

Pathogenesis of Acute Respiratory Distress Syndrome

Laura A. Huppert, MD¹ Michael A. Matthay, MD^{2,3} Lorraine B. Ware, MD⁴

¹ Department of Medicine, University of California, San Francisco, San Francisco, California

² Department of Medicine, Cardiovascular Research Institute, University of California, San Francisco, San Francisco, California

³ Department of Anesthesia, Cardiovascular Research Institute, University of California, San Francisco, San Francisco, California

⁴ Division of Allergy, Pulmonary, and Critical Care Medicine, Department of Medicine, Vanderbilt University School of Medicine, Nashville, Tennessee

Address for correspondence Lorraine B. Ware, MD, T1218 Medical Center North, 1161 21st Avenue S, Nashville, TN 37232-2650 (e-mail: lorraine.ware@vumc.org).

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Abstract

Acute respiratory distress syndrome (ARDS) is a syndrome of acute respiratory failure caused by noncardiogenic pulmonary edema. Despite five decades of basic and clinical research, there is still no effective pharmacotherapy for this condition and the treatment remains primarily supportive. It is critical to study the molecular and physiologic mechanisms that cause ARDS to improve our understanding of this syndrome and reduce mortality. The goal of this review is to describe our current understanding of the pathogenesis and pathophysiology of ARDS. First, we will describe how pulmonary edema fluid accumulates in ARDS due to lung inflammation and increased alveolar endothelial and epithelial permeabilities. Next, we will review how pulmonary edema fluid is normally cleared in the uninjured lung, and describe how these pathways are disrupted in ARDS. Finally, we will explain how clinical trials and preclinical studies of novel therapeutic agents have further refined our understanding of this condition, highlighting, in particular, the study of mesenchymal stromal cells in the treatment of ARDS.

Keywords

- ▶ acute respiratory distress syndrome
- ▶ alveolar fluid clearance
- ▶ vectorial ion transport
- ▶ pulmonary edema
- ▶ mesenchymal stromal cells

Acute respiratory distress syndrome (ARDS) is a syndrome of acute respiratory failure caused by noncardiogenic pulmonary edema. The most common clinical disorders associated with the development of ARDS are bacterial and viral pneumonia. ARDS is also commonly caused by sepsis due to nonpulmonary sources, severe trauma, and aspiration of gastric contents, and less commonly by pancreatitis and drug reactions.¹ Criteria for the diagnosis for ARDS have changed over time; the current definition includes acute onset of impaired oxygenation (arterial hypoxemia with PaO₂/FiO₂ ratio <300 mm Hg) and bilateral infiltrates on chest imaging in the absence of left atrial hypertension as the dominant cause of pulmonary edema.² Based on the Berlin definition, ARDS is divided into three categories of severity depending on the degree of hypoxemia: mild (PaO₂/FiO₂ 200–300 mm Hg), moderate (PaO₂/FiO₂ 100–200 mm Hg), and severe (PaO₂/FiO₂ <100 mm Hg).² The prevalence of ARDS

in the United States is 5 to 35 cases/100,000 individuals annually, depending on the definitions utilized and study methodology.³ The mortality of ARDS is ~25 to 40% in most studies.^{4,5} Despite five decades of basic and clinical research, there is still no effective pharmacotherapy for this syndrome and the treatment remains primarily supportive with lung protective ventilation and a conservative fluid management strategy. Therefore, it is critical to study the pathogenesis and pathophysiology of ARDS to identify novel targeted therapies for this condition.

ARDS is a complex clinical syndrome with a heterogeneous clinical phenotype, which has made it more challenging to study. Nonetheless, since the first description of ARDS in 1967,⁶ advances in laboratory and clinical studies have yielded valuable insights into the mechanisms responsible for the pathogenesis and pathophysiology of this condition.

