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Endothelial LSP1 Modulates Extravascular Neutrophil Chemotaxis by Regulating Nonhematopoietic Vascular PECAM-1 Expression

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During inflammation, leukocyte–endothelial cell interactions generate molecular signals that regulate cell functions. The Ca^{2+}- and F-actin–binding leukocyte-specific protein 1 (LSP1) expressed in leukocytes and nonhematopoietic endothelial cells is pivotal in regulating microvascular permeability and leukocyte recruitment. However, cell-specific function of LSP1 during leukocyte recruitment remains elusive. Using intravital microscopy of cremasteric microvasculature of chimeric LSP1-deficient mice, we show that not neutrophil but endothelial LSP1 regulates neutrophil transendothelial migration and extravascular directionality without affecting the speed of neutrophil migration in tissue in response to CXCL2 chemokine gradient. The expression of PECAM-1–sensitive $\alpha_6\beta_1$ integrins on the surface of transmigrated neutrophils was blunted in mice deficient in endothelial LSP1. Functional blocking studies in vivo and in vitro elucidated that $\alpha_6\beta_1$ integrins orchestrated extravascular directionality but not the speed of neutrophil migration. In LSP1-deficient mice, PECAM-1 expression was reduced in endothelial cells, but not in neutrophils. Similarly, LSP1-targeted small interfering RNA silencing in murine endothelial cells mitigated mRNA and protein expression of PECAM-1, but not ICAM-1 or VCAM-1. Overexpression of LSP1 in endothelial cells upregulated PECAM-1 expression. Furthermore, the expression of transcription factor GATA-2 that regulates endothelial PECAM-1 expression was blunted in LSP1-deficient or LSP1-silenced endothelial cells. The present study unravels endothelial LSP1 as a novel cell-specific regulator of integrin $\alpha_6\beta_1$-dependent neutrophil extravascular chemotactic function in vivo, effective through GATA-2–dependent transcriptional regulation of endothelial PECAM-1 expression. *The Journal of Immunology*, **2015, 195: 2408–2416.**

Recruitment of neutrophils from blood stream to the inflamed tissue is a hallmark of acute inflammation. In many tissues, this is a sequential multi-step process of neutrophil–endothelial cell interactions characterized as the initial neutrophil tethering and rolling along and then firm adhesion of rolling neutrophils to the inflamed endothelium, the intraluminal crawling of neutrophils on the endothelial surface, and transendothelial migration of neutrophils prior to their migration and chemotaxis to the site of infection or injury (1–3). These multiple steps of neutrophil recruitment are orchestrated by a cascade of interactions involving adhesion molecules and a myriad of signaling events that are, in turn, regulated by the cross-talk between neutrophils and the vascular endothelial cell lining (4). Neutrophil chemotaxis is modulated by F-actin–binding proteins that dictate actin polymerization and cytoskeletal rearrangement (5). Previous studies have shown that the intracellular Ca^{2+}- and F-actin–binding leukocyte-specific protein 1 (LSP1), expressed in both neutrophils and endothelial cells, is critical in regulating transendothelial migration of neutrophils and microvascular permeability (6–8). LSP1 serves as a major substrate for both protein kinase C (PKC) as well as MAPK-activated protein kinase 2, downstream of p38 MAPK signaling (9, 10). These kinases are known to be involved in neutrophil migration and chemotaxis (11–14).

On account of its predominantly cytosolic presence and its association with the cytoskeleton, leukocyte LSP1 was reported to be crucial in transmission of signals that regulate leukocyte polarization and motility (15). On the contrary, however, nonhematopoietic endothelial-expressed LSP1 is localized primarily in the nucleus (6). In neutrophils, LSP1 is phosphorylated by the activation of p38 MAPK downstream of soluble chemoattractant receptor signaling and then colocalizes with F-actin, thus contributing to the stability of its polarization during chemotaxis (16, 17). A similar mechanism was observed in migrating dendritic cells, which showed enhanced phosphorylation of LSP1 concomitant with increased actin association in response to the viral protein gp120 (18). Surprisingly, these mechanisms are not operative in activation of endothelial LSP1, which was recently shown to be phosphorylated following ICAM-1–mediated adhesive engagement, but not by cytokine or chemokine stimulation alone (19).

Earlier studies on the phenotype of LSP1-deficient mice revealed a negative regulatory role of LSP1 in inflammation. These studies reported increased infiltration of neutrophils in the inflamed tissue of LSP1-deficient mice in experimental peritonitis (20), skin fibrosis (21), and arthritis (22). These observations were substantiated by increased migration of LSP1-deficient neutrophils in response to

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Abbreviations used in this article: KC, keratinocyte-derived chemokine; KO, knockout; LSP1, leukocyte-specific protein 1; PKC, protein kinase C; siRNA, small interfering RNA; WT, wild-type.

bacterial formyl peptide fMLF in vitro (22). Discordantly, however, LSP1-deficient neutrophils exhibited impaired chemotaxis speed and directionality, but enhanced superoxide production, in response to keratinocyte-derived chemokine (KC/CXCL1) gradient in vitro (23). By intravital microscopy of mouse cremasteric microvasculature in vivo, decreased transendothelial migration of neutrophils was demonstrated in LSP1-deficient mice in response to IL-1β or TNF-α, effects attributed to the supportive role of endothelial-expressed LSP1 in neutrophil extravasation (6). More recently, endothelial LSP1 was shown to regulate microvascular permeability by participating in endothelial dome formation during neutrophil transmigration (8).

The complexity of cell-specific LSP1 signaling has, thus, promulgated discrepancies in the putative role of LSP1 in vivo. Whether LSP1 modulates other steps of neutrophil recruitment such as intraluminal crawling and posttransendothelial extravascular chemotaxis is not known. Adhesion and transendothelial migration of neutrophils are mainly mediated by β_2 integrins (24). However, $\alpha_4\beta_1$ (VLA-4) integrins can also mediate neutrophil recruitment independent of β_2 (24–26). On the contrary, neutrophil extravascular chemotaxis was shown to be governed mainly by neutrophil β_1 integrins such as $\alpha_2\beta_1$, $\alpha_4\beta_1$, $\alpha_5\beta_1$, and $\alpha_6\beta_1$ (26–29). Upregulation of these neutrophil β_1 integrins is dependent on signaling events associated with engagement of β_2 integrin during transendothelial migration (30) but may also be associated with homophilic interactions of both neutrophil PECAM-1 and endothelial PECAM-1 (31). The modulatory role of neutrophil LSP1 on the expression and function of adhesion molecules, however, is incompletely understood. Neutrophil LSP1 was previously shown to regulate the function, but not the expression, of the β_2 integrin Mac-1 by modulating its translocation to the uropod (22). Similarly, the role of endothelial LSP1 in the expression and functions of adhesion molecules remain elusive.

