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TRPC6 Regulates CXCR2-Mediated Chemotaxis of Murine Neutrophils

Otto Lindemann,* Daniel Umlauf,† Svetlana Frank,‡ Sandra Schimmelpfennig,* Jessica Bertrand,† Thomas Pap,† Peter J. Hanley,‡ Anke Fabian,§ Alexander Dietrich,§ and Albrecht Schwab*

Unraveling the mechanisms involved in chemotactic navigation of immune cells is of particular interest for the development of new immunoregulatory therapies. It is generally agreed upon that members of the classical transient receptor potential channel family (TRPC) are involved in chemotaxis. However, the regulatory role of TRPC channels in chemoattractant receptor-mediated signaling has not yet been clarified in detail. In this study, we demonstrate that the TRPC6 channels play a pronounced role in CXCR2-mediated intermediary chemotaxis, whereas N-formyl-methionine-leucine-phenylalanine receptor–mediated end-target chemotaxis is TRPC6 independent. The knockout of TRPC6 channels in murine neutrophils led to a strongly impaired intermediary chemotaxis after CXCR2 activation which is not further reinforced by CXCR2, PI3K, or p38 MAPK inhibition. Furthermore, CXCR2-mediated Ca^{2+} influx but not Ca^{2+} store release was attenuated in TRPC6^−/− neutrophils. We demonstrate that the TRPC6 deficiency affected phosphorylation of AKT and MAPK downstream of CXCR2 receptor activation and led to altered remodeling of actin. The relevance of this TRPC6-defending defect in neutrophil chemotaxis is underscored by our in vivo findings. A nonseptic peritoneal inflammation revealed an attenuated recruitment of neutrophils in the peritoneal cavity of TRPC6^−/− mice. In summary, this paper defines a specific role of TRPC6 channels in CXCR2-induced intermediary chemotaxis. In particular, TRPC6-mediated supply of calcium appears to be critical for activation of downstream signaling components. The Journal of Immunology, 2013, 190: 5496–5505.

Being part of the innate immune system, neutrophils play a crucial role in the first host defense. During an inflammatory process neutrophils are recruited from the blood stream to the origin of inflammation. Initially, neutrophils are captured by adhesion molecules like E- and P-selectins that are expressed at the cell surface of endothelial cells after activation with proinflammatory cytokines like IL-1 and TNF-α (1, 2). The initial adhesion of neutrophils is followed by rolling and tight adhesion after activation by chemokines like IL-8 (for review see Ref. 3). This enables intravascular crawling and diapedesis of the neutrophils. After leaving the blood vessels, neutrophils are guided by chemoattractants to the site of inflammation. Depending on their origin chemoattractants can be classified in pathogen-derived end-target chemoattractants (e.g. fMLF or complement factor C5a) and host-derived intermediary chemoattractants (e.g. keratinocyte-derived cytokine [KC] or IL-8) (4). End-target chemoattractant signaling predominantly occurs via stimulation of the p38 MAPK, whereas intermediary chemoattractant signaling uses the PI3K/Akt pathway (4, 5).

Chemotaxis requires an “engine mechanism” for migration that underlies protrusion of the cell front and retraction of the rear end. In addition, cells need a “compass mechanism” for orientation in a chemotactic gradient. Ca^{2+} signaling is involved in both mechanisms. In many migrating cells including immune cells, a front-to-rear gradient with an increasing intracellular Ca^{2+} concentration toward the rear end has been described previously (6). The increased Ca^{2+} concentration at the rear end is related to myosin II contraction and calpain-mediated cleavage of focal adhesions resulting in the retraction of the uropod (7–9). Superimposed on the global front-to-rear gradient of the cytosolic Ca^{2+} concentration local Ca^{2+} microdomains at the cell front were detected. Microdomains of increased Ca^{2+} at the cell front in interaction with PI3K and Rac activity were proposed to be crucial for cell polarization and directed movement (10, 11). Hillson and Hallett (12) could detect similar Ca^{2+} microevents after chemokinetic stimulation of human neutrophils. It is well established that these intracellular Ca^{2+} signals are reinforced or triggered by the activation of G protein–coupled chemoattractant receptors (13, 14). However, so far, the molecular identity of involved Ca^{2+} channels and their functional significance in neutrophil chemotaxis are not yet well understood.

