During sepsis, acute lung injury (ALI) results from activation of innate immune cells and endothelial cells by endotoxins, leading to systemic inflammation through proinflammatory cytokine overproduction, oxidative stress, and intracellular Ca\(^{2+}\) overload. Despite considerable investigation, the underlying molecular mechanism(s) leading to LPS-induced ALI remain elusive. To determine whether stromal interaction molecule 1–dependent (STIM1-dependent) signaling drives endothelial dysfunction in response to LPS, we investigated oxidative and STIM1 signaling of EC-specific Stim1-knockout mice. Here we report that LPS-mediated Ca\(^{2+}\) oscillations are ablated in ECs deficient in Nox2, Stim1, and type II inositol triphosphate receptor (Itpr2). LPS-induced nuclear factor of activated T cells (NFAT) nuclear accumulation was abrogated by either antioxidant supplementation or Ca\(^{2+}\) chelation. Moreover, ECs lacking either Nox2 or Stim1 failed to trigger store-operated Ca\(^{2+}\) entry (SOCe) and NFAT nuclear accumulation. LPS-induced vascular permeability changes were reduced in EC-specific Stim1\(^{-/-}\) mice, despite elevation of systemic cytokine levels. Additionally, inhibition of STIM1 signaling prevented receptor-interacting protein 3–dependent (RIP3-dependent) EC death. Remarkably, BTP2, a small-molecule calcium release–activated calcium (CRAC) channel blocker administered after insult, halted LPS-induced vascular leakage and pulmonary edema. These results indicate that ROS-driven Ca\(^{2+}\) signaling promotes vascular barrier dysfunction and that the SOCe machinery may provide crucial therapeutic targets to limit sepsis-induced ALI.
Blockade of NOX2 and STIM1 signaling limits lipopolysaccharide-induced vascular inflammation

Rajesh Kumar Gandhirajan,1,2 Shu Meng,3 Harish C. Chandramoorthy,1,2 Karthik Mallilankaraman,1,2 Salvatore Mancarella,1 Hui Gao,4 Roshanak Razmpour,5 Xiao-Feng Yang,3 Steven R. Houser,4 Ju Chen,6 Walter J. Koch,2,3 Hong Wang,3 Jonathan Soboloff,1 Donald L. Gill,1 and Muniswamy Madesh1,2

1Department of Biochemistry, 2Center for Translational Medicine, 3Department of Pharmacology, 4Department of Physiology, Cardiovascular Research Center, and 5Department of Anatomy and Cell Biology, Temple University, Philadelphia, Pennsylvania, USA. 6Department of Medicine, UCSD, La Jolla, California, USA.

Introduction
The systemic inflammatory response in sepsis has devastating consequences resulting in high morbidity and mortality (1). It represents a major burden on the health care system, with more than 400,000 cases/year in the United States alone (1–4). Over the past decade, mortality from sepsis alone has remained greater than 25%, despite effective antimicrobial therapy. This highlights lack of understanding of the pathways operative in sepsis and the necessity for improved therapies. Impairment of pulmonary vascular integrity is a key feature in multiple pathological conditions, including acute lung injury (ALI), sepsis, lung inflammation, and ventilator-induced lung injury, each of which result in pulmonary edema (1, 5–7). Sepsis is a complex, serious medical condition consequent to an overwhelming immune response to infection. The systemic inflammatory response in sepsis can lead to rapid organ failure and death (1, 5). Bacterial endotoxin (LPS) ranks highest among risk factors contributing to ALI in sepsis (8). Endotoxins are known to activate innate immune responses, resulting in the production of a vast spectrum of inflammatory cytokines (1, 9). These proinflammatory cytokines are known to trigger vascular endothelial activation (5). The integrity of vascular endothelium is essential for controlling the flux of proteins, fluid, and immune cells across vessels into tissues. Systemic accumulation of LPS triggers leukocyte infiltration within the vascular wall and promotes vascular permeability (10). Therefore, maintenance of vascular integrity is crucial for vascular and tissue homeostasis. Although the LPS-induced signaling cascade has been widely studied in innate immune cells (11), the mechanisms mediating EC responses to LPS remain largely unknown.

Oxidative signaling and Ca2+ homeostasis are tightly linked cellular processes mediating control over signal transduction, metabolism, transcriptional regulation, cell proliferation, and cell death (12, 13). Oxidants are implicated in modulating intracellular Ca2+ pools through inositol 1,4,5-tris phosphate receptor (InsP3R) Ca2+ release channels and Ca2+ entry channels in the plasma membrane (14–16). STIM-induced Ca2+ entry through Orai channels is now established as an essential Ca2+ entry mechanism in non-excitable cell types (17–22). STIM proteins are Ca2+ store sensors and mediate the induction of cellular responses to a number of stress conditions, including elevated ROS, temperature changes, and hypoxia (14, 19, 23, 24). Although oxidants and Ca2+ are essential regulators of vascular signaling in pathophysiologic settings including innate inflammation (5), precisely how ECs respond to LPS remained unclear. Studies by us and others have demonstrated that ROS can modulate cytosolic Ca2+ signals through inositol 1,4,5-trisphosphate receptor (InsP3R) Ca2+ release channels in ECs (15). More recently, we revealed that ROS can induce STIM-mediated Ca2+ entry via Orai channels by activating STIM proteins through S-glutathionylation of an evolutionarily conserved N-terminal cysteine residue in the STIM1 protein (14). Although ROS overproduction...
is an established event upon LPS challenge, it remains unclear whether ROS/STIM1 signaling participates in TLR4-dependent EC activation, vascular permeability, and lung injury.

In most cells, the coordination of Ca²⁺ release and Ca²⁺ entry mechanisms gives rise to sustained Ca²⁺ oscillations essential for controlling cellular responses, including gene expression and cell fate (25). These responses are mediated by transcription factors, notably NF-kB (5) and NFAT (26). NFATs are members of a multi-gene Rel family of transcription factors. Nuclear localization of NFAT is primarily driven by Ca²⁺ oscillations mediated by a combination of InsP₃Rs and STIM/Orai channels, resulting in control of Ca²⁺-dependent transcription...
in many cell types (19, 26). Although the NFAT pathway is responsible for cytokine production in T cell activation, its role in EC proinflammatory molecule expression and vascular inflammation has not previously been established. Therefore, targeting ROS/STIM1 signaling pathways offers an alternate strategy for the development of new therapies against sepsis-related ALI. In this study, we reveal a crucial role for NOX2-dependent STIM1 activation in the control of the cytosolic oscillations that drive EC activation. We demonstrate the interdependence of ROS and Ca$^{2+}$ in eliciting proinflammatory signaling in ECs. Further, we show that LPS-mediated ALI is alleviated in EC-specific Stim1-knockout (Stim1$^{ΔEC}$) mice. We further show that post-administration of the Ca$^{2+}$ entry blocker N-(4-[3,5-bis(trifluoromethyl)-1H-pyrazol-1-yl]phenyl)-4-methyl-1,2,3-thiadiazole-5-carboxamide (BTP2) significantly alleviates pulmonary vascular inflammation and lung injury. Hence, we demonstrate the translational potential for a previously unstudied mechanism of EC activation.

