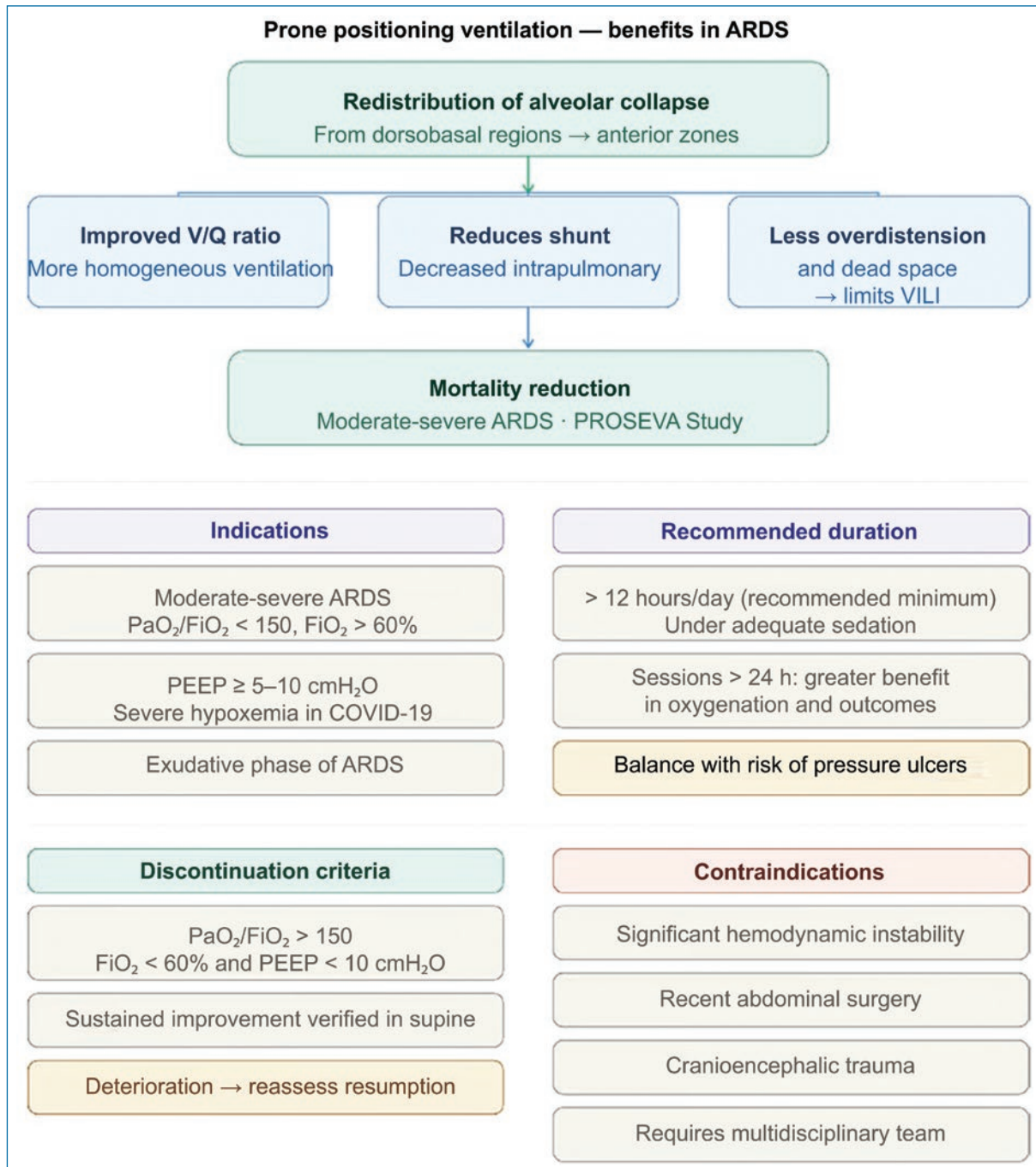


Figure 3. Physiological benefits and clinical considerations of prone positioning ventilation in acute respiratory distress syndrome (ARDS). The postural change redistributes alveolar collapse from the dorsobasal regions toward anterior zones, promoting more homogeneous ventilation of the pulmonary parenchyma. This results in improved ventilation/perfusion (V/Q) ratio, reduced intrapulmonary shunt, and decreased ventilator-associated lung injury (VILI). PEEP: positive end-expiratory pressure; ARDS: acute respiratory distress syndrome; V/Q: ventilation/perfusion ratio; VILI: ventilator-induced lung injury.

on limiting ventilator-induced injury, optimizing alveolar recruitment, and individualizing parameters according to each patient's pulmonary mechanics. Continuous monitoring of static and dynamic variables, alongside advanced regional assessment tools, allows precise

ventilation adjustments to minimize VILI. Likewise, interventions such as appropriate PEEP titration and prone positioning continue to play a central role in improving oxygenation and reducing mortality in moderate to severe cases. In this context, the pathophysiological

understanding of ARDS and the rigorous application of lung protection principles remain fundamental pillars for optimizing clinical outcomes in critically ill patients.

