The Ca\(^{2+}\) Sensor Stromal Interaction Molecule 1 (STIM1) Is Necessary and Sufficient for the Store-Operated Ca\(^{2+}\) Entry Function of Transient Receptor Potential Canonical (TRPC) 1 and 4 Channels in Endothelial Cells\(^{S}\)

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ABSTRACT

We addressed the requirement for stromal interaction molecule 1 (STIM1), the endoplasmic reticulum (ER) Ca\(^{2+}\)-sensor, and Orai1, a Ca\(^{2+}\) selective channel, in regulating Ca\(^{2+}\) entry through the store-operated channels mouse transient receptor potential canonical (TRPC) 4 or human TRPC1. Studies were made using murine and human lung endothelial cells (ECs) challenged with thrombin known to induce Ca\(^{2+}\) entry via TRPC1/4. Deletion or knockdown of TRPC4 abolished Ca\(^{2+}\) entry secondary to depletion of ER Ca\(^{2+}\) stores, preventing the disruption of the endothelial barrier. Knockdown of STIM1 (but not of Orai1 or Orai3) or expression of the dominant-negative STIM1\(^{K684E\rightarrowK685E}\) mutant in ECs also suppressed Ca\(^{2+}\) entry secondary to store depletion. Ectopic expression of WT-STIM1 or WT-Orai1 in TRPC4\((-/-)\)-ECs failed to rescue Ca\(^{2+}\) entry; however, WT-TRPC4 expression in TRPC4\((-/-)\)-ECs restored Ca\(^{2+}\) entry indicating the requirement for TRPC4 in mediating store-operated Ca\(^{2+}\) entry. Moreover, expression of the dominant-negative Orai1\(^{R91W}\) mutant or Orai3\(^{E81W}\) mutant in WT-ECs failed to prevent thrombin-induced Ca\(^{2+}\) entry. In contrast, expression of the dominant-negative TRPC4\(^{E647\rightarrow548\rightarrowK}\) mutant in WT-ECs markedly reduced thrombin-induced Ca\(^{2+}\) entry. In ECs expressing YFP-STIM1, ER-store Ca\(^{2+}\) depletion induced formation of fluorescent membrane puncta in WT but not in TRPC4\((-/-)\)-cells, indicating that mobilization of STIM1 and engagement of its Ca\(^{2+}\) sensing function required TRPC4 expression. Immunoprecipitation studies showed coupling of TRPC1 and TRPC4 with STIM1 on depletion of ER Ca\(^{2+}\) stores. Thus, TRPC1 and TRPC4 can interact with STIM1 to form functional store-operated Ca\(^{2+}\)-entry channels, which are essential for mediating Ca\(^{2+}\) entry-dependent disruption of the endothelial barrier.

Introduction

Ca\(^{2+}\) entry through store-operated channels (SOCs) in endothelial cells (ECs) mediates increased vascular permeability (Tiruppathi et al., 2006) and increases inflammatory gene expression (Bair et al., 2009). The transient receptor potential canonical (TRPC) family of channels are components of SOCs (Nilius and Droogmans 2001; Birnbaumer et al., 1996). We showed that human vascular ECs predominantly express isoform TRPC1 (Tiruppathi et al., 2006; Thippegowda et al., 2010). In addition, we showed that inflammatory mediators can induce the expression of TRPC1 in human vascular ECs via the nuclear factor-κB pathway (Paria et al., 2003, 2004, 2006). Increased TRPC1 expression was associated with augmented thrombin-induced Ca\(^{2+}\) entry and permeability in-
increase in human ECs (Paria et al., 2004). Deletion of TRPC4 in mice inhibited SOC activity in aortic (Freichel et al., 2001) and lung vascular ECs (Tiruppathi et al., 2002). Thrombin-induced increase in lung microvascular permeability was impaired in TRPC4 knockout (TRPC4(−/−)) mice (Tiruppathi et al., 2002). These findings show that TRPC1 and TRPC4 mediate SOC activity in ECs; however, the regulation of SOCs by ER-store Ca2+ release remains poorly understood. An understanding of their regulation is required for developing drugs targeting the Ca2+ entry pathways mediating inflammatory vascular diseases.

A number of studies have shown that Ca2+ entry through SOCs is mediated by interaction between TRPCs and stromal interaction molecule-1 (STIM1) (Huang et al., 2006; Worley et al., 2007; Zeng et al., 2008; Lee et al., 2010), an ER-resident Ca2+ sensing protein (Roos et al., 2005; Zhang et al., 2005). Most TRPCs interact with the C terminus of STIM1 (Yuan et al., 2007; Liao et al., 2009). TRPC1-STIM1 interaction in particular has been studied to address the underlying basis of SOC activity (Huang et al., 2006; Ong et al., 2007; Worley et al., 2007; Yuan et al., 2007). Zeng et al. (2008) showed the electrostatic interaction between TRPC1 acidic residues (Asp639, Asp640) and STIM1 basic residues (Lys684, Lys685) regulating TRPC1 gating. ER store Ca2+ release mediated assembly of STIM1 into puncta at ER/plasma membrane interface (Huang et al., 2006; Worley et al., 2007; Zeng et al., 2008; Lee et al., 2010) and in turn STIM1 puncta interacted with TRPCs to activate SOCs (Worley et al., 2007; Zeng et al., 2008).

Orai gene family members encode for channels mediating the Ca2+ release-activated Ca2+ (CRAC) current (Prakriya et al., 2006). Orai family members Orai1, Orai2, and Orai3 are tetraspanning membrane proteins (Feske et al., 2006). In human T cells, a point mutation in Orai1 caused severe combined immunodeficiency in patients with low Icrac activity (Feske et al., 2006). Expression of wild-type human Orai1 in patients with severe combined immunodeficiency in patients with low Icrac activity (Feske et al., 2006). Expression of wild-type human Orai1 in patients with severe combined immunodeficiency in patients’ T cells rescued store-operated Ca2+ entry and Icrac activity (Feske et al., 2006). Ong et al. (2007) showed that in the human salivary gland cell line, HSG, knockdown of Orai1 suppressed SOC-mediated Ca2+ entry by >90%, whereas knockdown of TRPC1 reduced Ca2+ entry by 50%. In human embryonic kidney (HEK) 293 cells, knockdown of either Orai1 or TRPC1 reduced SOC-mediated Ca2+ entry (Kim et al., 2009). Furthermore, coexpression of TRPC1, Orai1, and STIM1 in HEK293 cells showed greater SOC-mediated Ca2+ entry compared with coexpression of STIM1 with TRPC1 or Orai1 channels (Kim et al., 2009). In contrast, in Jurkat cells, the SOC-mediated Ca2+ entry and CRAC current were inhibited by knockdown of Orai1 but not altered by knockdown of TRPC1 or TRPC3 (Kim et al., 2009). These results suggest that molecular makeup of the SOCs varies depending on the cell type. In the present study, we focused on the question whether STIM1 and Orai1 proteins are both required and sufficient for the SOC function in ECs.