**Figure 2**

Stim1$^{ΔEC}$ mice have normal pulmonary vasculature and endothelial migration. (A) NOX2 protein levels in ECs. (B) Representative images and (C) quantification of DHE fluorescence in ECs derived from wild-type and Stim1$^{ΔEC}$ mice. Scale bar: 20 μm. (D) Representative images and quantification of gap closure in ECs derived from wild-type and Stim1$^{ΔEC}$ mice at 24 hours. (E) Assessment of pulmonary vascular distribution by 2-photon imaging in 5-week-old litter-matched wild-type and Stim1$^{ΔEC}$ mice after FITC-dextran administration. Bar graph shows quantification of mean alveolar space from E. Scale bar: 100 μm. Data are mean ± SEM.
research article

Table 1
Breeding ratio and body weight of WT and Stim1ΔEC mice

<table>
<thead>
<tr>
<th>Sex</th>
<th>Breeding ratio</th>
<th>Fertility (%)</th>
<th>Genotype</th>
<th>Body weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male Stim1ΔEC</td>
<td>15/15</td>
<td>100</td>
<td>WT</td>
<td>28.06 ± 1.29</td>
</tr>
<tr>
<td>Female Stim1ΔEC</td>
<td>2/6</td>
<td>33</td>
<td>Stim1ΔEC</td>
<td>25.63 ± 1.68</td>
</tr>
</tbody>
</table>

Breeding ratio values indicate male Stim1ΔEC mice bred with female heterozygotes or female Stim1ΔEC mice bred with male heterozygotes. Mean ± SEM values of WT and Stim1ΔEC mice body weight are shown.

*P < 0.3 compared with WT mice.

Results

EC-specific Stim1-knockout mice preserve normal pulmonary vasculature and endothelial migration. To investigate the in vivo role of STIM1-dependent Ca2+ entry pathways in ECs, we generated EC-specific Stim1 conditional knockout mice (Stim1ΔEC) by Flox-Cre recombination and efficacy of the STIM1 ablation were confirmed by immunohistochemistry of aortic endothelium (Figure 1C) and immunoblotting of enriched pulmonary ECs (Figure 1D). To further verify whether STIM1 expression is normal in immune cells, we stained leukocytes from spleen of wild-type and Stim1ΔEC mice for phenotypic surface markers and intracellular STIM1 expression. STIM1 protein expression was normal in CD45+ and CD3+ lymphocytes (Figure 1E). For functional studies, we measured SOCe in ECs derived from Stim1ΔEC, VE-Cre, or Stim1Δ1/Δ1 mice and observed loss of SOCe in Stim1ΔEC mice but not in controls (Figure 1F). Notably, ER Ca2+ levels were lower in Stim1ΔEC when compared with VE-Cre or Stim1Δ1/Δ1 mice ECs, as measured by store depletion using thapsigargin (Figure 1G). Our results are consistent with lower ER Ca2+ levels in ECs derived from hyperglycemic mice due to the downregulation of STIM1 and SERCA3 expression (27). To examine whether loss of STIM1 alters NOX2-mediated ROS production, we measured NOX2 protein expression and superoxide production in Stim1ΔEC ECs. NOX2 protein expression and superoxide production remained unaltered in Stim1ΔEC ECs (Figure 2, A–C). Although Stim1ΔEC mice maintained relatively normal body weight without any gross phenotypic abnormalities (Table 1), Stim1ΔEC female mice displayed a reproductive defect when bred with male heterozygote mice (Table 1). Further characterization of Stim1ΔEC mice revealed that endothelial migration (Figure 2D) and pulmonary vascular distribution (Figure 2E) were normal when compared with those in wild-type mice. Together, these data show that ECs lacking STIM1 retain normal angiogenic potential and vascular integrity.

LPS-mediated lung inflammation is attenuated in EC-specific Stim1-knockout mice. We previously demonstrated that oxidants promote InsP3, R, and STIM1-dependent Ca2+ signaling and cell injury in LPS-challenged cells (14, 15). These findings led us to speculate that blockade of the Ca2+ permeation pathway could prevent LPS-induced lung inflammation and vascular injury. In Stim1ΔEC mouse lungs, the relative alveolar space distribution was similar to that in controls (Figure 2E and Figure 3A). LPS-induced lung injury studies showed that leukocyte infiltration was significantly reduced in Stim1ΔEC mice (Figure 3, A and B), despite systemic elevation of proinflammatory cytokines (Figure 3C). Additionally, we measured proinflammatory cytokine levels in BAL fluid obtained from control and Stim1ΔEC mice. Interestingly, BAL fluid cytokine levels were elevated in control but remained unaltered in Stim1ΔEC mice (Figure 3D). These data suggest that the lack of STIM1 in endothelium resulted in reduced endothelial activation despite systemic proinflammatory cytokine elevation.

To further explore whether endothelial Stim1 deletion limits LPS-induced pulmonary vascular permeability, we administered LPS in VE-Cre, Stim1Δ1/Δ1, and Stim1ΔEC mice. Immunoblotting for ICAM-1 protein expression in Stim1ΔEC lung sections revealed lower ICAM-1 expression levels when compared with VE-Cre or Stim1Δ1/Δ1 controls (Figure 4 A and B). We next assessed the BAL fluid accumulation and lung wet/dry ratio, which are indications of lung edema. Examination of BAL protein and lung wet/dry ratio showed that Stim1ΔEC mice were protected from LPS-induced inflammatory changes in the lung (Figure 4, C and D). Although increase in systemic proinflammatory cytokine levels was observed in Stim1ΔEC mice, the absence of leukocyte infiltration, BAL fluid, and change in lung weight, revealed that STIM1 was required for LPS-induced EC activation and lung inflammation. We then assessed the vascular integrity in Stim1ΔEC mice challenged with LPS. Interestingly, the vasculature in LPS-treated Stim1ΔEC mice, comparable to that in their untreated counterparts, was intact, whereas the vasculature was leaky in LPS-treated control (VE-Cre and Stim1Δ1/Δ1) mice (Figure 4, E and F). These findings suggest that EC STIM1 is necessary for pathological changes during inflammation.

