S. aureus-serine protease-like protein B (SplB) activates PAR2 and induces endothelial barrier dysfunction

Arundhasa Chandrabalan[1], Pierre E Thibeault[1], Stefanie Deinhardt-Emmer[2], Maria Nordengrün[3], Jawad Iqbal[3], Daniel M Mrochen[3], Laura A Mittmann[4, 5], Bishwas Chamling[6, 7], Christoph A Reichel[4, 5], Rithwik Ramachandran[1], Barbara M Bröker[3], Murty N Darisipudi[3]

[1]Department of Physiology and Pharmacology, Schulich School of Medicine and Dentistry, University of Western Ontario, London, Ontario, Canada

[2]Section of Experimental Virology, Institute of Medical Microbiology, University Hospital Jena, Jena, Germany

[3]Department of Immunology, Institute of Immunology and Transfusion Medicine, University Medicine Greifswald, Greifswald, Germany

[4]Department of Otorhinolaryngology, University Hospital, Ludwig-Maximilians-University Munich, Munich, Germany

[5]Walter Brendel Centre of Experimental Medicine, University Hospital, Ludwig-Maximilians-University Munich, Munich, Germany

[6]Department of Cardiology, Internal Medicine B, University Medicine Greifswald, Greifswald, Germany

[7]DZHK (German Centre for Cardiovascular Research), Partner Site Greifswald, Germany

***Correspondence:**
Dr. V.S. Narayana Murty Darisipudi
Venkata.darisipudi@uni-greifswald.de

Address:
Department of Immunology
Institute of Immunology and Transfusion Medicine
University Medicine Greifswald
F. Sauerbruchstr. DZ 7
17475 Greifswald, Germany

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Abstract

Staphylococcus aureus (*S. aureus*) is a major cause of life-threatening systemic infection in humans. To cause blood stream infections such as sepsis and endocarditis, the bacteria must overcome the host's endothelial barrier. The serine protease-like proteins (Spls) of *S. aureus* are known to contribute to pneumonia and allergic airway inflammation in animal models, but their role in endothelial damage is unknown. Here we demonstrate that SplB induces proinflammatory cytokine release in primary human vascular endothelial cells (HUVECs) *in vitro*. Mechanistically, we show that SplB selectively cleaves and activates human proteinase-activated receptor-2 (PAR2), and induces biased signaling via β-arrestin-1 and -2 and NF-kβ. This activation did not trigger $G\alpha_{q/11}$-mediated calcium release nor ERK phosphorylation. Inhibition of PAR2 in HUVECs reduced the SplB-mediated cytokine release. Intravital microscopy of cremaster muscles in mice demonstrated that administration of SplB causes microvascular leakage. Neutralization of SplB with a monoclonal antibody retained the endothelial barrier. This study identifies PAR2 as a receptor and substrate for SplB and highlights its role in mediating endothelial damage.

Introduction

Staphylococcus aureus (S. aureus) is a ubiquitous Gram-positive bacterium that transiently or persistently colonizes the human nares and skin (1, 2). *S. aureus* causes many diseases ranging from soft tissue infections to systemic infections such as pneumonia, endocarditis, and sepsis. Systemic *S. aureus* infections are often associated with high morbidity and mortality. In addition, over the decades, *S. aureus* has developed resistance to several antibiotics and poses a challenge to clinicians and a burden to the global health care systems (3–7).

The endothelial barrier offers the first line of defense against invading pathogens. *S. aureus* secretes a wide range of virulence factors, toxins, and proteases that interact with various receptors on the endothelium (8–10), enabling invasion of host tissues by disruption of endothelial barrier. *S. aureus* interaction with the endothelium leads to the production of proinflammatory cytokines and triggers cell death (11, 12). Pore-forming toxins, leucocidin ED (LukED) and γ-Hemolysin AB (HlgAB) induce endothelial permeability via activating the Duffy antigen receptor for chemokines (DARC), which results in organ dysfunction and death in mice (13). Cell wall components of *S. aureus*, peptidoglycan G and lipoteichoic acid are also potent inducers of endothelial damage (ED) (14). It is also well known that proteases from both host and pathogen contribute to barrier disruption via interacting with a four-member family of G-protein coupled receptors (GPCRs) called proteinase-activated receptors (PARs, PAR1-4) (15, 16).

PARs are widely expressed in various cell types, including endothelial cells (17–19). PARs are activated through proteolytic cleavage of the receptor N-terminus at specific sites and unmasking of a tethered ligand (20–23). Activation of PARs leads to G-protein mediated β-arrestin recruitment and downstream signaling via effectors including extracellular signal-regulated kinase (ERK-1/2) mitogen-activated protein kinases (MAPK) and the nuclear factor-κβ (NF-κβ) cascade. This induces the release of cytokines and chemokines, thereby recruiting leukocytes to promote the innate immune response (24, 25).

PARs are also known as central players in allergy. PAR activation in epithelial cells of patients with inflamed airways promotes the induction of allergic asthma (26–30). Activation of PAR2 on mast cells induces degranulation, while eosinophils respond with superoxide production (31). Allergens of house dust mite (Der p 1, -3, -9) and mold *Penicillium citrinum* (Pen c 13) activate PAR2 (32, 33). The activation of PAR2 on epithelial cells and macrophages by serine proteases from German cockroach feces extract contributes to airway hypersensitivity (33). PARs can be

activated not only by allergens with proteolytic activity but also by endogenous proteases like by thrombin (PAR1, 3 and 4) and mast cell-derived tryptase (PAR2 and 4) (34).

