The pulmonary endothelium in acute respiratory distress syndrome: insights and therapeutic opportunities

Fraser R Millar,1 Charlotte Summers,2,3 Mark J Griffiths,1,4 Mark R Toshner,3 Alastair G Proudfoot1,5

ABSTRACT

The pulmonary endothelium is a dynamic, metabolically active layer of squamous endothelial cells ideally placed to mediate key processes involved in lung homeostasis. Many of these are disrupted in acute respiratory distress syndrome (ARDS), a syndrome with appreciable mortality and no effective pharmacotherapy. In this review, we consider the role of the pulmonary endothelium as a key modulator and orchestrator of ARDS, highlighting advances in our understanding of endothelial pathobiology and their implications for the development of endothelial-targeted therapeutics including cell-based therapies. We also discuss mechanisms to facilitate the translation of preclinical data into effective therapies including the application of biomarkers to phenotype patients with ARDS with a predominance of endothelial injury and emerging biotechnologies that could enhance delivery, discovery and testing of lung endothelial-specific therapeutics.

INTRODUCTION

The pulmonary vasculature is a homogenous layer of squamous endothelial cells lining the entire pulmonary circulation. Having initially been thought of as an inert, static structure, the lung endothelium is increasingly recognised as a dynamic, metabolically active organ that modulates several key regulatory functions including: leucocyte diapedesis, intravascular coagulation, vasomotor tone, and solute and fluid trafficking via regulation of barrier permeability.

The pulmonary endothelium is distinct from the systemic vascular bed, in that it is exposed to the highest oxygen tension, while maintaining low-pressure blood flow. Coupled with the lung possessing the highest abundance of endothelial cells relative to the total cell population and its vast surface area, it is ideally placed to interact with bloodborne cells and vasoactive mediators to sense mechanical, chemical and cellular stimuli. While this allows the endothelium to regulate local (and possibly systemic) inflammation, disruption of lung endothelial homeostatic mechanisms transforms it from a primarily anti-inflammatory phenotype to an activated proinflammatory phenotype that propagates lung parenchymal inflammation.1

Disruption of lung endothelial homeostasis manifests clinically as acute respiratory distress syndrome (ARDS). ARDS is characterised by acute inflammation of the gas exchange surface of the lung. Dysregulated inflammation promotes the pulmonary accumulation of leucocytes and platelets, while activation of procoagulant pathways and disruption of alveolar capillary membrane barrier function leads to hypoxia, hypercapnoea and pulmonary oedema. Thus, ARDS presents clinically with acute onset of breathlessness and hypoxaemia in the presence of diffuse pulmonary oedema on the chest radiograph, with the majority of patients requiring mechanical ventilation. Risk factors for ARDS can be divided into two groups, depending on whether injury to the lung is direct such as pneumonia, with predominantly epithelial injury, or indirect bloodborne insults, such as severe sepsis, with a predominance of endothelial injury (table 1). Although mortality in ARDS has temporally declined, it remains between 25% and 35%2 and there is currently no licensed effective pharmacotherapy, highlighting the need for novel therapeutic strategies. Contemporary management focuses on treatment of the underlying cause and organ support while avoiding iatrogenic injury, most notably with low tidal volume and pressure mechanical ventilation and a conservative fluid management strategy.3

In this article we focus on our current understanding of the role of the pulmonary endothelium in orchestrating and propagating ARDS, and further explore the endothelium as an emerging pharmacological target in ARDS. It is important to note that the pulmonary endothelium is structurally, morphologically and functionally distinct from the systemic vasculature (reviewed in refs. 4–5). Accordingly, this review will address data generated in relevant models of pulmonary endothelial injury, with reference to recent specific expert reviews where appropriate.

STRUCTURE AND FUNCTION OF THE PULMONARY ENDOTHELium

The pulmonary endothelium forms a single layer of mesenchyme-derived and non-fenestrated endothelial cells. This serves as a semipermeable barrier separating the pulmonary circulation from the lung interstitium, regulating macromolecule, nutrient, leucocyte and fluid transfer.

The integrity of this barrier is determined by homophilic interactions between neighbouring endothelial cells via intercellular junctions (tight junctions and adherens junctions (AJs); reviewed in ref. 6). These junctions link endothelial cells and are served by cytoskeletal microtubules and actin microfilaments to facilitate both maintenance of barrier function and modulation of signal transduction in response to the tethering and contractile

Correspondence to

Dr Alastair Proudfoot, Frederick Meijer Heart & Vascular Institute, Spectrum Health, Grand Rapids, Michigan, USA

Received 19 June 2015
Revised 9 February 2016
Accepted 12 February 2016
Published Online First 11 March 2016

forces exerted on the endothelium during mechanical ventilation.

