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Lung Derecruitment During Venovenous Extracorporeal Membrane Oxygenation: A Physiology-Based Clinical Framework

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ABSTRACT

Venovenous extracorporeal membrane oxygenation (VV ECMO) has transformed the management of severe acute respiratory distress syndrome (ARDS) by enabling ultra-lung-protective ventilation, thereby reducing ventilator-induced lung injury. However, this strategy creates a therapeutic paradox: the same reductions in tidal volume and transpulmonary pressure that protect the injured lung also promote progressive alveolar derecruitment and atelectasis, which may impede lung recovery and become an important barrier to liberation from extracorporeal support. Despite the frequency with which this problem is encountered, there is little guidance on the prevention, recognition, and management of lung derecruitment during prolonged VV ECMO support.

Current evidence supporting strategies to prevent or reverse derecruitment remains limited and is largely derived from physiologic studies, observational cohorts, and extrapolation from the broader ARDS literature. Conventional ventilator optimization, individualized positive end-expiratory pressure (PEEP), and driving-pressure minimization remain the foundation of management. Adjunctive therapies—including electrical impedance tomography-guided PEEP titration, prone positioning, spontaneous breathing, airway pressure release ventilation, verticalization, and emerging techniques such as negative pressure ventilation—have shown varying degrees of physiologic benefit, although high-quality evidence demonstrating improved patient-centered outcomes remains limited.

In this evidence-based clinical review, we summarize the mechanisms underlying lung derecruitment during VV ECMO, critically evaluate the available evidence supporting current recruitment strategies, and propose a practical framework to prevent and manage persistent lung derecruitment during prolonged VV ECMO support. Rather than advocating a single recruitment strategy, we propose an individualized approach that prioritizes lung protection while tailoring recruitment strategies to lung recruitability, respiratory mechanics, and the strength of the available evidence.

BACKGROUND

Lung-protective mechanical ventilation remains the cornerstone of acute respiratory distress syndrome (ARDS) management, reducing ventilator-induced lung injury (VILI) by limiting tidal volume, plateau pressure, and driving pressure [1-5]. For patients with severe respiratory failure who cannot maintain adequate gas exchange despite conventional ventilation, venovenous extracorporeal membrane oxygenation (VV ECMO) permits further reductions in ventilator intensity through extracorporeal gas exchange [2,3,6]. This strategy, commonly referred to as ultra-lung-protective ventilation, minimizes mechanical stress and strain on the injured lung and has become a fundamental principle of contempo-

rary VV ECMO management. It is supported by the ”baby lung” concept, which recognizes that only a small fraction of the injured ARDS lung remains available for ventilation [7].

However, ultra-lung-protective ventilation introduces an inherent physiologic paradox. The same reductions in tidal volume, transpulmonary pressure, and minute ventilation that minimize VILI also reduce end-expiratory lung volume and the mechanical forces required to maintain alveolar patency [1,3,7].

Importantly, lung derecruitment during VV ECMO should not be viewed as a complication of mechanical ventilation but rather as an anticipated consequence of prioritizing lung protection. Consequently, clinicians must balance two complementary physiologic objectives: minimizing VILI while preserving sufficient functional lung volume to facilitate recovery and eventual liberation from ECMO [3,6,7].

Several complementary strategies have been proposed to prevent or reverse lung derecruitment, including individualized positive end-expiratory pressure (PEEP), electrical impedance tomography (EIT)-guided ventilation, prone positioning, spontaneous breathing, airway pressure release ventilation (APRV), verticalization, and other emerging techniques. However, the supporting evidence remains heterogeneous, consisting predominantly of physiologic investigations, observational studies, and extrapolation from the broader ARDS literature, with few comparative studies specifically evaluating patients receiving VV ECMO. Consequently, management frequently relies on physiologic principles and individualized assessment rather than high-quality comparative evidence. In this review, a clinical decision framework for lung derecruitment during VV ECMO will be described. Table 1 provides an overview.

MAIN TEXT

Pathophysiology of Lung Derecruitment During VV ECMO

Lung derecruitment during VV ECMO is not attributable to a single pathophysiologic process but rather reflects the cumulative effects of severe lung injury, ultra-lung-protective ventilation, and prolonged critical illness. Understanding these mechanisms provides the physiologic rationale for the recruitment strategies discussed throughout this review. Figure 1 outlines the principles described.

The foundation of contemporary ARDS ventilation is the ”baby lung” concept introduced by Gattinoni and colleagues, which recognizes that only a relatively small proportion of the injured lung remains available for ventilation [7]. Rather than being uniformly diseased, the ARDS lung consists of normally aerated, poorly aerated, and completely collapsed lung units. Consequently, even conventional tidal volumes can generate excessive stress and strain within the remaining aerated lung, predisposing patients to VILI [5,7]. VV ECMO permits further reductions in tidal volume, plateau pressure, and driving pressure, minimizing stress on the remaining ”baby lung” while facilitating lung recovery [1-4,6,8-10].