The species *S. aureus* harbors a broad spectrum of extracellular virulence factors, among them several proteases, namely aureolysin, V8 protease (SspA), the staphopains A and B (ScpA and SspB), the exfoliative toxins A and B, and the serine protease-like proteins (Spls) A-F (35, 36). Extracellular proteases of *S. aureus* are known to play an important role in the pathogenesis (37–42). For example, the V8 protease and staphopains of *S. aureus* have been shown to alter the integrity of the airway epithelial barrier, thereby promoting lung damage (43). Less is known about the functions of the serine protease-like proteins (Spls). Spls promoted the dissemination of *S. aureus* in a rabbit model of pneumonia (39), and SplA has been reported to cleave mucin-16 (44). The substrates of the other Spls are still elusive. We recently reported that the Spls (A-F) have allergenic properties in humans and mice (37, 40). Administration of SplD to the trachea of mice induced allergic asthma, which was associated with an increased number of PAR2-positive infiltrating cells in the lungs compared to control animals (37). These studies highlight the interaction of Spls with the host immune system, though the substrates involved are obscure.

Here we studied the effects of SplB on the endothelial barrier. We found that SplB induces the production of proinflammatory cytokines in primary endothelial cells *in vitro.* Importantly we find that SplB mediated inflammation in endothelial cells is dependent on the cell surface GPCR PAR2, which we identify as a cellular protease sensor and host substrate of SplB. In mice, administration of SplB leads to microvascular damage. Our results indicate a role of *S. aureus*-SplB in endothelial inflammation and identify PAR2 antagonisms as a potential therapeutic target.

Material and methods

In vitro experiments with HUVECs

Primary human umbilical vein endothelial cells (HUVECs) were isolated by collagenase treatment as previously described (45). The investigation conforms to the principles outlined in the Declaration of Helsinki for the use of human tissues (46). Informed consent was obtained from all the mothers donating umbilical cords in accordance with the responsible Ethics Committee. Cells were maintained at 37 °C and 5% CO_2 in MCDB 131 medium (Pan Biotech) supplemented with 10% fetal calf serum (FCS, Life Technologies), 1 ng/mL bovine fibroblast growth factor (bFGF), 0.1 ng/mL epidermal growth factor (EGF), 1 µg/mL hydrocortisone, 1% penicillin and streptomycin, 2 mM Glutamine, 500 µL heparin, and 2 mL endothelial cell growth supplement (ECGS). All other supplements were obtained from Gibco, Thermoscientific. The cells were passaged 3-5 times before use. For stimulation experiments, cells were seeded into either in 12- or 24-well plates at a density of 2.5 x 10^5 cells/mL and serum-starved overnight in medium containing only 1% FCS. On the following day, cells were incubated in medium containing 2% FCS with or without the PAR2 negative allosteric modulator (AZ3451, Sigma Aldrich) or a NF-κβ inhibitor (Bay11-0782, Invivogen) 45 minutes before stimulation with recombinant SplB or SLIGRL-NH_2 (PAR2 activating peptide, PAR2-AP, Tocris, Wiesbaden-Nordenstadt, Germany). Cell-free supernatants were collected and analyzed for cytokines by ELISA or a bead-based multiplex assay (LegendPlex^{TM}) according to the manufacturer's instructions.

Immunofluorescence

Primary human umbilical vein endothelial cell (HUVEC) monolayers were stimulated with SplB (10 µg/mL) for 6 h. Cells were fixed with 4% paraformaldehyde for at least 30 minutes at 37°C and permeabilized with 0.1 % saponin buffer for 1 h at room temperature (RT) followed by primary antibodies to rabbit anti-human VE-cadherin and anti-human intercellular adhesion molecule 1 (ICAM 1) overnight at 4 °C. Secondary antibodies were goat anti-rabbit conjugated Cy5. Cells were mounted with fluorescence mounting media (Dako). Images were acquired using an Axio Observer.Z1 microscope (Zeiss).

PAR cleavage assay with SplB

PAR-reporter cells were generated as previously described (47–49). Briefly, Chinese Hamster Ovary (CHO) cells were stably transfected with constructs expressing human PAR1, PAR2 or PAR4 tagged with an N-terminal nano luciferase (nLuc) and a C-terminal enhanced yellow fluorescent protein eYFP. Cells were routinely cultured in Ham's F-12 Nutrient Mix with 1 mM

sodium pyruvate, 100 U/mL penicillin, 100 µg/mL streptomycin, 1 mM L-glutamine, and 10% heat-inactivated fetal bovine serum (FBS, Gibco, ThermoFisher Scientific) and 600 µg/mL G418 sulfate (Invitrogen, ThermoFisher Scientific). The PAR-reporter cells were seeded in a 96-well culture plate at a density of 1 x 10^4 cells per well and cultured for 48 h. Cells were rinsed three times with Hanks' Balanced Salt Solution (HBSS, Gibco ThermoFisher Scientific) containing $CaCl_2$ and $MgCl_2$ and incubated with 100 µL HBSS at 37 °C for 15 minutes. 50 µL of the supernatant from each well was transferred to a 96-well plate to obtain the basal luminescence. The cells were then treated with SplB (5 µg/mL) or increasing concentrations of human plasma thrombin (PAR1 and PAR4 agonist, Calbiochem-EMD Millipore) or porcine trypsin (PAR2 agonist, Type IX-S, 13000-20000 BAEE units/mg protein, Sigma Aldrich) or HBSS in a volume of 50 µL for 15 minutes at 37 °C. 50 µL of the supernatant was removed from treated wells and the luminescence values were again recorded on a plate reader (Mithras LB 940, Berthold Technologies) in the presence of the nano luciferase substrate furimazine (2 µL/mL, Promega).

