Release of cellular tension signals self-restorative ventral lamellipodia to heal barrier micro-wounds

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Basic mechanisms by which cellular barriers sense and respond to integrity disruptions remain poorly understood. Despite its tenuous structure and constitutive exposure to disruptive strains, the vascular endothelium exhibits robust barrier function. We show that in response to micrometer-scale disruptions induced by transmigrating leukocytes, endothelial cells generate unique ventral lamellipodia that propagate via integrins toward and across these “micro-wounds” to close them. This novel actin remodeling activity progressively healed multiple micro-wounds in succession and changed direction during this process. Mechanical probe-induced micro-wounding of both endothelia and epithelia suggests that ventral lamellipodia formed as a response to force imbalance and specifically loss of isometric tension. Ventral lamellipodia were enriched in the Rac1 effectors cortactin, IGGAP, and p47phox and exhibited localized production of hydrogen peroxide. Together with Apr2/3, these were functionally required for effective micro-wound healing. We propose that barrier disruptions are detected as local release of isometric tension/force unloading, which is directly coupled to reactive oxygen species–dependent self-restorative actin remodeling dynamics.

Introduction

Maintenance of tissue barriers requires the ability to cope with diverse biomechanical strains. The vascular endothelium serves as the critical partition between the blood circulation and the interstitium, and failure of this barrier has devastating consequences (Aird, 2007). Endothelia function in the constitutive presence of extreme biomechanical stresses such as variable fluid shear, stretch, and hydrostatic pressure. Yet most of the body’s ~5,000 m² of endothelium (Hwa et al., 2005) is a simple and thin (<1 µm; Feng et al., 2002) monolayer of endothelial cells attached to a basement membrane via integrin receptors and held to each other by intercellular adherens, tight, and gap junctions (Bazzoni and Dejana, 2004). The fundamental cellular and molecular mechanisms that maintain integrity of this tenuous structure remain poorly understood.

Among the significant biomechanical challenges faced by the endothelium is the trafficking of blood and stem cells. There are many settings in which such cells must repeatedly cross the vasculature to enter and leave the circulation, a process termed diapedesis or transendothelial migration (Sage and Carman, 2009). This requires localized breakage of cell–cell and cell–matrix adhesions in the endothelium and the formation of micron-scale transcellular pores and paracellular gaps that accommodate diapedesis. Such discontinuities serve as physiological passageways, yet also represent a liability to vascular integrity and hence could be regarded as “micro-wounds.” Diapedesis micro-wounds form largely as a result of mechanical forces exerted by the trafficking cells through F-actin protrusions such as pseudopodia and invasive podosomes (Ley et al., 2007; Carman, 2009a,b).

In vitro transmigration pores and gaps disappear rapidly after diapedesis (Shaw et al., 2001; Carman and Springer, 2004; Sage and Carman, 2009). The fundamental cellular and molecular mechanisms that maintain integrity of this tenuous structure remain poorly understood.
Cinamon et al., 2004; Yang et al., 2005; Millán et al., 2006). In vivo, remarkably little leakage of blood plasma (or macromolecular tracers) into tissues is evident at sites of leukocyte transepithelial migration (Thureosn-Klein et al., 1986; Gawlowski et al., 1993; Sage and Carman, 2009; Kim et al., 2009; He, 2010). Moreover, even under conditions of frequent leukocyte trafficking, open (i.e., leukocyte-free) pores or gaps are rarely seen (Marchesi and Florey, 1960; De Bruyn et al., 1971; Campbell, 1972; Chamberlain and Lichtman, 1978; Cho and De Bruyn, 1986; Feng et al., 1998; Hoshi and Ushiki, 1999; Woodfin et al., 2011). Finally, leukocyte-independent mechanical stresses can also produce appreciable steady-state endothelial micro-wounding in vivo, but without significant vascular breakdown (McNeil and Ito, 1990; Yu and McNeil, 1992). Thus, existence of proactive mechanisms that efficiently reestablish integrity are strongly implied. In this study we address the critical question of how micro-wounds are “healed” after diapedesis or direct mechanical micro-disruption. We uncover a novel role of Rac-1 and reactive oxygen species (ROS)–dependent actin remodeling activity—directed ventral lamellipodia (VL)—that serve this function. This, together with additional biomechanical manipulations in endothelia and epithelia, lead us to propose a general tension-based model for integrity sensing whereby localized tension loss during adhesion rupture positively signals its own repair.

Results

Leukocyte-driven endothelial micro-wounds are closed efficiently

To investigate endothelial remodeling during diapedesis, we used in vitro models of inflammatory leukocyte recruitment. Monolayers of human dermal or lung microvascular endothelial cells (MVECs) were transfected with a fluorescent membrane marker (i.e., mYFP, mDsRed, or ICAM-1-GFP) and activated with TNF. Coincubated lymphocytes avidly adhered to, spread on, and transmigrated across these monolayers through formation of ~3–6-µm transcellular pores and paracellular gaps (Fig. 1 a, yellow lines). When imaged over time, we confirmed that pores and gaps rapidly closed (Fig. 1 a, red lines) after completion of diapedesis events and that endothelial cells possessed a robust capacity to restore numerous discontinuities concomitantly and successively.

Transcellular pore closure is initiated by newly described VL

We hypothesized that the closure of transcellular pores might involve a “purse string” mechanism, whereby F-actin would accumulate symmetrically around the pore and contract. Strikingly, we found that transcellular pore closure proceeded through a largely asymmetric process. Dynamic bursts of actin formed on one side of the pore and then rapidly moved across it (Fig. 1 b and Video 1, Part I, A). These were initiated just before or after the final exit of the lymphocyte from the pore and then propagated for a mean of 16.38 ± 1.2 µm (width of 12.71 ± 1.07 µm, velocities of 2.91 ± 0.18 µm/min) with lifetimes of 6.38 ± 0.5 min before being extinguished (Fig. 1 c).

For a minority (~20%) of events the actin bursts were initiated precisely at the border of the pore and traveled just to the opposite edge where they disappeared along with the micro-wound (Fig. S1 a and Video 2, Part I, type A). In the majority of cases (~80%) these actin structures exhibited propagation outside the confines of the pore. That is, they initiated at sites adjacent to the micro-wound (~0.5–15 µm away; mean of 4.61 ± 0.49 µm) and/or moved beyond its distal edge after closing it (~0.5–30 µm; mean of 8.17 ± 0.99 µm; Fig. 1 d; Fig. S1, b and c; and Video 2, Part I, type B and C). At high lymphocyte/diapedesis density single bursts processively traveled through and closed multiple endothelial pores (Fig. S1 c and Video 2, Part I, type C). During propagation outside of the pore the mDsRed intensity doubled, suggesting membrane folding (Fig. 1 e and Video 1, Part II). Similar results were found using a range of molecularly distinct membrane markers (e.g., farnesylated GFP, GPI-GFP, and R18; unpublished data). This implies that the actin bursts are contained in membrane surface protrusions (i.e., lamellipodia- or ruffle-like structures).