We (Freichel et al., 2001; Tiruppathi et al., 2002; Paria et al., 2004; Sundivakkam et al., 2009) have identified the role of TRPC1- and TRPC4-mediated SOC function in ECs; however, regulation of TRPC function in these cells seems to be more complex. A siRNA knockdown study in human umbilical vein endothelial cells (HUVECs) showed that STIM1 or Orai1 knockdown abolished both SOC and Icrac currents, whereas knockdown of TRPC1 or TRPC4 had no effect (Abdullaev et al., 2008). Although the role of Orai’s in mediating Icrac-dependent Ca2+ entry has been well described in immune cells (Prakriya et al., 2006), their function in ECs is less clear. Thus, we addressed the role of STIM1 and Orai1 in activating SOCs in ECs. Our results show that TRPC1/4 interaction with STIM1 without involvement of Orai1 is required and sufficient for functional SOC in ECs.

**Materials and Methods**

**Reagents.** Endothelial growth medium (EGM-2) was obtained from Lonza Walkersville, Inc. (Walkersville, MD). Hanks’ balanced salt solution (HBSS) and trypsin were from Invitrogen (Carlsbad, CA). Fetal bovine serum (FBS) was from Hyclone (Logan, UT). Human α-thrombin was obtained from Enzyme Research Laboratories (South Bend, IN). Protease-activated receptor-1 (PAR-1) activating peptide (TFLLRNPNDK-NH2) was synthesized as C-terminal amide (Tiruppathi et al., 2002). Fura-2 AM was purchased from Invitrogen (Carlsbad, CA). Anti-TRPC1 pAb, anti-TRPC4 pAb, hOrai1-siRNA, and mouse (m) specific siRNAs for TRPC1, TRPC4, Orai1, Orai2, and Orai3 were obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-STIM1 monoclonal antibody (mAb) was from BD Biosciences Transduction Laboratories (Lexington, KY). Control scrambled siRNA (sc-siRNA), mSTIM1-siRNA, and hSTIM1-siRNA were from Dharmaco (Lafayette, CO). Antibodies specifically react with Orai1, Orai2, and Orai3 were from Santa Cruz Biotechnology (Santa Cruz, CA). Yellow fluorescent protein (YFP)-WT-STIM1, YFP-STIM1K684E-K685E.

**Fig. 1.** TRPC, STIM, and Orai expression in ECs from WT and TRPC4(−/−) mice. A, RT-PCR analysis of mRNA expression. Total RNA from ECs of WT and TRPC4(−/−) mice was isolated, and RT-PCR was performed to determine the expression of transcripts for TRPCs (TRPC1, TRPC3, TRPC4, TRPC5, TRPC6, TRPC7) and GAPDH (glyceraldehyde-3-phosphate dehydrogenase) (left). RT-PCR was performed to determine the expression of transcripts for STIMs (STIM1 and STIM2), Ora1s (Orai1, -2, -3) and GAPDH using total RNA from WT-ECs (right). Experiment was repeated three times. The results from representative experiments are shown. B, Western blot analysis. ECs from WT and TRPC4(−/−) mice were lysed and immunoblotted with antibodies specific to TRPC1, TRPC4, STIM1, Orai1, or β-actin. Representative blot is shown at left. Immunoreactive protein bands were quantified by densitometry relative to β-actin. Results shown are mean of 3 experiments (right).
mutant, mCherry-hOrai1 and mCherry-Orai1R31W mutant, dominant-negative TRPC4E647Δ-648KK mutant, and TRPC1P662A pore mutant constructs were prepared as described previously (Zeng et al., 2000; Tang et al., 2000). WT-mTRPC4 eDNA in pcAGGS-IRS-GFP vector was prepared as described previously (Freichel et al., 2008; Kim et al., 2009). WT-ECs and TRPC4(-/-) mice were used for experiments. Human lung microvascular ECs (HLMVECs) and HUVECs were obtained from Lonza Walkersville Inc. HLMVECs were grown in EGM-2MV supplemented with 15% FBS, and HUVECs were grown in EGM-2 supplemented with 10% FBS (growth media from Lonza Walkersville Inc.). Both cell types were used between passages 4 and 6.

Reverse Transcription-PCR. Total RNA from m/hECs was isolated using TRIzol reagent. RT was performed using oligo (dT) primers and superscript RT (Invitrogen) following the manufacturer’s instructions. Species specific primers were used to amplify TRPCs, STIMs and Orais (see details in Supplemental Methods).

Cytosolic Ca2+ (\([\text{Ca}^{2+}]_i\)) Measurement. The cytoplasmic Ca2+ concentration (\([\text{Ca}^{2+}]_i\)) in ECs was measured using the Ca2+-sensitive fluorescent dye Fura-2/AM (Tiruppathi et al., 2002; Sundivakkam et al., 2009). Cells were grown to confluence on gelatin-coated glass coverslips and then washed two times with serum-free medium and incubated for 2 h at 37°C in culture medium containing 1% FBS. Cells were washed once and loaded with 3 μM Fura-2/AM.

![Figure 2](image.png)

**Fig. 2.** Impaired store-operated Ca2+ entry (SOCE) in TRPC4(-/-) ECs. A, left, basal Fura-2 340/380 ratio was measured in the presence of nominal extracellular Ca2+ (1.5 mM) in WT and TRPC4(-/-) mice ECs. Results shown are mean ± S.E. of five experiments. A, right, Fura-2 loaded ECs from WT and TRPC4(-/-) mice were used to measure thrombin (50 nM)-induced increase in \([\text{Ca}^{2+}]_i\), in presence of extracellular Ca2+. NS, not significant. B, left, basal Fura-2 340/380 ratio was measured in the absence of extracellular Ca2+ in WT and TRPC4(-/-) mice ECs. Results are mean ± S.E. of five experiments. B, right, Fura-2 loaded cells placed in Ca2+- and Mg2+-free HBSS were stimulated with thrombin (Thr). Change in peak fluorescence ratio (340/380) for Ca2+ entry over basal was calculated. Results shown are mean ± S.E. of four experiments carried out in duplicate (bottom). * significant difference in \([\text{Ca}^{2+}]_i\) entry in TRPC4(-/-)-ECs compared with WT-ECs. C, thapsigargin (1 μM)-induced Ca2+ entry was measured as in B. Arrow indicates time at which cells were stimulated with Tg. * significant difference in \([\text{Ca}^{2+}]_i\) entry in TRPC4(-/-)-ECs compared with WT-ECs.
for 30 min. After loading, cells were washed with HBSS and the coverslips were transferred on a perfusion chamber at 37°C and imaged using a semimotorized microscope (Axio Observer D1; Carl Zeiss GmbH, Jena, Germany) equipped with an AxioCam HScm camera (Carl Zeiss) and a Fluor 40× oil immersion objective. Light was provided by the DG-4 wavelength switcher (Princeton Scientific Instruments, Monmouth Junction, NJ). A dual excitation at 340 and 380 nm was used, and emission was collected at 520 nm. The AxioVision physiology software module was used to acquire the images at 1-s intervals, and the data were analyzed off-line. In each experiment, 20 to 30 cells were selected to measure change in [Ca2+]i.

**Transendothelial Electrical Resistance.** The real-time change in endothelial monolayer resistance (TER) was measured to assess endothelial barrier function (Tiruppathi et al., 1992). Before the experiment, confluent endothelial monolayer was kept in 1% FBS containing medium for 2 h and then thrombin- or PAR-1 agonist peptide-induced change in TER was measured. Data are presented in resistance normalized to its value at time 0 as in Tiruppathi et al. (1992).