STIM1-dependent Ca2+ signaling contributes to endothelial NFAT activation. We previously showed that inhibition of STIM1/Orai1-mediated Ca2+ entry prevented oxidative stress–induced cell death (14, 28). Since endothelial STIM1 deficiency prevents LPS-induced vascular permeability, we examined pulmonary vascular Ca2+ levels in situ. Lungs were isolated from vehicle- and LPS-treated wild-type mice after 20 hours. Lung slices were stained with the Ca2+ indicator Fluo-4 and the endothelial marker AcLDL (Figure 5A). Viable lung slices were subjected to multiphoton confocal imaging, and Ca2+ levels were measured. As expected, basal cytoplasmic Ca2+ levels were elevated in LPS-treated when compared with untreated wild-type mouse lung slices (Figure 5, A and B). To determine whether STIM1-dependent Ca2+ signaling was involved in LPS-induced endothelial Ca2+ elevation, we measured dynamic Ca2+ changes in primary ECs isolated from wild-type and Stim1ΔEC mice. Interestingly, LPS treatment triggered sustained Ca2+ oscillations in wild-type but not in Stim1ΔEC ECs (Figure 5C). Since Ca2+ oscillations are essential for NFAT nuclear translocation and transcriptional activation (29), we next assessed NFATC3-GFP translocation in wild-type and Stim1ΔEC ECs after LPS challenge. Consistent with our sustained Ca2+ oscillation data (Figure 5C), Stim1ΔEC ECs showed a significant reduction in nuclear accumulation of NFATC3-GFP compared with wild-type ECs (Figure 5, E and F). Further, we measured NFAT activity in wild-type and Stim1ΔshRNA knockdown (KD) ECs (Supplemental Figure 4A; supplemental material available online with this article; doi:10.1172/JCI65647DS1) after stimulation with LPS. LPS-induced NFAT luciferase activity was markedly reduced in Stim1ΔKD ECs when compared with wild-type ECs (Figure 5G). Similarly, the Ca2+ blocker BTP2 also near completely inhibited NFAT translocation upon LPS exposure (Supplemental Figure 1, A and B). Interestingly, NFAT-driven cytokine expression levels were downregulated in ECs derived from Stim1ΔEC mice (Figure 5H). Thus, these data suggest that STIM1-mediated Ca2+ entry is necessary for LPS-induced NFAT activation and inflammatory cytokine production.
gp91phox, InsP3RII, and STIM1 are necessary for LPS-induced endothelial Ca²⁺ oscillations. LPS is a potent inducer of ROS through TLR4 (30, 31). We have previously shown that in lymphocytes, LPS-induced oxidative stress alters Ca²⁺ signaling (14). It is plausible that similar events occur in pulmonary vascular endothelium following LPS challenge and trigger increased vascular permeability. To test this hypothesis, we treated wild-type murine pulmonary vascular ECs (MPMVECs) with LPS (1 μg/ml). MPMVECs stably expressing the hydrogen peroxide (H₂O₂) sensor HyPer-Cyto exhibited a significant elevation of H₂O₂ levels after LPS challenge (Supplemental Figure 2, A and B). As expected, LPS stimulation triggered asynchronous Ca²⁺ oscillations in MPMVECs when compared with the untreated control cells (Supplemental Figure 2, A and B). Interestingly, we found that pretreatment with the NOX2 inhibitor diphenyleneiodonium (DPI) abrogated Ca²⁺ oscillations (Supplemental Figure 2, E and H). We examined whether LPS promotes Ca²⁺ oscillations in other cell types, including fibroblasts and lung epithelial and macrophage cell lines. Interestingly, LPS was not able to stimulate Ca²⁺ oscillations in fibroblasts and lung alveolar epithelial cell lines (Supplemental Figure 2, J and K). However, as expected, the J774.A1 macrophage cell line elicited basal Ca²⁺ oscillations due to constitutive phagocytic NOX2 activity (Supplemental Figure 2J). Additionally, LPS-induced Ca²⁺ oscillations were enhanced in J774.A1 macrophages, which are DPI sensitive (Supplemental Figure 2, K and L). We next examined whether extracellular Ca²⁺ entry is required for LPS-induced Ca²⁺ oscillations. Either chelating extracellular Ca²⁺ using EGTA or blocking Ca²⁺ entry using BTP2 prevented LPS-induced Ca²⁺ oscillations (Supplemental Figure 2, F–H). These data collectively suggest that endogenous ROS production is essential but requires Ca²⁺ entry to trigger EC Ca²⁺ oscillations.

Figure 3
Genetic ablation of Stim1 in endothelium limits LPS-induced leukocyte infiltration and BAL inflammatory cytokines. VE-Cre, Stim1⁰⁰, and Stim1⁴EC mice were challenged with LPS (1 mg/kg; i.p.). Saline was used as a vehicle control. (A) Representative photomicrographs of H&E-stained lung sections. (B) Quantification of alveolar leukocyte infiltration. (C) IL-1α, IL-1β, IL-2, IL-6, TNF-α, and G-CSF were measured in sera from mice. (D) IL-1α, IL-1β, IL-2, IL-6, TNF-α, and G-CSF were measured in BAL fluid from VE-Cre, Stim1⁰⁰, and Stim1⁴EC mice. Data are mean ± SEM. *P < 0.05, **P < 0.01, ***P < 0.001.
We further verified the observed pharmacological effects in ECs lacking the NOX2 subunit gp91phox. Similarly, gp91phox–/– ECs failed to elicit LPS-induced Ca2+ oscillations (Supplemental Figure 3, C and F, and Supplemental Videos 3 and 4). However, treatment of ECs derived from wild-type mice with LPS triggered Ca2+ oscillations (Supplemental Figure 3, A, B, and F). Sustained Ca2+ oscillations operate through the coordinated activation of both store-derived Ca2+ release and store-operated Ca2+ entry channels (25, 32). In non-excitable cells such as ECs, InsP3Rs are the major ER Ca2+ release channels activated by InsP3 produced when phospholipase C–coupled (PLC-coupled) receptors are activated (33). We have previously shown that ROS evokes intracellular Ca2+ mobilization in ECs (15, 34). To identify the intracellular Ca2+ release component in LPS-induced Ca2+ oscillations, we treated wild-type MPMVECs with LPS in the presence of the PLC inhibitor U73122 or the potent InsP3R inhibitor xestospongin B (XesB), and the results revealed suppression of Ca2+ oscillations mediated by both LPS and the glutathione-depleting agent L-buthionine sulfoximine (BSO) (our unpublished observations). Interestingly, similar to Stim1ΔEC ECs (Supplemental Figure 3, E and F, and Supplemental Videos 5 and 6), ECs lacking only InsP3R II also did not show any Ca2+ oscillations after LPS treatment (Supplemental Figure 3, D and F). These results suggest that LPS-induced NOX2-mediated Ca2+ oscillations in ECs require InsP3RII-mediated Ca2+ release in addition to STIM1-dependent Ca2+ entry.