Tight junctions are formed by the fusion of the outer layers of the plasma membranes and are comprised of occludins, claudins and junctional adhesion molecules coupled to cytoplasmic proteins and linked to the endothelial cell actin cytoskeleton by the zonula occludens family. AJs are composed of cadherins, primarily vascular endothelial cadherin (VE-cadherin), that bind intracellular catenins (including p120-catenin, a VE-cadherin stabilising protein) that in turn bind to other protein partners in the actin cytoskeleton. AJs are mediated by calcium-dependent association of cadherin proteins and regulate the paracellular transport (the predominant pathway) of cells and solutes between the blood and the interstitium. Hence AJs, and specifically VE-cadherin, are key regulators of paracellular permeability, which determines leucocyte transmigration and oedema formation while cell membrane scaffolding proteins called caveolins regulate transendothelial trafficking (transcytosis) of macromolecules including albumin. Data suggest that transcellular permeability increases may precede and subsequently trigger paracellular permeability via Src-mediated phosphorylation of caveolin-1. Endothelial cells are tethered to the extracellular matrix (ECM) via interaction between cell surface integrins and their ECM ligands, which are organised in focal adhesion plaques.

A negatively charged extracellular layer of proteoglycans, glycoproteins and glycosaminoglycans (GAGs) that line intimal surfaces, the endothelial glyocalyx, may act as an additional barrier to large molecules and circulating cells. Data from a murine ARDS model suggested that the glyocalyx-modulated neutrophil diapedesis via heparinase-mediated glyocalyx shedding and consequent exposure of neutrophil adhesion molecules, while in vitro human data proposed that the sialic acid component of the glyocalyx maintained barrier function via regulation of cell-matrix and cell-cell interactions. Despite these and other observations (reviewed in ref. 14), it remains unclear whether and how the glyocalyx contributes to the pathogenesis of human ARDS.

The endothelium performs additional regulatory roles in gas exchange, vascular tone and coagulation (reviewed in ref. 15). As an integral component of the alveolar-capillary unit, it is structurally and functionally optimised to facilitate perfusion-ventilation matching. Hence, lung endothelial cells regulate the synthesis and metabolism of vasoactive compounds such as nitric oxide and endothelin-1, potent regulators of pulmonary vascular tone. Furthermore, the endothelium also produces both prothrombic and antithrombotic substances which act both locally and remotely to regulate coagulation. It separates blood-borne cellular (eg, platelets) and humoral (eg, coagulation factors) components of the coagulation cascade from prothrombotic substances in the lung interstitium and alveolar space.

PULMONARY ENDOTHELIAL ACTIVATION IN ARDS Pathobiology

In health, the lung endothelium adopts a predominantly inhibitory effect on inflammation and coagulation. However, upon ‘activation’ by a range of stimuli including hypoxia, cytokines (eg, tumour necrosis factor α (TNF) and interleukin (IL) 1β), chemokines (eg, IL-8), thrombin and bacterial endotoxins, including lipopolysaccharide (LPS) and interactions with activated inflammatory cells, a shift towards a proinflammatory phenotype occurs. Indeed, dysregulated endothelial activation and the resultant loss of homeostatic mechanisms are aspects of ARDS pathobiology that may distinguish it from self-limiting, localised insults, for example bacterial pneumonia.

Accordingly, lung endothelial cells are increasingly recognised as orchestrators of the inflammatory response. In experimental influenza models, the pulmonary endothelium was a key regulator of innate cellular and cytokine responses, if not the actual source of cytokine release. In addition, endothelial cells express various leucocyte adhesion molecules including intracellular adhesion molecule-1 (ICAM-1), vascular cell adhesion molecule-1 (VCAM-1) and E-selectin. These proinflammatory responses may exhibit calcium dependency; TNF and IL-8 release from lung microvascular endothelial cells stimulated with LPS correlated with an increase in intracellular calcium, while cytosolic calcium oscillations induced proinflammatory gene transcription and endothelial E-selectin expression. Reactive oxygen species (ROS) and reactive nitrogen species production by activated cells saturate local antioxidants and contribute to tissue injury directly via downregulation of VE-cadherin, upregulation of neutrophil adhesion molecule expression and release of neutrophil chemotactic factors.

| Table 1 Indirect and direct ARDS—distinguishing features |
|---------------------------------|-----------------|
| Causes                          | Direct ARDS     |
| Severe sepsis                   | Pneumonia       |
| Trauma                         | Aspiration      |
| Blood product transfusion (TRALI)| Smoke inhalation|
| Pancreatitis                    | Pulmonary contusion|
| Cardiopulmonary bypass          | Reperfusion injury|
| Burns                           |                 |
| Clinicopathological hallmarks   | Proposed biomarkers |
| Neutrophil alveolitis           | Angiplastin-2    |
| Hyaline membranes               | von Willebrand factor|
| Microthrombi                    | Soluble thrombomodulin|
| Imaging and plasma evidence of (non-pulmonary) pathology, for example, pancreatitis | Interleukin 8|
|                                | Soluble ICAM-1  |

ARDS, acute respiratory distress syndrome; ICAM-1, intracellular adhesion molecule 1; TRALI, transfusion associated lung injury.
Activated endothelial cells also assume a procoagulant phenotype to limit damage to lung microvasculature and localise infection. This is characterised by increased expression of platelet adhesion molecules, intra-alveolar and intravascular fibrin deposition, and release of activators of the extrinsic coagulation cascade, in particular nitric oxide. Moreover, upregulation and activation of tissue factor and loss of the ability to activate protein C and S results in capillary thrombosis and extravascular fibrin deposition, thereby contributing to the increased dead-space fraction that correlates with clinical outcomes.