In the current study, we explored the cell-specific molecular mechanisms by which LSP1 regulates different steps of CXC chemokine CXCL2-induced neutrophil recruitment in chimeric LSP1-deficient mice by using intravital microscopy and time-lapsed video analysis. By analyzing the expression of adhesion molecules on neutrophils and endothelial cells, we further investigated the cell-specific mechanisms involved in extravascular chemotaxis of transmigrated neutrophils regulated by LSP1 in endothelial cells.

Materials and Methods

Mice

Five- to seven-day-old and 8–16-wk-old LSP1-deficient (knockout [KO]) mice, on the 129/SvJ background, generated as described previously (20) and transferred from the University of Toronto, and the control wild-type (WT) 129/SvJ mice were used in this study with the approval of animal protocols from University Committee on Animal Care and Supply at the University of Saskatchewan. All surgeries were performed under ketamine-xylazine anesthesia, as described (7), and all efforts were made to minimize animal suffering. Bone marrow chimeric mice were generated according to a previously described protocol (6) and housed in specific pathogen-free facilities for 6–8 wk to allow full humoral reconstitution before use in experiments. Bone marrows from WT mice transplanted into WT and KO mice are designated as WT→WT and WT→KO mice, and bone marrows from KO mice transplanted into WT and KO mice are designated as KO→WT and KO→KO mice, respectively. Chimeric mice generated according to this protocol were confirmed to have ∼99% of leukocytes from donor mice (32). The neutrophil responses determined in WT→WT and KO→KO mice in this study were found to be indistinguishable from those in WT and KO mice, respectively (N. Xu and L. Liu, unpublished observations and Ref. 6).

Intravital microscopy

The mouse cremaster muscle preparation was used to study dynamic leukocyte-endothelial interactions in microvasculature as described previously (6, 7, 11, 33). For induction of neutrophil recruitment, a piece of agarose gel (∼1 mm^3) containing the optimal concentration of murine chemokine CXCL2 (0.5 μmol/l; R&D Systems, Minneapolis, MN) was placed and held on the surface of the cremaster muscle in a preselected area 350 μm from and parallel to the observed postcapillary venule. Leukocyte rolling velocity (μm/s), leukocyte rolling flux (cells/min), and the number of adherent (cells/100-μm venule) and emigrated neutrophils (cells/235 × 208 μm^2 field) were determined in the cremasteric postcapillary venule (25–40 μm diameter) using video-playback analysis (6, 7, 11, 33). By using ImageJ software (National Institutes of Health) and time-lapsed video analysis, neutrophil intraluminal crawling, transmigration time, and extravascular chemotaxis were quantified as described previously (11, 33, 34). Chemotaxis index was calculated by dividing the chemotaxis distance (distance in the direction of chemotactic gradient) by the total migration distance in tissue. At least 40 cells were tracked and analyzed for each group. Where indicated, functional blocking Abs against α_6 (3 mg/kg; clone NKI-GoH3; Serotec, Oxford, U.K.) and the respective isotype control (3 mg/kg; rat IgG2a κ; eBioscience, San Diego, CA) were administered i.v. 30 min prior to the placement of CXCL2-containing gel.

Isolation of neutrophils and FACS analysis

Neutrophils from murine femurs and tibia were isolated using three-step Percoll (GE Healthcare, Baie d'Urfe, QC, Canada) gradient (72, 64, and 52%) centrifugation at 1060 × *g* for 30 min as described (19).

Acute mouse peritonitis was induced to obtain emigrated neutrophils 4 h after an i.p. injection of CXCL2 (0.5 μg in saline). Neutrophils were then lavaged and harvested from the peritoneum (with ≥95% purity), and integrin expression was determined as described previously (11) using the following FITC-conjugated fluorescent Abs and the respective isotype controls (purchased from eBioscience, San Diego, CA) against α_2 (CD49b, 1:250 dilution; clone HMa2), α_4 (CD49d, 1:200 dilution; clone R1-2), α_5 (CD49e, 1:200 dilution; clone HMa5-1), α_6 (CD49f, 1:100 dilution; clone GoH3), and β_1 (CD29, 1:100 dilution; clone HMb1-1). For FACS analysis, neutrophils were gated on a linearly plotted forward scatter–side scatter dot plot.

PECAM-1 expression in murine peripheral blood neutrophils was determined following a previously reported protocol (35) with minor modification. Mouse blood was collected by cardiac puncture in a heparinized syringe. A blood sample (100 μl) was incubated with FITC-conjugated anti-mouse CD31 mAb (1:100 dilution; clone 390; eBioscience) for 30 min at room temperature. The erythrocytes were lysed using a lysis buffer (Beckman Coulter, Mississauga, ON, Canada). The cells were then washed and analyzed by flow cytometry.

Harvest of murine primary endothelial cells

Primary murine endothelial cells were isolated from the lungs and hearts of 5–7-d-old WT and KO mice according to a previously described protocol (19). Briefly, endothelial cells were immunomagnetically isolated using anti–ICAM-2 (CD102) Ab (clone 3C4; BD Pharmingen, Quebec City, QC, Canada), cultured, and passaged once on laminin-coated 24-well plates after reaching confluence. The purity of isolated endothelial cells after isolation and at the time of experiment was determined by immunocytochemistry and image analysis as described (36). CD31 (PECAM-1) and nuclei of the cells were labeled using rabbit anti–PECAM-1 (PA5-24411; Thermo Fisher Scientific, Mississauga, ON, Canada) and Alexa Fluor 488–conjugated goat anti-rabbit IgG (Life Technologies, Burlington, ON, Canada) Abs and stained with Hoechst (Life Technologies), respectively. Purity at the time of experiment was ≥90%, (n = 6; for each sample, a minimum of 500 cells was analyzed).

In vitro chemotaxis assay

Time-lapsed video microscopy was used to determine speed of migration and directionality of chemotaxis in response to CXCL2 chemokine gradient using a previously described method with slight modifications (37, 38). Transmigrated neutrophils were harvested by peritoneal lavage 4 h after an i.p. injection of 1% oyster glycogen (Sigma-Aldrich, Oakville, ON, Canada). Neutrophils were then resuspended at 3 × 10^6/ml in DMEM cell culture medium containing 10% FCS and 15 mmol HEPES, and 6 μl cell suspension containing functional blocking Abs against α_6 (10 μg/ml) or the respective isotype control (10 μg/ml) were seeded into the narrow channel of an uncoated ibiTreat Chemotaxis^{2D} μ-Slide (ibidi, Martinsried, Germany). The slide was then incubated in a humidified incubator at 37°C and 5% CO_2 to allow neutrophils to adhere, and nonadherent cells were removed by flushing the channel. The two opposing reservoirs adjacent to the channel were filled with cell-free medium, and 18 μl 1 μmol/l CXCL2 was introduced in one reservoir. Neutrophil migration was recorded for

60 min at 37˚C using an ibidi heating and incubation chamber on an inverted microscope (Applied Precision) equipped with a digital color video camera. The DMEM cell culture medium was supplemented with 15 mmol/l HEPES to maintain stable pH of the medium during the chemotaxis assay. Time-lapsed video analysis of chemotaxis was performed using ImageJ software (National Institutes of Health), and at least 60 cells were tracked and analyzed for each group.