**Figure 4**

*Stim1* deletion in endothelium attenuates LPS-induced pulmonary vascular dysfunction. (A) Representative immunohistochemistry images of ICAM-1 using PE in lung sections from treated mice. Scale bar: 20 μm. (B) Quantification of ICAM-1 expression based on fluorescence intensity. (C) BAL protein content and (D) lung weight changes are a functional measure of EC activation associated with increased vascular permeability. (E) A 0.1- to 0.15-ml bolus of FITC-dextran (70 kDa, 5% w/v) was injected into the animals via facial vein. Anesthetized animals were placed under an intravital 2-photon imaging system, and images were acquired. Vascular permeability was assessed based on fluorescence intensity in the extravascular space. Scale bar: 100 μm. (F) Quantification of extravascular FITC-dextran fluorescence intensity. Data are mean ± SEM. **P < 0.01, ***P < 0.001.
Figure 5
STIM1-mediated NFAT activity is necessary for LPS-induced proinflammatory gene expression in ECs. (A) Ex vivo imaging of pulmonary vascular Ca\(^{2+}\) levels in freshly prepared lung slices from wild-type mice challenged with LPS (1 mg/kg) for 20 hours. AcLDL was used as an endothelial marker. Scale bar: 50 μm. (B) Quantification of Fluo-4 fluorescence was measured from multiple regions of the lung slices. ECs from wild-type and Stim1\(^{ΔEC}\) mice were challenged with LPS (1 μg/ml) for 16 hours. ECs were loaded for 30 minutes with Fluo-4/AM. (C) Representative traces from wild-type and Stim1\(^{ΔEC}\) ECs. (D) Quantification of oscillation frequency. ECs from wild-type and Stim1\(^{ΔEC}\) mice were transduced with adenovirus encoding NFATc3-GFP for 36 hours. Following adenoviral transduction, ECs were treated with LPS for 16 hours. (E) Representative images showing NFAT nuclear translocation. Scale bar: 20 μm. Arrowheads indicate the nuclear translocated NFAT. (F) Quantification of nuclear NFAT-positive cells. (G) NFAT-dependent luciferase activity was measured in wild-type and Stim1 KD ECs 16 hours after LPS (1 μg/ml) treatment. (H) Quantification of cytokine protein expression in wild-type and Stim1\(^{ΔEC}\) ECs treated with LPS for 16 hours. Data are mean ± SEM. *P < 0.05, **P < 0.01, ***P < 0.001.
Figure 6

NOX2-derived ROS promotes STIM1-dependent Ca\(^{2+}\) entry and NFAT activation after LPS stimulation. Wild-type, gp91\(^{phox-/-}\), and Stim1 KD ECs were treated with LPS (1 \(\mu\)g/ml) for 16 hours. (A–C) Extracellular Ca\(^{2+}\) was removed for 5 minutes prior to assessment of SOCe activity in (A) wild-type, (B) gp91\(^{phox-/-}\), and (C) Stim1 KD ECs. Wild-type, gp91\(^{phox-/-}\), and Stim1 KD ECs were transduced with adenovirus encoding NFATc3-GFP for 36 hours and then treated with LPS (1 \(\mu\)g/ml) for an additional 16 hours. (D) Quantification of nuclear NFAT-positive cells. (E) gp91\(^{phox-/-}\) cells loaded with Fluo-4 were treated with thapsigargin (2 \(\mu\)M) under nominally Ca\(^{2+}\)-free conditions, followed by addition of 2 mM Ca\(^{2+}\) where indicated to assess SOCe. (F) Flu-4–loaded gp91\(^{phox-/-}\) ECs were treated with (right) or without (left) superoxide (xanthine + xanthine oxidase [O\(_2\)-]; 10 nmol/min). (G) gp91\(^{phox-/-}\) ECs were transduced with AdNFATc3-GFP for 36 hours, and nuclear NFATc3-GFP was quantified after O\(_2\)- exposure. Scale bar: 20 \(\mu\)m. (H) gp91\(^{phox-/-}\) ECs were transfected with either STIM1 wild-type or STIM1 C56A mutant constructs. Extracellular Ca\(^{2+}\) was removed for 5 minutes prior to the measurement of SOCe activity in Flu-4–loaded ECs. (I) gp91\(^{phox-/-}\) ECs transiently expressing either wild-type or STIM1 C56A plasmids were transduced with AdNFATc3-GFP for 36 hours, and nuclear NFATc3GFP was quantified. Scale bar: 20 \(\mu\)m. All data are the mean ± SEM of 3 independent experiments, each experiment consisting of triplicate analyses of 20–30 cells. **P < 0.01, ***P < 0.001.
We and others have previously shown that paracrine-derived superoxide triggers Ca\textsuperscript{2+} influx in ECs (16, 36, 37). To examine whether the loss of \textit{gp91 phox} impacts endothelial Ca\textsuperscript{2+} entry, we pretreated ECs with thapsigargin and measured Ca\textsuperscript{2+} entry. ECs exhibited robust store-operated Ca\textsuperscript{2+} entry, indicating that loss of \textit{gp91 phox} does not account for their failure to trigger LPS-induced Ca\textsuperscript{2+} oscillations, Ca\textsuperscript{2+} entry, and/or NFAT activation (Figure 6E and see Figure 6, B and D). The specificity of the \textit{gp91 phox} ablation on NOX2 function was further revealed in experiments showing that paracrine-derived superoxide triggers both Ca\textsuperscript{2+} oscillations (Figure 6F and Supplemental Video 7) and NFAT activation (Figure 6G) in \textit{gp91 phox}–/– ECs. Finally, we asked whether ROS-independent activation of STIM1 promotes SOCe and NFAT nuclear accumulation. Ectopic expression of constitutively active STIM1 C56A but not wild-type STIM1 triggered constitutive Ca\textsuperscript{2+} entry (Figure 6H and ref. 14) and NFATc3-GFP nuclear translocation in \textit{gp91 phox}–/– ECs (Figure 6I). These results demonstrate that NOX2-dependent STIM1 activation is a crucial step for LPS-induced Ca\textsuperscript{2+} entry and NFAT activation in ECs.