Clinical and therapeutic significance

While potentially potentially propagating injury, the expression and release of proinflammatory molecules has driven research first into using these molecules as biomarkers of ARDS and second as putative pharmacological targets. Moreover, there is increasing evidence that the alveolar and vascular compartments are biologically distinct despite the alveolar capillary membrane disruption seen in ARDS supporting the notion that ‘phenotypical signatures’ identifying patients with site-predominant injury (endothelial vs epithelial) could be generated.

Angiopoietin-2 (Ang-2) is an endothelial growth factor, produced by endothelial cells, that regulates vascular permeability, promoting cell death and vascular regression. An incremental rise in plasma Ang-2, suggestive of progressive endothelial injury predicted mortality in patients with sepsis-related ARDS. Similarly, higher circulating GAG levels (reflecting the integrity of the glyocalyx) were found in those patients with non-pulmonary insults (ie, patients with indirect ARDS) although these did not predict outcome. In other studies, plasma levels of soluble thrombomodulin (TM), the circulating form of a transmembrane endothelial glycoprotein with antithrombotic and anti-inflammatory capabilities, and von Willebrand factor (vWF), a glycoprotein produced by endothelial cells, predicted mortality in ARDS. Finally, endothelial-derived microparticles (EMPs), submicron vesicles formed during membrane blebbing that shuttle proteins, organelles, lipids and RNA are an emerging biomarker of lung endothelial activation (reviewed in ref. 30), particularly in the context of mechanical stretch. Hence, EMP levels were elevated in human macrovascular endothelial cells and animals exposed to pathological mechanical stress as well as endotoxin.

Using unbiased latent class analysis, a recent study identified two distinct cohorts of patients with ARDS who differed predominantly in their inflammatory profile and more significantly divergent responses to the application of different ventilator strategies. While this study did not differentiate endothelial injury from epithelial injury, it suggests that patient endotyping may hold value in predicting response to therapy. Coupled with evidence from biomarker studies outlined above, it is becoming increasingly plausible that researchers may soon be able to enrol subphenotypes of patients with ARDS with a predominance of endothelial injury to enrich enrolment in trials, thus optimising trial design and potential outcomes.

The expression of cell surface receptors and adhesion molecules also provides a putative platform to apply advances in pulmonary endothelial immunotargeting. Coupled with advanced drug delivery systems (such as liposomes, nanocarriers and host carriers) this methodology may facilitate targeting of specific aspects of lung endothelial injury in ARDS. For example, antioxidants conjugated with antibodies to the endothelial determinant Platelet/Endothelial Cell Adhesion Molecule 1 (PECAM-1) inhibited endothelial activation and reduced VCAM-1 expression in murine lung injury. Similarly, dexamethasone-loaded nanogels targeted to ICAM-1 accumulated in murine LPS-injured lungs and blocked expression of ICAM-1 and VCAM-1 at 24 h. In an effort to both target the lung endothelium and enhance biological effect, researchers have fused single-chain fragments of PECAM-1 antibodies to recombinant TM and endothelial protein C receptor (EPCR). Using this dual-targeting approach, a fivefold increase in receptor activation compared with isolated TM or EPCR targeting was observed as well as amelioration of lung injury parameters. Translation of these methods to clinical use will be challenging and costs may be prohibitive; nonetheless, these novel methods of targeted drug delivery hold promise.

MECHANISMS OF ENDOTHELIAL BARRIER DISRUPTION AND INJURY IN ARDS

Loss of barrier integrity, characterised by the formation of reversible intercellular gaps between endothelial cells, is accepted as the ultrastructural basis for the increased permeability pulmonary oedema observed in ARDS. A range of circulating (TNF, IL-6, LPS), released (ROS, histamine) and physical (mechanical stretch) effectors disrupt the endothelial barrier, principally by causing activation of the actin-myosin contractile apparatus which causes dispersion of cortical actin filaments and increased prominence of stress fibres which extend throughout the cytoplasm. Actin-myosin contraction of these stress fibres increases tension and is proposed to cause cell contraction, pulling cells apart and compromising barrier integrity. Contractile machinery is regulated by the phosphorylation status of the critical actin binding protein, myosin light chain (MLC) on Ser-19 or Ser-19/Thr-18. This is controlled through an interplay of the calcium/calmodulin-dependent MLC kinase (MLCK, phosphorylation) and Rho-regulated MLC phosphatase (MLCR dephosphorylation). Hence, MLCK in particular, plays an essential role in both barrier disruption and restoration in an agonist-specific manner (figure 1).

Although data specific to the lung endothelium is comparatively limited, regulatory small GTPases including RhoA, Rac1, cell division control protein 42 (Cdc42) and Rap1 are central intracellular regulators of the actin cytoskeleton and thus barrier function. Broadly, Rho negatively regulates barrier function and Cdc42 and Rap1 signalling enhance barrier function. RhoA through its regulated signalling circuitry, including the serine-threonine Rho-associated protein kinase (ROCK), induces phosphorylation of MLC (via MLCK) as well as inhibition of MLC. Cdc42 directly regulates cortical actin organisation as well as a host of proteins including coflin, MLCK and neural-Wiskott Aldrich syndrome protein that affect actin organisation and cell adhesion to the ECM. Ras-related C3 botulinum toxin substrate 1 (Rac1) can either positively or negatively regulate barrier function in a stimulus-dependent manner, while Rap1 enhances barrier function via inhibition of Rho and activation of Cdc42, as well as a cooperative association with VE-cadhairin.