Calcium signaling

Calcium mobilization after PAR activation was measured as previously described with some modifications (50). Briefly, HEK293 cells were maintained in Dulbecco's Modified Eagle's Medium (DMEM, Gibco, Thermoscientific) supplemented with 1 mM sodium pyruvate, 100 U/mL penicillin, 100 µg/mL streptomycin, 2 mM L-glutamine, and 10% heat-inactivated FBS. Cells were seeded at a density of 1 x 10^4 cells/mL in a 96-well black cell culture plate pre-coated with poly-D-lysine and cultured for 48 h. The cells were rinsed twice with phosphate-buffered saline solution (PBS, Invitrogen) and incubated with Fluo-4 NW calcium indicator (50 µL per well, Life Technologies) for 30 minutes at 37 °C in the dark and for additional 15 minutes at RT. Ca^{2+} influx was measured as a change in intracellular fluorescence on a microplate reader FlexStation3 (Molecular Devices). The real-time fluorescence spectra were recorded for a total run time of 180 s. The baseline values were recorded for 20 s before the addition of agonists as indicated. In some conditions, cells were pre-treated with $G\alpha_{q/11}$ inhibitor (YM-254890, 1µM) (51) for 10 minutes at RT before treating with the agonist. Calcium ionophore (A23187, 6µM, Sigma-Aldrich) was used to establish the maximum response possible in the cells.

β-arrestin recruitment assay

Recruitment of β-arrestin-1 or -2 was measured using bioluminescence resonance energy transfer (BRET) (52). Briefly, HEK293 cells were transiently transfected with plasmids encoding eYFP tagged PAR2 (PAR2-eYFP) and renilla luciferase (rluc) tagged β-arrestin-1 or -2 for 24 h. Cells were transferred to an opaque white 96-well plate at a density of 2.5 x 10^4 cell/mL and cultured for an additional 24 h before incubation with HBSS alone or different concentrations of

trypsin (PAR2 agonist, 0.3-10 nM) or SplB (5 µg/mL) for 20 minutes at 37 °C. The rluc substrate h-coelenterazine (5 µM) was added 10 minutes before taking the measurement. Emission of eYFP and luminescence of rluc was measured on a Mithras LB 940 plate reader (Berthold Technologies).

Western blot analysis

PAR2-knockout (KO) HEK293 cells were generated using CRISPR/Cas9 as previously described (52). Western blot analysis of ERK MAPKinase was done as previously described (52). Briefly, Wild-type (WT) or PAR2 KO HEK293 cells were seeded at a density of 4×10^5 cells/mL in a 12-well plate and serum-starved for 2 h to reduce basal levels of ERK phosphorylation. Following serum starvation, cells were stimulated with either SplB (5 µg/mL) or trypsin (10 nM) for 10 minutes. Control wells received only buffer (HBSS). Cells were harvested in NP-40 based lysis buffer supplemented with protease and phosphatase inhibitor cocktail. Proteins in the cell lysates were separated on 4-12% Bis-Tris precast gels (Invitrogen) in MES buffer, blotted with primary antibody to phosphorylated ERK (pERK; p44/42 Thr202/Tyr204) or total ERK (tERK; p44/42) followed by an HRP-conjugated anti-rabbit secondary antibody (1:1000). Chemiluminescence was measured using ECL detection reagent (GE Healthcare) on an iBright CL1000 (Invitrogen). All antibodies were obtained from Cell signaling Technology, Massachusetts, USA.

SplB cleavage site on PAR2

To determine the cleavage site(s) of SplB on PAR2, a peptide representing the hPAR2 N-terminal domain spanning the tethered ligand region, GTNRSSKGRSLIGKVDGTSHV-NH_2, was synthesized using Fmoc chemistry on a peptide synthesizer (Syrowave, Biotage). The purity of the peptide was 98% as assessed by analytical reversed-phase HPLC-MS. Peptide and enzyme solutions were dissolved and/or diluted in 25 mM 4-(2-hydroxyethyl)-1-piperazine ethanesulfonic acid (HEPES, Fisher Scientific). The peptide (100 µM in a total volume of 100 µL) was incubated with either trypsin (10 nM) or SplB (50 µg/mL) for 60 minutes at 37 °C. The reaction was terminated by adding ice-cold 0.1% trifluoroacetic acid (TFA) in H_2O (100 µL) as described previously (53) and subjected to MALDI-MS analysis (AB Sciex 5800 TOF/TOF MS, UWO MALDI MS Facility, Western University). Cleavage sites (//) were identified from any additional m/z peaks (peptide fragments) observed in the mass spectrum of the enzyme-treated peptide.

Intravital microscopy of cremaster muscles

The surgical preparation of the cremaster muscle was performed as described elsewhere (54). Briefly, 6-8 week old male C57BL/6 mice were anesthetized with ketamine/xylazine (100 mg/kg ketamine and 10 mg/kg xylazine; *i.p*), and the left femoral artery was cannulated in a retrograde manner using a polyethylene-10 catheter (inner diameter 0.28 mm, Portex) for the administration of substances. The right cremaster muscle was exposed through a ventral incision of the scrotum. The muscle was opened ventrally in a relatively avascular zone and spread over the transparent pedestal of a custom-made microscopy stage. Epididymis and testicle were detached from the cremaster muscle and replaced in the abdominal cavity. The muscle was superfused with warm-buffered saline throughout the procedure. Leakage of intravenously applied FITC dextran (Sigma-Aldrich) to the perivascular tissue was analyzed in animals after intrascrotal stimulation with SpIB. In selected experiments, animals also received monoclonal antibodies directed against SpIB. All animal experiments were carried out in accordance with German animal protection laws and approved by local animal protection authority (Regierung von Oberbayern, Munich, Germany)

Statistical analyses

The cytokine data in Figure 1 are expressed as mean ± SD of three independent experiments. The t-test was utilized to determine statistical significance vs control, *p<0.05. The luminescence measurements in the PAR cleavage assay are presented as the percentage of the maximum response to thrombin (3 U/mL) or trypsin (100 nM). The cleavage data are presented as the mean ± SEM of at least three independent experiments performed in duplicates. Two-way ANOVA was utilized to determine statistical significance relative to the HBSS control, ***p<0.001. BRET ratio (eYFP/rluc) was calculated for each condition, and the net BRET ratios were obtained after normalizing to the buffer condition. The BRET data are represented as mean ± SEM of four independent experiments performed in duplicate. Two-way ANOVA was utilized to determine statistical significance relative to the response obtained with HBSS, *p<0.05, **p<0.01, ****p<0.0001. The Western blot analysis data are expressed as ratio pERK to tERK mean ± SEM of three independent experiments. Two-way ANOVA was utilized to determine statistical significance vs relative response obtained with HBSS in the same cell line, *p<0.05. The immunofluorescence data are expressed as mean MFI ratio of VE-Cadherin and ICAM-1 mean ± SD of three independent experiments. The t-test was utilized to determine statistical significance vs control, *p<0.05. The vascular leakage data in mice are expressed MFI of FITC mean ± SD of 3-5 animals per group. The t-test was utilized to determine statistical significance vs control, *p<0.05 vs SplB-mAb.