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When the lung is injured by infection, trauma, or inflammatory conditions, inflammatory pathways are activated. The inflammatory response can aid in pathogen clearance, but excess inflammation can also contribute to alveolar damage—specifically greater endothelial and epithelial permeabilities—resulting in the accumulation of protein-rich alveolar edema fluid. Once pulmonary edema fluid accumulates in the interstitium and air spaces of the lungs, it causes increased work of breathing and impaired gas exchange resulting in hypoxemia, reduced carbon dioxide excretion, and ultimately acute respiratory failure. In uninjured lungs, active ion transport across the alveolar epithelium creates an osmotic gradient that drives alveolar fluid clearance (AFC).⁷ However, in ARDS, the osmotic gradient is disrupted and AFC is reduced, further compounding the decreased capacity to remove edema fluid from the distal airspaces of the lung.

In this review, we will first describe how increased inflammation causes endothelial and epithelial permeabilities, ultimately resulting in the accumulation of pulmonary edema fluid. Second, we will explain why AFC is reduced in this condition, highlighting key molecular pathways involved. Finally, we will summarize how clinical trials and the study of novel therapeutics offer further insight into ARDS pathophysiology.

Pathogenesis of ARDS: Excess Inflammation, Endothelial, and Epithelial Permeabilities

There are several pathophysiologic derangements that are central to the development of ARDS, including dysregulated inflammation and increased lung endothelial and epithelial permeabilities. Initially, acute lung injury is driven by dysregulated inflammation. Microbial products or cell injury-associated endogenous molecules (danger-associated molecular patterns) bind to Toll-like receptors on the lung epithelium and alveolar macrophages and activate the innate immune system.⁸ Mechanisms of innate immune defense, such as the formation of neutrophil extracellular traps and histone release,

can be beneficial in capturing pathogens but may worsen alveolar injury.⁹ The immune system also generates reactive oxygen species, leukocyte proteases, chemokines, and cytokines that help neutralize pathogens, but can also result in worsening lung injury.¹⁰ In essence, there is a delicate balance between effective immune activation to combat infection and excessive or dysregulated activation that contributes to alveolar injury.

In addition to excessive inflammation in ARDS, another central pathophysiologic derangement is the disruption of the lung microvascular barrier due to increased endothelial and epithelial permeabilities (► Fig. 1A, B). In healthy lungs, endothelial stabilization is mediated by vascular endothelial cadherin (VE-cadherin), which is an endothelial-specific adherens junction protein that is required for to maintain endothelial barrier integrity in lung microvessels.¹¹ During lung injury, increased concentrations of thrombin, tumor necrosis factor- α (TNF- α), vascular endothelial growth factor, and leukocyte signals in the lungs destabilize the VE-cadherin bonds, resulting in increased endothelial permeability and the accumulation of alveolar fluid.¹² The importance of VE-cadherin bonds has been confirmed in mouse models. Specifically, alveolar fluid accumulates in a mouse model of lipopolysaccharide (LPS)-induced lung injury, but when the VE-cadherin bonds are stabilized by genetic alterations that prevent breakdown or by blocking VE phosphodiesterase, there is reduced edema formation.^{13,14} In sum, the inflammatory-induced damage to lung endothelium results in increased capillary permeability, and thus leads to pulmonary edema formation.

In addition to endothelial permeability, lung epithelial permeability is also an important factor in ARDS pathogenesis.^{15,16} The alveolar epithelial barrier is similar to its endothelial counterpart but has E-cadherin junctions instead of VE-cadherin junctions, and it is substantially less permeable. Under pathologic conditions, neutrophil migration causes epithelial injury by disrupting intercellular junctions and causing apoptosis and denudation, ultimately resulting