**siRNA Transfection.** ECs grown to ~70% confluence on gelatin-coated culture dishes were transfected with target siRNAs or sc-siRNA using DharmaFECT transfection reagent as per the manufacturer’s instructions. At 72 h after transfection, cells were used for Ca2+ measurements or harvested for Western blot analysis.

**cDNA Transfection.** ECs or HEK293 cells transfected with YFP-WT-STIM1, YFP-STIM1K684E-K685Emutant, mCherry-hOrai1, mCherry-Orai1K681W, CFP-Orai1K681W, WT-mTRPC4, dominant-negative TRPC4mK687-689KR mutant, or TRPC1F562A pore mutant expression constructs were used to measure change in [Ca2+]i. ECs or HEK293 cells grown to 80% confluence were transfected with indicated plasmid DNA using Superfect reagent (QiAGEN, Valencia, CA) in serum-free medium as in Sundivakkam et al. (2009). ECs were used for experiments 72 h after transfection, whereas HEK293 cells were used for experiments 48 h after transfection. Cells expressing YFP, mCherry, CFP, or GFP were selected to measure change in [Ca2+]i, as in Zeng et al. (2008) and Lee et al. (2009).

**Immunoprecipitation.** ECs grown to confluence were challenged with agonists were washed three times with phosphate-buffered saline at 4°C and lysed in lysis buffer as in (Sundivakkam et al., 2009). Lysate protein (300 μg) was subjected to immunoprecipitation. Insoluble material was removed by centrifugation (13,000g for 15 min) before overnight immunoprecipitation with 1 μg/ml antibody at 4°C. Protein A/G-agarose beads were added to each sample and incubated for 1 h at 4°C. Immunoprecipitates were gently washed three times with wash buffer (Tris-buffered saline containing 0.5% Triton X-100, 1 mM Na3VO4, 1 mM NaF, 2 μg/ml aprotinin, 2 μg/ml pepstatin A, 2 μg/ml aprotinin, and 44 μg/ml phenylmethylsulfonfonyl fluoride). Immunoprecipitated proteins were resolved on SDS-polyacrylamide gel electrophoresis and immunoblotted with appropriate antibodies.

**Immunoblotting.** EC lysates or immunoprecipitates were resolved by SDS-polyacrylamide gel electrophoresis on a 10% separating gel under reducing conditions and transferred to Duralose membrane. Membranes were blocked with (5% dry milk in 10 mM Tris-HCl, pH 7.5, 150 mM NaCl, and 0.05% Tween 20) for 1 h. Membranes were incubated with indicated primary antibody (diluted in blocking buffer) overnight. After three washes, membranes probed with anti-TRPC4 pAb to determine TRPC4 expression (see details under Materials and Methods) were washed and immunoblotted with anti-TRPC4 pAb to determine TRPC4 expression (top). The membrane was stripped and probed with anti-β actin mAb as loading control (bottom). B and C were used to measure thrombin (Thr)- or Tg-induced Ca2+ store release-mediated Ca2+ entry as described in Fig. 2B. Arrows indicate time of addition of thrombin or Tg. A representative profile is shown in left. Change in peak fluorescence ratio (340/380) for Ca2+ entry over basal was calculated. Results shown are mean ± S.E. of four experiments carried out in duplicate. NS, not significant; *, significant difference in the Ca2+ entry in WT-ECs transfected with sc-siRNA compared with TRPC4-siRNA.

Fig. 3. TRPC4 expression is required for thrombin- or Tg-induced Ca2+ entry in mECs. A, WT-ECs transfected with control siRNA (sc-siRNA) or mouse (m) TRPC4-siRNA (see details under Materials and Methods) were lysed and immunoblotted with anti-TRPC4 pAb to determine TRPC4 expression (top). The membrane was stripped and probed with anti-β actin mAb as loading control (bottom). B and C, WT-ECs transfected with sc-siRNA or mTRPC4-siRNA were used to measure thrombin (Thr)- or Tg-induced Ca2+ store release-mediated Ca2+ entry as described in Fig. 2B. Arrows indicate time of addition of thrombin or Tg. A representative profile is shown in left. Change in peak fluorescence ratio (340/380) for Ca2+ entry over basal was calculated. Results shown are mean ± S.E. of four experiments carried out in duplicate. NS, not significant; *, significant difference in the Ca2+ entry in WT-ECs transfected with sc-siRNA compared with TRPC4-siRNA.
were incubated with horseradish peroxidase-conjugated secondary antibody. Protein bands were detected by enhanced chemiluminescence method.

Confocal Imaging. ECs were transfected with YFP-WT-STIM1 (2 g/ml) construct as described above. At 48 h after transfection, cells washed, placed in HBSS, and then confocal live cell images of the YFP-tagged fluorescent protein were acquired near the surface of the cell using 514 nm laser excitation/530 nm LP emission filter with the pinhole set to achieve 1 Airy unit (0.5-μm optical sections). Image configurations acquired before and after thrombin stimulation were not changed, and the cells were maintained at 37°C.

Statistical Analysis. Comparisons were made with a two-tailed Student's t test. Experimental values were reported as mean ± S.E. Differences in mean values between two or more groups were determined by one-way analysis of variance. A p value <0.05 was considered statistically significant.

Results

Impaired Store-Operated Ca²⁺ Entry in TRPC4 Knockout Mouse Endothelial Cells. We first determined the expression of TRPCs, STIMs, and Orai in ECs from wild-type (WT) and TRPC4(−/−) mice by RT-PCR (Fig. 1A) and Western blot (Fig. 1B). We observed expression of transcripts for TRPC1, TRPC4, and TRPC6 in WT-ECs (Fig. 1A, left); TRPC1 and TRPC6 expression occurred at a low level compared with the TRPC4 transcript. In TRPC4(−/−)-ECs, the TRPC4 transcript was not detectable, whereas TRPC1 and TRPC6 expression was similar to WT-ECs (Fig. 1A, left), in agreement with our previous results (Tiruppathi et al., 2002). We also observed the expression of STIM1, STIM2, and Orai1 mRNA in WT-ECs (Fig. 1A, right).
ECs, the expression of STIM1, STIM2, and Orai1 mRNA was similar to WT-ECs (data not shown). We also performed Western blot analysis to determine the expression levels of TRPCs, STIM1, and Orai1 proteins in ECs from WT and TRPC4(-/-) mice. TRPC4 protein expression was predominant in WT-ECs, whereas TRPC4 protein expression was not observed in TRPC4(-/-)-ECs (Fig. 1B). In WT and TRPC4(-/-) ECs, we observed expression of TRPC1, STIM1, and Orai1 proteins at similar levels (Fig. 1B).