In vitro neutrophil transendothelial migration assay

Murine microvascular SVEC4-10EE2 endothelial cell line cells (American Type Culture Collection, Manassas, VA) were cultured onto tissue culture-treated polycarbonate transwell inserts (3-μm pore size; Corning, Corning, NY) until 85% confluence. After endothelial cells were treated with or without GATA-2–specific or nontargeting silencing RNA for 24 h, neutrophil transendothelial migration was examined as previously described (39, 40) with minor modification. In brief, freshly isolated murine neutrophils were suspended at 5×10^6 cells/ml in DMEM medium supplemented with 5% FBS. Neutrophils in suspension (1×10^6 cells) and chemoattractant (CXCL2; 200 ng/ml) were added to the top inserts and bottom wells, respectively. Neutrophils were allowed to migrate for 2 h at 37˚C in 5% CO_2. Then, 60 μl 0.5 mol/l EDTA was added to the bottom chamber, and the plate was incubated for 10–15 min at 4˚C. Inserts were removed from the well, and the total number of transmigrated cells in each bottom well was counted using a hemocytometer.

Gene silencing and overexpression

Murine microvascular SVEC4-10EE2 endothelial cells were cultured as described (19). Targeted gene silencing was achieved by a 48-h transfection of the cells with small interfering RNA (siRNA) specifically targeting LSP1 (Santa Cruz Biotechnology, Dallas, TX) or GATA-2 (Santa Cruz Biotechnology) and with siRNA transfection medium and reagent (Santa Cruz Biotechnology) according to the manufacturer's protocol (18). The control cells were transfected with negative control scrambled siRNA (Santa Cruz Biotechnology) having no homology to any known RNA sequence.

For overexpression of LSP1, mouse pCMV-SPORT6-LSP1 plasmids (Thermo Fisher Scientific), amplified using *Escherichia coli* DH5α and purified using the Plasmid Midi Kit (Qiagen), were transfected in endothelial cells using Lipofectamine 2000 (Life Sciences) according to the manufacturer's protocol.

Immunoblotting

Endothelial cells or neutrophils were lysed using RIPA buffer or Nuclear Extraction Kit (Cayman Chemical, Ann Arbor, MI). Proteins were solubilized in equal volume of Laemmli buffer at 95˚C, resolved by 10% SDS-PAGE, and thereafter transferred to a nitrocellulose membrane and immunoblotted as described previously (19). Briefly, the nitrocellulose membrane was blocked with 5% BSA at room temperature for 1 h and then incubated with rabbit anti–PECAM-1 (1:1000 dilution; Thermo Fisher Scientific), rat anti–ICAM-1 (1:1000 dilution; eBioscience), rat anti–VCAM-1 (1:1000 dilution; Abcam, Toronto, ON, Canada), rabbit anti–GATA-2 (1:1000 dilution; Santa Cruz Biotechnology), anti-LSP1 rabbit serum (1:1000 dilution; a generous gift from Dr. J. Jongstra, University of Toronto), or mouse anti–β-actin (1:2500 dilution; Santa Cruz Biotechnology) Ab. After incubation with HRP-conjugated respective secondary Ab (1:5000 dilution; Santa Cruz Biotechnology) for 1 h at room temperature, Ab binding was detected with ECL detection reagent (GE Healthcare). ImageJ software (v1.47; National Institutes of Health; http://rsbweb.nih.gov/ij) was used for densitometric quantification of the detected bands. Intensity values for the proteins were normalized to β-actin.

RT-PCR

RT-PCR was performed to determine PECAM-1, ICAM-1, and β-actin mRNA expression as described previously (41). Briefly, RNA was isolated from the cells using RNA isolation kit (Qiagen) and reverse-transcribed using reverse transcription kit (Qiagen). RT-PCR was performed using SYBR Green PCR kit (Qiagen) in an iCycler iQ apparatus (Bio-Rad, Hercules, CA) with primers targeting PECAM-1 (QT01052044; Qiagen), ICAM-1 (QT00155078; Qiagen), LSP1 (QT01046227; Qiagen), and β-actin (QT00095242; Qiagen). All PCRs were performed in triplicate and run for 30 cycles at 95˚C for 30 s, 55˚C for 30 s, and 72˚C for 40 s.

Confocal imaging

Whole-mount staining of cremaster muscle was performed to examine vascular PECAM-1 expression as described previously (8). Briefly, 3 h after an intrascrotal injection of TNF-α (0.1 μg; R&D Systems), the cremaster muscle was excised and fixed using 4% paraformaldehyde (10 min prior to and 1 h after excision of the muscle) and subsequently washed with PBS. The muscle was then permeabilized by 0.5% Triton X-100, blocked with 20% normal goat serum, and then incubated overnight at 4˚C with FITC-conjugated rat anti-mouse PECAM-1 Ab (1:250; eBioscience). The samples were then washed with 0.1% Tween-20, fixed on glass slides with fluorescent mounting medium (Sigma-Aldrich), and visualized with a laser scanning confocal microscope (LSM700; Zeiss).

Statistics

Data are shown as arithmetic mean ± SEM. Statistical analysis was made using Student *t* test or ANOVA with Tukey post hoc comparison test. *n* denotes the number of different mice, different batches of endothelial cells, or neutrophils studied in each group. The p values < 0.05 were considered statistically significant.

Results

To study the cell-specific functions of neutrophil LSP1 and endothelial LSP1 in CXC chemokine CXCL2-induced neutrophil recruitment in vivo, we used intravital microscopy to analyze different steps of recruitment in the cremasteric microvasculature of chimeric LSP1-deficient mice. First, we examined the intravascular dynamics of neutrophil recruitment in the presence of a CXCL2 chemokine gradient. After placing the CXCL2-containing gel, 350 μm from the venule, we observed that leukocyte rolling velocity and rolling flux were not significantly altered in all four types of chimeric mice (Fig. 1A, 1B). Chimeric mice deficient in endothelial LSP1 (KO→KO and WT→KO mice) tended to have lower neutrophil adhesion as compared with WT→WT and KO→WT mice (Fig. 1C). The number of transmigrated neutrophils was significantly lower in KO→KO and WT→KO mice as compared with WT→WT and KO→WT mice, suggesting that not neutrophil LSP1 but endothelial LSP1 is important in neutrophil transendothelial migration in response to CXCL2 (Fig. 1D). As most adherent neutrophils crawl to optimal sites in the vascular lumen for transmigration (34), we analyzed whether cell-specific LSP1 influences intraluminal crawling velocity. Fig. 1E shows that the velocity of intraluminal crawling of neutrophils was not significantly different in all four types of chimeric mice, indicating that neither endothelial LSP1 nor neutrophil LSP1 participates in intraluminal crawling in response to CXCL2 chemotactic gradient. Time-lapsed video analysis of neutrophil transmigration time revealed that comparing to WT→WT and KO→WT mice, transmigrating neutrophils in KO→KO and WT→KO mice took a longer time from the start of neutrophil transmigration to the first appearance of the whole neutrophil outside the venule in the tissue, underlining that endothelial LSP1 deficiency impairs endothelial cell function in promoting neutrophil transmigration (Fig. 1F).