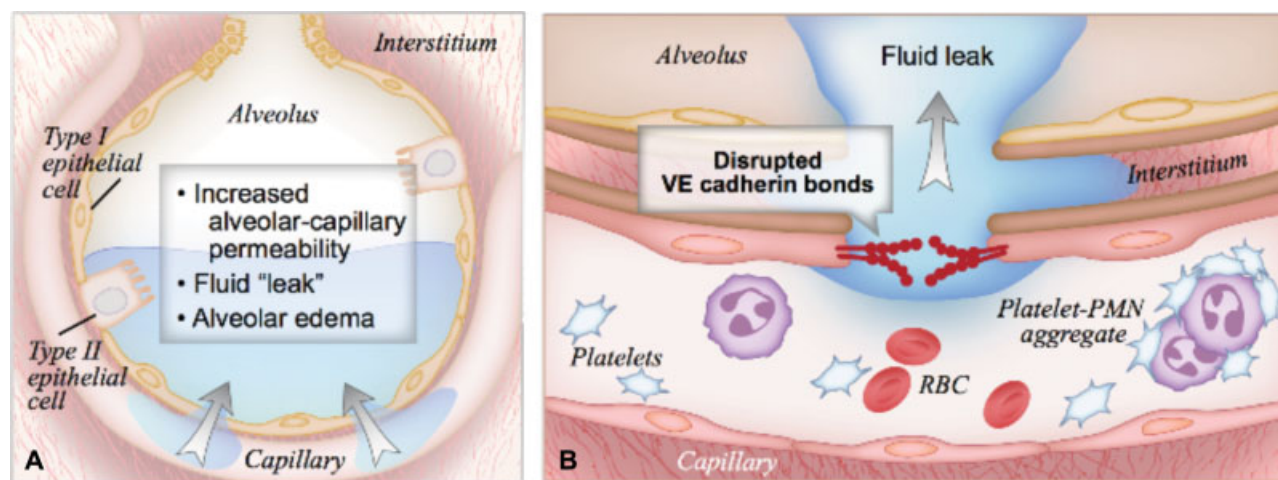


Fig. 1 Increased alveolar endothelial permeability in ARDS. (A) In ARDS, inflammatory molecules disrupt alveolar barrier function, resulting in the accumulation of alveolar edema fluid. (B) Specifically, disruption of VE-cadherin bonds causes increased endothelial permeability, and subsequent leakage of water, solutes, leukocytes, platelets, and other inflammatory molecules into the alveolar space. ARDS, acute respiratory distress syndrome; VE-cadherin, vascular endothelial cadherin.

in increased epithelial permeability.¹⁷ Restitution of epithelial integrity is critical for recovery and survival in acute lung injury. Neutrophil transmigration triggers repair of the lung epithelium via β -catenin signaling,¹⁸ offering a potential therapeutic target to accelerate epithelial repair.

Finally, it is also important to note that environmental and genetic factors contribute to the susceptibility and severity of ARDS. Exposure to ambient air pollutants has been linked to risk of ARDS; this association is strongest in patients at risk for ARDS due to severe traumatic injuries.^{19,20} Active and passive cigarette smoke exposures have been associated with the development of ARDS after blunt force trauma,²¹ lung transplantation,²² and nonpulmonary sepsis.²³ Chronic alcohol use increases the risk of acute lung injury.²⁴ Genetic variants have also been identified that confer increased risk of developing ARDS and are predictive of disease severity.²⁵ For example, genes involved in the inflammatory response and endothelial cell function, such as *PPFIA1* and *ANGPT2*, were identified as candidate genes for ARDS risk following major trauma.^{26,27} Genetic variants in the FAS pathway, which regulates apoptosis and endothelial cell injury, were also associated with increased risk of ARDS.²⁸ In African Americans, a candidate gene study identified that a T-46C polymorphism in the promoter region of the Duffy antigen/receptor for chemokines (*DARC*) gene was associated with higher mortality.²⁹ Additional studies are needed to better understand these environmental and genetic associations,

which may further contribute to our understanding of the molecular pathways involved in ARDS pathogenesis.

Slow Resolution: Alveolar Fluid Clearance Is Impaired in ARDS

Pulmonary edema can develop from increased pulmonary vascular pressure from left heart failure (cardiogenic pulmonary edema)³⁰ or due to lung parenchymal damage from increased endothelial and epithelial permeabilities (noncardiogenic pulmonary edema, as in ARDS, as described earlier).³¹ In both cases, the mechanism for the resolution of alveolar edema is the same: active ion transport across the alveolar epithelium creates an osmotic gradient that drives AFC.⁷