Other intracellular mediators include cyclic AMP (cAMP), nuclear factor kB (NF-kB) and focal adhesion kinase (FAK). An increase in cAMP levels in response to a range of mediators reduces vascular leakage through activation of protein kinase A (PKA) and the guanine exchange factor, exchange protein activated by cAMP (Epac). PKA inhibits RhoA activation and endothelial cell (EC) contraction and Epac (via Rap1) enhances VE-cadherin junctional integrity and actin reorganisation. FAK, a non-receptor tyrosine kinase regulates turnover...
of focal adhesion formation by binding to focal adhesion proteins as well as enhancing AJ formation; in experimental ARDS models (including conditional FAK deletion), decreased FAK expression was associated with lung oedema as well as albumin and neutrophil influx.

MLC-phosphorylation independent mechanisms of barrier disruption also exist. Endothelial cell apoptosis via mediators including TNF and influenza virus may contribute. Tyrosine phosphorylation of cytoskeletal proteins and adhesion molecules including VE-cadherin, β-catenin and p120 via tyrosine kinases including Src may induce disassembly of the catenin-cadherin complex while microtubule disassembly independent of MLCK and Rho has been reported. The angiopoietin-Tie2 signalling axis (the endothelial tyrosine kinase Tie2 and its circulating ligands Ang-1/4) merits specific mention as a mediator of barrier disruption as it represents one of the most extensively studied barrier-regulating mechanisms. Ang-1 is constitutively expressed in a range of cell types and mediates barrier integrity and endothelial quiescence via steady activation of the Tie2 receptor, which is abundantly expressed in endothelium. Ang-2, released from endothelial cells in response to a diverse range of mediators, acts as a functional antagonist of Ang-1 at the Tie2 receptor, mediating cytoskeletal rearrangement and junctional disruption. Thus, mice heterozygous for Ang-2 were protected from lung injury compared with wild type mice in sepsis models. Ang-2 may play additional roles in leucocyte endothelial interactions. In the clinic, circulating levels of Ang-2 correlated with increased pulmonary oedema and mortality in patients with ARDS and predicted the development of ARDS in critical illness, further supporting a central role for Ang-2 in the endothelial injury of ARDS.

The role of damage-associated molecular patterns (native molecules released after tissue injury) and in particular mitochondrial DNA (mtDNA) production in barrier disruption is an emerging area of investigation. Hence, circulating levels of mtDNA are elevated in critical illness. In this context, they are potent inducers of the inflammasome via toll-like receptor 9 (TLR9), activating leucocyte-mediated lung injury when injected in vivo and endothelial barrier disruption in vitro. A bacterial challenge in isolated mouse lungs induced mtDNA release which was associated with endothelial hyperpermeability; this effect was replicated with exogenous mtDNA and attenuated by blockade of TLR9. Further elucidation of mechanisms of mtDNA release and their interplay with ROS as well as intracellular signalling pathways are required but this represents an intriguing line of investigation, if not a potential therapeutic target. While previously thought to contribute primarily to lung epithelial injury and repair, pathogen-associated molecular pattern (PAMP) signalling via pattern recognition receptors (PRRs) may also contribute to lung endothelial barrier dysfunction. Accordingly, influenza virus infection upregulated PRR expression (specifically TNF receptor 1) in a range of relevant models including human lung autopsy specimens, with...
resultant endothelial leak and apoptosis following exposure to *Staphylococcus aureus*-derived PAMPs in vitro.\(^75\)

**CANDIDATE THERAPIES TO ENHANCE ENDOTHELIAL BARRIER FUNCTION**

The endogenous lipid growth factor sphingosine-1-phosphate (S1P) enhances barrier function through a series of signalling pathways that maintain cortical actin, focal adhesions and tight junctions (reviewed in ref. \(^76\)). S1P receptors are highly expressed on pulmonary endothelial cells. Accordingly, S1P and its analogues reduced vascular leakage in small and large animal lung injury models\(^77\)–\(^79\), as well as dampened the cytokine storm in a murine influenza model.\(^80\) The clinical application of S1P and its analogues is currently limited by systemic toxicity, most notably immunosuppression prompting the use of FTY720 (an S1P analogue) in multiple sclerosis.\(^89\) Moreover, in a murine model, prolonged application of S1P agonists worsened vascular leakage and promoted fibrosis\(^10\) while the S1P pathway has been linked to dysregulated fibrogenesis of idiopathic pulmonary fibrosis.\(^61\) Safer analogues with promising, if not superior, preclinical data may however be on the horizon.\(^82\)