Next, using time-lapsed video analysis, we examined neutrophil extravascular chemotaxis in response to CXCL2 chemotactic gradient. To this end, the extravascular speed of neutrophil migration was significantly reduced in KO→KO and KO→WT mice as compared with WT→WT and WT→KO mice, suggesting that LSP1 in neutrophils, but not in endothelial cells, is decisive in regulating the speed of neutrophil extravascular migration (Fig. 2A, 2B). Furthermore, as illustrated in Fig. 2A and 2C, chemotaxis index of extravascular neutrophils was significantly lower in KO→KO and WT→KO mice as compared with that in WT→WT and KO→WT mice, suggesting that endothelial LSP1 is pivotal in regulating the extravascular directionality of chemotaxing neutrophils.

In view of the surprising modulatory effects of endothelial LSP1 on the directionality of chemotaxing neutrophils in the tissue, we performed a further series of experiments to investigate whether integrin-dependent mechanisms participate in endothelial LSP1-regulated extravascular chemotaxis of emigrated neutrophils. Intraperitoneal injection of CXCL2 resulted in recruitment of neutrophils

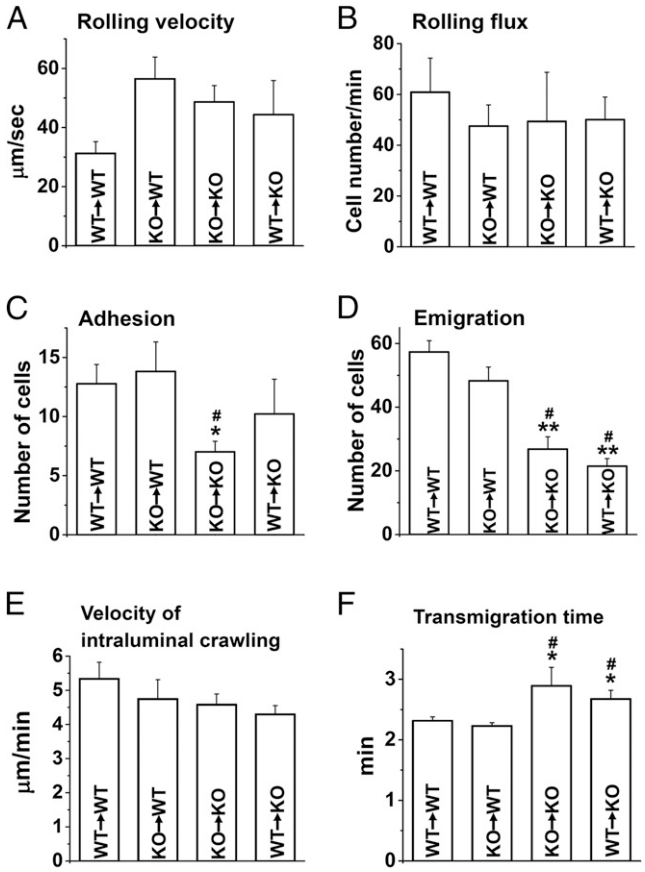

FIGURE 1. Cell-specific regulation of various neutrophil recruitment steps by LSP1. Means ± SEM ($n = 4$) of leukocyte rolling velocity (μm/s) (**A**), leukocyte rolling flux (cells/min) (**B**), and adherent (cells/100-μm venule) (**C**) and emigrated (cells/235 × 208 μm^2 field) neutrophils (**D**) in cremasteric postcapillary venules of WT→WT, KO→WT, WT→KO, and KO→KO chimeric mice determined at 90 min after stimulation with CXCL2 chemokine gradient. $^*p < 0.05$, $^{**}p < 0.01$ from WT→WT, $^{\#}p < 0.05$ from KO→WT. Means ± SEM ($n = 4$) of velocity of intraluminal crawling (μm/min) (**E**) and transmigration time (min) (**F**) determined within 90 min after stimulation with CXCL2 chemokine gradient. $^*p < 0.05$ from WT→WT, $^{\#}p < 0.05$ from KO→WT.

in the peritoneal cavity. Integrin expression on these emigrated neutrophils was analyzed using flow cytometry. Transmigrated neutrophils collected from peritoneal cavity of WT mice, as compared with the unstimulated bone marrow neutrophils, had 5-fold higher surface expression of β_1 integrins (N. Xu and L. Liu, unpublished observations and Ref. 30). Increased expression of α_6 and β_1, but not α_2, α_4, or α_5 integrins, on the transmigrated neutrophils was significantly lower in KO→KO and WT→KO mice as compared with WT→WT and KO→WT mice, suggesting that not neutrophil LSP1, but endothelial LSP1 participates in mediating the upregulated expression of $\alpha_6\beta_1$ integrins on transmigrated neutrophils (Fig. 3A). Because the expression of only $\alpha_6\beta_1$ integrins on transmigrated neutrophils was significantly altered in mice with endothelial LSP1 deficiency, we sought to address the question of whether $\alpha_6\beta_1$ integrins participate in regulating endothelial LSP1-sensitive extravascular directionality of chemotaxing neutrophils. We analyzed chemotaxis index and speed of migration of transmigrated neutrophils after functionally blocking α_6 in cremasteric microvasculature of WT mice and corroborated those observations by determining these parameters using an in vitro μ-slide chemotaxis assay. As depicted in Fig. 3B and 3C, the i.v. administration of anti-α_6 blocking Abs in WT mice or treatment of transmigrated WT neutrophils in the medium in vitro with anti-α_6 blocking Abs did not significantly change the speed of migration, but significantly mitigated chemotaxis index as compared with the treatment with isotype control Abs, indicating that upregulated $\alpha_6\beta_1$ integrin on transmigrated neutrophils regulates the directionality of extravascular neutrophil chemotaxis both in vivo and in vitro.