Recent evidence indicated that members of the family of canonical or classical transient receptor potential (TRPC) channels are attractive candidates to fulfill this task. Activation of TRPC channels via G protein–coupled receptors and phospholipase C (PLC) can occur directly via diacylglycerol (DAG) (receptor operated calcium entry [ROCE]) as described for the TRPC3/6/7
subfamily (for review see Ref. 15). Store-operated calcium entry, however, is mediated by STIM and Orai proteins via inositol 1,4,5-trisphosphate–mediated depletion of intracellular Ca\(^{2+}\) stores probably in concert with TRPC channels (for review see Ref. 16). TRPC6 predominantly regulates ROC1-mediated Ca\(^{2+}\) entry (17, 18). There has been increasing evidence in the past years that TRPC channels are involved in directed cell migration (19–23). TRPC6 channels have been shown to be related to regulation of actin dynamics during podocyte migration (24), cross-regulation of TRPC5 in migration of endothelial cells (25) and MIP-2–induced migration and actin dynamics of murine neutrophils (21). However, so far it is not known whether TRPC6 channels are involved in neutrophil chemotaxis and whether TRPC6 channels can be assigned to end-target or intermediary chemotractant signaling.

Using wild-type (WT) and TRPC6-deficient (TRPC6\(^{-/-}\)) neutrophils, we show that TRPC6 channels play a crucial role in CXCR2-mediated intermediary chemotaxis, whereas they are not required for IMLF-mediated end-target chemotaxis. Consequently, less neutrophils are recruited into the peritoneal cavity of TRPC6\(^{-/-}\) mice in a model of a nonseptic peritonitis. Collectively, our data indicate that TRPC6 channels may be a therapeutic target for inflammatory diseases such as asthma that are driven by intermediary chemotractants.

**Materials and Methods**

**Animals**

For all experiments neutrophils from 8- to 10-wk-old male/female 129Sv/C57BL/6j WT and TRPC6\(^{-/-}\) (26) mice were used. Only cells from 129Sv/C57BL/6j littermates were analyzed. Experimental protocols were approved by the local committee for animal care.

**Reagents Abs and inhibitors**

Fibronectin, fMLF, casein, Histopaque 1077, and Histopaque 1119 were purchased from Sigma-Aldrich (Steinheim, Germany). RPMI 1640 medium was obtained from Biochrom (Berlin, Germany), DMEM was purchased from Invitrogen (Darmstadt, Germany), and HBSS as well as PBS were purchased from PAA (Pasching, Austria). The CXC2R antagonist SB225002, the platelet-activating factor receptor (PAF) antagonist ABT-491, the PI3K inhibitor LY 294002 and the p38 MAPK inhibitor SKF-8602 were obtained from Calbiochem (Gibbstown, NJ). The anti-β-actin Ab was purchased from Sigma-Aldrich, the anti-GAPDH Ab from Dianova (Hamburg, Germany), and the anti-CXCR2 Ab from Novus Biologicals (Littleton, CO), Oregon Green 488 phalloidin was provided from Invitrogen, and the anti–phospho-Akt Ab as well as the anti-p38 MAPK Ab were obtained from Cell Signaling Technology (Danvers, MA).

**Cell culture**

Murine myelocytic leukemia (WEHI-3B) cells were cultivated in bicarbonate-buffered DMEM containing 4 mM \(\text{L-glutamine, 10}\% \text{FCS (Invitrogen)}\). 100 U/ml penicillin and 100 \(\mu\)g/ml streptomycin (Biochrom, Berlin, Germany) in a 37°C humidified atmosphere of 5% \(\text{CO}_2\). As a source growth factors WEHI-3B–conditioned medium is used to differentiate bone marrow neutrophils (27, 28). For production of WEHI-3B–conditioned medium cells were cultivated until reaching confluence. After 4 additional days, the supernatant was collected, cells were pelleted (1300 rpm, 15 min), and the supernatant was sterile filtrated. Aliquots were frozen and stored for later use.