Results

SplB induces proinflammatory cytokines in primary human endothelial cells

To assess whether SplB has the ability to induce endothelial inflammation *in vitro*, we stimulated primary human umbilical vein endothelial cells (HUVECs) with SplB for 24 h. As shown in Figure 1, SplB significantly enhanced the interleukin (IL)-6 release and tended to increase the release of TNFα, IL-18, and IL-23.

SplB cleaves PAR2 but not PAR1 and PAR4

Since PARs are major targets of many bacterial proteases and mediate the production of cytokines in various host cells, including endothelial cells (55, 24), we hypothesized that SplB cleaves and activates PARs. To study this, CHO cells expressing nLuc-PAR1-eYFP, nLuc-PAR2-eYFP, or nLuc-PAR4-eYFP were treated with SplB and the cleavage of the N-terminal nLuc tag was monitored (Figure 2A). Thrombin (PAR1 and PAR4 activating enzyme) and trypsin (PAR2 agonist) were used as positive controls and cleaved the N-terminal tags over the expected range of concentrations (Supplementary Figure 1A-C). Cells treated with HBSS only served as negative controls. As shown in Figure 2A, SplB selectively cleaved PAR2 with no cleavage evident for the PAR1 and PAR4. SplB (5 μg/ml) displayed significant activity at PAR2 producing a nLuc cleavage signal that was ~20% of the maximal cleavage of PAR2 elicited by trypsin (100 nM).

SplB induces β-arrestin-1 and -2 recruitment to PAR2 but does not activate $G\alpha_{q/11}$ or MAPK

Following the observation that SplB can cleave PAR2, we sought to determine whether this could activate PAR2 signaling. It has been shown that PAR2 activation by trypsin triggers robust calcium release, which is dependent on $G\alpha_{q/11}$ signaling pathway (56). HEK293 cells that endogenously express PAR2 were treated with increasing concentrations of trypsin or SplB as indicated. As expected, trypsin triggered calcium mobilization from the cells in a dose-dependent manner (Supplementary Figure 2), which was dependent on $G\alpha_{q/11}$ as inhibition of the latter completely abolished calcium mobilization (51) (Figure 2B). To our surprise, SplB (5μg/ml) did not induce calcium mobilization from the cells (Figure 2C) despite the significant cleavage of the PAR2 N-terminus by this enzyme (Figure 2A). These results demonstrate that SplB does not activate PAR2 signaling via the $G\alpha_{q/11}$ pathway.

Since PAR2 can signal through β-arrestins, we assessed β-arrestin-1 and/or -2 recruitment to PAR2 using a BRET assay. For this, HEK293 cells expressing PAR2-YFP and luciferase- β-arrestin-1 or -2 fusion proteins were treated with either SplB or increasing concentration of

trypsin as indicated. As expected, trypsin treatment resulted in the recruitment of β-arrestin-1 and -2 in a dose-dependent manner (Figure 2D). SplB followed the same trend and significantly triggered the recruitment of both β-arrestins (Figure 2D) compared to HBSS treatment. The net BRET ratios (YFP to luciferase) of β-arrestin-1 and -2 obtained for trypsin were 0.08 ± 0.01 and 0.09 ± 0.01, respectively. Whereas SplB showed net ratios of 0.05 ± 0.01 for both arrestins.

PAR2 activation of β-arrestins is reported to scaffold activated ERK 1/2. To assess whether cleavage of PAR2 by SplB results in ERK phosphorylation, we treated WT or PAR2-KO HEK293 cells with either SplB or trypsin and analyzed the ERK signaling pathway by Western blot. SplB did not trigger a significant increase in ERK phosphorylation compared to untreated cells (Figure 2E). In contrast, trypsin-stimulated PAR results in significantly increased ERK phosphorylation compared to untreated controls (Figure 2E). As expected, neither trypsin nor SplB was able to induce ERK phosphorylation in cells lacking PAR2 (Figure 2E). In recent work, we demonstrated that PAR2-mediated ERK phosphorylation in HEK293 cells occurs downstream of $G\alpha_{q/11}$ signaling (56), and this is consistent with the observations that SplB stimulation of PAR2 does not induce $G\alpha_{q/11}$ signaling.

SplB does not cleave PAR2 at the trypsin cleavage site

Since SplB and trypsin show a similar pattern in terms of PAR2 cleavage and recruitment of both β-arrestin-1 and -2, we hypothesized that SplB cleaves PAR2 at the trypsin cleave site. To determine this, we examined a peptide representing the hPAR2 N-terminal domain spanning the trypsin cleavage site, GTNRSSKGRSLIGKVDGTSHV-NH_2 (Supplementary Figure 3A), and incubated with trypsin or SplB for 60 minutes. The digestion mixture was then subjected to MALDI-MS analysis to identify the possible peptide fragments. Consistent with previous findings (57, 58), trypsin cleaved the synthetic peptide at the expected $R^{36}//S^{37}$ (major site) and $K^{34}//G^{35}$ sites within the 60 minutes reaction time (Supplementary Figure 3B). However, SplB did not cleave at this region as no peptide fragmentation was detectable (Supplementary Figure 3C), indicating that the SplB cleavage site on hPAR2 lies outside of this region and needs to be investigated further.