We next asked on which surface (i.e., dorsal/apical or ventral/basal) these protrusions formed. Total internal reflection fluorescence (TIRF) microscopy (using mYFP; Fig. 2 a) and interference-contrast reflection microscopy (IRM; not depicted), complementary modalities for detecting close (<100 nm) cell–substrate apposition, showed that the pore-closing protrusions (without exception in 24 measurements) formed underneath the endothelium. Further confirmation of this was obtained using spinning-disk confocal imaging (Fig. 2 b and Video 3). Ultrastructural electron microscopy views of basal F-actin–rich VL were also detected (Fig. 2, c and d).

We considered that the unique ventral orientation of these protrusions was due in part to roles for integrin–substrate interaction. Both α5 and β3 integrins showed enrichment in VL compared with adjacent regions (Fig. 2 e, i and ii). Addition of function-blocking antibodies against both αβ1 and αβ3 caused VL to lift off the substrate and retract (Fig. 2 e, iii and iv, red arrowheads) and failed pore closure (Fig. 2 e, iii–v). Whereas 97.3% of pores closed within 10 min in control settings, only 7.1% closed in the presence of blocking antibody. Thus, endothelial VL require integrin–matrix adhesion to effectively propagate.

Endothelia form distinct “ventral waves” that coexist with VL

Our characterization of VL up to this point indicated some resemblance to ventral F-actin waves (VW) observed in motile Dictyostelium discoideum, fibroblasts, neutrophils, and tumor cells (Vicker, 2002; Weiner et al., 2007; Case and Waterman, 2011). As with VL, VW exhibit integrin-mediated basal propagation. However, VW do not form membrane protrusions until they reach a cell border (indicated by an absence of membrane folding/doubling [Bretschneider et al., 2004]) and travel as clusters of actin punctae rather than a continuous leading edge. Via combined fluorescence and IRM imaging we found that resting endothelial cells spontaneously formed VW, but not VL (Fig. S2 a). The VW traveled in all directions (at 1.1 ± 0.96 µm/min) and exhibited frequent turning (36%), bifurcation (68%), and
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of 12.9 ± 1 µm) traveled peripherally (at 2.8 ± 0.2 µm/min; life-
time of 6.3 ± 0.6 min) to fill the gaps and reestablish overlapping
contacts with the neighboring endothelial cells (Fig. 3, a and b). Where-
as in 63% of events the lamellipodia were initiated at
the endothelial cell edge, 37% of them were initiated ≥1 µm
away (with doubled mDsRed intensity; Fig. 3, a [i] and c).

Live imaging of VL-driven gap closure showed rapid assem-
bl y of VE-cadherin-GFP punctae into linear arrays to reestablish
the adherens junctions (Fig. 3 d). Live-cell imaging followed by
fixation, staining, and reimaging of the same field showed that
within 5 min of gap closure, adherens junctions with strongly co-
localized endogenous VE-cadherin and β-catenin were reconsti-
tuted and indistinguishable from adjacent unperturbed junctional
segments (Fig. 3 e, iii).

Thus, despite clear distinctions in transcellular pores and
paracellular gaps, endothelial cells use similar VL mechanisms
for their closure. The same was true for diapedesis of granulocytes
(Fig. S1 d and Video 2, Part II, ex.1) and monocytes (not depicted)
self-annihilation upon intersection (Fig. S2, b, c, and e). What
regulates, and the functional roles for, these wound-independent
VVW remain unknown.

During diapedesis, VW and VL could be seen to coexist
both independently at distinct locations and coordinately at sites
of wound closure (Fig. S2 d). A subset of VL (≈20%) was fol-
lowed by VW-type actin punctae that traveled ~2–3 µm behind
the leading edge and continued to propagate after VL extinction
(Fig. S2 d and Video 4, Part I, ex. 3). Thus, although VL and VW
can each form independently in endothelium, these two modes
of actin propagation can coexist and possibly interchange during
pore closure events.

**VL initiate closure of paracellular
diapedesis gaps**

We next focused on the closure of paracellular diapedesis gaps.
Here we found again a process involving local bursts of lamellip-
oidal activity (Fig. 3 a and Video 1 B). These structures (width
of 12.9 ± 1 µm) traveled peripherally (at 2.8 ± 0.2 µm/min; life-
time of 6.3 ± 0.6 min) to fill the gaps and reestablish overlapping
contacts with the neighboring endothelial cells (Fig. 3, a and b).
Whereas in ~63% of events the lamellipodia were initiated at
the endothelial cell edge, ~37% of them were initiated ≥1 µm
away (with doubled mDsRed intensity; Fig. 3, a [i] and c).

Live imaging of VL-driven gap closure showed rapid assem-
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Figure 1. Transcellular endothelial micro-wounds are closed efficiently after diapedesis through bursts of lamellar activity. Live-cell imaging of lymphocyte diapedesis through MVECs. (a) DIC and fluorescence imaging of migrating T cells (cyan outlines) on an ICAM-1-GFP–expressing endothelial cell (green). Open diapedesis pores (1–3) and gaps (a and b) associated with T cells in the process of diapedesis are outlined in yellow. The subsequent time points show opening of additional pores (4–7) and gaps (c and d) formed by other T cells initiating diapedesis. The progressive closure of the pores and gaps after completion of each diapedesis event is denoted by a switch from yellow to red outlines. (b) Representative time series of a pore closure event in MVECs coexpressing actin-GFP and mDsRed. Yellow outline shows an open transcellular pore associated with a T cell (cyan outline) that has nearly completed diapedesis. A pore closing structure (CL; white arrows and dashed line) is evident as a burst of actin and membrane traveling across the pore to close it. See Video 1, Part I. (c) Analysis of width and dynamics of >68 individual pore closing structures. (d) Percentage of three classes (Fig. S1 a) of pore closing types (i) and quantitative analysis of CL travel distances (ii and iii). n > 100. (e) Doubling/Folding of membrane during pore closure. (i). Arrows indicate actin protrusions initiated at the edge of the pore (blue) and at distant sites (white). White line shows location of a fluorescence intensity line scan analysis (ii) with regions that are part of (CL) and outside of (non-CL) the closure structure indicated. (iii) Membrane fluorescence analysis in CL and non-CL structures. n = 15. Error bars represent SEM. See Video 1, Part II. Bars, 5 µm.
majority emerged from preexisting actin filaments within ∼5 µm of a pore or gap. Such “parent filaments” were of varied radial and tangential orientations with respect to the micro-wound and had all undergone discernible retraction, breakage, or distortion during the diapedesis event (Fig. 4). These filaments briefly (10–40 s) formed a discrete node of increased actin density, which then transitioned to small VL that were visible as either a small crescent on one side of the filament, a spade on both sides or at the end of a filament, or a fan between two of them (Fig. 4 a). In a subset of events, the node was evident as a discrete spike (∼300–600 nm in length). Quantitation showed that spikes projected at angles between 45° and 80°, but averaged ∼70° (69.1 ± 1.9; Fig. 4 b, iii), suggesting possible involvement