**Isolation of murine neutrophils**

Femur and tibia of 8- to 10-wk old mice were removed and bone marrow was flushed with Ca\(^{2+}\)/Mg\(^{2+}\)-free HBSS (HBSS\(^{-/-}\)) containing 25 mM HEPES and 10% FCS. Larger bone marrow chunks were separated using a plastic pipette and a 70-μm mesh. Cells were pelleted (4°C, 1000 rpm, 10 min), resuspended in 1 ml HBSS\(^{-/-}\) and added on top of a Histopaque 1077/Histopaque 1119 gradient. After centrifugation (1800 rpm, 30 min) the polymorphonuclear neutrophils (PMNs) containing layer was separated, washed twice (4°C, 1000 rpm, 10 min) with HBSS\(^{-/-}\) (+25 mM HEPES and 10% FCS), and neutrophils were cultivated in suspension for 16 h in RPMI 1640 medium supplemented with 10% WEHI-3B–conditioned medium, 10% heat-inactivated FCS (Invitrogen), 100 U/ml penicillin, and 100 \(\mu\)g/ml streptomycin in a 37°C humidified atmosphere of 5% \(\text{CO}_2\).

**Nonseptic peritonitis assays**

A nonseptic peritonitis was induced by injecting 1 ml of a 9% casein (Sigma-Aldrich, Steinheim, Germany) solution in PBS into the peritoneal cavity of 10- to 12-wk-old male C57BL/6j mice. After 5 h, 5 ml sterile PBS was injected into the peritoneal cavity. The peritoneal exudates were collected through a short cut and cell count was quantified with a CASY TT cell counter (Roche, Mannheim, Germany). Moreover, the percentage of leukocytes in the peritoneal exudates was determined via Hemacolor staining (Merck, Darmstadt, Germany).

**Preparation of chemokine mixture**

A nonseptic peritonitis was induced in mice as described above. Peritoneal exudates were collected after 5 h and cells were pelleted (1500 rpm, 10 min) and discarded. The protein concentration of the peritonitis supernatant was determined with the Pierce BCA Protein Assay Kit (Thermo Scientific, Rockford, IL) and adjusted to 4.5 mg/ml with HBSS. Aliquots of this chemokine-mixture were frozen and stored for later experiments.

**In vitro three-dimensional chemotaxis assays**

Neutrophils from overnight suspension cultures were pelleted (4°C, 1000 rpm, 10 min), resuspended in RPMI 1640 containing 25 mM HEPES and stored at 4°C until use. Chemotaxis experiments were performed in fibronectin-coated (1 \(\mu\)g/cm\(^2\), Sigma-Aldrich, Steinheim, Germany) chemotaxis chambers (ibi, Martinsried, Germany). Cells were seeded in a three-dimensional collagen I (2.1 mg/ml [pH 7.4]; BD Biosciences, Heidelberg, Germany) matrix in HBSS. A chemokine gradient was established by supplementing HBSS with chemokine-mixture (final concentration 4.5 mg/ml) plus 100 μg/ml penatblue (Chroma, Münster, Germany), KC (final concentration 0.38 μM) plus 100 μg/ml penatblue or with fMLF (final concentration 1 μM) plus 100 μg/ml penatblue. When applicable the experimental solutions were supplemented with the following blockers (final concentrations in parenthesis): CXCR2 blocker SB225002 (500 nM), PAFR blocker ABT-491 (50 μM), PI3K inhibitor LY 294002 (10 μM), p38 MAPK inhibitor SB203580 (1 μM). Notably, the concentration of the blockers was uniform in the chemotaxis chambers.

Cell migration was recorded in 5-s intervals for 30 min at 37°C using video cameras (models XC-ST70CE and XC-77CE, Hamamatsu, Japan) and PC-vision frame grabber boards (Hamamatsu, Herrsching, Germany). Acquisition of image stacks was controlled by HiPic video cameras (models XC-ST70CE and XC-77CE, Hamamatsu/Sony, Herrsching, Germany). The tracking allowed the calculation of parameters such as migratory velocity (micrometers per minute) and translocation (micrometers) by using self-made JAVA programs and the National Institutes of Health ImageJ software (http://rsb.info.nih.gov/ij/) (29). Migration was defined as the movement of the cell center per time unit, the velocity was calculated applying a three point difference quotient. Translocation was determined as the distance between the cells’ positions at the start and the end of the experiment. The chemotaxis index was defined as a quotient of the translocation in the direction of the chemokine gradient and the total distance covered during the course of the experiment.