The upregulation of $\alpha_6\beta_1$ integrins on transmigrated neutrophils is fostered by homophilic PECAM-1 interactions during neutrophil–endothelial cell interactions (31). We, therefore, hypothesized that decreased surface expression of $\alpha_6\beta_1$ on transmigrated neutrophils in endothelial-specific LSP1 deficiency could be a result of deranged PECAM-1 expression. Accordingly, additional in vivo and in vitro experiments were performed to explore whether endothelial or neutrophil LSP1 modulates PECAM-1 expression. Using fluorescence confocal imaging, we visualized the cremasteric microvasculature to examine vascular and neutrophil PECAM-1 expression in WT and LSP1 KO mice. As depicted in Fig. 4A, LSP1 KO mice showed a remarkable decrease in microvascular PECAM-1 expression as compared with WT mice. Leukocyte PECAM-1–dependent fluorescence in cremasteric venule was, however, similar in both WT and KO mice. These results indicate that endothelial LSP1 regulates endothelial PECAM-1 expression, whereas neutrophil LSP1 does not regulate PECAM-1 expression in neutrophils. Additionally, using flow cytometric determination of PECAM-1–dependent fluorescence

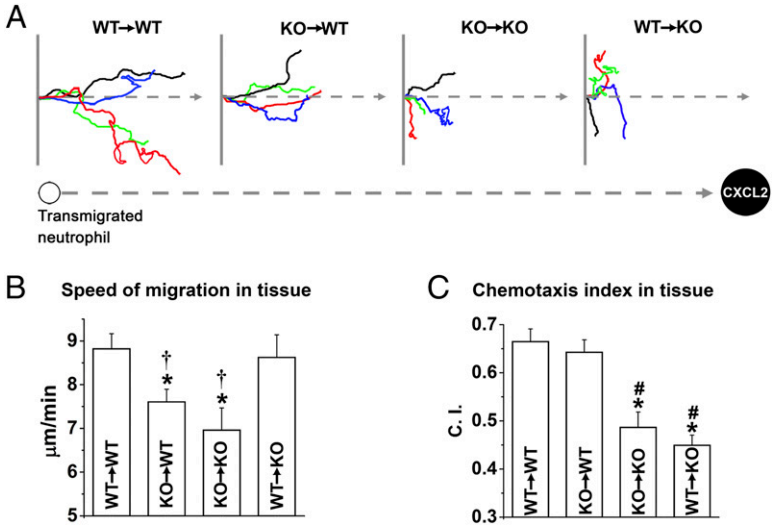

FIGURE 2. Cell-specific regulation of extravascular neutrophil migration by LSP1. (**A**) Representative original tracings (four traces for each one of the four types of chimeric mice) of extravascular migrating neutrophils in cremaster muscle tissue. (**B**) Means ± SEM ($n = 6$) of speed of neutrophil migration (μm/min) in extravascular cremasteric tissue of WT→WT, KO→WT, WT→KO, and KO→KO chimeric mice determined within 90 min after stimulation with CXCL2 chemokine gradient. $^*p < 0.05$ from WT→WT, $^{\dagger}p < 0.05$ from WT→KO. (**C**) Means ± SEM ($n = 6$) of chemotaxis index (C.I.) of neutrophil chemotactic migration in extravascular cremasteric tissue of WT→WT, KO→WT, WT→KO, and KO→KO chimeric mice determined within 90 min after stimulation with CXCL2 chemokine gradient. $^*p < 0.05$ from WT→WT, $^{\#}p < 0.05$ from KO→WT.

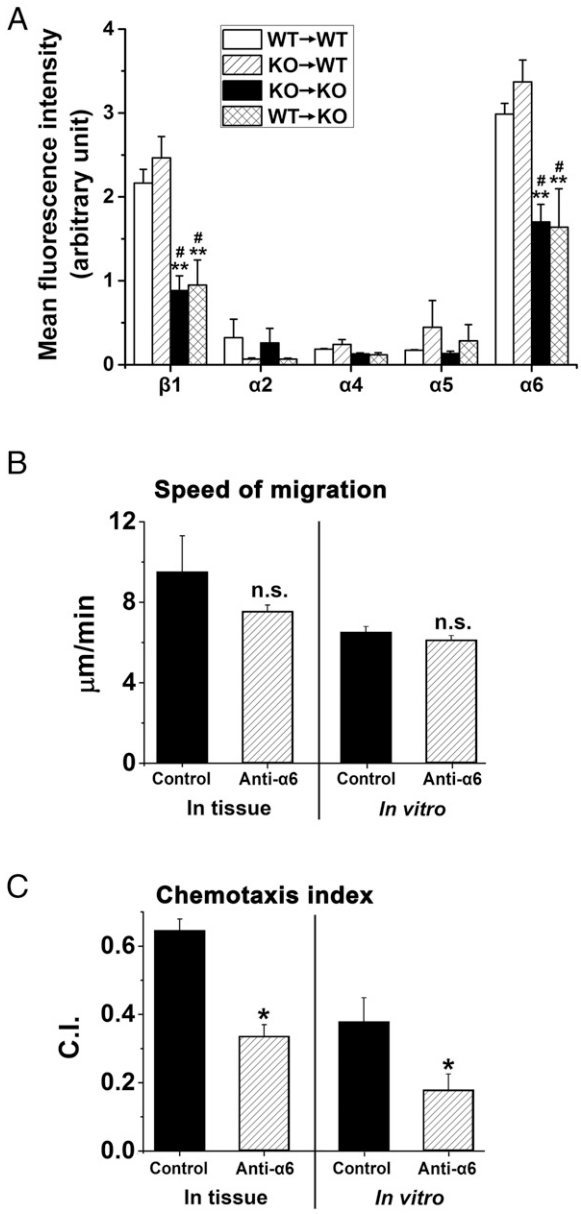

FIGURE 3. Endothelial LSP1-sensitive $\alpha_6\beta_1$ integrin expression orchestrates the directionality of extravascular neutrophil migration. (**A**) Means ± SEM (n = 3; arbitrary units) of integrin-dependent fluorescence intensity quantified in transmigrated neutrophils obtained from peritoneal cavities of WT→WT, KO→WT, WT→KO, and KO→KO chimeric mice by peritoneal lavage 3 h after an i.p. injection of CXCL2. $^{**}p < 0.01$ from WT→WT, $^{\#}p < 0.05$ from KO→WT. (**B** and **C**) *Left bars*, Means ± SEM (n = 3) of the speed of neutrophil migration (µm/min; B) and chemotaxis index (C.I.; C) in extravascular cremasteric tissue of WT mice determined within 90 min after stimulation with CXCL2 chemokine gradient (In tissue; *left bars*). Functional blocking anti-α_6 Abs or the respective isotype control Ig were administered i.v. 30 min prior to stimulation with CXCL2 chemokine gradient. *Right bars*, Means ± SEM (n = 3) of the speed of neutrophil migration (µm/min; B) and chemotaxis index (C.I.; C) determined in vitro on a µ-slide during 60 min after stimulation with CXCL2 chemokine gradient (In vitro; *right bars*). Neutrophils were harvested from oyster glycogen-stimulated peritoneal cavity of WT mice. Functional blocking anti-α_6 Abs or the respective isotype control Ig were added to these isolated and transmigrated neutrophils in cell culture medium and allowed to adhere 30 min prior to contact with CXCL2 chemokine gradient in µ-slide. $^{*}p < 0.05$ from isotype control.