SplB induced IL-6 release is dependent on PAR2-NF- κβ signaling cascade

We next sought to determine whether SplB triggered cytokine production in endothelial cells was mediated by PAR2. We treated primary HUVECs with SplB or a PAR2-AP with or without a PAR2 negative allosteric modulator AZ3451 and analyzed the supernatants for IL-6. Treatment of cells with SplB induced production of IL-6, while the response to the PAR2-AP was mild as compared to the high basal levels of IL-6 as seen in untreated cells (Figure 2F). Inhibition of PAR2 in SplB treated cells lowered the cytokine release (almost) to the background level (Figure

2F). It has been reported that some PAR2 activating proteases induce cytokine production via the NF-κβ pathway. Blockade of NF-κβ signaling completely abolished the IL-6 release, both spontaneous and induced by SplB (Figure 2G), indicating that SplB induces IL-6 cytokine release in endothelia in an NF-κβ-dependent fashion. This results in NF-κβ activation and the release of IL-6.

SplB induces endothelial barrier disruption *in vitro* and *in vivo*

Many proteases, bacterial toxins, and cytokines are known to disrupt the endothelial barrier. Previous studies have demonstrated that proteases that activate the PAR2 induce endothelial barrier disruption. Having demonstrated that SplB activates PAR2 and induces proinflammatory cytokines in endothelial cells, we asked whether this bacterial protease is able to damage the endothelial barrier. To address this, SplB-exposed HUVEC monolayers were subjected to immunofluorescence analysis for the expression of VE-cadherin and ICAM-1, two essential components that maintain the integrity of the endothelial barrier. In the SplB treated cells the amount of available VE-cadherin was significantly diminished while ICAM-1 expression was upregulated, resulting in a strong reduction of the mean fluorescence intensity (MFI) ratio between VE-cadherin and ICAM-1 (Figure 3A). This suggests that *S. aureus* SplB weakens the endothelial barrier integrity. Next, we employed intravital microscopy to observe the integrity of the endothelial barrier *in vivo* in a mouse model of microvascular leakage. Consistent with our observations *in vitro*, administration of SplB in mice leads to massive leakage of FITC dextran across the vasculature to the perivascular space in the murine cremaster muscle. Treatment of animals with a SplB-neutralizing monoclonal antibody before SplB administration almost abolished the SplB effect (Figure 3B). These results demonstrate that *S. aureus*-SplB induces endothelial dysfunction via disruption of cell-cell junctions.

Discussion

Our study demonstrates that one of the extracellular *S. aureus*-serine protease-like proteins (Spls), SplB, induces endothelial dysfunction *in vitro* and *in vivo*. Spls are a group of six proteases, namely SplA to SplF encoded by the *spl* operon (59), whose functions are yet to be fully explored. The Spls show high sequence homology among themselves and structural homology to *S aureus* V8 protease (59). Except for SplA, which cleaves mucin-16 on the human epithelial cells (44), no biologically relevant substrates for Spls were identified so far. Here we report that SplB cleaves human PAR2 but not PAR1 and PAR4, which identifies the first biologically relevant and therapeutically tractable substrate and/or receptor for SplB.

PARs (PAR1-4) are a family of 7-transmembrane G-protein coupled receptors, activated after proteolytic cleavage of the N-terminus at a specific site by extracellular proteases. This event creates a new N-terminal domain, which acts as a tethered ligand that activates the receptor (60, 58). The canonical activator, trypsin, cleaves hPAR2 between R^{36}//S^{37} and K^{34}//G^{35}, revealing a tethered ligand with the sequence "SLIGKV" (57, 58). Similar to trypsin, cockroach E1-E3 and Pen C proteases cleave PAR2 at the canonical cleavage site, R^{36}//S^{37}, whereas neutrophil-derived enzymes cleave PAR2 downstream of this tethered ligand region. For example, proteinase-3 cleaves at V^{48}//T^{49}, V^{55}//E^{56}, T^{57}//V^{58}, V^{61}//D^{62}, D^{62}//E^{63}, cathepsin-G at F^{59}//S^{60}, F^{64}//S^{65} and S^{65}//A^{66}, and elastase at V^{42}//D^{43}, V^{48}//T^{49}, V^{53}//T^{54}, V^{58}//F^{59}, A^{66}//S^{67} and S^{67}//V^{68} (58). Cleavage of PAR2 by these neutrophil enzymes are known to trigger signalling responses that are distinct from those elicited by the canonical activator trypsin (60). To determine the SplB cleavage sites on hPAR2, we treated a peptide spanning the N-terminal domain of the trypsin cleavage region with SplB. We observed that SplB did not cleave the peptide, indicating that SplB recognition sites are distinct from the trypsin target site as seen for the neutrophil derived enzymes. It also signifies the specificity of SplB in choosing its substrate and fits the published preferred cleavage motifs of SplB, WELQ//Q, WELQ//N and WELQ//G (61, 62).

PARs are expressed in various host cells, including epithelial and endothelial cells. However, the expression patterns vary with the tissues. PAR2 can couple to multiple signalling effectors including $G\alpha_{q/11}$, $G\alpha i$ and $G\alpha_{12/13}$ and β-arrestins. Depending on the effector being engaged, PAR2 activation leads to different intracellular signaling cascades, activates ERK-1 and 2 MAP kinases and NF-κβ leading to transcriptional regulation of various genes including the induction of proinflammatory cytokines (58, 47). We observed that SplB and PAR2-AP induced proinflammatory cytokine release in primary endothelial cells in a PAR2 dependent manner. In addition, the observed cytokine response was completely abolished in the presence of NF-κβ inhibitor, indicating that SplB triggers the PAR2-NF-κβ axis. The signaling pathways downstream of PAR2 and upstream of NF-κβ need further investigation.