To gain insights into VL regulatory mechanisms, we analyzed their initiation dynamics. We found, in >400 observations, that VL only formed in response to micro-wounding and that the majority emerged from preexisting actin filaments within ∼5 µm of a pore or gap. Such “parent filaments” were of varied radial and tangential orientations with respect to the micro-wound and had all undergone discernible retraction, breakage, or distortion during the diapedesis event (Fig. 4). These filaments briefly (10–40 s) formed a discrete node of increased actin density, which then transitioned to small VL that were visible as either a small crescent on one side of the filament, a spade on both sides or at the end of a filament, or a fan between two of them (Fig. 4 a). In a subset of events, the node was evident as a discrete spike (∼300–600 nm in length). Quantitation showed that spikes projected at angles between 45° and 80°, but averaged ∼70° (69.1 ± 1.9; Fig. 4 b, iii), suggesting possible involvement
We compared directionality of VL propagation with that of the transmigrated lymphocyte. Although ~38% of the VL moved parallel to the direction of the subendothelial lymphocyte, VL mostly traveled in a direction that was orthogonal or antiparallel to that of the T cell (Fig. 5 c). Aborted transmigration events, whereby the T cell reversed direction to the apical side after forming a pore or gap, were closed similarly (e.g., Video 1 B). Hence, VL propagation directionality is not coupled to the migration direction of the leukocyte that formed the micro-wound.

Our analysis also indicated a capacity of VL to adjust their direction. Initially, ~20% of VL were poorly oriented toward their target micro-wound. These then steered toward the pore or gap, turning as much as 180° (Fig. 5 d). During closure of gaps the majority of VL propagated peripherally, but ~28% traveled along the axis of the adherens junctions (Fig. 5 a, iii). Furthermore, pores/gaps were often healed by two or more VL that moved in different directions toward the micro-wound (Fig. 5 b and Video 4, Part II, ex. 1). Thus, VL initiation locus and propagation direction are not prescribed by the axes of symmetry within the endothelial cell, as is the case for leading edge lamellipodia and dorsal ruffles (Chhabra and Higgs, 2007).

Figure 3. VL initiate closure of paracellular diapedesis gaps. (a) Dynamic epifluorescence (red) and TIRF (green) imaging of a paracellular diapedesis gap (yellow line) closure in an MVEC by a membrane protrusion (VL, arrowhead). Strong TIRF signal (i) and doubling of epifluorescence intensity (ii–iii) demonstrate propagation as VL. n > 30. (b) Analysis of width and dynamics of VL. n > 35. (c) Percentage of three VL classes (i) and analysis of VL travel distances (ii). n > 100. (d) Dynamic imaging of mDsRed (red) and VE-cadherin-GFP (green) during gap closure. Cyan arrowheads indicate VL-mediated restoration of intercellular contacts followed by accumulation of VE-cadherin. (e) MVECs expressing mDsRed were imaged during gap closure (cyan arrowhead; i), fixed and stained for VE-cadherin and β-catenin (ii), and subjected to Pearson’s colocalization analysis (iii). n > 18. Bars, 5 µm. All values are mean ± SEM.
nodes protruded against the underlying substrate as indicated by IRM (Fig. 6 b, ii). They quickly expanded, merged, and coordinate travel (23.9 ± 3.6 µm at 2.6 ± 0.2 µm/min) toward and across the micro-wound with mixed VL and VW characteristics. Multiple, successive probe-induced transcellular micro-wounds could be efficiently healed in this way (Video 5, Part I). Of note, in contrast to transcellular diapedesis, the probe-mediated transcellular wounds were associated with elevation of intracellular calcium, which was typically reversed in 10–60 s (Fig. S3, b and c). This suggests that probe micro-wounds involve tearing, followed by rapid repair, of the plasma membrane. Such repair can occur in virtually all cells through a strictly calcium-dependent process (McNeil and Kirchhausen, 2005; Bement et al., 2007). Analysis of calcium flux and VL initiation kinetics on a per-wound basis showed that VL formed only after the reversal of intracellular calcium flux. A subset of cells that failed to normalize calcium failed to form VL (Fig. S3 c, iii). Moreover, pharmacological elevation of calcium at later stages of micro-wound healing caused immediate retraction of the VL (unpublished data). These results suggest that VL do not require Micromechanical transcellular disruptions promote VL

The aforementioned findings imply that the principal cues driving VL formation and propagation might be mechanical, rather than a result of diapedesis itself. To test this, we designed a system for creating leukocyte-independent mechanical micro-wounds using a tungsten probe (Fig. 6 a). By driving the probe directly across endothelial cells, we could form survivable transcellular micro-wounds in a spatiotemporally controlled manner (Fig. 6 b). Such cell piercing resulted in breakage of adhesions and cytoskeleton, which was coupled to a short-lived phase (10–40 s) of membrane retraction, whereby the transcellular micro-wound expanded from a diameter of 1 µm to 28.7 ± 1.4 µm. Within 20 to 180 s (mean of 40 s) of probe micro-wounding, dozens of 1–3-µm actin enrichment nodes/spikes appeared within the 28.6 ± 2.8-µm radius of the wound edge (Fig. 6 b, arrowheads; Fig. S3 a; and Video 5, Part I). These nodes formed mostly at the ends, or on the side, of radially retracted filaments, but also on tangentially oriented filaments within the retracting network (Fig. 6 b, ii and iii). Such
and, in fact, are inhibited by elevated intracellular calcium. Thus, for endothelial micro-wounds involving membrane damage, membrane repair/cell survival and barrier restoration are sequential, mechanistically distinct processes.

**Micromechanical monolayer disruptions promote VL in non-wounded neighbors**

Micro-wounding of a cell near its junction caused paracellular gaps to form. Here the directly wounded cell and its untouched/nonwounded neighbor (which did not flux calcium) retracted from each other and then each formed extensive restorative VL/VW emanating specifically from the zones of retraction (Video 5, Part II). We also frequently observed robust VL in nonwounded neighbors in the absence of junction disruption. In such cases, transcellular micro-wound expansion could be relayed to distant (~5–40 µm) intact junctions, as demonstrated by translation of the unbroken junction in the direction parallel to pore expansion (Fig. 7a and Fig. S3d, note green and blue dashed lines; and Video 6). Selectively, at these zones of retraction, unwounded neighbors formed VL that moved toward the.
wound and expanded under the wounded neighbor in similar fashion to cryptic lamellipodia seen in scratch wounding and collective cell migration (Farooqui and Fenteany, 2005; Fig. 7 a, Fig. S3 d, and Video 6). Similar responses were seen in probe-wounded MDCK epithelial monolayers (Fig. S4). Neighbor responses were unaltered by continuous washing (unpublished data), suggesting that these were not regulated by gradients of factors released from the wounded cell. Moreover, similar retraction and response behaviors could also be seen in cells separated from the wounded cell by one or more nonwounded cells (i.e., rough equivalents to “submarginal” cells in scratch wounds; unpublished data). Together our findings suggest that closure of transcellular and paracellular discontinuities, initiated by diapedesis or mechanical probe, involves similar VL/VW mobilization responses and points toward mechanical changes as potential signals for these responses.