To determine whether loss of TRPC4 in ECs influences basal intracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(i\)), we measured fura-2 340/380 ratio in the presence and absence of extracellular Ca\(^{2+}\) in ECs from WT and TRPC4(-/-) mice. We observed no significant differences in basal [Ca\(^{2+}\)]\(i\)] between WT and TRPC4(-/-) ECs (Fig. 2, A and B, left). Next, we measured thrombin-induced rise in intracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(i\)) using ECs from WT and TRPC4(-/-) mice. Thrombin-induced increase in [Ca\(^{2+}\)]\(i\), was reduced by 80% in TRPC4(-/-)-ECs compared with WT-ECs (Fig. 2A, right). We also measured thrombin-induced Ca\(^{2+}\) entry in ECs from WT and TRPC4(-/-) mice. In these experiments, we first depleted the ER Ca\(^{2+}\) stores with thrombin in the absence of extracellular Ca\(^{2+}\) to open channels and then reapplied Ca\(^{2+}\) to the extracellular medium to assess Ca\(^{2+}\) entry (i.e., SOCE) through the open channels. This protocol allowed separation of Ca\(^{2+}\) release from Ca\(^{2+}\) entry. Thrombin produced a similar initial peak increase in [Ca\(^{2+}\)]\(i\), in WT and TRPC4(-/-) ECs (Fig. 2B, right). In WT-ECs, restoring Ca\(^{2+}\) in the extracellular medium after thrombin-induced store-depletion caused an increase in Ca\(^{2+}\) entry (Fig. 2B, right). In contrast to WT-ECs, re-addition of Ca\(^{2+}\) to the extracellular medium after store depletion caused no significant Ca\(^{2+}\) entry in TRPC4(-/-)-ECs (Fig. 2B, right and bottom). We also observed that thapsigargin (Tg)-induced Ca\(^{2+}\) entry was blocked in TRPC4(-/-)-ECs (Fig. 2C).

Because thrombin activates the dominant PAR-1 in ECs, we measured PAR-1 agonist peptide (TFLLRNPNVDK)-induced Ca\(^{2+}\) entry in WT and TRPC4(-/-) mice ECs. We observed the peptide-induced Ca\(^{2+}\) entry in WT-ECs was similar to thrombin (Supplemental Fig. 1, A and B), whereas the response was reduced by 80% in TRPC4(-/-)-ECs (Supplemental Fig. 1, A and B). We also investigated the effects of gadolinium (Gd\(^{3+}\)) and 2-aminoethoxydiphenyl borate on thrombin-induced Ca\(^{2+}\) entry in WT-ECs. Gd\(^{3+}\) (10 μM) abolished thrombin-induced Ca\(^{2+}\) entry in WT-ECs (Supplemental Fig. 2A). In addition, 2-aminoethoxydiphenyl borate (30 μM) markedly reduced thrombin-induced Ca\(^{2+}\) entry in WT-ECs (Supplemental Fig. 2B). These findings demonstrate the importance of TRPC4 expression in SOCE in mECs.

To address the functional relevance of the TRPC4 in mECs,
we measured PAR-1 activation-mediated changes in TER to assess EC retraction (i.e., cell shape change), a prerequisite for the increase in endothelial permeability (Wysolmerski and Lagunoff, 1990; Tiruppathi et al., 1992). Exposure of WT-ECs with either thrombin or PAR-1 agonist peptide produced a ~40% maximum decrease in TER whereas this effect was significantly reduced in TRPC4(−/−)-ECs (Supplemental Fig. 3) indicating that TRPC4 expression in ECs contributes significantly to the thrombin-induced increase in endothelial permeability.

**TRPC4 Knockdown Suppresses SOCE in mECs.** We addressed whether TRPC4 gene knockdown suppresses SOCE in mECs. In these experiments, we transfected control siRNA (sc-siRNA) or mTRPC4-specific siRNA in WT-ECs and determined TRPC4 protein expression in these cells. In TRPC4-siRNA transfected cells, TRPC4 expression was markedly suppressed compared with control or sc-siRNA transfected cells (Fig. 3A). We determined Ca²⁺ entry after thrombin-induced ER store Ca²⁺ depletion in control, sc-siRNA and TRPC4-siRNA transfected cells. We observed thrombin-induced Ca²⁺ entry in control and sc-siRNA transfected cells (Fig. 3B) whereas in TRPC4-siRNA transfected cells, thrombin-induced Ca²⁺ entry was abolished (Fig. 3B). We also observed that Tg-induced Ca²⁺ entry was blocked >80% in TRPC4-siRNA transfected WT-ECs (Fig. 3C). Next we transiently expressed the WT-mTRPC4β isoform in TRPC4(−/−)-ECs. TRPC4 re-expression rescued the thrombin-induced Ca²⁺ entry in TRPC4(−/−)-ECs (Fig. 3D). We also expressed the dominant-negative TRPC4EE6470648KK mutant in WT-ECs and observed that thrombin-induced Ca²⁺ entry was markedly reduced in TRPC4EE6470648KK-mutant expressing cells compared with control cells (Fig. 3E). These results collectively support the concept that TRPC4 expression contributes to SOCE in mECs.

Because TRPC1 is expressed in mECs and hetero-oligomerizes with TRPC4 to form a functional SOCE complex (Hofmann et al., 2002), we knocked down TRPC1 by transfecting mTRPC1-specific siRNA in WT-ECs and determined Ca²⁺ entry after ER store Ca²⁺ depletion with either thrombin or Tg. In TRPC1-siRNA transfected cells, TRPC1 protein expression was inhibited by 80% compared with control (Fig. 4A), but TRPC1 knockdown resulted in ~15% inhibition of Ca²⁺ entry induced by either thrombin or Tg (Fig. 4, B and C). To further address the role of TRPC1, we transfected TRPC1F562A, a pore-mutant expression construct, in WT-ECs and measured thrombin- or Tg-induced Ca²⁺ entry. Expression of the mutant construct in WT-ECs had no significant effect on SOCE (Fig. 4D). Next we determined the effect of stored Ca²⁺ release on the interaction between TRPC1 and TRPC4. We observed that thrombin- or Tg-induced store depletion increased the association between TRPC1 and TRPC4 (Fig. 4, E–G). These results suggest that TRPC1 is not essential for pore forming subunit channel complex but may provide scaffold for TRPC4 in mECs.
STIM1 Signaling Is Required for SOCE in mECs. To address the role of STIM1 in the mechanism of SOCE in mECs, we transfected mSTIM1-specific siRNA into WT-ECs and determined the expression of STIM1. In STIM1-siRNA–transfected cells, STIM1 protein expression was reduced 90% (Fig. 5A) whereas in sc-siRNA-transfected cells, STIM1 expression was not altered (Fig. 5A). To determine whether STIM1 knockdown influences basal intracellular Ca²⁺ ([Ca²⁺]ᵢ), we measured Fura-2 340/380 ratio in the presence and absence of extracellular Ca²⁺ in control, sc-siRNA, and STIM1-siRNA transfected ECs. We did not observe significant differences in basal [Ca²⁺]ᵢ in STIM1-siRNA transfected ECs compared with control or sc-siRNA transfected cells (Fig. 5B). Next we measured Ca²⁺ entry in control, sc-siRNA-, or STIM1-siRNA–transfected cells after depleting ER-store Ca²⁺ with thrombin. Thrombin-induced Ca²⁺ entry was markedly reduced in STIM1-siRNA–transfected WT-ECs (Fig. 5C) whereas in sc-siRNA-transfected WT-ECs, the response was similar to control WT-ECs. Tg-induced Ca²⁺ entry was also inhibited in STIM1-siRNA–transfected cells but not in sc-siRNA-transfected or in control WT-ECs (Fig. 5D). These findings show that STIM1 expression is required for SOCE in mECs.