PAR2 can also interact intracellularly with heterotrimeric G-proteins that act as effectors in the subsequent signaling (21, 20). It has been shown that PAR2 activation by trypsin triggers robust calcium release, which is dependent on $G\alpha_{q/11}$-signaling pathway (56). We observed that SplB cleavage of PAR2 did not result in $G\alpha_{q11}$-mediated calcium release and ERK phosphorylation (pERK) downstream of PAR2, while trypsin, a known PAR2 activating enzyme, induced robust calcium mobilization and pERK. This is in line with previous observations that PARs can elicit distinct responses referred to as "biased agonism," a characteristic feature in which ligands or

proteases of various origins activate the same receptors but induce different signaling responses (63, 52, 24).

Extracellular proteases of various origins activate PAR2 on endothelial cells and induce the production of proinflammatory cytokines and chemokines, the latter involved in the disruption of the endothelial barrier (64, 65) by downregulating the expression of VE-cadherin, an essential component of the barrier (9). SplB induced a similar response in human primary endothelial cells that was characterized by the release of proinflammatory cytokines and a strong reduction of VE-cadherin. Other mechanisms are also possible for PAR2 regulation of the endothelial cytoskeleton. PAR2 activation of the small Rho GTPase Cdc42 is implicated in remodelling of the actin cytoskeleton and exocytosis (66). *S. aureus* is similarly reported to engage Cdc42 in order to invade human endothelial cells (67). Whether *S. aureus* regulation of Cdc42 involves PAR2 remains to be examined.

Our results unveiled that SplB induces endothelial barrier disruption *in vivo* in mice. Therapeutic blockade of SplB with a monoclonal antibody retained the barrier integrity. To overcome the endothelial barrier must be crucial for *S. aureus*, since a wide range of virulence factors and proteases secreted by *S. aureus* can induce endothelial dysfunction (9, 43, 14, 8). Here we identified yet another virulence factor of *S. aureus* that contributes to barrier disruption. It is plausible that SplB-induced barrier disruption *in vivo* is mediated by the disturbance of VE-cadherin homeostasis.

Endothelial dysfunction is also a hallmark of allergic asthma (68), and PAR2 signaling has been implicated in disturbing the endothelial barrier integrity and the development of the disease (63, 9, 27, 32, 33, 29). Many allergen-derived proteases mediate endothelial dysfunction via activating PAR2 on mucosal endothelial and epithelial cells (14). Allergens of house dust mite activate PAR2 on multiple cells in the lung (69). Mice deficient for PAR2 or subjected to therapeutic PAR2-blockade displayed a strongly reduced influx of eosinophils in bronchoalveolar lavage fluid (BALF) and lung tissue compared to WT counterparts (32, 70). Deficiency of PAR2 protected mice from cockroach allergen-induced airway inflammation and airway hyperresponsiveness (71). We previously demonstrated that administration of SplD in mice induces allergic asthma, which was associated with increased numbers of PAR2-positive infiltrating cells in the lungs, but SplD did not cleave PAR2 (40). It is plausible that SplD-induced type 2 lung inflammation triggered mast cells to release endogenous proteases, which in turn recruited and activated inflammatory cells (macrophages and T cells) in PAR2 dependent manner.

Taken together, the results clearly show that *S. aureus* SplB activates endothelial cells via PAR2 and contributes to the disruption of the endothelial barrier. This identifies a novel mechanism that *S. aureus* uses to invade the host.

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Figure legends

Figure 1. SplB induces proinflammatory cytokines *in vitro.* (A) Primary human endothelial cells were left untreated or treated with SplB (10 µg/mL) for 24 h and the supernatants were analyzed for indicated cytokines by cytokine bead array. Data are mean ± SD of three independent experiments performed in duplicates.

Figure 2. SplB cleaves PAR2 and induces downstream signaling via the β-arrestin-NF-κβ pathway. (A) nLuc-hPAR1/2/4-eYFP CHO cells were left untreated (HBSS) or treated with SplB (5 µg/mL) and the PAR cleavage was measured. Data are mean ± SEM of at least three independent experiments performed in duplicates. (B-C) PAR2 triggered calcium mobilization was measured in HEK293 cells treated with either trypsin (100 nM) in the presence or absence of YM254890 (1 µM) (B), or SplB (5 µg/mL) or A23187 (6 µM) (C). Data are mean ± SEM of three independent experiments. (D) Recruitment of β-arrestin-1 or -2 to PAR2 in response to SplB (5 µg/mL) or increasing concentrations of trypsin as indicated. BRET ratios (eYFP/rluc) were obtained after normalizing to the buffer condition. Data are mean ± SEM of four independent experiments performed in duplicates. (E) WT or PAR2-KO HEK293 cells were treated with SplB (5 µg/mL) or trypsin (10 nM). The cell lysates were subjected to SDS-PAGE and blotted for total ERK (tERK) or phosphorylated ERK (pERK). Data are mean ± SEM of three independent experiments performed in duplicates. (F, G) Primary human endothelial cells were stimulated with SplB or PAR2-AP in the presence or absence of inhibitors to PAR2 (F) or Bay11-0782 (G) for 45 min. After 24 h, cell-free supernatants were analyzed for IL-6 by ELISA. Data in F and G are mean ± SD of two independent experiments performed in duplicates or triplicates. A and D-E: Two-way ANOVA was utilized to determine statistical significance, *p<0.05, **p<0.01, ***p<0.001. G: One-way ANOVA was utilized to determine statistical significance, **p<0.0001 vs buffer, $^{\#\#\#}p$<0.01, SplB vs SplB-Bay11-0782.
YM254890: $G\alpha_{q/11}$ inhibitor; A23187: Calcium ionophore; Bay11-0782: NF-κβ signaling inhibitor; AP: Activating peptide; iPar2: PAR2-inhibitor

Figure 3. SplB induces endothelial dysfunction both *in vitro* and *in vivo.* (A) Primary human endothelial cell-monolayers were stimulated with PBS or SplB. The cells were fixed with 4% PFA before being subjected to immunofluorescence for the indicated markers. Red: VE-cadherin, Yellow: ICAM-1. The mean fluorescence intensity (MFI) ratio of VE-Cadherin and ICAM-1 was calculated. Data are mean ± SD of three independent experiments. (B) Leakage of intravenously applied FITC-dextran to the perivascular tissue was analyzed in animals after intrascrotal stimulation with SpIB with or without pre-treatment with SplB-monoclonal antibody

(mAb). Data are mean ± SD of 3-5 animals per group. A-B: A t-test was utilized to determine statistical significance, *p<0.05 vs buffer (A) and *p<0.05 vs SplB + mAb (B).