A putative tension-loss signal for repair after adhesion rupture

Next, we used our probe-induced micro-wound model to understand how the endothelium perceives perturbations in the mechanical force balance. Specifically we took advantage of the wound-induced cell retractions (i.e., viscoelastic recoil), which are a well-established reflection of local dissipation/relaxation of preformed isometric tension (Kumar et al., 2006; though calcium flux might also contribute to pore expansion in transcellular probe wounding). By placing the probe in different subcellular locations we formed wounds that recoiled asymmetrically in one or more zones and showed visible stretching/tensing in adjacent ones. Consistently, retraction areas were the preferred sites of VL formation (Fig. 7 a, Fig. S3 d, and Video 6). Within these areas filaments experiencing the most significant viscoelastic recoil formed actin nodes (Fig. 7, Fig. S3 e, and Video 7). For example, in Fig. 7 b several radially oriented filaments in an untouched cell (blue dashed lines) undergo significant recoil after wounding of a neighboring cell. These then rapidly formed actin nodes that transitioned into VL. Nearby filaments that were more tangentially oriented (Fig. 7 b, magenta lines) and did not recoil failed to form VL (Video 7, ex.1). Additionally, retraction/tension release could be seen to propagate from radial (Fig. S3 e, dashed blue lines) to tangential filaments through cross-links in the actin network. In such cases, both radial and tangential filaments, and often specifically their intersection, formed sites for VL nodes (Fig. S3 e and Video 7, ex. 2). These findings suggest that local loss of tension accompanying adhesion rupture is a key activator of the VL/VW recovery response.

To further test this idea, we pretreated endothelial cells with compounds that block tension development, including the Rho kinase inhibitor Y27632, the myosin light chain kinase inhibitor ML-7, and the myosin II inhibitor blebbistatin. All treatments reduced stress fibers, but left a finer actin network intact (unpublished data). Micro-wounding in the continuous presence of drug resulted in decreased rates of wound expansion/recoil (Fig. 8 a, i), demonstrating that tension was indeed reduced (Kumar et al., 2006). Y27632, which least effectively reduced tension, modestly delayed VL formation (Fig. 8 a, ii) and, as a result, decreased the efficiency of recovery (Fig. 8 a, iii). ML-7 yielded a greater disruption in both tension and VL initiation/recovery efficiency. In both cases, both radial and tangential filaments, and often specifically their intersection, formed sites for VL nodes (Fig. S3 e and Video 7, ex. 2). These findings suggest that local loss of tension accompanying adhesion rupture is a key activator of the VL/VW recovery response.
isometric tension before micro-wounding blunts the efficiency of VL responses.

Finally, as a complementary test of the role of tension loss in signaling VL, we designed a substrate compression/de-stretch experiment to enforce uniaxial decrease in isometric tension without micro-wounding, adhesion rupture, or generation of free space (Fig. 8 b, i). Thus, endothelial cells were grown on uniaxially prestretched silicone membranes and then imaged during an acute 10% compression of the substrate. Immediately (~30 s) after substrate de-stretch, endothelial cells generated bursts of new lamellar activity preferentially in the direction antiparallel to the compression (Fig. 8 b, ii and iii; and Video 8). This activity was initiated largely at, or just behind, the cell edge typically at the ends of filaments that were at least partially aligned with the axis of de-stretch (Fig. 8, b [iii] and c; and Video 8).

**VL are functionally dependent on Rac1, cortactin, and Arp2/3**

Based on similarity to migratory leading edge lamellipodia and findings that Rac1 can be modulated positively by tension release (Houk et al., 2012) we examined the role of Rac1 in VL formation. Overexpression of a dominant-negative Rac1, but not RhoA, significantly decreased VL velocity and increased pore/gap closure time after diapedesis (Fig. 9 a). Acute treatment with the Rac1 inhibitor NSC23766 caused immediate arrest of VL (Fig. 9, b and c; and Video 9, Part I). Drug washout resulted in rapid and synchronized mobilization of multiple steered VL that closed the micro-wounds accumulated during drug treatment (Fig. 9, b and c; and Video 9, Part I). Acute addition (contrasting the pretreatment experiment in Fig. 8 a) of the inhibitor Y27632 did not affect VL (Video 9, Part II). GFP fusions of the Rac1 effectors cortactin and IQGAP were dynamically recruited to and enriched in both initiation node and leading edge of VL (Fig. 9, d and e). In contrast, markers for a range of vesicular compartments (e.g., caveolae and endosomes) or microtubules were either not enriched or were excluded from VL (Fig. 9 d). Dominant-negative, but not wild-type, cortactin significantly decreased VL velocity and inhibited diapedesis micro-wound healing (Fig. 9 f). Addition of NSC23766 during probe micro-wounding caused immediate collapse of VL (Fig. 9 g). CK-666, an inhibitor of the Rac1-regulated actin nucleator Arp2/3, also reversibly blocked VL and micro-wound healing (Fig. 9 h).

**VL require local p47Phox-dependent production of ROS**

Endothelial cell migration and migratory leading edge lamellipodia are regulated by discretely localized production of hydrogen peroxide ($\text{H}_2\text{O}_2$) by the Rac1 effector/NADPH oxidase subunit p47phox, which acts in concert with cortactin and IQGAP (Ikeda et al., 2005; Touyz et al., 2005; Moldovan et al.,...
Discussion

This study was designed to investigate the mechanisms that complete diapedesis and restore endothelial barrier integrity. Although providing an answer to this question, our findings unveil basic mechanisms for tissue homeostasis with potentially broad relevance. We reveal VL as a novel type of actin remodeling in endothelia and epithelia that is distinct from known lamellipodia or dorsal ruffles (Chhabra and Higgs, 2007) and serves to close diapedesis pores/gaps. VL are nucleated from preexisting actin filaments and exhibit the unique ability to propagate under cells independently of radial axes of cell symmetry and to dynamically change direction in response to additional discontinuities. These findings raise important new questions about fundamental mechanisms for nucleation of actin assemblies and coordination of their propagation, which point toward interesting roles for mechanotransduction.