Complementing this concept is the open lung strategy, which seeks to maximize the amount of aerated lung participating in gas exchange while minimizing repetitive alveolar opening and closing (atelectrauma) [7]. Under conventional ARDS management, these principles are largely complementary. During VV ECMO, however, they may become competing physiologic priorities. The profound reductions in tidal volume and transpulmonary pressure made possible by extracorporeal support reduce mechanical stress but also decrease end-expiratory lung volume and the forces required to maintain alveolar stability. Consequently, clinicians must balance lung protection with preservation of functional lung volume [3,7].

Atelectasis is broadly defined as partial lung collapse resulting in reduced or absent gas exchange. In ARDS, alveolar collapse results from multiple overlapping mechanisms, including inflammatory edema and surfactant dysfunction that reduce alveolar stability and promote collapse [7,11]. Importantly, these processes are dynamic. As inflammation resolves and edema clears, the amount of recruitable lung may change substantially, influencing both respiratory mechanics and the response to recruitment strategies. During VV ECMO, these intrinsic abnormalities are compounded by prolonged sedation, diaphragmatic inactivity, airway secretion retention, reduced spontaneous breathing, and the very low transpulmonary pressures associated with ultra-lung-protective ventilation, promoting progressive derecruitment and loss of functional lung volume [3,6,8-10].

Beyond its radiographic appearance, lung derecruitment has important physiologic consequences. Progressive loss of aerated lung increases respiratory system elastance, worsens ventilation-perfusion matching, and may increase pulmonary vascular resistance through hypoxic pulmonary vasoconstriction [7]. The resulting reduction in functional lung volume may delay pulmonary recovery and become a major barrier to liberation from extracorporeal support. Because lung recruitability varies considerably among patients and throughout the course of ARDS, successful management depends on recognizing not only the presence of derecruitment but also the degree of recruitable lung, making careful assessment of recruitability the critical first step in individualized ventilator management [7,11].

Cardiac Considerations in Lung Recruitment

An important consideration during lung recruitment is its impact on pulmonary vascular resistance and right ventricular (RV) afterload. Both alveolar underdistention and overdistention increase pulmonary vascular resistance and RV afterload. This careful balance requires ongoing evaluation of RV function with each recruitment effort.

Point-of-care ultrasound allows serial assessment of RV function as ECMO and ventilator support are titrated. Point-of-care ultrasound allows for assessment of global RV size and function and interventricular septal position; tricuspid annular plane systolic excursion and tricuspid annular systolic tissue Doppler velocity (S') can be used to assess RV systolic function. In patients with adequate echocardiographic views and a measurable tricuspid regurgitant jet, point-of-care ultrasound can also be used to estimate and monitor RV systolic pressure. Careful hemodynamic monitoring during recruitment should therefore be accompanied by serial ultrasound assessment of RV size and function.

Assessment of Lung Recruitability

After understanding the mechanisms responsible for lung derecruitment, the next critical step is determining whether collapsed lung remains recruitable. Because recruitability varies considerably among patients and throughout the course of ARDS, accurate assessment is essential when selecting ventilatory and adjunctive recruitment strategies. No single imaging modality or physiologic measurement reliably distinguishes recruitable from non-recruitable lung. Consequently, assessment should integrate imaging, respiratory mechanics, gas exchange, and the patient's overall clinical trajectory [7,11].

Distinguishing reversible alveolar collapse from irreversible consolidation or fibrosis remains one of the greatest challenges during VV ECMO. Radiographic atelectasis alone does not reliably predict successful recruitment, underscoring the need for multimodal assessment [11].

Chest Radiography

Chest radiography remains the most widely used imaging modality for assessing lung aeration during VV ECMO because it is readily available and easily repeated at the bedside. Although portable radiographs identify lobar collapse, diffuse atelectasis, pleural effusions, and evolving consolidation, they

are limited in estimating recruitable lung because of poor spatial resolution and substantial interobserver variability. Consequently, chest radiography is best suited for monitoring changes in lung aeration over time rather than determining recruitability [11].

Computed Tomography

Computed tomography remains the reference standard for assessing lung morphology and quantifying recruitable lung. It differentiates normally aerated, poorly aerated, collapsed, and hyperinflated lung while identifying alternative causes of impaired gas exchange, including pleural effusions, mucus plugging, and pneumothorax. However, transporting critically ill patients receiving VV ECMO carries substantial risk; therefore, computed tomography should generally be reserved for situations in which the findings are expected to alter management [11].