intensity, we revealed that the surface expression of PECAM-1 on peripheral blood neutrophils did not vary between WT and KO mice (mean fluorescence intensity, 224.8 ± 23.2 and 243.4 ± 49.7 arbitrary units after background subtraction [mean ± SEM]; n = 3, respectively) (Supplemental Fig. 1). To corroborate these findings and to determine whether LSP1 regulates other adhesion molecules, we analyzed PECAM-1 and ICAM-1 protein expression in primary endothelial cells from WT and KO mice. As shown in Fig. 4B, PECAM-1, but not ICAM-1, expression was significantly reduced in endothelial cells of LSP1 KO mice as compared with WT mice. To support these data, we determined PECAM-1 protein expression after siRNA-targeted silencing of LSP1 in murine microvascular SVEC4-10EE2 endothelial cells. As a result, siRNA-targeted silencing of endothelial LSP1 significantly reduced PECAM-1 (Fig. 4D), without any effect on ICAM-1 (Fig. 4D) and VCAM-1 (Supplemental Fig. 2) expression in these murine endothelial cells. Silencing LSP1 using gene targeted-siRNA significantly suppressed LSP1 mRNA (Fig. 4C) and protein expression (Fig. 4D), indicating the experimental efficiency of LSP1 silencing in these endothelial cells. Additional experiments explored whether overexpression of endothelial LSP1 modulates PECAM-1 expression. Fig. 4E shows that overexpression of LSP1 in SVEC4-10EE2 endothelial cells resulted in increased PECAM-1. To confirm the cell-specific regulation of PECAM-1 expression by LSP1, we detected PECAM-1 expression in mouse bone marrow neutrophils. As shown in Fig. 4F, neutrophil PECAM-1 expression was not significantly different in either genotype (KO or WT mice). These results and our fluorescence confocal imaging studies shown in Fig. 4A suggest that endothelial LSP1 regulates PECAM-1 expression in endothelial cells, whereas neutrophil LSP1 does not regulate PECAM-1 expression in neutrophils.

We performed an additional series of experiments to disclose the underlying molecular mechanisms of endothelial LSP1-sensitive PECAM-1 expression. As shown in Fig. 5A, targeted siRNA silencing of LSP1 in murine SVEC4-10EE2 endothelial cells significantly blunted PECAM-1, but not ICAM-1, mRNA levels, suggesting that LSP1 transcriptionally regulates PECAM-1 expression in endothelial cells. To elucidate the transcriptional regulation of PECAM-1 by LSP1, we explored the participation of the transcription factor GATA-2 that is expressed in microvascular endothelial cells (42). As shown in Fig. 5B, GATA-2 expression in LSP1-deficient murine primary endothelial cells was significantly lower as compared with that in WT endothelial cells. Furthermore, silencing LSP1 in SVEC4-10EE2 endothelial cells significantly mitigated GATA-2 expression (Fig. 5C), alluding to LSP1 sensitivity of endothelial GATA-2 expression. Overexpression of LSP1 in these endothelial cells significantly increased the expression of GATA-2 (Fig. 5D). To validate the role of LSP1-sensitive GATA-2 expression in selectively regulating endothelial PECAM-1 expression, we silenced GATA-2 and analyzed adhesion molecule expression. Silencing endothelial GATA-2 significantly attenuated GATA-2 and PECAM-1, but not ICAM-1, protein expression in endothelial cells, confirming the endothelial cell LSP1-specific regulation of PECAM-1 expression by GATA-2 (Fig. 5E). We also explored whether endothelial cell GATA-2 indeed plays a role in neutrophil transmigration. In vitro neutrophil transendothelial migration assay revealed that targeted GATA-2 silencing in SVEC4-10EE2 endothelial cells significantly reduced neutrophil transendothelial migration in response to CXCL2, confirming that endothelial cell GATA-2 is an important regulator of neutrophil transendothelial migration (Fig. 5F).

Discussion

The present observations disclose the hitherto unknown endothelial cell–specific role of LSP1 in regulating integrin-dependent neutrophil functions during neutrophil recruitment. By using intravital microscopy and time-lapsed video analysis of multiple steps of