**Intracellular calcium measurements**

Neutrophils from overnight suspension cultures were pelleted (4°C, 1000 rpm, 10 min), resuspended in RPMI 1640 containing 25 mM HEPES and stored at 4°C until use. Ca\(^{2+}\) measurements were performed in fibronectin coated (1 \(\mu\)g/cm\(^2\)) μ-slide 1 chambers (ibi, Martinsried, Germany). Cells were preincubated for 20 min with RPMI 1640 containing 25 mM HEPES and 3 μM of the Ca\(^{2+}\) dye Fura-2-AM (Calbiochem) at room temperature. After dye loading cells were seeded into μslide for 10 min at 37°C and was washed finally with 1 ml Ringer solution (122.5 mM NaCl, 5.4 mM KCl, 1.2 mM CaCl\(_2\), 0.8 mM MgCl\(_2\), 5.5 mM \(\text{Na}_2\)HPO\(_4\), 5.5 mM \(\text{Na}_2\)HPO\(_4\), 1.2 mM CaCl\(_2\), 0.8 mM MgCl\(_2\), 5.5 mM \(\text{Na}_2\)HPO\(_4\), 5.5 mM \(\text{Na}_2\)HPO\(_4\)) and 0.1 mM HEPES [pH 7.4]) or Ca\(^{2+}\) free Ringer solution (122.5 mM NaCl, KCl, 5 mM EGTA, 0.8 mM MgCl\(_2\), 5.5 mM \(\text{Na}_2\)HPO\(_4\), 5.5 mM \(\text{Na}_2\)HPO\(_4\)) and 0.1 mM HEPES [pH 7.4]). Experiments were carried out at room temperature. Excitation wavelength alternated between 340 and 380 nm, and the fluorescence emission was recorded at 500 nm. Images were acquired in 5-s intervals. Maximum fluorescence, camera and data acquisition were controlled by MetaMorph software (Visitron Systems, Puchheim, Germany). Fluorescence intensity was measured over the whole cell area and was corrected for background fluorescence. During measurements, a 5-min control period with Ringer
solution or Ca\(^{2+}\) free-Ringer solution was followed by 10 min stimulation with 1 \(\mu\)M fMLF, 0.13 \(\mu\)M KC, or 1.125 mg/ml chemokine mixture. At the end of each experiment, the measurements were calibrated by applying 2 \(\mu\)M ionomycin (MP Biomedicals, Solon, OH) containing Ringer solution with 5 mM EGTA or 5 mM Ca\(^{2+}\). Cytosolic Ca\(^{2+}\) concentration [Ca\(^{2+}\)] was calculated as described before (30) and area under the curve was calculated as integral calculated for the time period following the application of the agonist.

The manganese (Mn\(^{2+}\)) quenching method was used for indirectly measuring chemotactant-induced Ca\(^{2+}\) influx (23, 31). Mn\(^{2+}\) enters the cell via Ca\(^{2+}\) channels, binds to Fura-2 with higher affinity than Ca\(^{2+}\) and thereby decreases the Ca\(^{2+}\)-bound Fura-2 fluorescence intensity. The decrease of Ca\(^{2+}\)-bound Fura-2 fluorescence intensity is used as an indirect measure of Ca\(^{2+}\) influx. Fura-2 was excited at its isobestic point at 365 nm, where the emitted fluorescence at 500 nm is independent of changes in [Ca\(^{2+}\)]. Fura-2 loaded neutrophils were seeded into ibidi slides for 10 min at 37\(^{\circ}\)C and washed gently with 1 ml Mn\(^{2+}\) Ringer solution (122.5 mM NaCl, 5.4 mM KCl, 250 nM MnCl\(_2\), 0.8 mM MgCl\(_2\), 5.5 mM t-glucose, and 10.0 mM HEPES [pH 7.4]). Experiments were carried out at room temperature and images were acquired in 5-s intervals. During measurements, a 3-min control period with Mn\(^{2+}\) Ringer solution was followed, in the continued presence of Mn\(^{2+}\), by 15 min stimulation with 1 \(\mu\)M fMLF or 0.13 \(\mu\)M KC. Fluorescence intensity was measured over the whole-cell area and was corrected for background fluorescence. Regression analysis of fluorescence intensity over time was performed to determine the change in fluorescence quenching \(\Delta\) m (%/h) before and after chemokinetic stimulation.