Based on the preclinical and clinical data outlined above, the Tie2 axis represents an attractive therapeutic target. A stable inhibitor of VE-cadherin inhibition, a pharmacological inhibitor of VE-cadherin (VE-cadherin) activation, AKB-9778, which activates Tie2,\(^84\) blocked lung neutrophil recruitment in LP-induced mice and stabilised lung endothelial junctions via Rap1.\(^85\) A novel Tie-2 agonist rescued mice from severe influenza up to 3 days after infection.\(^39\) Improvements in vascular leak were attributed to Tie-2-mediated attenuation of endothelial cell apoptosis as cellular proliferation was unaffected. Notably, maintenance of barrier function did not impair leukocyte transmigration. This observation supports data from a study in systemic circulation suggesting independent regulation of these two processes.\(^86\)–\(^87\)

The renin-angiotensin system (RAS) is a complex network orchestrating blood pressure, electrolyte and fluid homeostasis, which has been implicated in the pathogenesis of ARDS. ACE2 is an endogenous modulator of RAS highly expressed in the lung endothelium and alveolar epithelium\(^88\) which diverts potentially injurious angiotensin II (Ang II) signalling via conversion of Ang II to Ang 1–7 and inactivation of angiotensin receptors, thus negatively regulating RAS.\(^89\) Studies in knockout mice have demonstrated that loss of ACE2 worsened sepsis and acid aspiration induced lung injury.\(^90\)–\(^92\) ACE2 is reported to be the receptor for the severe acute respiratory syndrome (SARS) coronavirus induced lung injury.\(^90\) More recently, compelling data suggest that ACE2 has a central role in the development and progression of the potentially lethal avian influenza viruses H5N1\(^92\) and H7N9.\(^93\)–\(^94\) Gain of function ACE1 polymorphisms are also associated with ARDS susceptibility and worse outcome.\(^95\)

None of these studies offer clear mechanistic insight but ACE2 signalling in the lung is likely to be mediated by alveolar epithelial cells.\(^96\)\(^97\) A Phase Ila trial of a recombinant ACE2 compound in patients with both direct and indirect ARDS, Clinical Trials.gov ID: NCT01397635, has recently completed recruitment and interim results are awaited.

Pleomorphic, anti-inflammatory, immunomodulatory and antioxidant effects are exerted by 3-hydroxy-3-methylglutaryl coenzyme A reductase inhibitors (statins) on endothelial cells to promote cytoskeletal rearrangement, decrease oxidative stress and modulate gene expression.\(^97\)–\(^98\) Hence, statins attenuated vascular leak in a range of murine ALI models.\(^99\)–\(^100\) Despite promising preclinical data, including an in vivo human inhaled LPS model,\(^101\) these findings were not translated into clinical improvements in two recent clinical trials.\(^102\)–\(^103\) Given the extensive data supporting a biological effect on the endothelium, it is intriguing to speculate that these trials may have been enriched by the enrolment of specific endotypes of patients with indirect ARDS to optimise outcomes.

A recent phase I clinical trial of 26 patients demonstrated mortality benefit in ARDS (n=37) treated with interferon-β-1a.\(^104\) The proposed mechanisms of benefit were modulation of inflammation (possibly neutrophil endothelial interactions) and endothelial barrier function via CD73-mediated dephosphorylation of AMP. While non-randomised, the mortality benefit (24% absolute reduction) in this study suggests that targeting the lung endothelium may hold promise as a viable therapeutic strategy in ARDS. A randomised controlled trial is imminent to confirm these findings. This study was also notable by the generation of human (ex vivo) data to support animal data prior to early phase trials, a paradigm that should be increasingly adopted.

The pleiotropic effects of the tyrosine kinase inhibitor imatinib, particularly in attenuation of vascular permeability induced by a broad range of mediators (discussed in ref. \(^105\)), have stimulated study into its efficacy as a barrier-enhancing agent in ARDS. Despite imatinib’s association with peripheral oedema,\(^106\) case reports have suggested clinical improvements in idiopathic vascular leak\(^107\) and bleomycin-induced lung injury.\(^108\) Supporting these clinical observations these clinical observations, imatinib attenuated thrombin and histamine-induced barrier dysfunction in vitro\(^109\) and pulmonary vascular leak in clinically relevant murine models.\(^105\)\(^109\) Given its multiple sites of action (table 2), further mechanistic work is required to progress imatinib as a potential therapy in ARDS.

Other candidate therapies have shown promise, but again mechanistic understanding in the pulmonary vasculature is not sufficiently advanced. Atrial natriuretic peptide (ANP) protects against LPS-mediated lung microvascular leakage by blocking NF-κB activity.\(^110\) while concurrently enhancing VE-cadherin localisation to AJ.\(^111\) Recent murine data support an additional role for ANP in microtubule stabilisation, an emerging mechanism in regulation of endothelial cell permeability.\(^112\) Of note, a previous small clinical trial demonstrated physiological improvements with an infusion of ANP.\(^113\) Adrenomedullin (AM), a ubiquitously expressed peptide hormone that binds calcitonin receptor-like receptor on lung endothelial cells promoting intercellular adherence, improved endothelial barrier function in preclinical acute lung injury (ALI) and ventilator associated lung injury (VALI) models.\(^114\)–\(^116\) Given the abundance of binding sites on the pulmonary endothelium, AM also holds promise as a lung endothelial imaging tool using 99mTc-technetium labelling.\(^117\) Finally, hepatocyte growth factor has recently been shown to suppress LPS-induced endothelial activation and barrier disruption possibly via a guanine nucleotide exchange factor.\(^118\)\(^119\)

A summary of the mediators and mechanisms of barrier disruption and enhancement is outlined in table 2 and figure 2.