Next we ectopically expressed YFP-WT-STIM1 or YFP-mutant-STIM1K684E-K685E (dominant negative mutant) in ECs from WT and TRPC4 (−/−) mice. Previous studies have shown that YFP-tagged STIM1 interacts with and gates TRPC channels (Zeng et al., 2008; Yuan et al., 2009). YFP fluorescence allowed identification of transfected cells for Ca²⁺ imaging. In WT-ECs expressing YFP-WT-STIM1, thrombin-induced Ca²⁺ entry was enhanced compared with control cells (Fig. 5E). By contrast, in WT-ECs expressing YFP-STIM1K684E-K685E, thrombin-induced Ca²⁺ entry did not occur (Fig. 5E). We also expressed YFP-WT-STIM1 or YFP-mutant-STIM1K684E-K685E in TRPC4 (−/−)-ECs. Expression of either YFP-WT-STIM1 or YFP-STIM1K684E-K685E failed to rescue thrombin-induced Ca²⁺ entry in TRPC4 (−/−)-ECs (Fig. 5F). Thus, STIM1-TRPC4 cosignaling is required for SOCE in mECs.

To further delineate the role of TRPC4 in SOCE, we expressed YFP-WT-STIM1 in ECs of WT and TRPC4 (−/−) mice and used confocal imaging to observe STIM1 mobilization as the result of ER-store Ca²⁺ release. In WT-ECs expressing YFP-WT-STIM1, we noted that thrombin- or thapsigargin stimulation caused formation of STIM1 puncta in a time-dependent manner (Fig. 6, A–F). STIM1 puncta appeared within 10 s of thrombin or Tg addition to cells and persisted over a period of 350 s. These findings show that STIM1 expression is required for SOCE in mECs.
These results indicate that TRPC4 expression is essential for the STIM1 mobilization, an obligatory step in the activation of SOCE in mECs.

Orai Family Channels Are Not Required for SOCE in mECs. We determined the expression of Orai family channels in mECs. We observed that Orai1 was dominantly expressed in mECs (Fig. 1, A and B). Orai2 expression was not detectable, whereas Orai3 was expressed at low levels compared with Orai1 in mECs (Fig. 7A). Because Orai1 is predominantly expressed in mECs, we suppressed Orai1 expression by transfecting WT-ECs with mOrai1-specific siRNA. In Orai1-siRNA–transfected cells, Orai1 protein expression was reduced by more than 80% compared with control or sc-siRNA-transfected WT-ECs (Fig. 7A). We did not observe any significant change in thrombin- or Tg-induced Ca^{2+} entry in Orai1 depleted WT-ECs compared with control WT-ECs (Fig. 7, B and C). Furthermore, we observed that Gd^{3+} blocked thrombin-induced Ca^{2+} entry in Orai1-depleted WT-ECs (Supplemental Fig. 5). Although, Orai2 was not detectable in mECs, we transfected mOrai2-siRNA and measured thrombin-induced Ca^{2+} entry in WT-ECs. Thrombin-induced Ca^{2+} entry was not significantly altered in Orai2-siRNA transfected cells compared with sc-siRNA or control cells (Fig. 7D). Next, we suppressed Orai3 in WT-ECs with mOrai3-siRNA and used these cells to measure thrombin-induced Ca^{2+} entry. Orai3 suppression also had no significant effect on thrombin-induced Ca^{2+} entry (Fig. 7E).

To further test the role of Orai proteins in mECs, we ectopically expressed mCherry-tagged Orai1 in ECs from WT and TRPC4(−/−) mice and measured thrombin-induced Ca^{2+} entry. In this experiment, we selected only mCherry-expressing cells for Fura-2 imaging to assess Ca^{2+} entry. We...
observed no significant effect on thrombin-induced Ca\textsuperscript{2+} entry in WT-ECs expressing mCherry-tagged Orai1 (Fig. 7F). In addition, we observed that the expression of mCherry-tagged Orai1 in TRPC4\textsuperscript{(-/-)}-ECs failed to restore thrombin-induced Ca\textsuperscript{2+} entry in these cells (Fig. 7F). We used HEK293 cells as positive control cells to test Orai1 function. HEK293 cells expressed STIM1 and Orai1 proteins, and silencing of Orai1 markedly reduced Tg-induced Ca\textsuperscript{2+} entry (Supplemental Fig. 6). TG-induced Ca\textsuperscript{2+} entry was significantly increased in mCherry-tagged Orai1 expressing HEK293 cells compared with control cells (Supplemental Fig. 6) and coexpression of mCherry-tagged Orai1 with YFP-STIM1 in HEK293 cells further increased Tg-induced Ca\textsuperscript{2+} entry compared with the cells expressing only mCherry-tagged Orai1 (Supplemental Fig. 6). Next, we expressed dominant-negative Orai1\textsuperscript{K381W} and Orai3\textsuperscript{K381W} mutants in WT-ECs to inhibit SOCE (Fig. 7G). These results collectively support the conclusion that Orai family proteins are not involved in the mechanism of SOCE in mECs.

**STIM1 Knockdown Prevents SOCE in Human ECs.**

Because the above studies were in mECs and hECs predominantly express TRPC1 (Tiruppathi et al., 2006), we tested whether Orai1 regulates this channel in hECs, and thereby SOCE. Using HLMVECs, we observed expression of the SOC constituents TRPC1, TRPC4, STIM1, Orai1, and Orai3 (Fig. 8A; Supplemental Fig. 7A). We suppressed individually endogenous expression of TRPC1, TRPC4, STIM1, or Orai1 by transfecting target-specific siRNA in HLMVECs. TRPC1 knockdown in HLMVECs inhibited >80% of thrombin-induced Ca\textsuperscript{2+} entry (Supplemental Fig. 7B), whereas TRPC4 knockdown suppressed ~50% thrombin-induced Ca\textsuperscript{2+} entry (Supplemental Fig. 7B). We also expressed the TRPC1\textsuperscript{F562A} pore mutant and dominant-negative TRPC4\textsuperscript{E647-648KK} mutant in HLMVECs. TRPC1\textsuperscript{F562A} pore-mutant expression blocked ~70% of the thrombin-induced Ca\textsuperscript{2+} entry (Supplemental Fig. 7C) whereas expression of the TRPC4\textsuperscript{E647-648KK} mutant inhibited ~25% of the thrombin-induced Ca\textsuperscript{2+} entry (Supplemental Fig. 7C). These results indicate that TRPC1 is the dominant channel in HLMVECs SOCs. Similar to results in mECs above, STIM1 knockdown markedly reduced thrombin-induced Ca\textsuperscript{2+} entry in HLMVECs (Fig. 8, B and C). Tg-induced Ca\textsuperscript{2+} entry was also suppressed in STIM1 knockdown HLMVECs (data not shown). However, Orai1 knockdown had no significant effect on thrombin-induced Ca\textsuperscript{2+} entry (Fig. 8, D and E) in HLMVECs. These results demonstrate that TRPC1-STIM1 cosignaling is essential for SOCE in HLMVECs.

This observation is different from the recent report indicating that knockdown of Orai1 but not TRPC1 or TRPC4 suppressed thrombin-induced Ca\textsuperscript{2+} entry in HUVECs (Abdullaev et al., 2008). To reconcile these differences, we performed knockdown experiments using HUVECs. Knockdown of TRPC1, Orai1, or STIM1 markedly reduced thrombin-
induced Ca\(^{2+}\) entry in HUVECs (Supplemental Fig. 8). These results show in HUVECs (as distinct from hEC and mEC results) that Orai1 (Abdullaev et al., 2008) and TRPC1 (Thippagar et al., 2010) are both essential for SOCE.