We hypothesized that transcellular diapedesis micro-wounds might be healed by purse strings that heal seemingly similar to mechanical cues the endothelium uses discretely regulated Rac1 and NADPH oxidase signaling that coordinates unique actin remodeling dynamics to heal disruptions in its barrier.
of actin via a calcium-, Rho-, and tubulin-independent mechanism. Though transient calcium flux (and membrane tear and repair) was evident in probe-generated single-cell wounds in other settings (McNeil and Kirchhausen, 2005; Bement et al., 2007). However, in sharp contrast to purse strings, pores were closed through an asymmetric propagation of actin via a calcium-, Rho-, and tubulin-independent mechanism. Though transient calcium flux (and membrane tear and repair) was evident in probe-generated single endothelial cell

Figure 9. VL depend on Rac1, cortactin, and Arp2/3. (a) MVECs were coexpressing mDsrRed and GFP dominant-negative Rac1 (DN Rac1) or RhoA (DN RhoA) and imaged during T cell diapedesis. VL velocity (i), wound closure time (ii), and diameter (iii) were measured. (b) MVECs expressing mYFP were imaged during T cell diapedesis and addition of Rac1 inhibitor NSC23766 (red phase) and after drug washout (blue phase). The cumulative percentage of wound closure was plotted as a function of time. n = 5. (c) A representative imaging of reversible VL blockade. [top left] Two DIC and mYFP panels show three transcellular pores recently vacated by T cells (T1–T3). Subsequent panels are after addition (red outline) or washout (blue outline) of NSC23766. Arrowhead indicates pore closing VL rapidly mobilized after washout. See Video 9. (d) MVECs coexpressing mDsrRed and GFP-fused actin, cortactin, IQGAP, tubulin, Caveolin-1, CD63, Lamp1, VAMP2, and an endosomal marker (ENDO) were imaged during T cell diapedesis. mDsrRed-normalized intensities of each GFP construct were quantified in VL versus non-VL regions. n > 5. (e) Representative images of cortactin enrichment both in initiation nodes (N) and VL leading edges (VL; arrowheads). (f) VL velocity (i) and diapedesis wound closure time (ii) in MVECs expressing wild type (WT) or dominant-negative cortactin-GFP (DN). All values are mean ± SEM. Statistical significance is indicated with p-values as follows: ***, P < 0.001; *, P < 0.05. (g, i) Actin-GFP–expressing MVECs were mechanically micro-wounded. VL (arrowheads) that formed specifically in zones of recoil (blue shading) and collapsed upon addition of NSC23766. Green line traces location used for kymograph of this process (ii). (h) Kymograph of MVECs micro-wounded in the presence of Arp2/3 inhibitor CK-666, and VL (cyan arrowhead) initiation after drug washout. n = 10. Bars, 5 µm.
transcellular discontinuities whether or not plasma membrane damage is involved. The preceding discussion raises the fundamental question of how discontinuities are perceived by barrier cells. Intact endothelia and epithelia exist under isometric tension in which contractile forces are balanced by cell–matrix and cell–cell adhesion (Chicurel et al., 1998; Vogel and Sheetz, 2006; DuFort et al., 2011; Gomez et al., 2011). The process of diapedesis involves intricate leukocyte protrusive dynamics that cause breakage of cell–cell and cell–matrix adhesions and distortions of membrane and cytoskeleton in endothelia/epithelia (Chin and

wounds, these pores also closed through VL. This different response is likely related to distinctions in cell morphology and function. Contractile rings are seen after wounding of large spherical cells (e.g., *Xenopus laevis* oocytes), where they function to restore the cortical cytoskeleton of individual cells. On the contrary, endothelial cells are thin and flat and function collectively as a barrier. VL might, thus, be favored for closing transcellular wounds in endothelia as a contractile process would be liable to disrupt the barrier elsewhere (i.e., promote paracellular gaps; Wojciak-Stothard and Ridley, 2002). Moreover, as a calcium-independent activity, VL can respond to diverse para- and transcellular discontinuities whether or not plasma membrane damage is involved.

The preceding discussion raises the fundamental question of how discontinuities are perceived by barrier cells. Intact endothelia and epithelia exist under isometric tension in which contractile forces are balanced by cell–matrix and cell–cell adhesion (Chicurel et al., 1998; Vogel and Sheetz, 2006; DuFort et al., 2011; Gomez et al., 2011). The process of diapedesis involves intricate leukocyte protrusive dynamics that cause breakage of cell–cell and cell–matrix adhesions and distortions of membrane and cytoskeleton in endothelia/epithelia (Chin and

Figure 10. **VL are enriched in and functionally dependent on NADPH oxidase activity.** (a) MVECs coexpressing p47^phox^DsRed and actin-GFP were imaged live during T cell diapedesis. p47^phox^ was enriched in ventral (IRM) actin-rich initiation nodes (N) and in VL leading edge (arrowheads). See Video 10. (b) Representative ratiometric images of H_{2}O_{2} production in (i) pore- and (ii) gap-closing VL in MVECs expressing the biosensor mHyPer during T cell diapedesis. (c) Quantification of p47^phox^ (i) and H_{2}O_{2} (ii) enrichment in VL; n > 13. (d, i) Representative NADPH oxidase inhibition/washout imaging experiment. After multiple T cell diapedesis events on MVECs expressing mYFP, apocynin was added. Arrows indicate multiple pores and gaps that persisted for 15 min, but were rapidly healed by steered VL (arrowheads) after drug washout. See Video 10. Experiments as in d (i) were performed with VAS-2870, DPI, PEG-catalase, and DMSO (control) and quantified by cumulative wound closure analysis, shown as a continuous line plot (ii) and bar graph of single pre/post-washout time points (iii). n > 5. (e) MVECs coexpressing mDsRed and mHyPer were imaged during probe wounds and after addition of VAS-2870. Representative mDsRed images (i), kymograph (ii), mHyPer ratiometric images (iii), and quantitation (iv) are shown. n = 3. Values represent mean ± SEM. Statistical significance is indicated with p-values as follows: ***, P < 0.001; *, P < 0.05. Bars, 5 µm.
tractable force change dynamics. and associated signaling mechanisms is difficult. We therefore epithelial cells. Because of the multiplicity and small size of di-
spots of maximal changes in forces felt by the endothelial and
that the nodes of VL initiation would likely coincide with hot-
Parkos, 2007; Ley et al., 2007; Carman, 2009a). We envisioned thecytoskeleton, and of the plasma membrane (Orr et al., 2006; Vogel and Sheetz, 2006; Geiger et al., 2009; DuFort et al., 2011; Gomez et al., 2011; Sinha et al., 2011). Our study provides highly physiological examples of what happens when ruptures ultimately occur. Importantly, similar VL recuperative responses were seen in endothelia and epithelia after both leukocyte- and mechanical probe–induced micro-wounding. These findings extend and complement the field of mechanobiology, offering new ways to think about how cells/tissues perceive mechanical information and how they monitor and respond to changes in integrity.