Before discussing AFC in ARDS, it is important to review how alveolar fluid is normally cleared in the uninjured lung. In the uninjured lung, vectorial ion transport across the intact alveolar epithelial layer creates an osmotic gradient that drives fluid from the alveoli into the lung interstitium (—Fig. 2A). After fluid is cleared into the interstitium, it can be drained by lymphatics or reabsorbed into the vasculature based on the balance of forces described in Starling equation. It was initially thought that only alveolar epithelial type II cells were involved in vectorial ion transport, but subsequent studies demonstrated an important role for alveolar epithelial type I cells as well.³² The transport of sodium ions is the most important driver for the generation of the osmotic

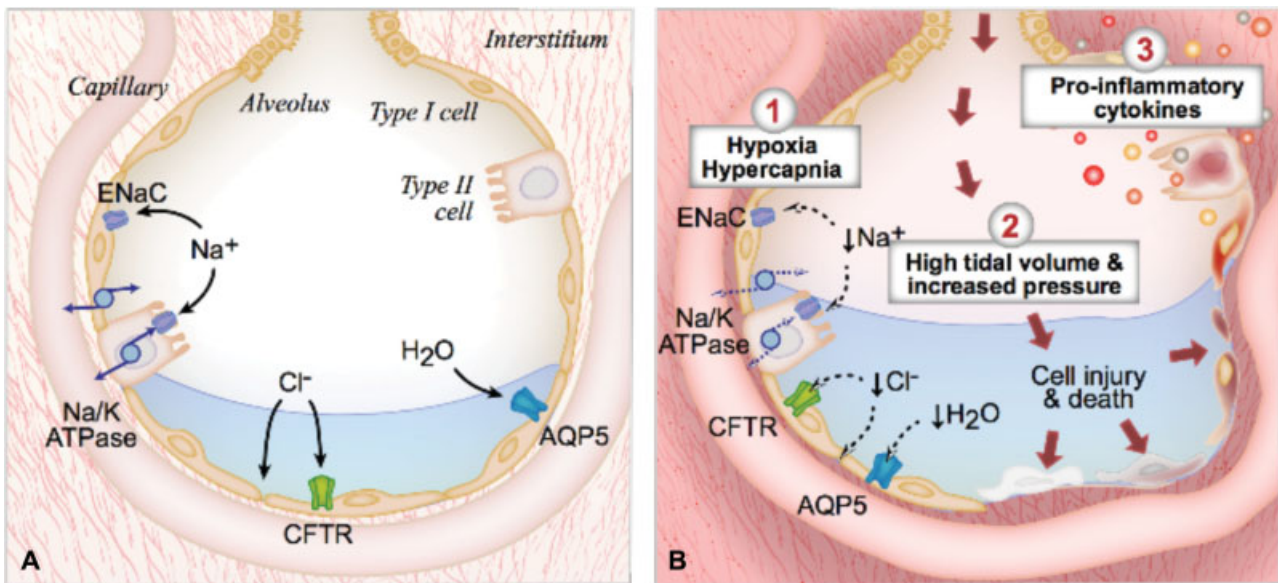


Fig. 2 Alveolar fluid clearance pathways in the uninjured lung versus the lung affected by ARDS. (A) In the uninjured lung, fluid is effectively cleared from the alveolar space by vectorial ion transport. Shown are the interstitial, capillary, and alveolar compartments of the lung, with pulmonary edema fluid in the alveolus. Both type I and type II alveolar cells are involved in transepithelial ion transport. Sodium (Na^+) is transported across the apical side of the type I and type II cells through the ENaC, and then across the basolateral side via the sodium/potassium ATPase pump (Na/K-ATPase). Chloride (Cl^-) is transported via the CFTR channel or by a paracellular route. Additional cation channels also transport ions across the alveolar epithelium (not shown). This vectorial ion transport helps achieve effective alveolar fluid clearance. Specifically, water (H_2O) moves down the osmotic gradient through aquaporin channels, such as AQP5 or via an intracellular route (not shown). In the uninjured lung, this vectorial ion transport helps achieve effective alveolar fluid clearance. (B) In lungs affected by ARDS, fluid is less effectively cleared from the lungs. First, hypoxia/hypercapnia results in downregulation of ENaC transcription and trafficking and less efficient function of the Na/K-ATPase. Second, high tidal volumes and elevated airway pressures injure the alveolar epithelium, inducing inflammation and cell death. Third, ARDS results in the formation of proinflammatory cytokines, which induce alveolar injury and cause reduced alveolar fluid clearance. ARDS, acute respiratory distress syndrome; AQP5, aquaporin 5; CFTR, cystic fibrosis transmembrane conductance regulator; ENaC, epithelial sodium channel.

gradient: sodium is transported through the epithelial sodium channel (ENaC) on the apical surface, driven by the Na/K ATPase on the basolateral surface.^{33,34} In animal models, this pathway is essential for survival; knockout of the α -subunit of ENaC in mice results in the inability to remove alveolar fluid at birth, causing respiratory failure and premature death.³⁵ In addition to ENaC, nonselective cation channels, cyclic nucleotide-gated channels, and the cystic fibrosis transmembrane conductance regulator chloride channels also help maintain the osmotic gradient.³⁶ Once the vectorial ion gradient is established, aquaporins facilitate the movement of water across the epithelial surface, but are not required for fluid transport.³⁷ This system of active ion-driven alveolar fluid reabsorption is the primary mechanism that removes alveolar edema fluid under both physiologic and pathological conditions.^{38,39} However, in the setting of ARDS, the capacity to remove alveolar edema fluid is reduced, which is termed impaired AFC. Patients with ARDS who have impaired AFC have decreased survival.^{40,41}

There are multiple physiologic and molecular mechanisms that cause a reduction in AFC in ARDS (► **Fig. 2B**). First, the primary physiologic respiratory impairments that characterize ARDS, hypoxia and hypercapnia, can directly impair AFC. ENaC transcription and trafficking are downregulated and the Na/K-ATPase functions less efficiently under states of low oxygen or high carbon dioxide, in part because reactive oxygen species trigger endocytosis and cell necrosis.^{42–44} Therefore, supplemental oxygen and correction of hypercapnia can enhance the resolution of alveolar edema by helping to maintain active sodium transport across the lung epithelium.

Second, biomechanical stress in the lung can reduce AFC. High tidal volumes and elevated airway pressures injure the alveolar epithelium, inducing cell death and inflammation, which further reduces AFC.⁴⁵ If pulmonary hydrostatic pressures are elevated, the rate of net AFC is also reduced. These findings help explain the success of lung protective ventilation and conservative fluid strategies in reducing the morbidity and mortality of ARDS.^{46,47}

Third, we now better understand the molecular mechanisms that contribute to the reduction in AFC in ARDS. Specifically, ARDS pulmonary edema fluid contains high levels of proinflammatory cytokines including interleukin (IL)-1 β , IL-8, TNF- α , and transforming growth factor- β 1.^{48–50} When excessive levels of cytokines are present, they cause alveolar injury and reduced AFC.^{51–54} This was elegantly demonstrated in an *in vitro* model of polarized human type II alveolar cells in 2006. Specifically, the authors showed that there are increased levels of cytokines and decreased levels of ion transport proteins in the presence of ARDS edema fluid compared with a plasma control.^{55,56} Specifically, it is thought that the inflammatory edema fluid causes alveolar cell injury and necrosis, negating the tight epithelial barrier needed to establish an osmotic gradient and offsetting the effects of vectorial ion transport.^{57,58} Cell necrosis and fluid accumulation in turn can trigger an even more pronounced inflammatory and immune response.⁵⁹ There are no current therapies that directly modify AFC, although lung protective ventilation itself reduces proinflammatory cytokines such as IL-6 and IL-8.⁶⁰

Ultimately, resolution of ARDS requires repair of the endothelial and epithelial barriers to allow for effective reabsorption of the alveolar edema fluid, as well as removal of inflammatory cells and cytokines from the airspaces and the lung interstitium. To repair the alveolar epithelial barrier, type II cells must proliferate and differentiate.⁶¹ Progenitor cells are present in the bronchoalveolar junctions that aid in the regeneration of the endothelial and epithelial barrier,⁶² and macrophages also contribute to tissue repair.⁶³ With repair of the endothelial and epithelial barrier, reabsorption of alveolar edema fluid can occur more efficiently via vectorial transport.

In addition to repairing the microvascular barrier, the resolution of ARDS requires clearance of neutrophils, monocytes, and anti-inflammatory molecules by macrophages^{64,65} and lymphocytes.⁶⁶ In a mouse model of influenza pneumonia, depletion of alveolar macrophages lead to an increased number of neutrophils and neutrophil extracellular traps, as well as slower recovery from lung injury.⁶⁷ Similarly, in a mouse model of endotoxin-induced lung injury, CD4 + CD25+ regulatory T cells suppressed cytokine secretion and enhanced neutrophil apoptosis, aiding in faster resolution of lung injury.⁶⁶

Clinical Trials and Novel Therapeutics Offer Further Insight about ARDS Pathogenesis

Since the first description of ARDS 50 years ago, there have been numerous clinical trials evaluating the efficacy of physiologic and pharmacologic interventions. Not only have these trials defined clinical practices but they also have enhanced our understanding of the pathophysiology of this condition.

Multiple clinical trials have supported the use of lung protective ventilation, with lower tidal volumes and airway pressures, to reduce mortality in ARDS.^{46,68–70} Follow-up studies investigated why this strategy is effective. In a rat model of ARDS, resolution of alveolar edema was threefold faster with a tidal volume of 6 mg/kg as opposed to 12 mg/kg, in part due to decreased lung epithelial injury.⁴⁴ Similarly in human studies, patients who were subjected to lung protective ventilation had reduced markers of lung epithelial injury⁷¹ and reduced proinflammatory molecules (neutrophils, IL-6, IL-8, and soluble TNF receptor 1).^{60,72}

Another central concept in ARDS treatment is the utilization of a conservative fluid management strategy, which was first suggested to be effective in the late 1970s⁷³ and was later confirmed by a large ARDS Network Trial.⁷⁴ The beneficial effect of a conservative fluid strategy is thought to be due to the fact that lowering vascular pressures reduces transvascular fluid filtration across the injured alveolar capillary barrier. There is also evidence that a conservative fluid strategy results in decreased plasma levels of angiotensin-2, suggesting that this strategy also has a protective effect on the vascular endothelium.⁷⁵ Further studies are needed to better understand the molecular mechanisms underlying this process.

Given that ARDS is a proinflammatory state, there have also been numerous clinical trials evaluating anti-inflammatory agents as a potential treatment for ARDS. However, clinical trials of glucocorticoids,^{76–78} granulocyte macrophage colony-

stimulating factor,⁷⁹ and antioxidants⁸⁰ have not shown clinical utility to date. Similarly, it was hypothesized that anticoagulant therapy may be effective in ARDS treatment given the known interplay between procoagulant and proinflammatory pathways. However, a trial testing activated protein C did not reduce mortality in patients with nonseptic ARDS.⁸¹ While none of these trials suggests clinical benefit in ARDS treatment, it is possible that these therapies only improve outcomes in certain subphenotypes of ARDS. There is significant clinical and biological heterogeneity in ARDS, and recent studies suggest that there are two distinct and consistent subphenotypes of this condition.^{82,83} Approximately 30% of patients have a hyperinflammatory subphenotype, which is characterized by increased inflammatory markers, more severe acidosis and shock, and worse clinical outcomes. Future clinical trials should consider these subphenotypes, as they may help us better understand ARDS pathophysiology and also may respond differentially to therapeutic interventions. For example, a large randomized controlled clinical trial of simvastatin therapy in ARDS showed no mortality difference in the treatment versus placebo groups,⁸⁴ but secondary analysis showed decreased mortality in the patients with the hyperinflammatory subphenotype of ARDS,⁸⁵ suggesting some role for anti-inflammatory treatments in this subphenotype.