Lung Ultrasound

Lung ultrasound provides a practical bedside assessment of lung aeration without radiation exposure or patient transport. Findings such as B-lines, subpleural consolidations, dynamic air bronchograms, and aeration scores correlate with changes in lung aeration and may provide insight into recruitment potential. Because ultrasound can be repeated frequently, it is particularly useful for monitoring response to recruitment interventions. However, interpretation remains operator-dependent and may be limited by obesity, extensive dressings, or subcutaneous emphysema [11].

Esophageal Manometry

Esophageal manometry provides an estimate of pleural pressure, allowing calculation of transpulmonary pressure and potentially aiding individualized PEEP titration. In patients with elevated pleural pressure due to obesity, reduced chest wall compliance, fluid overload, or other causes, higher PEEP may be required to maintain alveolar patency. PEEP can be titrated using esophageal pressure measurements to maintain an appropriate end-expiratory transpulmonary pressure while avoiding excessive inspiratory lung stress.

Electrical Impedance Tomography

EIT provides continuous, noninvasive bedside assessment of regional ventilation and has emerged as a promising tool for individualized ventilator management during VV ECMO. Unlike conventional imaging, EIT provides real-time visualization of regional ventilation, allowing identification of both alveolar collapse and overdistension during changes in PEEP or ventilator settings. Although widespread adoption remains limited by equipment availability and clinician familiarity, EIT represents one of the most promising approaches for individualized assessment of lung recruitability [12,13].

Bronchoscopy

Bronchoscopy serves an important complementary role when persistent lobar collapse or mucus plugging is suspected. Beyond its diagnostic utility, it enables therapeutic removal of obstructing secretions that may restore ventilation to previously collapsed lung regions. However, it should be viewed as an adjunctive intervention rather than a primary tool for assessing lung recruitability.

Recruitment-to-Inflation Ratio

The recruitment-to-inflation (R/I) ratio provides a bedside, ventilator-derived estimate of PEEP-induced lung recruitment. The technique compares the volume recruited during a change in PEEP with the inflation of the aerated lung, allowing recruitability to be assessed without advanced imaging [14,15]. Higher R/I ratios generally indicate greater potential for PEEP-induced recruitment and may help inform individualized PEEP selection.

Clinical Integration

No single imaging modality is sufficient to determine lung recruitability during VV ECMO. Assessment should integrate imaging findings with respiratory mechanics, gas exchange, the stage of ARDS, and the patient's overall clinical trajectory. The objective is not simply to identify atelectasis but to determine whether sufficient recruitable lung remains to justify escalation of recruitment strategies while maintaining lung-protective ventilation [11,16].

Prevention of Progressive Lung Derecruitment

Once lung recruitability has been assessed, the primary objective shifts from identifying alveolar collapse to preventing further derecruitment while preserving the principles of ultra-lung-protective ventilation. Although recruitment maneuvers and adjunctive therapies often receive considerable attention, preventing progressive lung collapse remains the cornerstone of ventilatory management during prolonged VV ECMO support. Maintaining functional lung volume by carefully optimizing conventional ventilator settings is generally preferable to attempting recruitment after extensive alveolar collapse has occurred.

The challenge lies in balancing two competing physiologic objectives. Excessive reductions in airway pressure and tidal volume may accelerate alveolar collapse, whereas excessive airway pressures intended to maintain recruitment may reintroduce VILI by overdistending the remaining aerated lung. Consequently, ventilator management during VV ECMO should not be viewed as selecting a single "optimal" ventilator strategy but as continuously adjusting ventilatory support to preserve lung protection while minimizing progressive derecruitment [3,7].

Conventional Ventilator Management

Central to ventilator management in this patient population is preventing the progression of atelectasis. The introduction of VV ECMO permits substantial reductions in tidal volume, plateau pressure, respiratory rate, and inspired oxygen concentration, allowing clinicians to minimize ventilator-induced lung injury while maintaining adequate gas exchange. However, these same ventilator adjustments may reduce end-expiratory lung volume and promote progressive alveolar collapse if not carefully individualized [1-4].

Current Extracorporeal Life Support Organization guidelines recommend maintaining plateau pressures below 25 cm H2O while utilizing at least moderate levels of PEEP during VV ECMO. These recommendations emphasize lung protection while maintaining sufficient alveolar recruitment to limit derecruitment and atelectrauma. Rather than applying a uniform ventilator strategy to all patients, ventilator settings should be individualized according to respiratory mechanics, lung recruitability, gas exchange, and the patient's stage of illness [6].