Permutations of this phenomenon will likely have relevance for diverse adhesion and cell ruptures. For example, physiological extremes in shear and/or stretch cause constitutive tearing of aortic and skin endothelia, which seem to be repaired efficiently by incompletely characterized mechanisms (McNeil and Ito, 1990; Yu and McNeil, 1992). Our findings also have implications for collective cell migration during tissue wound healing, angiogenesis, and development. A hallmark of this process is that followers (e.g., submarginal cells of a tissue wound) migrate actively in coordination with the leaders. It is proposed that mechanical tension or “tugging” transmitted through intercellular adhesions is critical to stimulate polarization and cryptic lamellipodia in submarginal cells (Farooqui and Fenteany, 2005; Friedl and Gilmour, 2009; Tambe et al., 2011). However, this seems somewhat inconsistent with findings that lamellar activity is potently suppressed by tension (Kolega, 1986; Raucher and Sheetz, 2000; Katsumi et al., 2002; Shifrin et al., 2009; Ehrlicher et al., 2011; Gauthier et al., 2011; Houk et al., 2012). Our studies instead predict that extremes in tension could result in localized adhesion ruptures and that the released tension would drive new lamellar bursts that effectively spur lagging followers to catch up. This is consistent with the finding that, indeed, endothelial and epithelial migrations follow local orientations of maximal principal stress (Tambe et al., 2011) and that gaps are seen frequently in collective migration studies. Based on empirical observations, the idea that cycles of gap formation and lamellar closure could drive collective migration has been proposed before but in terms of regulation by free space rather than tension (Radice, 1980). Our nonwounded neighbor and substrate compression studies suggest that the former, but not the latter, is dispensable for VL initiation.

The principle of tension breakage driving actin polymerization is supported by observations in disparate systems. Mechanical rupture of actin gels growing on beads creates local tension release that drives the physicochemical enhancement of actin assembly and comet formation (Paluch et al., 2006). The ends of broken filaments similarly provide a direct source of free barbed ends available for new growth (Chhabra and Higgs, 2007), as was evident to varying degrees during probe- and diapedesis-induced micro-wound healing. Unbroken actin filaments and filament segments upstream of a break, which we observed as prominent VL nucleation sites, can also serve as conformation-based tension sensors by differentially binding distinct function-modifying proteins under low versus high strain (Galkin et al., 2012). Integrins, which were critical for VL propagation, are also excellent candidates as mechanosensors of micro-wounding (Orr et al., 2006; Geiger et al., 2009). Whatever the ultimate initiation cue, our studies show that VL are strongly dependent on Rac1 activity, which is known to undergo spatially restricted and reversible repression in response to tension

Probe-induced transcellular micro-wounding showed that subcellular regions of retraction correlated with zones of VL initiation. Such retraction can be taken as a well-established readout for dissipation of the preexisting isometric tension (Rajfur et al., 2002; Kumar et al., 2006; Ma et al., 2009; Murrell et al., 2011). In cases of asymmetric retraction, adjacent nonretracting regions/filaments showed little VL response. Importantly, recoil transferred from a wounded cell to a nonwounded neighbor through discrete segments of intact junction produced avid and localized VL responses in the neighbor. This result suggested that no direct cell damage, intercellular adhesion rupture, or generation of free space was necessary to stimulate VL. Similar experiments done with continuous media perfusion ruled out chemical gradients in driving these neighbor responses. We therefore hypothesized that the localized decrease in tension (i.e., force unloading) associated with micro-wounding provides a primary positive signal for VL formation. This was supported by our finding that dissipating tension pharmacologically before wounding resulted in both slower recoil and slower VL initiation. Conversely, acute imposition of uniaxial tension release through substrate compression promoted rapid VL-type responses that were biased toward the direction of tension loss. This latter experiment, that is completely independent of wound initiation. Such a tension-based model helps to explain how VL can respond from a distance and participate in both transcellular and paracellular micro-wound closure (as broken tension is transmitted throughout the monolayer (Gomez et al., 2011)). The findings that nascent VL rapidly tweak their orientation of growth to ensure movement toward the micro-wounds and that mature VL can further adjust their directionality in response to additional discontinuities suggest that biomechanical and/or biochemical feedback exists. One possibility is that the low-tension zone created by the micro-wound is simply permissive for continued VL propagation, whereas adjacent zones of higher (i.e., basal) tension are not, creating a funnel effect. This would be consistent with the observed steering toward new wounds (as a new trench redirects water flow) and the quenching of VL after completion of wound healing, which presumable restores basal tension.

Existing paradigms for tissue mechanobiology focus on how force loading of sensitive elements within cells (e.g., integrins, actin filaments, and ion channels) triggers protective remodeling responses that help cells resist rupture of adhesions, of the cytoskeleton, and of the plasma membrane (Orr et al., 2006; Vogel and Sheetz, 2006; Geiger et al., 2009; DuFort et al., 2011; Gomez et al., 2011; Sinha et al., 2011). Our study provides highly physiological examples of what happens when
(Kolega, 1986; Raucher and Sheetz, 2000; Katsumi et al., 2002; Gauthier et al., 2011). It was shown recently that acutely releasing tension in the uropod of migrating neutrophils produced rapid derepression of Rac1 that was coupled to new bursts of leading edge lamellipodia (Houk et al., 2012). We postulate that our studies recapitulate such results, but in the context of a cell monolayer and with the function of restoring integrity rather than promoting cell migration. New findings that the Rac1 inhibitor FliGAP is rapidly sequestered by filament A (an actin crosslinking protein) upon release of actin network tension provide at least one plausible molecular mechanism for such events (Shifrin et al., 2009; Ehrlicher et al., 2011).

Downstream of Rac1, VL critically depended on Arp2/3, as well as discrete local production of ROS, specifically H2O2, which is driven by coordinated function of cortactin, IQGAP, p47phox, and likely NOX2. Indeed, a range of antioxidants/inhibitors of H2O2 caused profound disruption of VL responses. Interestingly, H2O2 has been shown recently to stimulate lamellipodia by recruiting Arp2/3 (Taulet et al., 2012). Thus, whereas oxidative H2O2 has been shown recently to stimulate lamellipodia by recruiting Arp2/3 (Taulet et al., 2012). Thus, whereas oxidative stress and excessive ROS production are generally viewed as harmful to tissues (Griendling et al., 2000; Lum and Roebuck, 2001; Rodrigues and Granger, 2010; Drummond et al., 2011; Browning et al., 2012), our studies define a specific protective/homeostatic role for ROS in the maintenance of tissue integrity. The rapid production, short half-life, and limited diffusion distance of H2O2 makes it particularly well suited, when formed at low levels, for regulating complex subcellular dynamics such as those of VL micro-wound healing (Terada, 2006).

Collectively, our work illustrates that the barrier function of the endothelium relies on an enormous self-restorative capacity rather than structural robustness. Inherent in this idea is an ability to effectively monitor and respond to local barrier disruptions. This investigation points toward a putative role for broken tension and force unloading as a critical signal of adhesion or cell rupture that is coupled to newly appreciated ROS-dependent recuperative actin dynamics. These findings suggest new concepts for how pathological breakdown of tissue barriers may occur. Whereas excessive disruptive inputs are usually targeted as culprits in vascular dysfunction, failure of the normal homeostatic remodeling could be equally important.