Funding

The present work received no funding.

Conflicts of interest

The authors declare no conflicts of interest.

Ethical considerations

Protection of persons and animals. The authors declare that no experiments were performed on human beings or animals for this research.

Confidentiality, informed consent, and ethical approval. The study does not involve personal patient data and does not require ethical approval. The SAGER guidelines do not apply.

Statement on the use of artificial intelligence. The authors declare that they did not use any form of generative artificial intelligence in the writing of this article.

References

- Cannon JW, Gutsche JT, Brodie D. Optimal strategies for severe acute respiratory distress syndrome. *Crit Care Clin*. 2017;33(2):259-75. <https://doi.org/10.1016/j.ccc.2016.12.010>.
- Grasselli G, Zangrillo A, Zanella A, Antonelli M, Cabrini L, Castelli A, et al. COVID-19 Lombardy ICU Network. Baseline characteristics and outcomes of 1591 patients infected with SARS-CoV-2 admitted to ICUs of the Lombardy Region, Italy. *JAMA*. 2020;323(16):1574-81. <https://doi.org/10.1001/jama.2020.5394>.
- Gattinoni L, Chiumello D, Caironi P, Busana M, Romitti F, Brazzi L, et al. COVID-19 pneumonia: different respiratory treatments for different phenotypes? *Intensive Care Med*. 2020;46(6):1099-102. <https://doi.org/10.1007/s00134-020-06033-2>.
- Cairo JM. Pilebeam's mechanical ventilation - E-Book: Physiological and Clinical Applications. Elsevier Health Sciences; 2023.
- Lachmann B. Open up the lung and keep the lung open. *Intensive Care Med*. 1992;18(6):319-21. <https://doi.org/10.1007/bf01694358>.
- Cui Y, Cao R, Wang Y, Li G. Lung recruitment maneuvers for ARDS patients: a systematic review and meta-analysis. *Respiration*. 2020;99(3):264-76. <https://doi.org/10.1159/000501045>.
- Gibson PG, Qin L, Puah SH. COVID-19 acute respiratory distress syndrome (ARDS): clinical features and differences from typical pre-COVID-19 ARDS. *Med J Aust*. 2020;213(2):54-6.e1. <https://doi.org/10.5694/mja2.50674>.
- Warrillow S, Austin D, Cheung W, Close E, Holley A, Horgan B, et al. ANZICS guiding principles for complex decision making during the COVID-19 pandemic. *Crit Care Resusc*. 2020;22(2):98-102. <https://doi.org/10.51893/2020.2.sa1>.
- Leach R, Bolanaki M, Behringer W, Prescott HC, Freund Y. The 2026 Surviving Sepsis Campaign guidelines: a turning point for emergency medicine. *Eur J Emerg Med*. 2026;33(3):139-40. <https://doi.org/10.1097/mej.0000000000001348>.
- dos Santos CC, Slutsky AS. The contribution of biophysical lung injury to the development of bio-trauma. *Annu Rev Physiol*. 2006;68:585-618. <https://doi.org/10.1146/annurev.physiol.68.072304.113443>.
- Piacentini E, Wysocki M, Blanch L. A new automated method *versus* continuous positive airway pressure method for measuring pressure-volume curves in patients with acute lung injury. *Intensive Care Med*. 2009;35(3):565-70. <https://doi.org/10.1007/s00134-008-1322-2>.
- Amato MBP, Meade MO, Slutsky AS, Brochard L, Costa ELV, Schoenfeld DA, et al. Driving pressure and survival in the acute respiratory distress syndrome. *N Engl J Med*. 2015;372(8):747-55. <https://doi.org/10.1056/nejmsa1410639>.
- Galettke W, Feiler C, Muth T, Ruehle K-H, Borsch-Galettke E, Randerath W. Reference values for dynamic and static pulmonary compliance in men. *Respir Med*. 2007;101(8):1783-9. <https://doi.org/10.1016/j.rmed.2007.02.015>.
- Grasso S, Terragni P, Mascia L, Fanelli V, Quintel M, Herrmann P, et al. Airway pressure-time curve profile (stress index) detects tidal recruitment/hyperinflation in experimental acute lung injury. *Crit Care Med*. 2004;32(4):1018-27. <https://doi.org/10.1097/01.ccm.0000120059.94009.ad>.