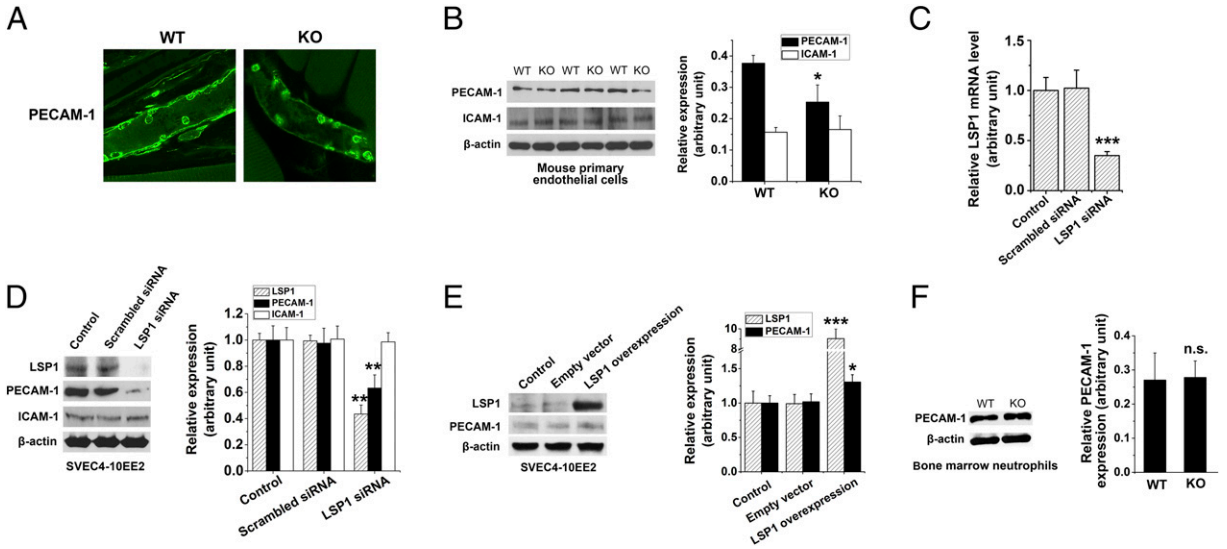

FIGURE 4. Endothelial LSP1-sensitive vascular PECAM-1 expression. (**A**) Confocal micrographs (representative of five independent experiments) of PECAM-1–dependent fluorescence in cremasteric postcapillary venules of WT (*left panel*) and LSP1-deficient (KO; *right panel*) mice. (**B**) Original Western blot and means ± SEM ($n = 3$) of PECAM-1 and ICAM-1 protein expression (relative to β-actin) determined in murine primary endothelial cells isolated from WT and KO mice. $*p < 0.05$ from WT. (**C**) Relative LSP1 mRNA level (relative to β-actin) in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of treatment with negative control scrambled siRNA or LSP1-targeted siRNA. $***p < 0.001$ from scrambled siRNA treatment. (**D**) Representative original Western blot and means ± SEM ($n = 4$) of LSP1, PECAM-1, and ICAM-1 protein expression (relative to β-actin) determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of treatment with negative control scrambled siRNA or LSP1-targeted siRNA. $**p < 0.01$ from scrambled siRNA treatment. (**E**) Representative original Western blot and means ± SEM ($n = 4$) of LSP1 and PECAM-1 protein expression (relative to β-actin) determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of transfection with murine pCMV-SPORT6-LSP1 plasmids or empty vector as negative control. $*p < 0.05$, $***p < 0.001$ from the control empty vector. (**F**) Representative original Western blot and means ± SEM ($n = 4$) of PECAM-1 protein expression (relative to β-actin) determined in neutrophils isolated from bone marrows of WT and KO mice.

neutrophil recruitment, our data demonstrate that endothelial, but not neutrophil, LSP1 is important in the transendothelial migration of neutrophils in response to chemokine CXCL2, confirming the role of endothelial LSP1 as a gatekeeper for neutrophil transendothelial migration (6). It is our novel and surprising finding that the nonhematopoietic, endothelial LSP1 further regulates the directionality, but not the speed, of extravascular migrating neutrophils in tissue after they leave the vasculature. This effect on the directionality of migrating neutrophils in tissue is, at least in part, due to endothelial, but not neutrophil, LSP1-dependent transcriptional regulation by GATA-2 of endothelial PECAM-1 expression, which dictates the expression of $\alpha_6\beta_1$ integrins on the surface of transmigrating neutrophils.

In this study, we demonstrate that, in the absence of endothelial LSP1 alone, CXCL2-elicited rolling and adhesion of neutrophils is not substantially affected, whereas transendothelial migration of neutrophils is markedly reduced. A similar effect was previously reported upon stimulation of leukocyte recruitment by chemokine KC/CXCL1 and cytokines TNF-α and IL-1β (6). Transendothelial migration of neutrophils is preceded by Mac-1–dependent intraluminal crawling mediated by endothelial ICAM-1 (34). Despite a previous report showing that neutrophil LSP1 modulates Mac-1 functions (22), our results do not find alterations in neutrophil intraluminal crawling. However, our data of unaltered ICAM-1 expression in LSP1-deficient endothelial cells substantiate our observation that LSP1 signaling does not participate in intraluminal crawling of neutrophils.

Mechanistically, extravascular migration of neutrophils is effectively accomplished by high-affinity interactions of β_1 integrins with proteins of the extracellular matrix (30). We observed that deficiency of neutrophil, but not endothelial, LSP1 resulted in decreased speed of migration in response to CXCL2. Consistent with our findings, LSP1-deficient neutrophils were previously shown to exhibit reduced speed of neutrophil migration in KC/CXCL1 gradient in vitro (23). Surprisingly, our results show that the directionality of chemotaxing neutrophils toward CXCL2 gradient was affected in mice with endothelial cell-specific deficiency of LSP1 in contrast to previous reports showing that neutrophil chemotaxis toward KC/CXCL1 gradient was neutrophil LSP1 dependent (23). It is documented that the inhibitory effect of α_6 blocking on neutrophil recruitment is chemoattractant specific and involves reduced transendothelial migration, and the impact of α_6 blocking on extravascular chemotaxis was not determined (29, 30, 43). However, our in vitro and in vivo results demonstrate that functionally blocking α_6 did not affect the speed of neutrophil migration but impaired the directionality, an observation that has not been reported previously. Along this line, LSP1-deficient endothelial cells, therefore, render decreased $\alpha_6\beta_1$ expression on the transmigrating neutrophils during neutrophil–endothelial cell interactions, resulting in impaired directionality of extravascular neutrophil migration in the tissue. In our in vivo study, the effect of α_6 functional blocking on the directionality, not the speed of migration, suggests the possible involvement of interactions between α_6 integrin and its ligand laminin and the subsequent signaling in dictating extravascular chemotactic directionality of emigrated neutrophils. However, the results of our in vitro α_6 functional blocking studies in uncoated, but serum-containing chemotaxis μ-slide indicate that in addition to laminin binding, α_6 integrin may also be probably involved in other signaling events such as integrin cross-talk or binding to serum proteins, which could determine the directionality of extravascular neutrophil chemotaxis. Extravascular neutrophil locomotion requires coordinated engagement and detachment of different integrins and their ligands. Apart from ligand binding, integrins are also