Initial Ventilator Strategy Post-VV ECMO Cannulation

The initial ventilator settings in patients immediately post-VV ECMO cannulation are individualized to each patient and type of lung injury. Ventilator support should not be reflexively or abruptly reduced to ultra-lung-protective settings immediately after VV ECMO cannulation, as rapid reductions in airway pressure may promote loss of end-expiratory lung volume and derecruitment. While specific strategies differ depending on underlying pathology, in all patients, the initial focus should be on safety. This includes avoiding overly rapid correction of respiratory acidosis due to risk of intracranial bleeding or ischemic stroke. Attention to minute ventilation achieved by the ventilator in conjunction with the new CO2 clearance provided by the ECMO circuit is important to reduce the risk of over-correction of CO2 in the immediate post-cannulation period. Following cannulation, the ventilator strategy typically focuses on lung rest, with targets including plateau pressure <25 cm H2O, driving pressure <15 cm H2O, and main-

tenance of sufficient PEEP to limit derecruitment [17]. Pressure-control ventilation is often used to achieve these targets in patients with ARDS.

In patients with conditions that may benefit from minimizing positive airway pressure, such as bronchopleural fistula, tracheobronchial injury, or pneumothorax, lower-PEEP strategies may be appropriate. In these situations, ECMO can provide gas exchange while airway pressures are minimized to facilitate healing; however, this strategy may come at the expense of derecruitment of unaffected lung regions.

While ECMO facilitates the ability to achieve both lung rest and adequate oxygenation and ventilation, these lung-protective strategies may result in alveolar derecruitment. For this reason, using the techniques described above to assess for recruitable lung is important to prevent significant derecruitment in the immediate post-cannulation phase.

Individualized Positive End-Expiratory Pressure

PEEP remains the primary ventilator intervention for preventing progressive alveolar derecruitment during VV ECMO. Appropriate PEEP increases end-expiratory lung volume, reduces cyclic alveolar opening and closing, and may improve ventilation-perfusion matching while limiting atelectrauma. However, excessive PEEP may overdistend the remaining aerated lung, impair venous return, and increase right ventricular afterload. Consequently, the objective of PEEP titration is not maximal alveolar recruitment but preservation of functional lung volume while maintaining the principles of ultra-lung-protective ventilation [6,8,13].

Numerous strategies have been proposed to individualize PEEP, including oxygenation-based approaches, pressure-volume relationships, respiratory system compliance, transpulmonary pressure measurements, and EIT. Despite these approaches, no single method has consistently demonstrated superiority in patients receiving VV ECMO [13].

In clinical practice, clinicians should resist the temptation to increase PEEP solely to improve radiographic appearance. Instead, PEEP should be individualized based on respiratory mechanics, recruitability, and evidence of overdistension, recognizing that preserving functional lung volume—not radiographic improvement—is the therapeutic objective.

Driving Pressure and Mechanical Power

Driving pressure has emerged as one of the ventilator variables most strongly associated with mortality in ARDS and has become an important target during ultra-lung-protective ventilation. During VV ECMO, reductions in driving pressure may reflect improved lung protection, but they should always be interpreted in the context of changing respiratory mechanics and lung recruitability [18].

Mechanical power provides a complementary physiologic framework by integrating tidal volume, airway pressures, respiratory rate, and inspiratory flow into a single measure of the energy transferred from the ventilator to the lung. Although optimal mechanical power targets during VV ECMO remain uncertain, minimizing unnecessary mechanical energy while preserving functional lung volume is a rational extension of lung-protective ventilation principles [18].

Importantly, neither driving pressure nor mechanical power should be considered in isolation. Both should be interpreted alongside respiratory compliance, imaging findings, and the patient's overall clinical trajectory.

Physiologic Monitoring

Because lung recruitability changes throughout the course of ARDS, serial physiologic assessment is essential to optimize ventilator management. Changes in respiratory system compliance, driv-

ing pressure, gas exchange, and imaging findings may provide insight into evolving lung mechanics and the effectiveness of preventive strategies.

EIT has emerged as a promising bedside tool for individualized ventilator management. By providing continuous, real-time assessment of regional ventilation distribution, EIT enables clinicians to identify alveolar collapse and overdistension and to guide individualized PEEP titration. Although widespread adoption remains limited by equipment availability and clinician experience, EIT represents an important step toward physiology-guided ventilator management during VV ECMO [13].

Clinical Integration

Preventing progressive lung derecruitment should be prioritized over recruitment whenever possible. Conventional ventilator optimization—including individualized PEEP selection, minimizing driving pressure and mechanical stress, and serial physiologic reassessment—remains the foundation for preserving functional lung volume during prolonged VV ECMO support. Adjunctive recruitment therapies should be viewed not as substitutes for meticulous ventilator management but as complementary interventions reserved for patients with persistent derecruitment despite optimization of conventional care.