- Amato MB, Barbas CS, Medeiros DM, Magaldi RB, Schettino GP, Lorenzi-Filho G, et al. Effect of a protective-ventilation strategy on mortality in the acute respiratory distress syndrome. *N Engl J Med*. 1998;338(6):347-54. <https://doi.org/10.1056/nejm199802053380602>.
- Acute Respiratory Distress Syndrome Network; Brower RG, Matthay MA, Morris A, Schoenfeld D, Thompson BT, Wheeler A, et al. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. *N Engl J Med*. 2000;342(18):1301-8. <https://doi.org/10.1056/nejm200005043421801>.
- Brochard L, Roudot-Thoraval F, Roupie E, Delclaux C, Chastre J, Fernandez-Mondéjar E, et al. Tidal volume reduction for prevention of ventilator-induced lung injury in acute respiratory distress syndrome. The Multicenter Trial Group on Tidal Volume reduction in ARDS. *Am J Respir Crit Care Med*. 1998;158(6):1831-8. <https://doi.org/10.1164/ajrccm.158.6.9801044>.
- Marini JJ, Gattinoni L. Management of COVID-19 Respiratory Distress. *JAMA*. 2020;323(22):2329-30. <https://doi.org/10.1001/jama.2020.6825>.
- Briel M, Meade M, Mercat A, Brower RG, Talmor D, Walter SD, et al. Higher vs lower positive end-expiratory pressure in patients with acute lung injury and acute respiratory distress syndrome: systematic review and meta-analysis. *JAMA*. 2010;303(9):865-73. <https://doi.org/10.1001/jama.2010.218>.
- Writing Group for the Alveolar Recruitment for Acute Respiratory Distress Syndrome Trial (ART) Investigators; Cavalcanti AB, Suzumura EA, Laranjeira LN, Paisani D de M, Damiani LP, Guimarães HP, et al. Effect of lung recruitment and titrated Positive End-Expiratory Pressure (PEEP) vs low PEEP on mortality in patients with acute respiratory distress syndrome: a randomized clinical trial. *JAMA*. 2017;318(14):1335-45. <https://doi.org/10.1001/jama.2017.14171>.
- Rampon GL, Simpson SQ, Agrawal R. Prone positioning for acute hypoxemic respiratory failure and ARDS: A Review. *Chest*. 2023;163(2):332-40. <https://doi.org/10.1016/j.chest.2022.09.020>.
- Guérin C, Reigier J, Richard J-C, Beuret P, Gacouin A, Boulain T, et al. PROSEVA Study Group. Prone Positioning in Severe Acute Respiratory Distress Syndrome. *N Engl J Med*. 2013;368(23):2159-68. <https://doi.org/10.1056/nejmoa1214103>.
- Qadir N, Sahetya S, Munshi L, Summers C, Abrams D, Beitler J, et al. An update on management of adult patients with acute respiratory distress syndrome: an official American Thoracic Society Clinical Practice Guideline. *Am J Respir Crit Care Med*. 2024;209(1):24-36. <https://doi.org/10.1164/rccm.202311-2011st>.
- Kang H, Subinuer K, Tong Z. Effect of extended prone positioning in intubated COVID-19 patients with acute respiratory distress syndrome: a systematic review and meta-analysis. *J Intensive Care Med*. 2024;39(11):1164-72. <https://doi.org/10.1177/08850666241252759>.
- Keenan Chong WH, Dan Ong WJ, Khan FA, Sajeed S, Souza JD, Kansal MG, et al. Clinical benefits of prolonged *versus* standard prone positioning in mechanically ventilated COVID-19 patients with acute respiratory distress syndrome: a systematic review, meta-analysis, and trial-sequential analysis. *Aust Crit Care*. 2026;39(2):101531. <https://doi.org/10.1016/j.aucc.2026.101531>.
- Berger do Rosário M, da Silva DW, Wawrzyniak IC, Ziegelmann PK, Rios Vieira SR, Boniatti MM, et al. Extended prone positioning in ARDS: a systematic review and meta-analysis. *Respir Care*. 2026;71(4):417-25. <https://doi.org/10.1177/19433654251405270>.
- Papazian L, Aubron C, Brochard L, Chiche J-D, Combes A, Dreyfuss D, et al. Formal guidelines: management of acute respiratory distress syndrome. *Ann Intensive Care*. 2019;9(1):69. <https://doi.org/10.1186/s13613-019-0540-9>.
- Kallett RH. A comprehensive review of prone position in ARDS. *Respir Care*. 2015;60(11):1660-87. <https://doi.org/10.4187/respcare.04271>.