Materials and methods

Antibodies and reagents

The function-blocking anti-αvβ3 and α5β3 integrin antibodies UM-609 and P1D6, respectively, were obtained from EMD Millipore and used at 20 µg/ml. Inhibitors of Ras signaling used included NSC276532 (inhibitor of TIAA/TRIO activation of Rac1; 500 µM; EMD Millipore), Y27632 (Rho kinase inhibitor; 90 µM; Sigma-Aldrich). The modulator of intracellular calcium, thapsigargin (2 µM), was purchased from Sigma-Aldrich. Inhibitors of cytokoskeletal tension included Y27632, ML-7 (the myosin light chain kinase inhibitor; 10 µM; R&D Systems), and blebbistatin (Myosin II inhibitor; 10 µM; Sigma-Aldrich). Specific inhibitor of Arp2/3 was accomplished with CK666 (100 µM; Sigma-Aldrich). Inhibitors of NADPH oxidase signaling used included VAS-2870 (Nox2/4 inhibitor; 15 µM; Enzo Life Sciences), DPI (non-specific Nox inhibitor/Flavoprotein inhibitor; 12.5 µM; Sigma-Aldrich), apocynin (inhibitor of p47phox assembly into Nox complex/H2O2 scavenger; 1 mM; Sigma-Aldrich), PEG-catalase (H2O2 degrading enzyme; 200 U/ml; Sigma-Aldrich), and Tempol (superoxide dismutase/catalase mimetic; 500 µM; Sigma-Aldrich). Lipid dye R18 (Octadecyl Rhodamine B) was obtained from Life Technologies.

Cell culture

Studies of human blood were approved by the institutional review board at the Beth Israel Deaconess Medical Center, Harvard Medical School. Preparation of primary human blood cells was performed as described previously (Carman et al., 2003; Carman and Springer, 2004). In brief, granulocytes and peripheral blood mononuclear cells were separated from whole blood by standard Ficoll-Hypaque (Sigma-Aldrich) buoyant density centrifugation. Granulocytes were further purified from contaminating red blood cells by hypotonic lysis, resuspended in HBSS supplemented with 1 mM CaCl2, and MgCl2, 20 mM Hepes, pH 7.4, and 1% human serum albumin (buffer A), and used immediately. Monocytes and lymphocytes were each isolated from PBMC with negative selection isolation kits (Miltenyi Biotec). Monocytes were maintained in buffer A and used immediately. Effectors were generated by culturing T cells in RPMI supplemented with 10% FBS and 1 µg/ml PHA for 3 d, followed by culture in 20 ng/ml IL-2 for 3–6 d. Flow cytometric analysis demonstrated that these cells were 97% CD3 positive. Primary human dermal, lung, and cardiac microvascular endothelial cells and human umbilical vein endothelial cells (Lonza) were cultured on 20 µg/ml of fibronectin-coated substrates and maintained in EBM-2MV media as described previously (Carman et al., 2007). CHO epithelial cells stably transfected with ICAM-1 GFP were generated and cultured as described previously (Carman et al., 2007). MDCK epithelial cells were obtained from American Type Culture Collection.

Plasmids and transfections

mYFP, mDsRed, pEGFP-c, pEGFP-C2, and pEGFP-C1. pEndo plasmids were purchased from Takara Bio Inc. The GFP-based ratiometric H2O2 biosensor HyPer was obtained from Evrogen. Membrane-targeted DsRed was generated by over-oligo-extension PCR to add a N-terminal palmitoylation sequence. Membrane-targeted Hyper was generated by two rounds of site-directed mutagenesis followed by insertion of the fornasyl group through unidirectional subcloning. Other DNA constructs were gifts from P. Turowski (VE-cadherin-GFP; University College London, London, UK), K. Burrage (Rac1 N17-GFP and RhoA N19-GFP; University of North Carolina, Chapel Hill, NC), F.W. Luscinskas (contactin-GFP and contactin3F-GFP; Brigham and Women’s Hospital, Boston, MA), T. Terada (p47phox-DisRed; University of Texas Southwestern Medical Center, Dallas, TX), T. Kirchhausen (CD63-GFP and LAMP1-GFP; Immune Disease Institute, Boston, MA), M. Liscanti ( Caveolin-1-GFP; Thomas Jefferson University, Philadelphia, PA), E. Masuda (VAMP2-GFP; Rigel Pharmaceuticals, San Francisco, CA), and B. Werle-Haller (integrin j3-GFP; University of Geneva, Geneva, Switzerland). Integrin a5-GFP and Arp3-GFP were purchased from Addgene. MVEC transient transfection was done by Nucleofection according to the manufacturer’s instructions (Amaxa Inc.). Experiments were conducted 48–72 h after transfection.

Leukocyte transendothelial migration

Live-cell imaging of leukocyte diapedesis was performed as described previously (Carman et al., 2007). In brief, confluent monolayers of transfected MVECs were grown on fibronectin (20 µg/ml)-coated Delta-L live-cell imaging dishes (Biostats) and stimulated for 24 h with 10 ng/ml TNF. MVECs were fixed and twice and imaged in buffer A and maintained in buffer A and then added to endothelial cell monolayers and subject to live-cell time-lapse imaging (see Epifluorescence, TIRF, and spinning disk confocal microscopy). In all cases, selected imaging fields contained intact confluent endothelial monolayers. However, because transfection efficiencies are typically 30–50%, fluorescent transfectants were variously coexpressed by fluorescent and nonfluorescent MVECs. For some experiments function-blocking antibodies or pharmaceutical agents were added during leukocyte diapedesis and, as indicated, subsequently removed by washing five times with buffer A. For select studies, leukocyte–endothelial cell interactions were performed under physiological laminar shear flow using an FCS2 parallel plate flow chamber (Biostats) as described previously (Carman et al., 2007). In brief, MVEC monolayers were assembled as the lower wall in a parallel-wall flow FCS2 chamber, which was then perfused with buffer A at 37°C using a syringe pump (Harvard Apparatus). Leukocytes in buffer A were infused at 0.3 dye/cell for 30 s to allow accumulation, and then were subjected to 4 dye/cm² shear force during continuous live-cell imaging at 37°C.

Epifluorescence, TIRF, and spinning disk confocal microscopy

All live-cell time-lapse imaging was performed at 37°C in buffer A with 10–60s intervals using the following fluorochromes: GFP, YFP, DsRed, HyPer, Fura-2, and Cy5. Epifluorescence, differential interference contrast (DIC), and IRM were performed on a microscope (Axiovert 200M; Carl Zeiss).
were divided into quadrants to define the cell sides that were oriented parallel to the axis of de-stretch versus the cell ends in the perpendicular orientation (see schematic in Fig. B c, i). We then measured the side and end perimeter lengths that exhibited new lamellae activity and expressed them as a fraction of total side and end perimeter lengths. This was repeated for multiple cells in multiple experiments.