**INTERACTIONS OF THE LUNG MICROVASCULATURE WITH NEUTROPHILES AND PLATELETS**

Neutrophils are central to the initiation and propagation of inflammation and injury in ARDS and neutrophilic alveolitis is a
Their importance in ARDS is highlighted by the observation that a decline in respiratory function is seen in neutropenic patients with ARDS upon recovery of neutrophil counts. Pathway analysis of differential gene expression in sepsis-induced ARDS compared with sepsis alone identified a preponderance of genes regulating neutrophil homeostasis and activation, further supporting the notion of the role of neutrophil inflammation.

Despite extensive data from models of the systemic circulation (eg, murine cremaster vessels and human umbilical vein endothelial cells), our mechanistic understanding of the role of the pulmonary endothelium in neutrophil sequestration is limited. As a consequence of the unique pulmonary capillary microanatomy, the site and mechanisms of neutrophil sequestration are different from the systemic microcirculation. For example, owing to space constraints in the alveolar capillary bed, neutrophils must change their shape to pass through. Moreover, neutrophil rolling on the endothelial surface does not occur. Owing to space constraints in the alveolar capillary bed, neutrophil adhesion molecule expression (ICAM-1) has been proposed; however, precise identification of the cognate receptors for neutrophils on lung endothelium remains elusive and further study in refined animal models and novel human models is an urgent unmet need.

Clarification of the role of neutrophil migration in barrier disruption is also required. Activated neutrophils exert negative effects on barrier permeability via secretion of various products such as TNF, complement component 5a and arachidonic acid but it remains unclear whether neutrophil migration through the endothelium is damaging per se. As outlined above, recent data support the concept that neutrophil migration and endothelial barrier disruption may be independently regulated.

Recent work has focused on the role of the transient receptor potential structurally, a disturbance that results from a dysfunction of sensory proteins (TRP channels), specifically TRP vanilloid 4 (TRPV4) receptor, particularly as it is expressed on both neutrophils and the pulmonary endothelium, and specific inhibitors are available. TRPV4 signalling has been implicated in endothelial dysfunction secondary to mechanical stress possibly via calcium influx.

Table 2  Mediators and mechanisms of barrier disruption and enhancement

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Target</th>
<th>Mechanisms</th>
<th>Refs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barrier disruption</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Endothelial glycoplyx</td>
<td>Unknown</td>
<td>Loss of endothelial homeostatic mechanisms</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Disruption of cell-cell and cell-matrix interactions</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased leucocyte adhesion</td>
<td></td>
</tr>
<tr>
<td>LPS</td>
<td>TLR4</td>
<td>Intracellular calcium influx via DAG-induced TRPC6 channel activation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduced FAK expression</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MLCK activation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IL-6R</td>
<td>NF-κB induced inflammatory cytokine release</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expression of contractile proteins</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cytokine release</td>
<td></td>
</tr>
<tr>
<td>mtDNA</td>
<td>TLR9</td>
<td>Intracellular calcium influx</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cytokine release</td>
<td></td>
</tr>
<tr>
<td>ROS</td>
<td>NADPH oxidase</td>
<td>Intracellular calcium influx and MLCK activation</td>
<td></td>
</tr>
<tr>
<td>Thrombin</td>
<td>PAR1</td>
<td>Intracellular calcium influx and activation of MLCK and RhoA</td>
<td></td>
</tr>
<tr>
<td>TNF</td>
<td>TNFR1</td>
<td>Promotion of NF-κB induced inflammatory cytokine release and upregulation of leucocyte ligands, for example, ICAM-1</td>
<td></td>
</tr>
<tr>
<td><strong>Barrier enhancement</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE2</td>
<td>Not applicable</td>
<td>Negative regulation of RAS via inactivation of angiotensin receptors</td>
<td></td>
</tr>
<tr>
<td>Adrenomedullin</td>
<td>CLR complex</td>
<td>Attenuation of MLCK phosphorylation</td>
<td></td>
</tr>
<tr>
<td>Ang1</td>
<td>Tie2</td>
<td>Adherens junction assembly via Rac1 activation of NF-κB signalling</td>
<td></td>
</tr>
<tr>
<td>ANP</td>
<td>NF-κB</td>
<td>Prevents against LPS mediated NF-κB signalling</td>
<td></td>
</tr>
<tr>
<td>HGF</td>
<td>MET</td>
<td>Activates Rac-dependent cytoskeletal rearrangement</td>
<td></td>
</tr>
<tr>
<td>IFNβ1a</td>
<td>CD73</td>
<td>Upregulation of CD73-enhancing adenosine activity via adenosine dephosphorylation</td>
<td></td>
</tr>
<tr>
<td>Imatinib</td>
<td>c-Ab1</td>
<td>Augmented Rac1 signalling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Arg</td>
<td>Cytoskeletal rearrangement</td>
<td></td>
</tr>
<tr>
<td>PDGFR</td>
<td></td>
<td>Inhibition of LPS-induced NF-κB signalling</td>
<td></td>
</tr>
<tr>
<td>S1P</td>
<td>S1P Receivers</td>
<td>Stabilisation of AJs via Rac1</td>
<td></td>
</tr>
<tr>
<td>Statins</td>
<td>HMG-coenzyme A reductase</td>
<td>Abrogation of VEGF signalling via RhoA inhibition and Rac1 activation</td>
<td></td>
</tr>
</tbody>
</table>
activation in a murine acid injury model. Further, chimerical mouse models demonstrated that attenuation of lung injury was contingent on endothelial TRPV4 as opposed to leucocyte TRPV4 although deletion of TRPV4 on neutrophils did abrogate injury in isolated perfused mouse lungs.