Recruitment Strategies for Persistent Lung Derecruitment

Despite meticulous optimization of conventional ventilator management, some patients continue to develop progressive alveolar derecruitment during prolonged VV ECMO support. In these situations, adjunctive recruitment strategies may improve lung aeration, respiratory mechanics, and gas exchange. However, the available evidence remains heterogeneous and consists primarily of physiologic studies, observational cohorts, and small clinical series, with relatively few comparative studies evaluating patient-centered outcomes. Consequently, recruitment interventions should not be viewed as routine components of VV ECMO management but rather as individualized therapies selected according to lung recruitability, respiratory mechanics, and the underlying mechanism of derecruitment. A summary of recruitment strategies is provided in Table 2, below.

Recruitment Maneuvers

Recruitment maneuvers transiently increase transpulmonary pressure to reopen collapsed alveoli through sustained increases in airway pressure or temporary elevations in PEEP. Although the physiologic rationale is compelling, these maneuvers may worsen hemodynamics and increase the risk of barotrauma.

Evidence supporting recruitment maneuvers during VV ECMO is limited. In the broader ARDS literature, a large, randomized trial demonstrated increased mortality with a strategy incorporating recruitment maneuvers and aggressive PEEP titration, while subsequent meta-analyses showed improved oxygenation without consistent reductions in mortality. Current American Thoracic Society guidelines recommend against prolonged recruitment maneuvers in patients with moderate-to-severe ARDS [19-21].

Clinical Perspective: Recruitment maneuvers should be reserved for carefully selected patients with demonstrable recruitable lung after optimization of conventional ventilator management.

Prone Positioning

Prone positioning redistributes transpulmonary pressure, recruits dependent lung regions, improves ventilation-perfusion matching, and reduces regional stress and strain, providing a strong physiologic rationale during VV ECMO [22].

Although prone positioning clearly reduces mortality in conventional ARDS, evidence during VV ECMO is less definitive. Retrospective studies con-

sistently demonstrate improvements in oxygenation and respiratory mechanics, and meta-analyses suggest possible improvements in short-term survival. However, the PRONECMO randomized trial did not demonstrate reductions in ECMO duration or 90-day mortality [23]. Collectively, these findings suggest that prone positioning consistently improves physiology, although reproducible patient-centered benefits remain unproven [16,22-27].

Clinical Perspective: Prone positioning has the strongest physiologic rationale and the most robust clinical evidence among adjunctive recruitment strategies and should generally be considered before less established interventions.

Spontaneous Breathing and Awake ECMO

Restoration of spontaneous breathing reestablishes diaphragmatic contraction, improves ventilation of dependent lung regions, and may reduce diaphragmatic atrophy associated with prolonged controlled mechanical ventilation [28-30].

Earlier tracheostomy, awake ECMO, and pressure support ventilation may facilitate this transition by reducing sedation requirements and promoting recovery of native lung function. Although observational studies demonstrate feasibility and favorable physiologic effects, evidence supporting improved recruitment or clinical outcomes remains limited [28-37].

Clinical Perspective: Spontaneous breathing strategies should be viewed primarily as tools to facilitate recovery and liberation from ECMO rather than primary recruitment interventions. Excessive spontaneous respiratory effort should be avoided to minimize patient self-inflicted lung injury.

Airway Pressure Release Ventilation

APRV maintains prolonged periods of elevated airway pressure, theoretically promoting sustained alveolar recruitment while minimizing repetitive opening and closing of unstable lung units.

Although APRV improves oxygenation and compliance in conventional ARDS, evidence during VV ECMO is limited to case reports and small series demonstrating feasibility, maintenance of ultra-lung-protective tidal volumes, and successful liberation from ECMO. Time-Controlled Adaptive Ventilation (TCAV) represents a promising modification that may further individualize recruitment while enhancing mucus clearance [38-40].

Clinical Perspective: APRV has a physiologic rationale for maintaining alveolar recruitment; however, evidence supporting its use during VV ECMO remains limited, and its routine use cannot be recommended.

Verticalization and Early Mobilization

Body position influences regional ventilation, diaphragmatic mechanics, and end-expiratory lung volume. Physiologic studies demonstrate improved lung aeration during progressive verticalization, although evidence demonstrating improved patient-centered outcomes remains limited [41-43].

Clinical Perspective: Verticalization should be considered an adjunct to rehabilitation and maintenance of lung aeration rather than a primary recruitment strategy.

Negative-Pressure Ventilation

Negative-pressure ventilation generates transpulmonary pressure by externally reducing thoracic pressure, potentially producing more physiologic lung expansion while limiting airway pressures. Current evidence is limited to isolated case reports demonstrating improved carbon dioxide clearance and successful liberation from ECMO [44,45].

Clinical Perspective: Negative-pressure ventilation remains investigational and should currently be considered a promising area for future research rather

than routine clinical practice.

Choosing Among Recruitment Strategies

No single recruitment strategy is appropriate for every patient receiving VV ECMO. Selection should be guided by the underlying mechanism of derecruitment, lung recruitability, respiratory mechanics, and the stage of recovery. In general, interventions supported by the strongest physiologic rationale and clinical experience, such as prone positioning, should be considered before less established therapies.