\textit{STIM1 signaling contributes to pulmonary vascular EC death}. Ca\textsuperscript{2+} is an important second messenger in many cell types, with pleiotropic effects on cell survival. Importantly, in ECs, Ca\textsuperscript{2+} signaling is crucial for the maintenance of barrier function and vascular tone (5). Having demonstrated that \textit{Stim1} \textit{fl/fl} mice are protected from inflammatory responses in lung, we speculated that STIM1 may contribute to EC death during inflammatory insults. Therefore, \textit{Stim1} KD ECs were treated with LPS or BSO as a positive control and stained with Annexin V/PI, a marker for cell death. LPS triggered significant cell death in wild-type ECs; however, ECs lacking STIM1 were protected from LPS-induced cell death (Figure 7, A and B). We next examined whether inhibition of NOX2-derived ROS also prevents LPS-induced cell death. Similar to \textit{Stim1} \textit{fl/fl} ECs, ECs lacking \textit{gp91 phox} were protected against LPS-induced cell death (Figure 7, A and B). We next extended our in vitro studies to determine whether pulmonary vascular endothelial injury is suppressed by CRAC channel inhibition in the LPS-induced inflammation model. First, we addressed this in an acute setting in which mice were administered LPS (1 mg/kg i.p.) for 24 hours. We performed immunolabeling of receptor-interacting protein 3 (RIP3), a necrotic cell death marker (38), in lung sections from wild-type and \textit{Stim1} \textit{fl/fl} control mice. EC-specific STIM1 ablation attenuated the otherwise increased RIP3 expression in VE-Cre and \textit{Stim1} \textit{fl/fl} control mice, indicating the essential role played by STIM1-mediated Ca\textsuperscript{2+} entry in EC death (Figure 8, A and B). To further examine the role of CRAC channel in EC death, we evaluated the effect of BTP2 in LPS-induced vascular RIP3 expression in vivo. Mice were injected with BTP2 (1 mg/kg i.p.) or vehicle 2 hours after LPS challenge. Lung sections were subjected to immunolabeling for RIP3, and the fluorescence intensity was measured in pulmonary vasculature. Importantly, blockade of Ca\textsuperscript{2+} entry by BTP2 significantly inhibited the vascular RIP3 protein expression resulting from LPS challenge (Figure 8, C and D). Thus, we propose that TLR4/NOX2/STIM1 signaling provides a potential mechanism by which LPS, at least in part, promotes vascular inflammation (Figure 8E).
Store-operated Ca\(^{2+}\) channel inhibition protects against LPS-induced lung injury. Pulmonary edema resulting from Gram-negative bacterial infection is the first indication of organ failure and the most common cause of sepsis-related death. Recent evidence from in vitro studies and our Stim\(^{1\Delta EC}\) mouse model data suggest that LPS-induced vascular permeability and lung inflammation are partly driven by a pulmonary endothelial NOX2/STIM1 pathway. To examine the therapeutic potential of this mechanism, we tested the highly effective small-molecule Ca\(^{2+}\) channel blocker BTP2 in an animal model of sepsis (39). Wild-type mice were administered LPS (1 mg/kg; i.p.) for 24 hours. Mice were also injected with BTP2 (1 mg/kg i.p.) or vehicle 2 hours after LPS challenge. LPS challenge markedly increased the serum proinflammatory cytokine levels within 6 hours (Figure 9A), followed by leukocyte infiltration at 24 hours, indicating the acute nature of LPS-induced lung injury (Figure 9, B and C). Interestingly, BTP2 administration not only prevented LPS-induced proinflammatory cytokine production (Figure 9A), but also reduced leukocyte infiltration in mouse lung (Figure 9, B and C). BTP2 alone had no effect on either serum cytokine levels or leukocyte infiltration (Figure 9, A–C). These data

Figure 8
LPS-induced RIP3 expression is downregulated in Stim\(^{1\Delta EC}\) mice. (A) Immunohistochemical labeling of RIP3 in lung endothelium from VE-Cre, Stim\(^{1\Delta EC}\), and Stim\(^{1\Delta EC}\) mice 24 hours after LPS challenge. Scale bar: 30 \(\mu\)m. (B) Quantification of RIP3 fluorescence intensity in A. (C) Immunohistochemical labeling of RIP3 in lung endothelium from C57BL/6 wild-type mice after i.p. delivery of saline (vehicle) or LPS (1 mg/kg; 24 hours). BTP2 (1 mg/kg) was delivered i.p. 2 hours after LPS challenge. Scale bar: 20 \(\mu\)m. (D) Quantification of RIP3 fluorescence intensity in C. (E) Proposed scheme depicts signal transduction cascade in LPS-induced vascular dysfunction during ALI. Data are mean ± SEM. **P < 0.01.
Figure 9
BTP2 attenuates LPS-induced lung inflammation and vascular endothelial integrity loss. C57BL/6 mice were challenged with LPS (1 mg/kg; i.p.), and BTP2 (1 mg/kg; i.p.) was delivered 2 hours after challenge. Saline was used as a vehicle. Samples were collected after 24 hours. (A) IL-1α, IL-1β, IL-2, IL-6, TNF-α, and G-CSF were measured in sera from mice. (B) Representative photomicrographs of H&E-stained lung sections. Original magnification, ×400. (C) Quantification of alveolar leukocytes infiltration. (D) Representative Western blot of ICAM-1 induction in ECs treated with LPS and/or BTP2. (E) Representative immunohistochemistry images of ICAM-1 using PE in lung sections from treated mice. Scale bar: 20 μm. (F) Quantification of ICAM-1 fluorescence intensity. (G and H) BAL protein content (G) and lung weight (H) changes are a functional measure of EC activation associated with increased vascular permeability. (I) A 0.1- to 0.15-ml bolus of FITC-dextran (70 kDa, 5%w/v) was injected into the animals via facial vein. Anesthetized animals were placed under an intravital 2-photon imaging system, and images were acquired. Vascular permeability was assessed based on fluorescence intensity in the extravascular space around 4–5 regions per mouse. Scale bar: 100 μm. (J) Quantification of extravascular FITC-dextran fluorescence. Cumulative data are the mean ± SEM of triplicates and are representative of 3 independent experiments with 3–6 per group as indicated.

*P < 0.05, **P < 0.01, ***P < 0.001.
show that 1 mg/kg BTP2 can abolish the systemic cytokine elevation resulting from CRAC channel activation. Vascular ECs sense a wide range of both physiological and pathological signals through various membrane-bound apical surface molecules. ICAM-1 is one such well-characterized molecule and is known to be elevated upon LPS challenge. We next evaluated whether Ca\(^{2+}\) entry blockade prevents accumulation of the vascular endothelial inflammatory marker ICAM-1. The increased expression of ICAM-1 protein by LPS exposure was inhibited in ECs treated with 5 \(\mu\)M BTP2 (Figure 9D). Similarly, BTP2 administration in LPS-treated mice led to significant inhibition of ICAM-1 protein expression in arterioles/venules of mice lung sections (Figure 9, E and F). The effect of BTP2 in LPS-induced lung injury reinforces the role of STIM1 in vascular inflammation.

LPS-induced vascular leakage leads to an increase in BAL fluid content (5); however, the role for Ca\(^{2+}\) entry in this response has not been established. We next evaluated the effect of SOCE channel blockade on the increased BAL protein accumulation and pulmonary edema resulting from LPS challenge. The increases in both BAL protein content and lung wet/dry ratio was inhibited in mice treated with 1 mg/kg BTP2 (Figure 9, G and H). Notably, BTP2 delivery alone had no effect on mouse lung wet/dry weight ratio but moderately elevated BAL protein levels in vehicle-treated controls (Figure 9 G and H). To evaluate the BTP2 effect on vascular integrity in vivo, we performed live vascular imaging using intravital multiphoton microscopy (see Methods for details). Interestingly, the loss of vascular integrity in LPS-challenged mouse lung as seen both qualitatively (Figure 9I) and quantitatively (Figure 9J) by extravascular FITC-dextran, was abrogated in the BTP2-treated group. Together, these results suggest that SOCE channel blockade is effective in preventing LPS-induced pulmonary vascular permeability and lung edema.