The concept that the lung endothelium may play a role in host defence by facilitating the depriming of neutrophils and hence providing protection from neutrophil-mediated remote organ injury, has been proposed. Data from an in vivo human model demonstrated that the healthy lung microvasculature retained injury , has been proposed. Data from an in vivo human model demonstrated that the healthy lung microvasculature retained injured and subsequently facilitated their depriming and release (into the systemic circulation) in an unprimed quiescent state. It is conceivable that failure of this mechanism, for example, as a consequence of endothelial injury in ARDS, may result in high circulating levels of primed neutrophils, which correlate with the severity of lung injury and which may mediate multi-organ dysfunction. Manipulation of this depriming mechanism may offer a novel therapeutic approach.

While platelets play a role in a range of pathobiological processes in ARDS (reviewed in ref. 143), our understanding of platelet endothelial interactions is underdeveloped and extrapolated from work on the systemic vasculature. In murine ARDS, platelets induce ICAM-1 expression on endothelial cells, propagating neutrophil extravasation. Experimental lung injury models have also demonstrated that platelets induce endothelial activation as evidenced by increased expression of vWF, P-selectin and tissue factor, such that platelet depletion and blockade of platelet binding ameliorated injury. Platelets also modulate endothelial barrier permeability through expression of a range of factors, including S1P (reviewed in ref. 147). Of note, however, in murine pneumonia, thrombocytopenia enhanced lung inflammation and endothelial cell activation suggesting that platelet depletion strategies may be detrimental. The interplay between neutrophil extracellular traps and platelets is an emerging narrative in lung injury secondary to blood transfusion and following lung transplantation. Platelet-endothelial interaction may also play a role in regulating alveologenesis (see below) and hence lung repair after injury.

MODULATION OF THE COAGULATION CASCADE

Activated coagulation and depressed fibrinolysis coupled with low circulating levels of endogenous anticoagulants contribute to the pathological and physiological features of ARDS. Moreover, it is becoming increasingly apparent that inflammation and coagulation in ARDS are intimately linked. Modulation of these effects has thus been an attractive therapeutic target.

The protein C pathway, in particular, has been the focus of extensive research, at least in the systemic circulation (reviewed in ref. 153). Activated protein C (APC) is generated from EPCR-bound protein C by TM-bound thrombin. EPCR s are expressed on both pulmonary artery and lung microvascular endothelial cells. In addition to its anticoagulant activity, APC manifests a myriad of cytoprotective effects, including antiapoptotic and anti-inflammatory effects through dissociation of APC from EPCR and activation of protease-activated receptor (PAR)-1 (and to a lesser extent PAR-3) biased signalling. In the lung macrovascular endothelium, APC enhanced barrier function in a context-specific fashion via S1P and RAC1-dependent mechanisms.

Despite extensive preclinical data, recombinant APC demonstrated no clinical efficacies in patients with ARDS and no reduction in barrier leak was demonstrated with recombinant APC therapy despite attenuation of the coagulopathy.
multicentre trial of modified (catalytic site irreversibly blocked) recombinant factor VIIa, similarly, showed no benefit. Thus, we have yet to fully harness the abilities of anticoagulants to modulate cell signalling, inflammation and barrier function, in particular via PAR signalling. These negative trial data may temper enthusiasm for ongoing research in this area. Nonetheless, PAR-1 antagonism has recently shown beneficial effects on neutrophil migration, cytokine release and barrier disruption in a murine pneumonia model suggesting that alternative targets in the pathway may hold therapeutic promise.

THE LUNG ENDOTHELIUM AND REPAIR IN ARDS

The observation that over half of patients with ARDS survive, suggests that the lung microvascular endothelium and epithelium have a significant capacity for repair and regeneration. The process of repair following ARDS involves both alveolar and endothelial cell reconstitution with restoration of barrier function facilitating removal of alveolar oedema and inflammatory debris. A comprehensive discussion of endothelial repair is beyond the scope of this article and readers are referred to recent expert reviews.