Another therapeutic strategy that has been proposed is to target molecules that stabilize endothelial and epithelial cell-cell junctions, given the central role of alveolar endothelial and epithelial permeabilities in ARDS pathogenesis. Sphingosine 1-phosphate (S1P) is a lipid that is recognized by G protein-coupled receptors on endothelial cells (e.g., S1Pr1) and mediates endothelial barrier integrity.⁸⁶ In both in vitro and in vivo models, S1P enhances pulmonary and systemic endothelial integrity,⁸⁷ and small-molecule agonists of endothelial S1Pr1 decrease cytokine and leukocyte recruitment in mouse models of influenza infection.⁸⁸ Specifically, S1P binds to S1Pr1 which induces actin cytoskeleton reorganization and localization of catenin and VE-cadherin molecules to the endothelial surface.⁸⁹ The Robo4/Slit2 signaling system also stabilizes the endothelial barrier. Slit2N inhibits tyrosine phosphorylation of VE-cadherin, preventing the internalization of VE-cadherin and the resultant increased endothelial permeability triggered by TNF- α , IL1, or LPS.⁹⁰ Studying proteins that help stabilize the endothelial and epithelial barriers has therapeutic potential, and also may offer further insight into the mechanisms that underlie endothelial and epithelial permeabilities.

Aside from targeting specific proteins that have therapeutic potential, most recently, mesenchymal stromal cells (MSCs) have been recognized as a promising new cell-based therapy for ARDS, further informing our understanding of ARDS pathogenesis. MSCs are bone marrow-derived cells that can differentiate in vitro into chondrocytes, osteoblasts, and adipocytes, although they do not have true stem cell properties in vivo.⁹¹ The therapeutic potential of MSCs has been studied in several medical and surgical conditions including sepsis,^{92,93} diabetes,⁹⁴ myocardial infarction,⁹⁵ hepatic failure,⁹⁶ acute renal failure,^{97,98} chronic obstructive pulmonary disease,⁹⁹ neurologic injuries,¹⁰⁰ graft-versus-

host disease,¹⁰¹ and trauma.¹⁰² Therefore, it was hypothesized that MSCs may also be beneficial in the treatment of ARDS. To test this hypothesis, several groups studied whether MSCs reduce the severity of lung injury in preclinical models. Treatment with MSCs improved survival and reduced pulmonary edema in *Escherichia coli* endotoxin-induced lung injury in mice.¹⁰³ Subsequent studies showed that MSCs attenuated lung injury caused by live bacteria in mouse, rat, and in ex vivo human lung models of lung injury.^{104–106} In addition, MSCs enhanced bacterial clearance and improved survival in murine models of sepsis.^{93,107}

Given the potential therapeutic benefit of MSCs in the treatment of ARDS, many groups have sought to understand their mechanism of action, and several possible mechanisms have been proposed to date (→ Fig. 3). Initially, it was thought that MSCs engrafted at the site of tissue injury and provided direct structural benefit.¹⁰⁸ However, with more detailed cell identification methods, engraftment is now thought to be a rare event of unclear physiologic significance.¹⁰⁹ Instead, the beneficial effect of MSCs does not require direct cell contact and several paracrine mechanisms have been proposed. First, it has been suggested that MSCs secrete proteins that have anti-inflammatory properties, and several have been identified to date: IL-1 receptor antagonist (IL1-ra),¹¹⁰ TNF- α stimulated gene six (TSG-6),¹¹¹ insulin-like growth factor 1,¹¹² and lipoxin A4.¹¹³ Of note, clinical trials studying systemic