**Western blotting**

Neutrophils were seeded in fibronectin-coated (1 \(\mu\)g/cm\(^{2}\)) cell culture dishes and stimulated for 1 min with the respective chemoattractant. Afterwards cells were lysed with radioimmunoprecipitation assay lysis buffer containing: 25 mM Tris-HCl (pH 7.6), 150 mM NaCl, 1% Nonidet P-40, 0.1% SDS, 0.5% sodium deoxycholate, protease inhibitor (Complete Mini; Roche), and phosphatase inhibitor (Phos Stop; Roche). The protein concentration of the lysates was determined with the Pierce Bicinchoninic Acid Protein Assay Kit (Thermo Scientific). Equal amount of proteins were transferred on nitrocellulose membranes (PROTRAN; Schleicher Schuell, Dassel, Germany). After blocking unspecific binding sites (5% fat-free milk and 0.5% Tween in PBS) proteins of interest were detected overnight using the following primary Ab's in the described blocking solution: anti-CXCR2 Ab (1:100), anti–phospho-Akt Ab (1:500) and anti–phospho-p38 MAPK Ab (1:1000). After washing three times for 10 min (PBS, 0.5% Tween), blots were incubated for 1 h with a peroxidase-conjugated secondary Ab with subsequent washing three times 10 min with PBS/0.5% Tween. Blots were developed using a chemiluminescence kit (SuperSignal West Femto, Pierce Biotechnology, Rockford, IL). Autoradiography was carried out with ChemiDoc XRS gel documentation system and Quantity One analysis software (Bio-Rad Laboratories, Hercules, CA). To control the loading of equal amounts of proteins, membranes were stripped after primary detection and subsequently probed with a monoclonal anti-\(\beta\)-actin (1:10,000) or anti-GAPDH (1:1,000) Ab. Western blots were repeated three times and were analyzed with densitometry. The protein amount was corrected by the amount of housekeeping genes and subsequently band intensity of TRPC6\(^{−/−}\) lysates was compared by referring them to the respective bands from WT lysates.

**F-actin staining**

Neutrophils were seeded on fibronectin-coated coverslips (1 \(\mu\)g/cm\(^{2}\)) for 10 min. After 40 s or 60 s stimulation with 1 \(\mu\)M fMLF or 0.13 \(\mu\)M KC, cells were fixed with 3.5% paraformaldehyde in PBS and permeabilized with 0.1% Triton X-100 in TBS. Unspecific binding sites were blocked with 3% BSA in PBS. Cells were incubated with Oregon Green 488–conjugated phalloidin for 45 min, and samples were covered with mounting medium (Dako, Carpinteria, CA). Images were taken under widefield fluorescence conditions using an inverted microscope (Axiovert 200; Zeiss, Jena, Germany) with a 100 \(\times\) 1.45 objective lens and a digital camera (model 9.0, RT-SE-Spot; Visirion Systems, Puchheim, Germany). Image acquisition was controlled by MetaVue software (Visirion Systems). Fluorescence intensity was measured over the whole cell area while values were corrected for background fluorescence. Fluorescence intensity was calculated in percentage of the mean intensity of unstimulated WT or TRPC6\(^{−/−}\) cells.

**Statistical analysis**

All experiments were repeated at least three times. Values are reported as mean values ± SEM. All data were tested for normality before performing any statistical analysis. For normally distributed data, the Student t test was used; otherwise, the Kruskal–Wallis or Mann–Whitney U test was used for statistical analyses. Differences between experimental groups reaching \(p \leq 0.05\) were considered significant.

**Supplemental material**

Supplemental Videos 1–4 are time-lapse videos showing chemokine mixture or fMLF-induced chemotaxis of WT or TRPC6\(^{−/−}\) neutrophils. Cells were seeded in chemotaxis slides in a three-dimensional collagen I matrix (see in vitro three-dimensional chemotaxis assays).