Recovery of Functional Lung Volume and Liberation from VV ECMO

Recovery from severe ARDS during VV ECMO is a gradual process that reflects resolution of the underlying lung injury, restoration of functional lung volume, and improvement in respiratory mechanics. Although improvements in oxygenation often receive the greatest clinical attention, successful liberation from extracorporeal support depends on recovery of sufficient native lung function to maintain gas exchange while preserving lung-protective ventilation. Consequently, liberation should be viewed not as a single event but as the culmination of sequential strategies aimed at preventing derecruitment, promoting lung recovery, and progressively returning the work of breathing to the native lung [6,8].

Importantly, restoration of functional lung volume often precedes complete radiographic resolution of pulmonary infiltrates. Consequently, readiness for liberation should be determined by improvements in respiratory mechanics, spontaneous tidal volume, gas exchange, and the ability to progressively reduce extracorporeal support, rather than by chest imaging alone.

Restoration of Native Lung Function

Successful liberation begins with objective evidence of lung recovery. Improvements in respiratory system compliance, increased spontaneous tidal volumes, reduced sweep gas requirements, maintenance of adequate oxygenation and carbon dioxide clearance despite progressive reductions in extracorporeal support, collectively suggest recovery of sufficient functional lung volume. These improvements should be interpreted alongside the patient's overall clinical trajectory, recognizing that recovery is often gradual and heterogeneous.

Rather than pursuing complete radiographic resolution before weaning, clinicians should focus on restoring sustainable native lung function while maintaining lung-protective ventilation.

Spontaneous Breathing and Awake ECMO

Earlier introduction of spontaneous breathing may help facilitate lung recovery while promoting liberation from extracorporeal support. "Awake" ECMO is a strategy that uses extracorporeal support for non-intubated, awake, spontaneously breathing patients. This approach may reduce several adverse effects associated with prolonged invasive mechanical ventilation, including VILI, ventilator-associated pneumonia, deep sedation, and diaphragmatic dysfunction. Although early studies have demonstrated the safety and feasibility of awake ECMO, the literature specifically evaluating its effect on lung derecruitment remains limited [28-30,35].

Pressure support ventilation is an intermediate strategy that allows spontaneous respiratory effort while providing ventilatory support. Compared with controlled mechanical ventilation, pressure support ventilation during VV ECMO has been associated with improved respiratory system compliance and reduced pulmonary shunt fraction, potentially reflecting better ventilation-perfusion matching and recruitment of dependent lung regions. However, excessive spontaneous respiratory effort should be avoided because patient self-inflicted lung injury

may negate the benefits of lung-protective ventilation [36,37,46].

Clinical Perspective: Spontaneous breathing strategies should primarily be viewed as tools to facilitate recovery of native lung function and liberation from ECMO, rather than as primary recruitment interventions. Careful patient selection and avoidance of excessive respiratory effort remain essential.

Tracheostomy

Early tracheostomy may facilitate liberation by reducing sedation requirements and enabling an earlier transition to spontaneous breathing and rehabilitation. In observational studies of patients receiving VV ECMO, earlier tracheostomy has been associated with shorter intensive care unit (ICU) length of stay, although survival benefits have been inconsistent. Registry analyses have similarly suggested that early tracheostomy facilitates recovery without clearly demonstrating reductions in mortality [31-33].

Beyond facilitating spontaneous breathing, tracheostomy may improve secretion clearance, patient comfort, communication, participation in physical therapy, and overall rehabilitation. These factors may collectively accelerate the restoration of native lung function, even when direct effects on mortality are difficult to demonstrate.

Clinical Perspective: Tracheostomy should be considered within the broader context of rehabilitation and liberation from ECMO, rather than solely as an airway procedure.

Rehabilitation and Early Mobilization

Recovery of functional lung volume extends beyond ventilator management alone. Progressive mobilization and rehabilitation restore diaphragmatic function, improve secretion clearance, reduce ICU-acquired weakness, and facilitate the transition to independent spontaneous breathing.

Verticalization increases end-expiratory lung volume and may improve regional lung aeration. Although evidence demonstrating improvements in patient-centered outcomes remains limited, early mobilization remains an important component of comprehensive ECMO recovery programs [41-43].

Clinical Perspective: Early rehabilitation should be viewed as an integral component of ECMO liberation because restoration of respiratory and physical function occurs simultaneously.

Liberation from VV ECMO

Liberation from VV ECMO should be individualized and guided by progressively reducing extracorporeal gas exchange requirements while maintaining adequate oxygenation, ventilation, and acceptable respiratory mechanics. Improvements in compliance, stable spontaneous tidal volumes, and tolerance of sweep gas reduction collectively provide greater reassurance of recovery than any single physiologic variable [6,8].