**Discussion**

We investigated the role of the ER-localized Ca\(^{2+}\)-sensing protein STIM1 and the CRAC channel protein Orai1 in activating the SOCE function of TRPCs in ECs. We observed expression of STIM1 and Orai1 in ECs from humans and mice. Knockdown of STIM1 suppressed SOCE activity of TRPC1 and TRPC4, indicating that STIM1 was essential for SOCE in ECs expressing these channels. Orai1 expression was not required for SOCE in primary human and mouse ECs. However, Orai1 was involved in regulating SOCE in HUVECs, consistent with evidence on the importance of Orai1 in mediating Ca\(^{2+}\) entry in these cells (Abdullaev et al., 2008). The difference with HUVECs may reflect the specialized nature and uniqueness of these cells, which are often, and perhaps incorrectly, used as a surrogate for ECs (Watson et al., 1995).

TRPC family members TRPC1, TRPC4, and TRPC5 form SOC channels (Hofmann et al., 2002), whereas TRPC3, TRPC6, and TRPC7 form receptor-operated channels (Nilius and Droog-
mans, 2001). We have shown that TRPC1 and TRPC4 are essential for the SOC function in ECs (Tiruppathi et al., 2002; Paria et al., 2004, 2006). Freichel et al. (2001) showed, using TRPC4(+/−) mice that TRPC4 is essential for SOCE in ECs. We also observed markedly reduced Ca\(^{2+}\) entry in TRPC4(+/−) mouse ECs in response to PAR-1 activation, resulting in a reduced lung vascular permeability response (Tiruppathi et al., 2002). In addition, TRPC4 mediates Ca\(^{2+}\) entry during transition from a proliferating to quiescent phenotype in the human dermal microvascular EC line (HMEC-1) (Graziani et al., 2010). These findings collectively indicate a key role for TRPC1 and TRPC4 in mediating Ca\(^{2+}\) store depletion in ECs.

Recent studies have demonstrated that Ca\(^{2+}\) entry through TRPC channels is influenced by their association with Orai1 and STIM1 (Liao et al., 2007; Yuan et al., 2007; Alicia et al., 2008; Jardin et al., 2008, 2009; Yuan et al., 2009). To address the role of STIM1 and Orai1 proteins in regulating SOCE mediated by TRPCs in ECs, we isolated cells from WT and TRPC4(−/−) mice and determined the expression of TRPCs, STIMs, and Orais. There was essentially similar expression of these proteins in WT-ECs and TRPC4(−/−)-ECs. Using Fura-2 to determine PAR-1-mediated Ca\(^{2+}\) entry, we observed the loss of Ca\(^{2+}\) entry in TRPC4(−/−)-ECs in response to PAR-1 activation or thapsigargin. On silencing TRPC4 expression using siRNA in WT-ECs, we also showed the loss of thrombin- or Tg-induced Ca\(^{2+}\) entry. However, silencing TRPC1 expression in WT-ECs inhibited ~15% of thrombin-induced Ca\(^{2+}\) entry. It is noteworthy that re-expression of TRPC4 in TRPC4(−/−)-ECs restored PAR-1-induced Ca\(^{2+}\) entry, whereas the expression of the dominant-negative TRPC4\(^{E647-648KK}\) mutant in WT-ECs markedly reduced PAR-induced Ca\(^{2+}\) entry. These key findings suggest that TRPC4 is responsible for SOCE in mECs, consistent with a previous report (Tiruppathi et al., 2002).
Because there was similar expression of STIM1 in WT and TRPC4(-/-) ECs, we next addressed the function of STIM1 in mediating SOCE. STIM1 knockdown by greater than 80% abolished SOCE activated by either thrombin or Tg, indicating that STIM1 signaling is required for TRPC4-mediated Ca^{2+} entry in ECs. STIM1 activation of Ca^{2+} entry through hTRPC1 involves electrostatic interactions between STIM1 Lys-rich domain (Lys684 and Lys685) and TRPC1 C-terminal Asp639 and Asp640 (Zeng et al., 2008). Ca^{2+} entry through TRPC1 channels can be blocked by expression of STIM1 Lys-rich domain mutant, STIM1K684E-K685E (Zeng et al., 2008). Like hTRPC1, mTRPC4 C-terminal contains negatively charged (Glu648 and Glu649) residues, indicating that charge interaction between STIM1 and TRPC4 activates Ca^{2+} entry through TRPC4 in mECs. To test this concept, we ectopically expressed YFP-dominant negative-STIM1K684E-K685E mutant (Zeng et al., 2008) in WT-ECs and found an unusually low Ca^{2+} entry in response to thrombin compared with control cells expressing WT construct (YFP-WT-STIM1). In contrast to our findings in WT-ECs, we did not observe thrombin-induced Ca^{2+} entry in TRPC4(-/-)-ECs expressing either YFP-WT-STIM1 or YFP-dominant negative-STIM1, indicating that TRPC4 is required for SOCE in mECs. These results show that TRPC4 interacts with STIM1 to activate SOCE in ECs.

To further define the role of STIM1 in the mechanism of TRPC4-mediated SOCE in ECs, we visualized STIM1 puncta formation secondary to ER stored-Ca^{2+} release after transducing YFP-STIM1. In WT-ECs, STIM1 puncta were clearly seen in response to thrombin or Tg. A representative profile is shown in B and C, left. Change in peak fluorescence ratio (340/380) for Ca^{2+} entry over basal was calculated and plotted in right. Results shown are the mean ± S.E. of four experiments carried out in duplicates. NS, not significant.

Fig. 7. Orai proteins function is not obligatory for SOCE in ECs. A, left, Western blot analysis of WT- mECs using specific antibodies that reacts with Orai1, Orai2, and Orai3. Orai1 expression was dominant, Orai2 expression was not detectable, and Orai3 expression was relatively low compared with Orai1. A, right, WT- mECs transfected with indicated concentrations of sc-siRNA or mOrai1-siRNAtransfection were used for Western blot to determine Orai1 expression. B and C, cells were used to measure thrombin- or Tg-induced Ca^{2+} entry. Arrows indicate time of addition of thrombin or Tg. A representative profile is shown in B and C, left. Change in peak fluorescence ratio (340/380) for Ca^{2+} entry over basal was calculated and plotted in right. Results shown are the mean ± S.E. of four experiments carried out in duplicates. NS, not significant.
The CRAC-channel protein Orai1 to form a functional SOC in different cell types (Ong et al., 2007; Cheng et al., 2008; Kim et al., 2009; Covington et al., 2010). In addition, TRPCs may interact with STIM1 and Orai1 to form a functional SOC (Ong et al., 2007; Cheng et al., 2008; Kim et al., 2009; Liao et al., 2009; Lee et al., 2010). However, we observed that Orai1
knockdown had no effect on SOCE induced by either thrombin or Tg. Ectopic expression of Orai1 in mECs of WT and TRPC4(−/−) mice also had no effect on thrombin-induced Ca2+ entry. Moreover, Orai1 expression failed to restore SOCE in TRPC4(−/−)-ECs. We also suppressed the expression of the other CRAC channel proteins Orai2 and Orai3 with siRNA in mECs. Suppression of either Orai2 or Orai3 had no effect on thrombin-induced Ca2+ entry in mECs. In addition, we expressed Orai1R91W and Orai3E81W mutants in WT-ECs and observed that expression of these mutants had no effect on SOCE. Because this lack of involvement of Orai1 could be species-specific, we investigated the contribution of TRPCs, STIMs, and Orais in the mechanism of SOCE in hECs, HLMVECs. We observed expression of TRPCs (TRPC1, TRPC4, and TRPC6), STIM1, Orai1, and Orai3 in HLMVECs. TRPC1 knockdown prevented >80% thrombin-induced Ca2+ entry in HLMVECs, whereas TRPC4 knockdown prevented ~50% of thrombin-induced Ca2+ entry, indicating the role of both TRPCs in activating SOCE in HLMVECs. We also suppressed expression of STIM1 and the dominant Orai protein Orai1 in HLMVECs and measured thrombin-induced Ca2+ entry after RNA silencing. Thrombin-induced Ca2+ entry was blocked in STIM1-depleted HLMVECs but not in the Orai1-depleted cells, consistent with the mEC results. Thus, Orai1 in contrast to STIM1 does not play a role in mediating SOCE in h/mECs.