Supplementary Figure 1. Thrombin cleaves PAR1 and 4, and trypsin cleaves PAR2. (A and C) nLuc-hPAR1/4-eYFP CHO cells were treated with thrombin and (B) nLuc-hPAR2-eYFP CHO cells with treated with trypsin; and the PAR cleavage was measured. Data are mean ± SEM of at least three independent experiments performed in duplicates.

Supplementary Figure 2. Trypsin induces calcium mobilization. HEK293 cells were treated increasing concentrations of trypsin as indicated. HBSS buffer served as a control. Calcium signaling traces were obtained Fluo-4 NW calcium indicator. Data are mean ± SEM of three independent experiments.

Supplementary Figure 3. SplB does not cleave PAR2 at the trypsin cleavage site. Human PAR2 N-terminal domain peptide spanning the tethered ligand region, GTNRSSKGRSLIGKVDGTSHV-NH_2, was incubated with either trypsin (10 nM) or SplB (50 µg/mL) for 60 minutes at 37 °C. The digestion mixture was analyzed for peptide fragmentation on MALDI-MS. Cleavage sites (//) were identified from any additional m/z peaks (peptide fragments) observed in the mass spectrum of the enzyme-treated peptide.

Figure 1

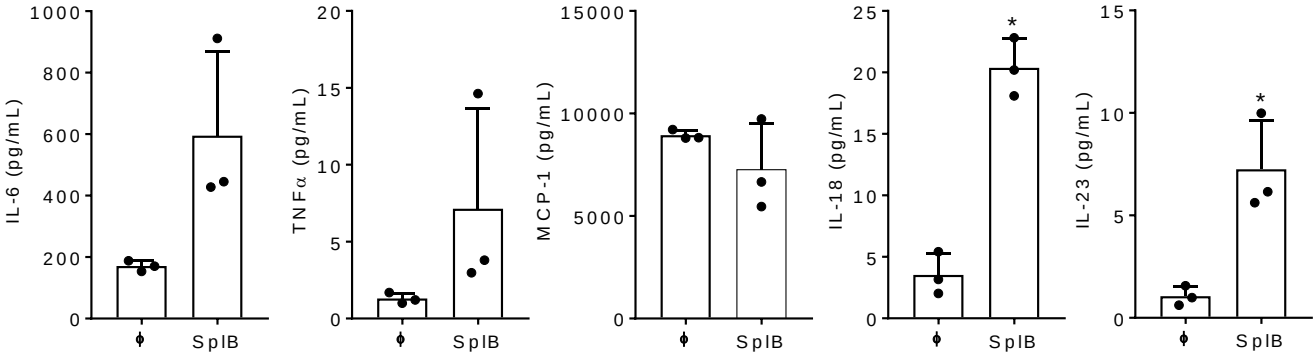