Image processing and analysis

All analysis was conducted using Axiosvision 4.6.3 and ImageJ software. Morphometric and dynamic features, including VL/VW width, propagation velocity, lifetime distance traveled, and directionality were performed with the aid of the Axiosvision Manual Cell Tracking Module and through direct tracing and measurement of VL outlines in sequential frames. To assess VL propagation directionality, a vector was established from sequential frames by connecting the VL initiation site and the final position before being extinguished. The VL vector was compared both with the radial axes of the endothelium (established by drawing a line from the center of the nucleus through the micro-wound toward the cell periphery) and the leukocyte migration vector. VL that exhibited change in direction were characterized by tracking propagation in sequential video frames (using the center point of the leading edge outline as a guide) and quantifying turns in the resulting track with the Axiosvision angle measurement tool. For membrane folding analysis, ROIs were drawn around actin-GFP–defined features (i.e., VL- or VW-type structures), as well as adjacent control areas. The mean fluorescence intensity of the corresponding, background-subtracted mDsRed images were then calculated for each VLA or VW, and normalized to control area for at least 10 separate events. VL enrichment analysis was conducted in MVECs coexpressing mYFP or mDsRed and a fluorescent fusion protein of interest. Background-subtracted mean fluorescence intensities for the protein of interest and for the membrane were obtained in ROIs representing the VL (defined by the 1-µm zone behind the VL leading edge) and non-VL areas. Fluorescence intensities of the protein of interest within VL were first normalized to the membrane signal and then to the corresponding (i.e., membrane normalized) control region. At least 10 separate events were measured for each analysis. Pearson’s analysis was performed on background-subtracted images using the Axiosvision colocalization module. Inhibition studies were assessed by direct measurement of VL propagation velocities and time required to close a pore/gap starting from the moment at which the leukocyte completely exited it. Alternatively, the percentage of pore/gaps in an imaging field that closed over time was expressed as cumulative kymographs. were generated using ImageJ software.

Transmission electron microscopy

Transmission electron microscopy was performed as described previously [Corman et al., 2007]. In brief, TNFα-activated endothelial cells grown on fibronectin-coated coverglass were incubated with T cells for the indicated times and then fixed with 2.5% glutaraldehyde and 2% paraformaldehyde in 1.0 M sodium cacodylate buffer, pH 7.4, for 2 h, post-fixed in 1.5% osmium tetroxide (OSO4) for 1 h, stained en bloc with uranyl acetate, dehydrated, and embedded in epoxy. Thin epon sections of 90 nm were cut with an ultramicrotome (Leica) and visualized with an electron microscope (CM-10; Philips) at an acceleration voltage of 80 kV. Images were taken on negative films. After development, the negative films were subjected to image scanning (using an Epson GT-X978 scanner and Epson File Manager software) and saved as tif files. Image brightness and contrast were adjusted in Adobe Photoshop software (CS4) and T cell and endothelial cell regions were highlighted with 15% opacity blue or green overlay, respectively, in Adobe Illustrator.

Statistical analysis

Results were presented as mean ± SEM for n ≥ 3. P-values were calculated via Student’s t tests in GraphPad Prism. Statistical significance is indicated with p-values as follows: ***, P < 0.001; **, P < 0.01; *, P < 0.05.

Online supplemental material

Fig. S1 shows the classification of pore closure events in diverse settings. Fig. S2 shows that VL coexist with VW in endothelial cells. Fig. S3 shows tension breakage and VL responses after mechanical micro-wounding in endothelial cells. Fig. S4 shows tension breakage and VL responses after mechanical micro-wounding in epithelial cells. Fig. S5 shows enrichment of p47phox in VL, validation of mHyper, and inhibition of VL by VAS-2870. Video 1 shows that leukocyte-driven endothelial micro-wounds are closed efficiently. Video 2 shows examples of three classes of pore-closing lamellipodia in diverse settings. Video 3 shows time-lapse spinning disk confocal imaging demonstrating that pore closing lamellipodia form on the ventral surface of endothelial cells. Video 4 shows that VL are initiated from preexisting actin.

Endothelial cells were loaded with Fura-2 AM (2 µg/ml; Molecular Probes) for 30 min at 37°C, washed with buffer A, and imaged live during both leukocyte diapedesis and mechanical micro-wounding. To conduct ratio-metric calcium flux analysis, a time series of 510-nm fluorescence images were captured after sequential excitation at 340 and 380 nm for each time point using standard Fura-2 filters (Chroma Technology Corp.) and a 40x Plan-Neofluar (NA 1.3) objective. Ratio-metric calcium flux was calculated as previously described (Ehrlich et al., 2004). In brief, images were acquired with a spinning disk confocal head (PerkinElmer) coupled to a microscope (Axiovert 200M) equipped with a 63× oil-PlanAchromat oil immersion objective (NA 1.46). Images were acquired with a camera (Cool Snap HQ CCD; Photometric) and Slidebook 4 acquisition software.

Imaging of intracellular H2O2

For imaging of intracellular H2O2, MVECs transfected with the mHyPer-GFP biosensor were sequentially excited at 488 nm while reading emission at 505 and 520 nm. Ratio-metric H2O2 production was calculated as: (488nmEX:500nmEM-background/420nmEX:500nmEM-background) for each cell using Axiovision as previously described (Sage et al., 2012). Two µM thapsigargin (Sigma-Aldrich) was added to samples as indicated as a positive control.

Calcium imaging

Endothelial cells were then plated on prestretched chambers and cultured for 3 h. Cells were transfected with PEG-catalase, or NSC23766 (not depicted). This analysis showed that basally-produced H2O2 was efficiently reduced to H2O by these compounds. Previously described (Katsumi et al., 2002). Specifically, individual cell perimeters were generated using ImageJ software.

Transmission electron microscopy

Transmission electron microscopy was performed as described previously [Corman et al., 2007]. In brief, TNFα-activated endothelial cells grown on fibronectin-coated coverglass were incubated with T cells for the indicated times and then fixed with 2.5% glutaraldehyde and 2% paraformaldehyde in 1.0 M sodium cacodylate buffer, pH 7.4, for 2 h, post-fixed in 1.5% osmium tetroxide (OSO4) for 1 h, stained en bloc with uranyl acetate, dehydrated, and embedded in epoxy. Thin epon sections of 90 nm were cut with an ultramicrotome (Leica) and visualized with an electron microscope (CM-10; Philips) at an acceleration voltage of 80 kV. Images were taken on negative films. After development, the negative films were subjected to image scanning (using an Epson GT-X978 scanner and Epson File Manager software) and saved as tif files. Image brightness and contrast were adjusted in Adobe Photoshop software (CS4) and T cell and endothelial cell regions were highlighted with 15% opacity blue or green overlay, respectively, in Adobe Illustrator.

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filaments and exhibit complex propagation features. Video 5 shows examples of closure events after transcellular and paracellular mechanical micro-wounding. Video 6 shows asymmetric cellular retraction and recovery after mechanical micro-wounding. Video 7 shows that release tone correlates with VL initiation on actin filaments. Video 8 shows that enforced substrate mechanical micro-wounding. Video 7 shows that tension release correlates with VL formation and pore closure. Video 10 shows the enrichment of, and functional requirement for, p47phox in VL.

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