**Results**

**Loss of TRPC6 channels decreases immune response in vivo**

To confirm the physiological relevance of the loss of TRPC6 channels, we investigated neutrophil recruitment during an inflammation in vivo. We induced a nonseptic peritonitis by injecting a 9% casein solution into the peritoneum of WT and TRPC6\(^{−/−}\)-deficient mice. After 5 h, the total number of invaded cells and the percentage of neutrophils were quantified. TRPC6\(^{−/−}\) mice showed a reduced number of invaded neutrophils (Fig. 1). The total number of invaded cells was diminished by 33% from 25.3 \(\times\) 10\(^6\) ± 4.1 (WT) to 17.0 \(\times\) 10\(^6\) ± 2.8 (TRPC6\(^{−/−}\)). The number of invaded neutrophils was reduced by 38% from 13.6 \(\times\) 10\(^6\) ± 1.8 (WT) to 8.46 \(\times\) 10\(^6\) ± 1.3 (TRPC6\(^{−/−}\)). Thus, on the basis of the number of invaded neutrophils, TRPC6\(^{−/−}\) mice develop a diminished peritoneal inflammation after casein treatment.

**Intermediary chemotaxis depends on TRPC6 channels**

For chemotaxis experiments, neutrophils were seeded in a three-dimensional collagen gel into ibidi chemotaxis slides. To mimic the physiological conditions encountered by neutrophils in vivo, we used a mixture of intermediary chemoattractants. For this purpose, we induced a nonseptic peritonitis with casein and isolated the cell-free supernatant of the peritoneal exudates from WT mice. Chemotaxis toward this intermediary chemokine mixture was strongly impaired in TRPC6\(^{−/−}\) neutrophils (Fig. 2A, Supplemental Videos 1, 2). Although the velocity of TRPC6\(^{−/−}\) neutrophils was almost identical as that of WT cells (10.3 ± 0.3 versus 11.6 ± 0.3 \(\mu\)m/min), the translocation and chemotaxis index was strongly reduced. Translocation decreased from 170.7 ± 7.0 \(\mu\)m (WT) to 106 ± 6.2 \(\mu\)m (TRPC6\(^{−/−}\)), and the chemotaxis index was reduced by 50% from 0.44 ± 0.01 (WT) to 0.22 ± 0.02 (TRPC6\(^{−/−}\)). These findings indicate that TRPC6 channels are predominantly involved in the “compass mechanism” of neutrophils in a gradient of intermediary chemokines. In contrast, their impact on the “migration engine” appears only marginal.

**FIGURE 1.** Inflammatory recruitment of neutrophils is impaired in TRPC6\(^{−/−}\) mice. Mean number of total cells (total) and neutrophils (PMNs) that were isolated from the peritoneal cavity of mice 5 h after i.p. casein injection (\(n = 7\) mice/group). Values are reported as mean values ± SEM. *\(p < 0.05\).
To analyze which chemokine receptors could be involved in the signaling events mediated by the ex vivo chemokine mixture, we inhibited two major intermediary chemokine receptors pharmacologically. CXCR2 binds a wide range of chemokines like KC, MIP-2, and LIX (32–35) and is classified as the most important receptor for CXC-motif chemokines in mice. To inhibit CXCR2-mediated chemotaxis, we used SB225002 (36, 37). Furthermore, ABT-491 was used to block PAFR-mediated chemotaxis (38, 39).

The CXCR2 inhibitor SB225002 reduced chemotaxis of WT neutrophils to the same extent as the lack of TRPC6 channels (Fig. 2A). When WT neutrophils were treated with SB225002, velocity was decreased by 16% to 9.7 ± 0.3 μm/min (Fig. 2B). Translocation and chemotaxis index were reduced by 45% to 94.2 ± 6.8 μm and 58% to 0.18 ± 0.03, respectively (Fig. 2C, 2D). Notably, CXCR2 blockade elicited absolutely no additional effect in TRPC6−/− neutrophils. Blocking the PAFR with ABT-491 produced similar results. PAFR blockade had a strong effect on WT neutrophils, whereas TRPC6−/− neutrophils were hardly affected. Velocity of WT cells was reduced by 21% to 9.4 ± 0.3 μm/min, translocation was decreased by 31% to 117.9 ± 14.4 μm, and chemotaxis index was diminished by 57% to 0.33 ± 0.04. In TRPC6−/− neutrophils, ABT-491 only slightly reduced the velocity by 11% to 9.2 ± 0.4 μm/min, whereas translocation and chemotaxis index were not affected.

These data indicate that ligands for both chemoattractant receptors, the CXCR2 and PAFR, are important components of the ex vivo chemokine mixture used in our experiments. Moreover, these findings suggest that TRPC6 channels are crucial for both CXCR2- and PAFR-mediated chemotaxis.