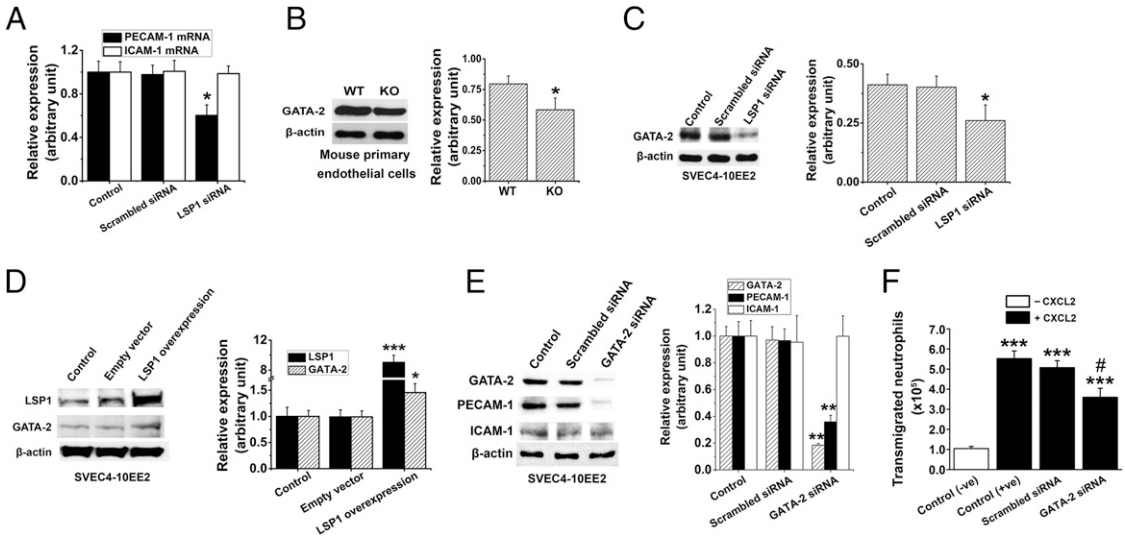

FIGURE 5. Endothelial LSP1-sensitive GATA-2 regulates PECAM-1 transcription. (**A**) Mean ± SEM of mRNA levels ($n = 6$) encoding PECAM-1 and ICAM-1 determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of treatment with negative control scrambled siRNA or LSP1-targeted siRNA. *$p < 0.05$ from scrambled siRNA treatment. (**B**) Representative original Western blot and means ± SEM ($n = 4$) of GATA-2 protein expression (relative to β-actin) determined in murine primary endothelial cells isolated from WT and KO mice. *$p < 0.05$ from WT. (**C**) Representative original Western blot and means ± SEM ($n = 4$) of GATA-2 protein expression (relative to β-actin) determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of treatment with negative control scrambled siRNA or LSP1-targeted siRNA. *$p < 0.05$ from scrambled siRNA treatment. (**D**) Representative original Western blot and means ± SEM ($n = 4$) of LSP1 and GATA-2 protein expression (relative to β-actin) determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of transfection with murine pCMV-SPORT6-LSP1 plasmids or empty vector as negative control. *$p < 0.05$, ***$p < 0.001$ from the control empty vector. (**E**) Representative original Western blot and means ± SEM ($n = 4$) showing GATA-2, PECAM-1, and ICAM-1 protein expression (relative to β-actin) determined in SVEC4-10EE2 endothelial cells in the absence (Control) or in the presence of treatment with negative control scrambled siRNA or GATA-2–targeted siRNA. **$p < 0.01$ from scrambled siRNA treatment. (**F**) Bone marrow–derived neutrophils (1×10^6) were allowed to migrate across SVEC4-10EE2 endothelial cells cultured on transwell inserts and treated with or without scrambled or GATA-2–targeting siRNA in response to CXCL2 (200 ng/ml) in the transwell systems. The number of cells that migrated across the endothelium into the bottom well was counted. Data shown are mean ± SEM of three independent experiments, all in triplicate. ***$p < 0.001$ versus negative control, #$p < 0.05$ versus scrambled siRNA-treated group.

involved in a wide range of immune function–related signaling events (30). Because of the complex nature and insufficient knowledge of leukocyte tissue chemotaxis, more investigations are needed to uncover the molecular mechanisms of extravascular neutrophil chemotaxis.

Extravasated neutrophils are also known to secrete soluble mediators such as LTB4, which is capable of attracting more neutrophils to the site of inflammation (44). The reduction in transmigration of LSP1-deficient neutrophils may possibly be attributed, in part, to the impaired secretion of such soluble mediators. However, whether transmigrated neutrophil-derived soluble chemoattractants are involved in regulating the directionality of neutrophil chemotaxis in tissue is unknown. Further research is warranted to investigate whether such inflammatory mediators are involved in extravascular chemotaxis of neutrophils.

Interestingly, PECAM-1–deficient neutrophils exhibit loss of directionalty during migration in vitro (45). This mechanism, however, may not be operative in endothelial LSP1-sensitive directionality changes of migrating neutrophils, as our results show that PECAM-1 expression was reduced in LSP1-deficient endothelial cells, but not in LSP1-deficient neutrophils. PECAM-1–dependent transendothelial migration of neutrophils was previously shown to be mediated by $\alpha_6\beta_1$ integrin, which is upregulated by homophilic interactions of neutrophil and endothelial cell PECAM-1 (31, 46). This cross-talk is supported by our present observation that implicates endothelial LSP1 sensitivity in regulating endothelial PECAM-1–modulated and $\alpha_6\beta_1$-dependent extravascular chemotaxis of neutrophils. Ample evidence underscores the importance of PECAM-1 in orchestrating leukocyte recruitment and microvascular permeability (47, 48). It is, therefore, tempting to speculate that endothelial LSP1-sensitive PECAM-1 expression contributes to the recently reported impairment in microvascular permeability during neutrophil recruitment in LSP1-deficient mice (7, 8).

Very little is known about the signaling mechanisms that regulate PECAM-1 expression in endothelial cells. Endothelial PECAM-1 expression was previously shown to be regulated by inflammatory cytokines (49) and by activation of NO synthase (50), PKC, and phospholipase A_2 (51). Transcriptional regulation of PECAM-1 was documented to involve modulation of its gene promoter activity by the p65 subunit of NF-κB (52). The zinc finger transcription factor GATA-2 was initially shown to be crucial in modulating gene expression in megakaryocytic and erythroid lineages (53). Mounting evidence suggests that GATA-2 plays an important role in nonhematopoietic endothelial cells (54, 55), where it is associated with PECAM-1 expression and participates in endothelial cell dedifferentiation (42, 56). PECAM-1 transcription was shown to be regulated by the putative TATA-less promoter region that contains relevant EGR-1 and GATA-2 *cis*-regulatory elements (55, 57, 58). In addition to regulating PECAM-1 expression, GATA-2 is decisive in endothelial-selective gene expression of endothelial NO synthase, endomucin, and VCAM-1 (42, 58–60). Recently, endothelial GATA-2 was shown to participate in regulating angiogenesis (61) and maintenance of vascular integrity (62). Although GATA-2 regulated the transcription of both PECAM-1 and VCAM-1 (M. Hossain and L. Liu, unpublished observations) in endothelial cells, we found that LSP1 selectively regulated GATA-2–mediated transcription of PECAM-1 but not ICAM-1 or VCAM-1 in these cells. Although both endothelial-specific PECAM-1 and GATA-2 were downregulated

in LSP1 deficiency, PECAM-1 expression was not altered in LSP1-deficient neutrophils. In light of the strategic nuclear localization of endothelial LSP1 (6) in contrast to its cytosolic presence in neutrophils (23), it is intriguing to consider the role of endothelial cell specificity of GATA-2 function (42, 58) in fostering cell-specific transcriptional regulation of PECAM-1 expression. Interestingly, endothelial GATA-2 was shown to be activated by PKC (63, 64). By the same token, LSP1 serves as a major substrate for PKC (9). However, the possible signaling cross-talk among these molecules requires further investigation. Remarkably, we observed that the expression of ICAM-1, unlike PECAM-1, was not altered in LSP1-deficient endothelial cells. Our result that silencing endothelial GATA-2 did not modify ICAM-1 expression is supported by a previous finding that K-7174, a GATA-specific inhibitor, did not attenuate TNF-α–induced ICAM-1 expression (60).

Collectively, our data provide novel mechanistic insight into the cell-specific functions of endothelial LSP1 in regulating GATA-2–dependent vascular PECAM-1 expression, and during neutrophil–endothelial cell interactions, in orchestrating $\alpha_6\beta_1$ integrin-dependent directionality of extravascular chemotaxing neutrophils.

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Disclosures

The authors have no financial conflicts of interest.

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