**Discussion**

Vascular endothelial dysfunction is an established event in acute inflammation (40–42). Upon bacterial insult, both autocrine- and paracrine-derived ROS affect the endothelium, leading to altered gene expression and protein modification, resulting in organ failure (43). We have shown previously that paracrine-derived ROS activates EC Ca\(^{2+}\) mobilization (15). However, what remained unclear is how autocrine-derived ROS-triggered Ca\(^{2+}\) oscillations could lead to acute inflammation–induced EC dysfunction. The present study investigated the possible effects of inhibiting ROS-induced Ca\(^{2+}\) signaling and, further, the effects of limiting Ca\(^{2+}\) signaling pathways in EC dysfunction. Importantly, we elucidated the role of STIM1 in EC dysfunction without altering the ROS signaling pathway that participates in microbical activity. Using this unique model, we detailed the tightly coupled roles played by NOX2-derived ROS and Ca\(^{2+}\) signaling in LPS-induced endothelial activation and the progression to ALI.

LPS is a major component of the bacterial cell wall widely used to induce ALI in murine models (41). LPS-challenged mice show typical pathological evidence of ALI, including increased circulating inflammatory cytokine levels, elevated pulmonary EC activation, higher vascular permeability, and increased alveolar fluid accumulation. ROS overproduction in ECs has been shown to contribute to LPS-induced ALI (44). Although upstream signaling pathways such as the PLC/PKC/P38K axis are reported to trigger LPS-induced ROS in macrophages (45) and ECs (46), ROS-driven signaling pathways that lead to EC death remain elusive. Our previous investigations showed that ROS production during LPS treatment plays a crucial role in the regulation of Ca\(^{2+}\) signaling, which can be prevented by antioxidant supplementation (14). Here, we show that LPS-mediated NOX2-dependent oxidative stress evokes cytosolic Ca\(^{2+}\) oscillations in ECs (Figure 5 and Supplemental Figures 2 and 3). Inhibition of NOX2 prevented LPS-induced Ca\(^{2+}\) oscillations, supporting our hypothesis that ROS is an essential trigger for LPS-mediated Ca\(^{2+}\) oscillations. However, depletion of extracellular Ca\(^{2+}\) or blockade of Ca\(^{2+}\) channels abrogated Ca\(^{2+}\) oscillations without interfering with ROS elevation in ECs. Similarly, depletion of glutathione using BSO to increase ROS gave rise to a sustained pattern of Ca\(^{2+}\) oscillations (our unpublished observations). Consistent with this, it has been proposed that cytosolic Ca\(^{2+}\) oscillations in ECs are induced by exogenous delivery of oxidants, hypoxia/reoxygenation, or S-glutathionylation (16, 47, 48).

LPS-induced ROS in ECs triggers ER Ca\(^{2+}\) release via PLC activation (16, 33), which is the initial trigger for Ca\(^{2+}\) oscillations. Interestingly, we found that InsP\(_3\)RI is uniquely required to maintain LPS-induced Ca\(^{2+}\) responses, despite the presence of both InsP\(_3\)RI and InsP\(_3\)RII in ECs. This reflects remarkably distinct InsP\(_3\)R specificity from classical GPCR agonist-induced Ca\(^{2+}\) oscillations which require InsP\(_3\)RI (49). These findings indicate that whereas the 3 distinct InsP\(_3\)R subtypes may all be capable of mediating Ca\(^{2+}\) oscillations, activators selectively engage specific InsP\(_3\)R subtypes. In addition to InsP\(_3\)R subtype specificity, maintenance of Ca\(^{2+}\) oscillations is shown to require SOCE (25, 32). SOCE requires STIM1, the ER luminal Ca\(^{2+}\) sensor, which, upon Ca\(^{2+}\) store depletion, translocates into ER/plasma membrane junctions and couples to activate Orai1 (50) and possibly transient receptor potential channels (TRPCs) (51, 52). However, we recently revealed that STIM1 can act independently of ER Ca\(^{2+}\) as a ROS sensor to induce Ca\(^{2+}\) entry (14). Our results using STIM1 C56A mutant constructs showed constitutive Ca\(^{2+}\) entry and NFAT activation in gp91phox–/– ECs (Figure 6, H and I). Hence, STIM1 can be engaged by ROS during ALI through two distinct mechanisms: InsP\(_3\)-mediated ER Ca\(^{2+}\) depletion and ROS-mediated STIM1 activation.

Agonist-induced Ca\(^{2+}\) oscillations influence a multitude of signaling pathways (29, 53). Ca\(^{2+}\) oscillations are known to alter inflammatory cytokine expression by differentially activating transcription factors including NFAT and NF-\(\kappa\)B (29). While the role of NF-\(\kappa\)B in LPS signaling is well established (54, 55), however, our study reveals an alternate inflammatory pathway that requires STIM1-dependent NFAT activity in ECs (Figure 5). Since NFAT mediates TNF-\(\alpha\) upregulation, our findings uncover a central role for Ca\(^{2+}\) in LPS-induced necrotic cell death. We further demonstrate that RIP3 upregulation is dependent on Ca\(^{2+}\) signals that are linked to LPS-induced necroptosis, consistent with previous findings (38).

A major finding in the present study is that post-insult delivery of BTP2 significantly lowers vascular permeability and lung edema. BTP2 is an enticing therapeutic candidate, as it inhibits SOCE without altering baseline intracellular Ca\(^{2+}\) levels, suggesting that it does not affect unstimulated cells. Furthermore, mice can tolerate a dosage of up to 30 mg/kg without any systemic toxicity (39). Although BTP2 inhibits the function of CRAC, TRPC3, and TRPC5 channels, while activating TRPM4 channels (56–58), using Sttim1c mice, we reveal STIM1-mediated Ca\(^{2+}\) entry as the critical contributor to LPS-induced EC activation and necrotic cell death, the key events in the initiation of ALI. These findings add to a growing list of pathophysiological conditions that are negatively contributed to by STIM1-mediated Ca\(^{2+}\) entry, including...
arterial thrombosis in ischemic brain infarction (59) and hypoxic damage to neurons (60). In contrast, STIM1/Orai1-dependent SOCMe is required for T and B cell activation (61), and mutations in STIM1 result in immunodeficiency and autoimmune syndromes (62). Recently, a type 1 diabetic mouse model study reported that downregulation of STIM1 and SERCA3 in coronary ECs enhanced the ER Ca\(^{2+}\) leak and store depletion (27). This is in agreement with our work demonstrating a requirement of STIM1 for ER Ca\(^{2+}\) homeostasis. Although STIM1 is necessary for endothelium-dependent relaxation, in our model system, STIM1-dependent Ca\(^{2+}\) signaling is contributing to vascular inflammation. These distinct and cell type–dependent roles for STIM1 highlight the need for future investigations directed at defining the contributions of STIM1 to other physiological and pathophysiological conditions.