Importantly, liberation should not be delayed solely because of persistent radiographic abnormalities. Structural lung recovery often lags behind physiologic improvement, and many patients can be successfully decannulated despite residual infiltrates, provided that sufficient functional lung volume has recovered to sustain native gas exchange.

Clinical Integration

Successful liberation from VV ECMO represents the culmination of the physiologic principles discussed throughout this review. Prevention of progressive derecruitment, individualized assessment of lung recruitability, optimization of conventional ventilator management, and selective application of adjunctive recruitment strategies all ultimately serve a common objective: restoring sufficient functional lung volume to safely return gas exchange and the work of breathing to the native lung.

DISCUSSION

The widespread adoption of VV ECMO has transformed the management of severe ARDS by enabling ultra-lung-protective ventilation and reducing VILI. However, this strategy creates an inherent physiologic paradox: the reductions in tidal volume and transpulmonary pressure that protect the injured lung also promote progressive alveolar derecruitment. Consequently, successful ventilator management during VV ECMO requires balancing lung protection with preservation of functional lung volume throughout the course of extracorporeal support [6].

A central concept of this review is that lung derecruitment should be anticipated rather than viewed as an isolated complication. Prevention through meticulous conventional ventilator management—including individualized PEEP selection, serial assessment of respiratory mechanics, and repeated evaluation of lung recruitability—should remain the foundation of care. Adjunctive recruitment strategies should be selected according to underlying physiology and the likelihood of recruitable lung rather than applied routinely. Importantly, the presence of derecruitment does not necessarily imply that recruitment is beneficial or safe. The therapeutic target should therefore be preservation or restoration of functional lung volume when recruitable lung is present, rather than normalization of radiographic aeration.

Despite increasing interest in recruitment therapies during VV ECMO, the supporting evidence remains limited. With the exception of prone positioning, most interventions are supported primarily by physiologic studies, observational cohorts, or small case series. Although many demonstrate improvements in lung aeration or respiratory mechanics, high-quality evidence demonstrating improved patient-centered outcomes remains scarce. Consequently, individualized, physiology-guided management remains more appropriate than protocolized treatment algorithms [23].

Future investigations should focus on physiology-guided ventilator management and prospective evaluation of recruitment strategies specifically in patients receiving VV ECMO. Technologies such as EIT and other bedside assessments of regional ventilation may enable more personalized ventilator management, although their effect on clinical outcomes remains uncertain [13].

Ultimately, successful VV ECMO management extends beyond maintaining extracorporeal gas exchange. The objective is to preserve and restore sufficient functional lung volume to safely transition gas exchange and the work of breathing back to the native lung.

CONCLUSIONS

Lung derecruitment is an anticipated consequence of prolonged ultra-lung-protective ventilation during VV ECMO and represents an important barrier to recovery and liberation from extracorporeal support. Prevention through meticulous conventional ventilator management should remain the foundation of care, while adjunctive recruitment strategies should be individualized according to lung recruitability, respiratory mechanics, and the strength of the available evidence.

Future studies should focus on physiology-guided ventilator management and prospective evaluation of recruitment strategies specifically in patients receiving VV ECMO to better define strategies that preserve functional lung volume while maintaining the benefits of ultra-lung-protective ventilation.

Ultimately, the goal of VV ECMO is not simply to protect the injured lung, but to preserve and restore sufficient functional lung volume to safely return gas exchange and the work of breathing to the native lung.

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Figure 1. The Physiologic Balance During VV ECMO: Lung Protection and Preservation of Functional Lung Volume