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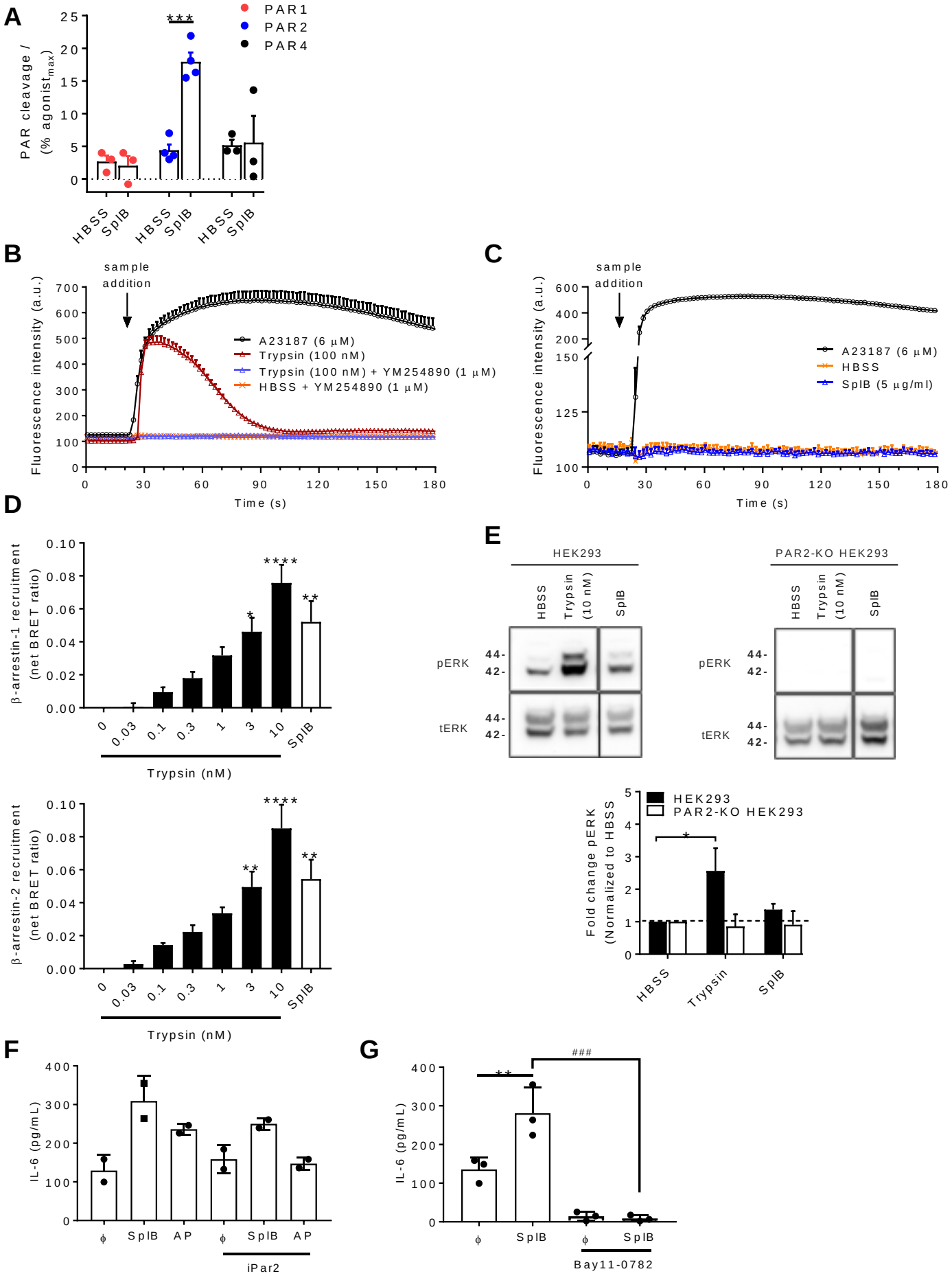
Figure 2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PAR cleavage / (% agonist$_{max}$)
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sample addition
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HBSS + YM254890 (1 μM)
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A23187 (6 μM)
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SplB (5 μg/ml)
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β-arrestin-1 recruitment (net BRET ratio)
Trypsin (nM)
β-arrestin-2 recruitment (net BRET ratio)
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PAR2-KO HEK293
HBSS
Trypsin (10 nM)
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Fold change pERK (Normalized to HBSS)
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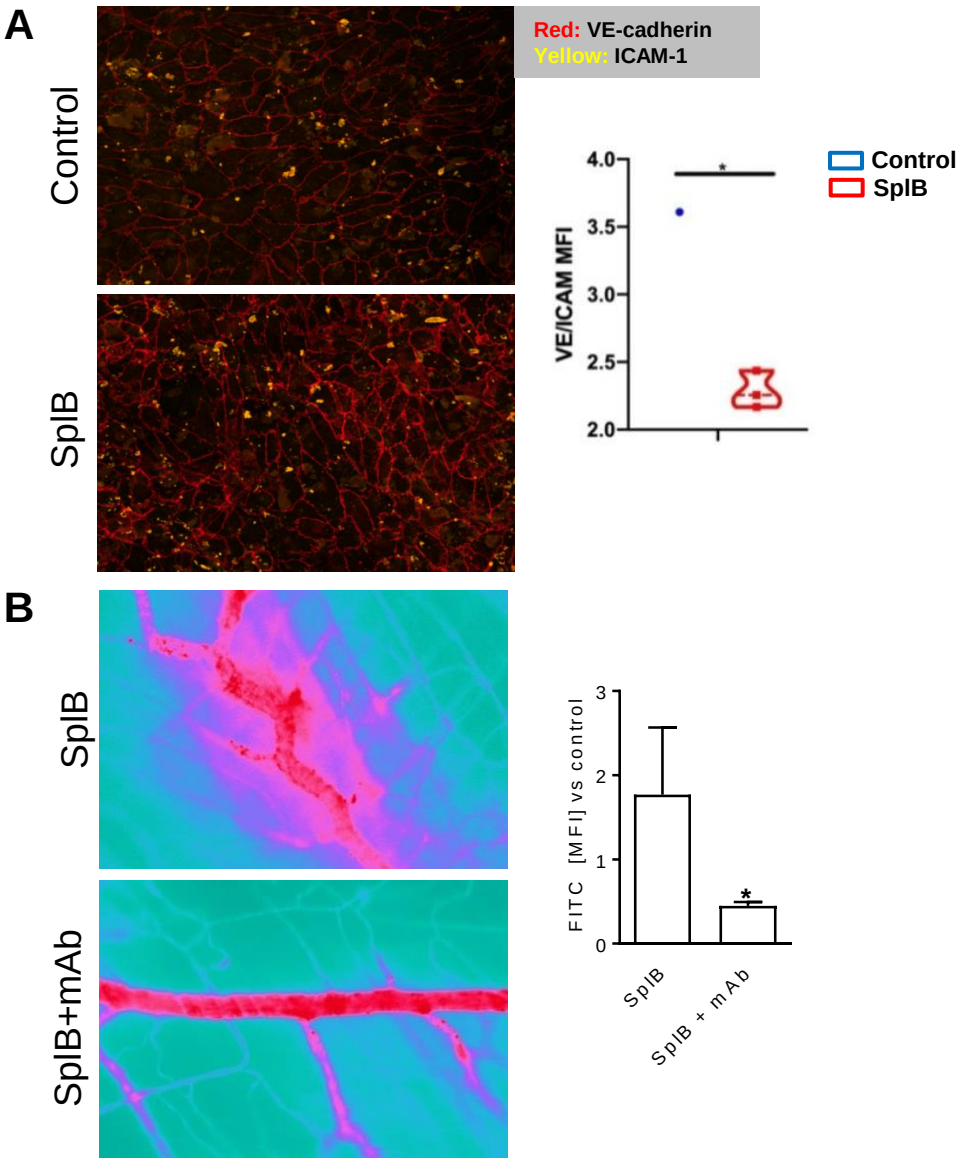
Bay11-0782

Figure 3


A
Red: VE-cadherin
Yellow: ICAM-1
Control
SplB
VE/ICAM MFI
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Control
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SplB
SplB+mAb
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SplB + mAb