In conclusion, our cellular studies showing ROS-dependent Ca\(^{2+}\) mobilization in ECs establish STIM1-mediated Ca\(^{2+}\) signaling as a crucial event in vascular inflammation during ALI. Future investigations must define the specific STIM1-mediated target machinery in order to design effective therapies to alleviate sepsis and ALI. While Stim1\(^{-/-}\) mice displayed normal baseline characteristics up to 8 weeks, future studies are necessary to understand the role of STIM1 in aging, cardiovascular, and chronic lung diseases. Although Orai channels are the major STIM targets, new information reveals the additional STIM/Orai complex regulators including POST, junctate, SARAF, and CRACR2A (19, 63–66) could also be considered as potential therapeutic targets. Importantly, therapeutic strategies targeting the Ca\(^{2+}\) signaling machinery have great advantage over antioxidant-based strategies, since they do not interfere with the microbicidal role of ROS.

Methods

Cell culture. MPMVECs were cultured in DMEM (Invitrogen) supplemented with 10% FBS, Glutamax (Invitrogen), 1% antibiotics, and 0.05% EC growth supplement (Upstate). Stim1 KD MPMVECs were maintained in DMEM with 10% FBS, 1% antibiotics, and 0.05% EC growth supplement Glutamax (1%) and puromycin (2 μg/ml, Invitrogen). MPMVECs stably expressing the ROS sensor HyPer-Cyto (Eurowgen) were maintained as above but in the presence of G418 (400 μg/ml Invitrogen). MEFs and an alveolar epithelial carcinoma cell line (A549) were maintained in DMEM supplemented with 10% FBS, 1% Glutamax, and 1% antibiotics. Murine macrophage (J774A.1) cell line was maintained in RPMI-1640 medium supplemented with 10% FBS, 1% Glutamax, 1% HEPES (Invitrogen), 1% sodium pyruvate (Invitrogen), 1% non-essential amino acids (Invitrogen), and 1% antibiotics.

Lungs from wild-type, Stim1\(^{+/+}\), Stim1\(^{+/}\), and VE-Cre mice were harvested, finely minced, and digested in 10 ml collagenase type II (2 mg/ml, Roche). Isolated cells were incubated with anti–PECAM-1 (1:1,000, eBioscience), and ECs bound with antibody were magnetically separated with mouse Anti-Rat Kappa Microbeads (Miltenyi Biotec), according to the manufacturer’s instructions.

Generation of stable Stim1 KD ECs. Lentiviruses were generated using 5 lentiviral shRNAs targeting different regions of Stim1 (MISSION shRNA NM_002467; Sigma-Aldrich) as previously described. ECs transduced with Stim1 specific lentiviruses (0.3 MOI) were selected with puromycin (2 μg/ml) for 6 days. After puromycin selection, clones were expanded, and STIM1 protein expression was quantified by immunoblotting using β-actin as loading control.

Measurement of [Ca\(^{2+}\)]\(_{i}\) mobilization. ECs adherent to 25-mm-diameter glass coverslips were loaded with the cytosolic Ca\(^{2+}\) indicator Fluo-4/AM (5 μM, Invitrogen) at room temperature for 30 minutes in extracellular medium (ECM) containing 121 mM NaCl, 5 mM NaHCO\(_3\), 10 mM Na-HEPES, 4.7 mM KCl, 1.2 mM KH\(_2\)PO\(_4\), 1.2 mM MgSO\(_4\), 2 mM CaCl\(_2\), 10 mM glucose, and 2.0% BSA, pH 7.4, in the presence of 100 μM sulphoraphane and 0.003% pluronic acid. After dye loading, the cells were washed and resuspended in the experimental imaging solution (ECM containing 0.25% BSA) and images were recorded every 3 seconds at 488-nm excitation using the Zeiss LSM510 META confocal imaging system with a x40/1.3 NA objective at room temperature. Cytosolic Fluor-4 changes were normalized and presented as F/Fo. To assess Ca\(^{2+}\) entry, Ca\(^{2+}\) free ECM was used in conjunction with 0.5 mM EGTA; 2 mM Ca\(^{2+}\) was added as indicated. Images were analyzed and quantified using ImageJ (NIH) or Zen 2009 (Zeiss) (15).

ROS measurements. MPMVECs stably expressing HyPer-Cyto (67, 68) — a mammalian expression vector encoding a fluorescent sensor, HyPer, that localizes in the cytoplasm and specifically senses submicromolar concentrations of H\(_2\)O\(_2\) — were treated with LPS or BSO for 16 hours, and confocal images were obtained with a Zeiss LSM510 using a x40/1.3 NA objective at room temperature and using a 488-nm laser at 2.5% power. Fluorescence was quantified using ImageJ as previously described (68). Alternatively, cells were loaded with H2DCFDA (10 μM) for 30 minutes at 37°C and images obtained as described above.

Immunoblot analysis. Cells were lysed in 1x RIPA lysis buffer (Pierce) supplemented with 0.5 mM DTT and 1x protease inhibitor cocktail (Roche). Protein determination was carried out using the Bradford method. Lysates were then heat at 90°C for 10 minutes and centrifuged briefly for 1 minute. Equivalent amounts of protein were resolved by NuPAGE 4%–12% Bis-Tris Gel (Invitrogen), transferred to nitrocellulose membranes, and immunoblotted using iBlot (Invitrogen). Membranes were probed with primary antibodies anti-STIM1 (44/GOK; BD Biosciences; 1:1,000), anti-gp91phox (53/gp91 [phox]; BD Biosciences; 1:1,000), anti-InsP\(_3\)RI (C-20; Santa Cruz Biotechnology Inc.; 1:1,000), anti-InsP\(_3\)RII (2/1P3R-3; BD Biosciences; 1:1,000), anti-InsP\(_3\)R (C-20; Santa Cruz Biotechnology Inc.; 1:500), anti-ICAM-1 (G-5; Santa Cruz Biotechnology Inc.; 1:500), and anti-β-actin (N-21; Santa Cruz Biotechnology Inc.; 1:500); and secondary antibodies goat anti-rabbit and anti-mouse conjugated to horse radish peroxidase (Santa Cruz Biotechnology Inc.; 1:2,000) were used and visualized with enhanced ECL substrate (Amersham).

Annexin V binding and PI staining. To assess the externalization of phosphatidylserine in the plasma membrane as marker for early stage of apoptosis, ECs adherent to 25-mm-diameter glass coverslips were incubated with the conjugate Annexin V–Alexa Fluor 488 (Invitrogen, 1 μg/ml) and propidium iodide (PI; Invitrogen; 0.5 μg/ml) for 15 minutes in Annexin V binding buffer (Invitrogen). Annexin V– and PI-stained cells were visualized by a Zeiss LSM510 confocal imaging system using a x40 oil objective and later quantified.