That Orai1 does not regulate SOCE in ECs is different from the findings of Abdullaev et al. (2008) showing an Orai1-dependent ICrAC channel mediated Ca2+ entry in HUVECs. We also showed quite a similar role of Orai1 in

Fig. 8. Effects of TRPC1, TRPC4, STIM1, or Orai1 knockdown on thrombin-induced Ca2+ entry in human ECs. A, RT-PCR was used to determine the mRNA expression profile for STIMs and Orais in HLMVECs and HUVECs. B, HLMVECs transfected with sc-siRNA or δSTIM1-siRNA were lysed and immunoblotted with anti-STIM1 mAb (top). The blots were stripped and probed with anti-β actin mAb as loading control (bottom). C, after transfection, cells were used to measure thrombin-induced Ca2+ entry (left). Arrows indicate time of addition of thrombin. Change in peak fluorescence ratio (340/380) for Ca2+ entry over basal was calculated (right). Results shown are mean ± S.E. of four experiments carried out in duplicate. *, significantly different from cells transfected with sc-siRNA. D, HLMVECs transfected with sc-siRNA or δOrai1-siRNA were immunoblotted with anti-Orai1 pAb (top). The blots were stripped and probed with anti-β actin mAb as loading control (bottom). E, cells were used to measure thrombin-induced Ca2+ entry (left). Arrow indicates time at which cells were stimulated with thrombin. Change in peak fluorescence ratio (340/380) for Ca2+ entry over basal was calculated (right). Results shown are mean ± S.E. of four experiments carried out in duplicate (right). NS, not significantly different from control or sc-siRNA transfected cells.
STIM1 was required for Ca\(^{2+}\) entry in ECs secondary to store depletion. These findings demonstrate the importance of the interaction between the Ca\(^{2+}\)-sensing STIM1 with SOCE channel TRPC1 or TRPC4 in mediating Ca\(^{2+}\) entry and disrupting the endothelial barrier. However, Orai1 was not required for activation of SOCE in ECs, although Orai1 protein was expressed, suggesting that it has another, as-yet-unrecognized function in ECs.

**Authorship Contributions**

*Participated in research design:* Sundivakkam, Freichel, Singh, and Yuan.

*Wrote or contributed to the writing manuscript:* Sundivakkam, Vogel, Malik, and Tiruppathi.

**References**


Graziani A, Poteser M, Heupel WM, Schleifer H, Krenn M, Drenckhahn D, Romanin J, Gómez LJ, Salido GM, and Rosado JA (2009) Dynamic interaction of STIM1-TRPC4 Mediates Ca\(^{2+}\) store depletion induces interaction between TRPC4 and STIM1 in ECs. A, WT-mECs were stimulated with Tg (1 μM) for different time intervals at 37°C. After Tg stimulation, cells were lysed and immunoprecipitated (IP) with anti-TRPC4 pAb. The precipitated proteins were immunoblotted (IB) with anti-STIM1 mAb (first) or Orai1 pAb (second). Total cell lysates were immunoblotted with anti-STIM1 mAb (third) or anti-Orai1 pAb (fourth).

B, WT-mECs treated with or without thornbin (50 nM) for 5 min at 37°C were lysed and immunoprecipitated with either anti-TRPC4 pAb or anti-STIM1 mAb. The precipitated proteins were immunoblotted with anti-STIM1 mAb (first) and anti-TRPC4 pAb (second).

C, WT-mECs treated with or without thornbin (50 nM) for 5 min at 37°C were lysed and immunoprecipitated with anti-TRPC4 pAb (first) and anti-STIM1 mAb (second). The precipitated proteins were immunoblotted with anti-STIM1 mAb (third) or anti-Orai1 pAb (fourth). Total cell lysates were immunoblotted with anti-STIM1 mAb (first) and anti-TRPC4 pAb (second). The precipitated proteins were immunoblotted with anti-Orai1 pAb (first). Total cell lysates were immunoblotted with anti-Orai1 pAb (second) or anti-TRPC4 pAb (third).

The experiments shown are from representative experiments.

regulating SOCE in HUVECs, suggesting that the discrepancy is related to the use of HUVECs, a specialized cell that does not reflect the complex characteristics of most ECs (Watson et al., 1995). Orai proteins are highly Ca\(^{2+}\)-selective (Salido et al., 2009), whereas TRPC proteins are nonselective cation channels permeable to Ca\(^{2+}\), Na\(^{+}\), and Cs\(^{+}\) (Salido et al., 2009). We observed expression of Orai1, Orai2, and Orai3 proteins in HUVECs; thus, Orai proteins may contribute to Ca\(^{2+}\)-selective SOC activity in HUVECs that may be required for specialized function of human umbilical veins. We observed that lung hlmECs dominantly express Orai1 isoform, and its knockdown had no significant effect on thrombin-induced Ca\(^{2+}\) entry, indicating that TRPCs function as a nonselective cation channel in ECs.

In summary, we showed that STIM1 activates TRPC1/4-mediated SOCE in ECs. Association between TRPC and


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The Ca\(^{2+}\) Sensor STIM1 is Necessary and Sufficient for the Store-Operated Ca\(^{2+}\) Entry Function of TRPCs in Endothelial Cells

Premanand C. Sundivakkam, Marc Freichel, Vandana Singh, Joseph P. Yuan, Stephen M. Vogel, Veit Flockerzi, Asrar B. Malik and Chinnaswamy Tiruppathi

Supplemental Methods:

**Reverse Transcription (RT)-PCR:** Total RNA from Mouse and Human lung endothelial cells (LECs) were isolated using TRIzol reagent. RT was performed using oligo (dT) primers and superscript RT (Invitrogen) following the manufacturer's instructions. RT product (2 µl) was amplified in a 50-µl volume containing 100 pmol primers and 2.5 units Taq DNA polymerase. PCR products were resolved using 1.2% agarose gel and identified by ethidium bromide staining. Species specific primers were used to amplify TRPCs, STIMs and Orais. Primers used were listed below:

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SUPPLEMENTAL RESULTS:

**Supplemental Figure 1:** In A, PAR-1 agonist peptide (40 μM)-induced increase in [Ca^{2+}], was measured in WT and TRPC4^{-/-} ECs. The experiment was repeated 3 times with similar results. In B, PAR-1 agonist peptide-induced stored-Ca^{2+} release and Ca^{2+} release-activated Ca^{2+} entry was measured in WT and TRPC4^{-/-} ECs (see details in Methods). Arrow indicates the time at which cells were stimulated with PAR-1 peptide (PAR-1 pep). Percentage change in peak fluorescence ratio (340/380) for Ca^{2+} entry over basal was calculated (right panel). Results shown are the mean ± SE of 4 experiments carried out in duplicate. (*) indicates significant reduction in Ca^{2+} entry in TRPC4^{-/-}-ECs when compared to WT-ECs.
Supplemental Figure 2: In A, Fura-2 loaded WT-mECs were used to measure thrombin-induced stored-Ca\(^{2+}\) release and Ca\(^{2+}\) release-activated Ca\(^{2+}\) entry in the presence and absence of indicated concentrations of Gd\(^{3+}\). Top Right Inset, Gd\(^{3+}\) different concentrations was added at the indicated time. In B, Fura-2 loaded WT-mECs were used to measure thrombin-induced stored Ca\(^{2+}\)-release and Ca\(^{2+}\) release-activated Ca\(^{2+}\) entry in the presence and absence of 30 µM 2-APB (see details in Methods). Arrows indicate time of thrombin (Thr) addition. The experiment was repeated 3 times. The results from representative experiments are shown.
Supplement Figure 3: The real-time change in TER was measured in response to PAR-1 activation. ECs from WT and TRPC4−/− mice were grown to confluence on gold electrodes (see details in Methods). Cells were washed and incubated with 1% FBS containing medium for at least 2 h before the addition of either 50 nM thrombin (A) or 40 µM PAR-1 peptide (B). Arrow indicates the time at which medium (control), thrombin, or PAR-1 peptide was added. The maximum decrease in TER at 60 min after thrombin or PAR-1 peptide challenge was shown in right panels. Values are means ± SE from 4 experiments carried out in duplicates. (*), indicates significantly different from WT-mECs.
Supplemental Figure 4: HEK293 cells were transfected with WT-mTRPC4β, YFP-STIM1, or WT-mTRPC4β plus YFP-STIM1 (see details in Methods). In A, at 48 h after transfection, cells were used for confocal imaging to determine Tg-induced STIM1 puncta. Results shown are from representative confocal images (top panels). STIM1 puncta formed after Tg addition at 150 sec was quantified (bottom panel). n = 5, in each group. (*), indicates significantly different from YFP-STIM1 alone expressing cells. In B, cells were used to measure Tg-induced Ca\(^{2+}\) entry. (*) indicates significantly different from controls. n = 25 in each group.

Supplemental Figure 5: Gd\(^{3+}\) blocks SOCE in Orai1 knockdown mECs. WT-ECs were transfected with control siRNA or Orai1-siRNA (see details in Methods). At 72 h after transfection, cells were used to measure thrombin-induced Ca\(^{2+}\) entry. In bottom right panel Gd\(^{3+}\) (10 µM) was added at the indicated time to inhibit Ca\(^{2+}\) entry.
**Supplemental Figure 6:** A: Orai and STIMs expression profile in HEK 293 cells. *Left panels,* total RNA from HEK293 cells was isolated and RT-PCR was performed to determine Orais (Orai1, Orai2, Orai3) and STIMs (STIM1, STIM2). *Right panel,* Orai proteins expression was determined by immunoblot (IB). The experiment was repeated three times with similar results. **B and C:** HEK 293 cells were transfected with Sc-siRNA or Orai1-siRNA. At 48 h after transfection, cells were used to determine Orai1 expression by Western blot or Tg-induced Ca\(^{2+}\) entry. Note that Orai1 knockdown reduced Tg-induced Ca\(^{2+}\) entry in HEK 293 cells. **D and E:** HEK 293 cells were transfected with either mCherry-Orai1, YFP-STIM1, or mCherry-Orai1 plus YFP-STIM1 (see details in Methods). At 48 h after transfection, cells were used to determine Tg-induced Ca\(^{2+}\) entry. Note that co-expression of mCherry-Orai1 with YFP-STIM1 increased Tg-induced Ca\(^{2+}\) entry.
Supplemental Figure 7, A and B: Effects of TRPC1 or TRPC4 knockdown on thrombin-induced Ca\(^{2+}\) entry in HLMVECs. In A, RT-PCR was used to determine the mRNA expression profile for TRPCs in HLMVECs (see details above). In B, HLMVECs were transfected with Sc-siRNA, hTRPC1-siRNA, or hTRPC4-siRNA. At 72 h after transfection, cells were lysed and immunoblotted with specific hTRPC1 or hTRPC4 antibodies. HLMVECs were transfected with indicated concentrations of Sc-siRNA, hTRPC1-siRNA, or hTRPC4-siRNA as above used to measure thrombin-induced Ca\(^{2+}\) entry. Arrow indicates time of addition of thrombin. A representative profile is shown in middle panel. Change in...
peak fluorescence ratio (340/380) for Ca\(^{2+}\) entry over basal was calculated. Results shown in *bottom panel* are the mean ± SE of 4 experiments carried out in duplicate. (*), indicates significant difference in the Ca\(^{2+}\) entry in cells transfected with Sc-siRNA compared to hTRPC4-siRNA or hTRPC1-siRNA.

**Supplemental Figure 7C:** TRPC1\(^{F562A}\) pore mutant inhibits SOCE in HLMVECs. HLMVECs transfected with TRPC1\(^{F562A}\) pore mutant or dominant-negative TRPC4\(^{EE647-648KK}\) mutant were used to measure thrombin-induced Ca\(^{2+}\) entry (*middle panel*). Expression of these mutants in HLMVECs was determined by Immunoblot (*top panels*). Results shown in *bottom panel* are the mean ± SE of 4 experiments carried out in duplicate. (*), indicates significant difference in the Ca\(^{2+}\) entry in cells transfected with TRPC1\(^{F562A}\) mutant or TRPC4\(^{EE647-648KK}\) mutant when compared to control cells.
Supplement Figure 8: Effects of STIM1 or Orai1 knockdown on thrombin-induced Ca\(^{2+}\) entry in HUVECs. In A, RT-PCR was used to determine STIM and Orai expression profile in HUVECs. In B, HUVECs were transfected with indicated concentrations of either Sc-siRNA or hSTIM1-siRNA. At 72 h after transfection, STIM1 expression (right panel-top) or thrombin-induced Ca\(^{2+}\) entry (left panel) were determined. Change in peak fluorescence ratio (340/380) for Ca\(^{2+}\) entry over basal was calculated. Results shown (right panel-bottom) are the mean ± SE of 4 experiments. (*), indicates significant difference in the Ca\(^{2+}\) entry in cells transfected with Sc-siRNA compared to STIM1-siRNA. In C, HUVECs were transfected with indicated
concentrations of either Sc-siRNA or hOrai1-siRNA. At 72 h after transfection, Orai1 expression (right panel-top) or thrombin-induced Ca\(^{2+}\) entry (left panel) were determined. Change in peak fluorescence ratio (340/380) for Ca\(^{2+}\) entry over basal was calculated. (*), denotes significant difference in the Ca\(^{2+}\) entry in cells transfected with Sc-siRNA compared to Orai1-siRNA.