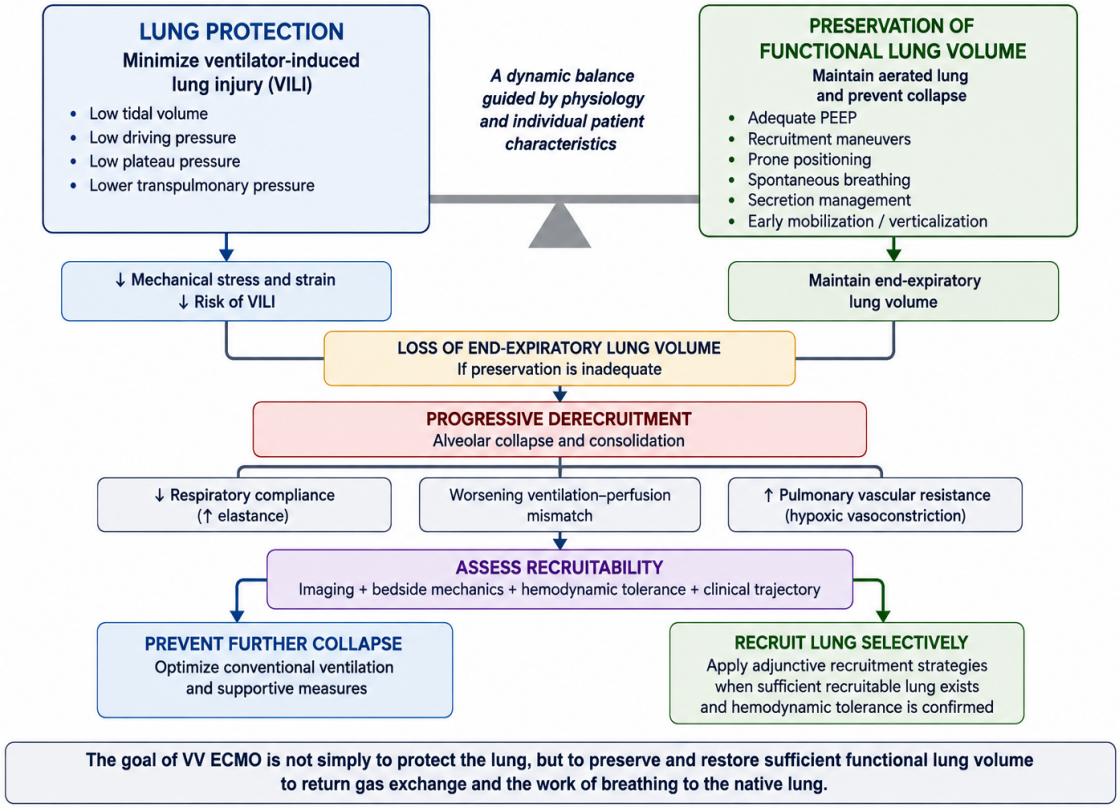


Table 1. Clinical Decision Framework for Lung Derecruitment During VV ECMO

Clinical Problem	Key Question	Recommended Clinical Approach
Progressive loss of lung aeration	**Why is derecruitment occurring?**	Understand the underlying physiology and competing goals of lung protection versus preservation of functional lung volume.
Persistent atelectasis	**Is the lung recruitable?**	Integrate imaging, respiratory mechanics, gas exchange, and clinical trajectory before attempting recruitment.
Recruitable lung identified	**How can further derecruitment be prevented?**	Optimize conventional ventilation using individualized PEEP, lung-protective ventilation, driving pressure, and serial physiologic assessment.
Safety of increased recruitment	**Can I recruit additional lung without risking further lung injury or hemodynamic consequences?**	Assess recruitability, respiratory mechanics, and hemodynamic tolerance during recruitment. Use imaging and esophageal manometry when appropriate to guide PEEP titration, with serial assessment of RV size and function by echocardiography or point-of-care ultrasound, systemic blood pressure, and indices of systemic perfusion.
Persistent derecruitment despite optimization	**Should adjunctive therapies be used?**	Select recruitment strategies according to recruitability, underlying physiology, and available evidence rather than routine application.
Improving native lung function	**Is the patient ready for liberation?**	Base liberation on restoration of functional lung volume, respiratory mechanics, and decreasing extracorporeal support rather than radiographic appearance alone.

Table 2. Summary of Recruitment Strategies During VV ECMO

Strategy	Physiologic Rationale	Evidence	Clinical Role
Recruitment maneuvers	Transient alveolar recruitment	Low	Selected patients only
Prone positioning	Recruitment and improved V/Q matching	Moderate	Preferred first-line adjunct
Spontaneous breathing / Awake ECMO	Diaphragm activation and dependent lung ventilation	Low–Moderate	Recovery and liberation
APRV / TCAV	Sustained recruitment	Low	Rescue therapy
Verticalization	Increased EELV and lung aeration	Low	Rehabilitation adjunct
Negative-pressure ventilation	Physiologic transpulmonary ventilation	Very Low	Investigational

V/Q: Ventilation/Perfusion; ECMO: Extracorporeal Membrane Oxygenation; APRV: Airway Pressure Release Ventilation; TCAV: Time-Controlled Adaptive Ventilation; EELV: End-Expiratory Lung Volume

KEY CLINICAL TAKEAWAYS

- **Anticipate lung derecruitment** during prolonged ultra-lung-protective ventilation.
- **Prioritize prevention** over rescue recruitment.
- **Assess recruitability** before escalating recruitment strategies.
- **Individualize ventilator settings** using patient physiology, not fixed protocols.
- **Select adjunctive recruitment therapies** based on recruitability, respiratory mechanics, and the strength of available evidence.
- **Prone positioning** has the strongest physiologic rationale and the most supportive clinical evidence.
- Focus on **restoration of functional lung volume** throughout recovery.
- Base **liberation from VV ECMO** on recovery of native lung function, not radiographic appearance.