**CXCR2-mediated chemotaxis requires TRPC6 channels**

To further substantiate our hypothesis that TRPC6 channels are required for CXCR2-mediated chemotaxis, we substituted the chemokine mixture with murine KC, a ligand of CXCR2. KC is supposed to be the murine equivalent of the human Gro-α (CXCL1) (32). For three-dimensional chemotaxis experiments, we used 0.38 μM KC. As shown in Fig. 3, KC is a very powerful chemoattractant for WT neutrophils. Importantly, chemotaxis of TRPC6−/− neutrophils toward KC was even more strongly impaired than chemotaxis toward the chemokine mixture (reduction of the chemotaxis index by 80% from 0.45 ± 0.02 in WT cells to 0.09 ± 0.03 in TRPC6−/− cells) (Fig. 3D). As in the previous experiments, velocity was hardly affected (reduction of 8% from 15.8 ± 0.4 to 14.5 ± 0.4 μm/min), whereas translocation was also markedly diminished (reduction by 42% from 235.7 ± 14.4 to 136.9 ± 10.7 μm). The dramatic phenotype of TRPC6−/− neutrophils was mimicked by inhibiting CXCR2 with SB225002. In the presence of SB225002, chemotaxis of WT cells toward KC was as inefficient as that of TRPC6−/− neutrophils without inhibition of CXCR2 (reduction by 72% from 0.45 ± 0.02 to 0.12 ± 0.03) (Fig. 3D). Moreover, SB225002 reduced the velocity of WT cells by 20% to 12.6 ± 0.4 μm/min and translocation by 57% to 102.0 ± 9.0 μm. In TRPC6−/− neutrophils, CXCR2 blockade with SB225002 elicited only small additional effects. Blockade of CXCR2 in TRPC6−/− cells reduced the chemotaxis index by 91% from 0.45 ± 0.02 (WT) to 0.04 ± 0.02 (SB225002 treated TRPC6−/−) with TRPC6 knockout accounting for 80% of this inhibition (see above). Moreover, velocity was reduced by 33%
from 15.8 ± 0.4 μm/min (WT) to 10.6 ± 0.3 (SB225002-treated TRPC6−/−), and translocation was diminished by 72% from 235.7 ± 14.4 μm (WT) to 66.5 ± 5.9 μm (SB225002-treated TRPC6−/−). Thus, the importance of TRPC6 channels in CXCR2-mediated chemotaxis toward the intermediary chemokine KC is further underlined by the observation that CXCR2 inhibition of TRPC6−/− cells elicited hardly any additive effect.

**fMLF-mediated end-target chemotaxis is TRPC6 independent**

To analyze the chemotaxis toward an end-target chemoattractant, we used 1 μM of the bacterially derived fMLF. In three-dimentional chemotaxis experiments both WT and TRPC6−/− neutrophils migrated in a directed fashion within the fMLF gradients. No obvious difference between WT and TRPC6−/− neutrophils could be seen in velocity, translocation, and chemotaxis index (Fig. 4). Fig. 4A shows individual trajectories of WT and TRPC6−/− neutrophils in fMLF gradients with similar patterns for both cell types. Fig. 4B–D display statistical evaluations. WT and TRPC6−/− neutrophils did not differ; they covered ~150 μm within 30 min, migrated at a rate ~13 μm/min, and their chemotaxis index was ~0.32.

**Loss of TRPC6 effects CXCR2-mediated PI3K and p38 MAPK activation**

To clarify the question of how the loss of TRPC6 channels influences CXCR2-mediated signaling, we applied inhibitors for two important downstream targets of CXCR2: PI3K and p38 MAPK. LY 294002 was used for PI3K inhibition, and SKF-86002 was applied for blockade of p38 MAPK. Inhibition of PI3K had a distinct effect on KC-mediated chemotaxis and translocation of WT neutrophils (Fig. 5A, 5C, 5D). Chemotaxis was reduced by 51% from 0.45 ± 0.02 to 0.22 ± 0.02, and translocation was diminished by 45% from 235.7 ± 14.4 to 128.7 ± 8.3. Velocity of WT neutrophils was only hardly affected by PI3K inhibition (reduction by 14% 15.8 ± 0.4 to 13.6 ± 0.5 μm/min) (Fig. 5B). In TRPC6−/− neutrophils, inhibition of PI3K with LY 294002 caused only minor additional effects. Blockade of PI3K in TRPC6−/− cells induced no significant additional effect on chemotaxis. Chemotaxis index of TRPC6−/− cells was reduced by 64% from 0.45 ± 0.02 (WT) to 0.16 ± 0.02 (LY 294002–treated TRPC6−/−). Furthermore, translocation was diminished by 52% from 235.7 ± 14.4 μm (WT) to 111.1 ± 8.3 μm (LY 294002–treated TRPC6−/−), and velocity was reduced by 20% from 15.8 ± 0.4 μm/min (WT) to 12.6 ± 0.6 (LY 294002–treated TRPC6−/−).