In addition to circulating progenitor cells, local populations of endothelial progenitor cells (EPCs) have been identified in the pulmonary microvascular endothelium and levels of EPCs are elevated in patients with ARDS. Retrospective analysis of lung tissue from patients with male-to-female haematopoietic stem cell transplant provides direct evidence of integration of male EPCs into female recipient pulmonary endothelium confirming the role of EPCs. However, the field of circulating EPCs remains controversial; their origin and function as well as their ability to effect repair under the hostile environment of clinical ARDS remains uncertain. Moreover, the cell most commonly studied, (identified by Asahara in 1997) is now recognised as a monocyte with angiogenic features and not a true endothelial progenitor. Furthermore, it has been demonstrated that the majority of endothelial repairs, at least after endotoxin-induced lung injury, was affected by tissue-resident progenitor cells, not circulating EPCs. Any therapeutic role of cell-based therapies may be anti-inflammatory, via secretion of paracrine factors, as opposed to mediating endothelial repair per se.

Alternatively, endothelial cells may modulate neovascularisation via crosstalk with their local niche. Hence, in murine pneumonectomy models platelet-endothelial interaction via stromal-cell derived factor-1 and lung endothelial vascular endothelial growth factor signalling (via the production of matrix metalloproteinase-14) induced alveologenesis. Similarly, lung endothelial cells were required to support alveolar stem cell differentiation in vitro and lung regeneration in vivo; this mechanism was thrombospordin-1 (an endogenous inhibitor of angiogenesis) dependent.

These data provide compelling evidence that the pulmonary endothelium participates in the resolution of ARDS. Whether manipulation of these endothelial niches or the administration and mobilisation of EPC populations is a feasible goal in ARDS requires further study. Further definition of the molecular pathways that regulate the crosstalk between endothelial cells and the reparative niche, particularly in the context of relevant ARDS models will be invaluable. While primarily directed towards resolution of alveolar epithelial inflammation and injury, data from a clinical trial of mesenchymal stem cells (ClinicalTrials.gov: NCT02097641) will hopefully provide additional insights, particularly regarding the effects of anti-inflammatory strategies on endothelial barrier function and a potential interplay with endothelial cells.

FUTURE DIRECTIONS

The identification and validation of robust biomarkers to phenotype patients with ARDS to either identify them as having a predominance of endothelial injury or to predict response to treatment would appear an integral component influencing the success of future trials of novel endothelial therapeutics in ARDS. The application of ‘omics’ technologies such as metabolomics (reviewed in ref. 174) will hopefully advance this field in the coming years facilitating personalised therapies within the next decade. Biomarker exploration will ideally also result in the identification of novel druggable targets. Building on the work by Calfee et al., enrichment of patient enrolment into focused clinical trials of novel endothelial-specific therapeutics using established biomarkers would appear to be a reasonable strategy to optimise patient outcomes.

Further, it is imperative that the heterogeneity between systemic and pulmonary vascular endothelium and between humans and animals is increasingly recognised. Developing better techniques to interrogate neutrophil-endothelial interactions in the lung would seem paramount; the continued development of live imaging in transgenic mice using fluorescent probes to label specific cell types and increased application of isolated perfused lung models as well as human ex vivo and in vivo models represent mechanisms to maximise the translation of preclinical data into effective therapeutics. It remains to be seen whether the so-called ‘lungs on a chip’, which combine biomimetic systems containing microfluidic channels lined by living human cells, will develop into tractable models for lung biology per se or specifically ARDS pathobiology. An IL-2-induced injury model recapitulated salient features of in vivo ARDS, which were attenuated by a novel TRPV4 antagonist. This technology has the potential to complement (if not replace) current ARDS research platforms, facilitating interrogation of hitherto underdeveloped aspects of lung endothelial biology and pharmacology in a coculture platform with biologically relevant cell types (alveolar epithelial cells, lung microvascular endothelial cells and leucocytes or platelets) exposed to physiologically relevant mechanical forces via a stretchable porous membrane. The applications of three-dimensional bioprinting for the study of lung biology similarly represents an enticing, if yet unrealised, prospect. Development of such innovative, humanised models coupled with the refinement of existing models will be central to the identification and testing of emerging therapeutics.

CONCLUSIONS

The pulmonary endothelium is increasingly seen as pivotal in both the progression and the resolution of ARDS and is therefore primed as a therapeutic target. Our understanding of endothelial biology, notably neutrophil-endothelial interactions in the lung vasculature, is a limitation to potential progress. Despite this, enhancement of endothelial barrier function, in particular, shows promise in preclinical models of ARDS and relevant late-phase human trials are imminent. Novel imaging techniques and innovative in vitro research platforms may facilitate translation of promising animal data into efficacious endothelial-specific therapies. Despite enthusiasm for their introduction, the use of cell-based therapies requires further characterisation of their phenotype, efficacy and safety. In the interim, the application of emerging technologies will assist the search for robust biomarkers of endothelial injury, which will inevitably enhance enrolment into future clinical trials of novel lung endothelial-targeted agents.
This work was supported by the Royal Brompton and Harefield NHS Foundation Trust, NIHR Respiratory Biomedical Research Unit, London, UK.

Collaborators Stefan Jovine.

Funding CS is a Wellcome Trust Postdoctoral Clinical Research Training Fellow (WT101692MA).

Competing interests CS was a co-investigator on a project grant funded by GlaxoSmithKline, which undertook preclinical assessment of the effects of a potential ARDS therapy on human neutrophils (2012–2014). MIG and CS have received consultancy fees from GlaxoSmithKline. MIG and AGP have had unrestricted project grant support from GlaxoSmithKline.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES