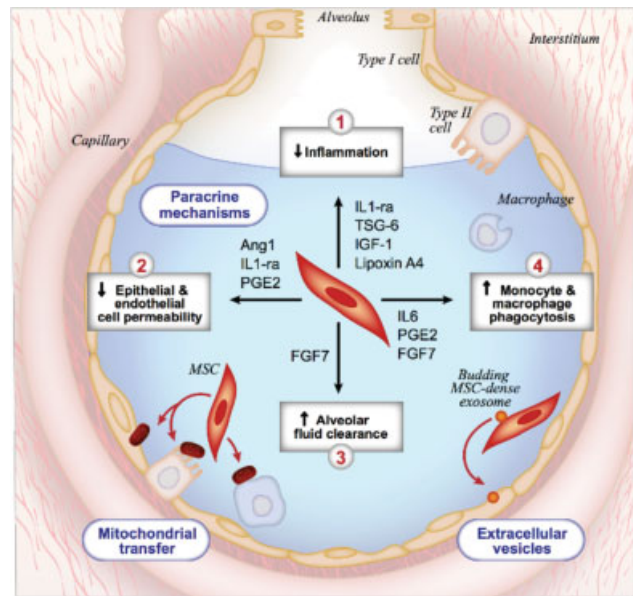


Fig. 3 Potential mechanisms for the therapeutic effects of MSCs in ARDS. To date, multiple preclinical studies have demonstrated the therapeutic benefit of MSCs in the treatment of ARDS, and this diagram depicts our current mechanistic understanding of this therapeutic effect. First, MSCs secrete paracrine factors that modulate tissue repair through four mechanisms: (1) anti-inflammatory effects on host cells, (2) reduction of alveolar epithelial permeability in the lung, (3) increased rate of alveolar fluid clearance, and (4) enhancement of host mononuclear cell phagocytic activity. Second, data suggest that MSCs directly transfer mitochondrial DNA to host cells, which also contributes to tissue repair and recovery. Third, MSCs secrete microvesicles that deliver micro RNA, RNA, proteins, and lipids to host cells. ARDS, acute respiratory distress syndrome; MSCs, mesenchymal stromal cells

anti-inflammatory agents have not been beneficial as previously described, but MSC therapy may provide anti-inflammatory effects that are multimodal and responsive to the cellular microenvironment in the lung. Second, there is evidence to suggest that MSCs affect lung endothelial and alveolar epithelial permeabilities via a paracrine mechanism, and the proteins angiopoietin-1, IL1- α , and prostaglandin E2 have been implicated in this process.^{114,115} Third, MSCs may secrete paracrine factors that improve AFC, with evidence to suggest that fibroblast growth factor 7 may be particularly important in this process.^{116,117} Fourth, apoptosis of both immune and structural cells occurs during ARDS, so it has been suggested that paracrine factors such as IL-6¹¹⁸ and keratinocyte growth factor¹⁰⁶ may have beneficial antiapoptotic effects. Finally, MSCs have the capacity to alter the polarization of alveolar macrophages to an M2-like proresolving phenotype.¹¹⁹

While numerous studies suggest that paracrine factors are responsible for the beneficial effects of MSCs, more recent studies propose alternative mechanisms of action. For example, there is some evidence to suggest that MSCs mediate tissue repair through direct transfer of mitochondrial DNA to host cells.^{120–122} Alternatively, it has been proposed that there are extracellular vesicles that bud off of MSCs and transfer biologically active material to host cells that have beneficial effects.^{123,124} Thus, there may be several mechanisms by which MSCs mediate the resolution of lung injury, and further studies are needed to clarify key mechanisms of action.

Based on these preclinical data, phases 1 and 2 clinical trials are currently testing whether MSCs have therapeutic potential in humans.¹²⁵ Most recently, a prospective, double-blind, multicenter, phase 2a randomized controlled trial demonstrated that it is safe to administer a single intravenous dose of MSCs in patients with moderate–severe ARDS,¹²⁶ so larger trials are needed to assess efficacy. Of note, the authors noted varying viability of the MSCs in this study, so it will be important to improve protocols to improve MSC viability in the future.

Conclusion

Over the past 50 years, there have been substantial advances in our understanding of ARDS pathogenesis. In vitro and in vivo studies have demonstrated that lung inflammation causes increased alveolar endothelial and epithelial permeabilities, resulting in the accumulation of pulmonary edema fluid. In ARDS, the mechanisms that typically remove pulmonary edema fluid are less effective. The study of novel therapeutic strategies, including cell-based MSC treatment, has further refined our understanding of ARDS pathophysiology, and may offer promising new treatment options for this condition. In addition, new therapies may be more effective if targeted to specific subphenotypes of ARDS defined by clinical and biological factors.

Conflict of Interest

This work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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