AdNFATc3 translocation assay. Recombinant adenovirus encoding NFATc3-GFP was used to evaluate nuclear translocation in cultured cells. Cells were infected with NFATc3-GFP (100 MOI) for 36 hours. Cells were then treated with LPS (1 μg/ml) or BSO (500 μM; Sigma-Aldrich) under different conditions for an additional 16 hours. Confocal monolayer snapshots were obtained with a Zeiss LSM 510 META at x40/1.3 NA objective, using a 488-nm laser. Cells with nuclear NFATc3-GFP were manually counted in 10 different monolayers and data expressed as percent nuclear translocation under the conditions indicated.

Luciferase assay. 10\(^6\) ECs were transfected with 4 μg of luciferase reporter plasmids with or without binding elements for NFAT in 96-well plates using Mirus LT-1 transfection reagent. After 36 hours, cells were stimulated with LPS (1 μg/ml) for an additional 24 hours. The cells were then lysed using 50 μl of 1x passive lysis buffer (Promega). The luciferase activity was detected using the Bright-Glo Luciferase Assay System (Promega) according to the manufacturer’s instructions (Victor x5 luminesmeter; PerkinElmer). Values were normalized with appropriate controls.
Generation of Stim1ΔEC mice and animal experiments. Stim1ΔEC mice were generated by breeding male Stim1fl/fl mice (69) with female B6.C3-Tg(Cdh5-Cre)7Mia/J (VE-Cre) mice (stock 006137, The Jackson Laboratory). Stim1ΔEC knockout mice were born with no developmental defects and were apparently healthy into adulthood. Germline transmission was confirmed by genotyping of DNA obtained from ear clips. EC-specific knockout of Stim1 expression was confirmed by protein detection by Western blot analysis in freshly isolated ECs from lung tissues and double staining using anti-CD31 (clone 390; eBiosciences; 1:50) and anti-STIM1 (44/GOK; BD Biosciences; 1:100) in aorta sections by immunohistochemistry. For LPS studies, C57BL/6 wild-type, Stim1ΔEC, Stim1fl/fl, and VE-Cre mice were i.p. administered LPS (E. coli O111:B4; Sigma-Aldrich; 1 mg/kg) or vehicle (sterile PBS). Blood samples were collected 6 hours later via the retro-orbital route for ELISA. In experiments using the small-molecule Ca2+ entry blocker BTP2 (EMD4Biociences; 1 mg/kg), an equal volume of vehicle control (DMSO) was administered i.p. 2 hours after LPS administration. Animals were euthanized, and lung tissues were then subjected to histological analysis at 24 hours.

Flow cytometry. Fluorochrome-tagged antibodies CD45 (50-F11) and CD3 (17A2) (eBioscience); rabbit STIM1 antibody (Sigma-Aldrich; catalog S6072); and goat anti-rabbit Alexa Fluor 488 secondary antibodies (Invitrogen) were used for surface and intracellular staining. Spleen lymphocytes from wild-type and Stim1ΔEC mice were first stained for surface markers, followed by STIM1 intracellular staining. Aqua LIVE/DEAD Fixable Dead Cell Stain (L34957, Molecular Probes, Invitrogen) was used to gate live cells. Samples were acquired on LSR II analyzers (BD Biosciences) and data analyzed using FlowJo software (Tree Star). Lymphocytes were gated with surface markers and assessed for STIM1 expression.

Endothelial migration assay. Wild-type and Stim1ΔEC ECs were seeded at a density of 1.0 × 104 cells/well in 6-well plates overnight to produce a confluent monolayer. A uniform 1.8-mm scratch running the entire length of the well was created using a sterile 200-μl tip. The wells were washed 3 times with PBS to remove the cell debris, and 2 ml fresh complete endothelial growth medium was added. After 24 hours, ECs were washed and fixed with CAMCO Quick Stain II as per the manufacturer’s instructions. The wells were photographed at multiple locations using a phase contrast microscope with x4 objectives. Migration was quantitated using ImageJ software (70), and the results were expressed as percent cell migration (71).

Measurement of inflammatory cytokines. The levels of proinflammatory cytokines 4 hours after systemic administration of LPS were assessed in mouse serum and BAL fluid using a Mouse Inflammatory Cytokines Multi-Analyte ELISA Array Kit (SA Biosciences) according to the manufacturer’s instructions.

Mouse tissue cytokine array. ECs derived from wild-type and Stim1ΔEC mice were treated with 1 μg/ml LPS for 16 hours. Tissue cytokite array was performed using the Proteome Profiler Mouse Cytokine Array Kit Panel A (R&D Systems) according to the manufacturer’s instructions.

Live lung slice preparation. For ex vivo imaging of lung microvessels, lungs were inflated with 1.5 ml of 2% agarose-HBSS at 37°C, and lungs were stiffened at 4°C as described previously (72). The stiffened lung tissue was placed in EMS-5000 tissue slicer (Electron Microscopy Sciences) and stiffened at 4°C as described previously (72). The stiffened lung tissue was placed in EMS-5000 tissue slicer (Electron Microscopy Sciences) and imaged using a UV transillumination chamber. The presence of the knockout band at 580 bp and the absence of WT band at 348 bp indicates the knockout genotype of Stim1.

Statistics. All statistical comparisons between groups were analyzed using 2-tailed Student’s t test. Differences in means among multiple data sets were analyzed using 1-way or 2-way ANOVA with the Bonferroni post-test unless otherwise indicated. P values less than 0.05 were
considered significant in all analyses. The data were computed using GraphPad Prism version 5.0.

Study approval. All animal experiments were approved by the Temple University IACUC (approval nos. 3303 and 3302).

Acknowledgments
This work was supported by NIH grants HL086699 (to M. Madesh), 1S10RR027327-01 (to M. Madesh), and 1R21HL109920-01 (to M. Madesh and J. Soboloff). We thank Anjana Rao (La Jolla Institute for Allergy and Immunology, La Jolla, California, USA), Suresh Joseph (Thomas Jefferson University, Philadelphia, Pennsylvania, USA), and Gary Koretzky (University of Pennsylvania, Philadelphia, Pennsylvania, USA) for providing the Stem 9b/l0 mice, InSPRJ antibody, and NFAT-luciferase plasmid construct, respectively. We are grateful to Aron B. Fisher, G. Scott Worthen, and Troy Stevens for critical comments on the results.

Received for publication July 5, 2012, and accepted in revised form November 30, 2012.

Address correspondence to: Muniswamy Madesh, Center for Translational Medicine, 950 MERB, 3500 N. Broad Street, Temple University, Philadelphia, Pennsylvania 19140, USA. Phone: 215.707.5465; Fax: 215.707.9890; E-mail: madeshm@upenn.edu.
902

The Journal of Clinical Investigation

http://www.jci.org Volume 123 Number 2 February 2013

IS. Local Ca(2+)-entry via Orai1 regulates plasma membrane recruitment of TRPC1 and controls cytosolic Ca(2+)-signals required for specific cell functions. Plas Biol. 2011;9(3):e1001025.