Blockade of p38 MAPK via SKF-86002 in WT and TRPC6−/− neutrophils caused very similar effects on chemotaxis as inhibition of PI3K (Fig. 5A–D). In WT cells, chemotaxis was reduced by 49% from 0.45 ± 0.02 to 0.23 ± 0.03, and translocation was diminished by 40% from 235.7 ± 14.4 to 141.4 ± 11.4. Velocity of WT cells was only minimally reduced by p38 MAPK inhibition (18% reduction from 15.8 ± 0.4 to 13.0 ± 0.5 μm/min). In TRPC6−/− cells, p38 MAPK inhibition was as ineffective as PI3K blockade in inducing any additional impairment of chemotaxis. The inhibition of p38 MAPK elicited a 71% reduction of chemotaxis from 0.45 ± 0.02 (WT) to 0.13 ± 0.03 (SKF-86002–treated TRPC6−/−). Moreover, translocation was diminished by 52% from 235.7 ± 14.4 μm (WT) to 113.1 ± 7.8 μm (SKF-86002–treated TRPC6−/−), and velocity was diminished by 22% from 15.8 ± 0.4 μm/min (WT) to 12.4 ± 0.5 (SKF-86002–treated TRPC6−/−). These data indicate that TRPC6 channels are required for the proper function of two components of the CXCR2.
signaling pathway, PI3K and p38 MAPK, which have a direct impact on chemotaxis of neutrophils.

This conclusion was confirmed with biochemical experiments. To this end, we compared phosphorylation of Akt and p38 MAPK via immunoblot. They are key elements of PI3K and MAPK pathways, respectively. CXCR2-mediated phosphorylation of Akt was reduced in TRPC6<sup>2/2</sup> cells after stimulation with chemokine mixture or KC (Fig. 5E, 5F). Phosphorylation of p38 MAPK was decreased in TRPC6<sup>2/2</sup> neutrophils after stimulation with chemokine mixture and increased in TRPC6<sup>2/2</sup> cells when activated with KC. Finally, we analyzed whether the attenuated response of TRPC6<sup>2/2</sup> neutrophils toward CXCR2 ligands is secondary to a reduced CXCR2 expression in TRPC6<sup>2/2</sup> cells. CXCR2 was expressed at identical levels in both WT and TRPC6<sup>2/2</sup> neutrophils (Fig. 5E).

**CXCR2-mediated Ca<sup>2+</sup> influx is reduced in TRPC6<sup>2/2</sup> neutrophils**

In the next set of experiments, we determined whether TRPC6 channels were involved in chemotactic-mediated Ca<sup>2+</sup> signaling. To this end, we measured the cytosolic Ca<sup>2+</sup> concentration of WT and TRPC6<sup>2/2</sup> neutrophils in response to 1 μM fMLF, the chemokine mixture, or 0.13 μM KC. Application of all chemotaxants led to a transient elevation of [Ca<sup>2+</sup>]<sub>i</sub>, with a fast rise and a slow decay toward baseline. These experiments are depicted in Fig. 5. The left panel displays mean [Ca<sup>2+</sup>]<sub>i</sub> over time, and the right panel represents the respective integrals calculated for the time period following the application of the agonist.

The chemokine mixture and KC elicited a transient rise of [Ca<sup>2+</sup>]<sub>i</sub> in WT and TRPC6<sup>2/2</sup> neutrophils (Fig. 6A<sub>i</sub>, 6A<sub>ii</sub>, 6B<sub>i</sub>, 6B<sub>ii</sub>). However, in TRPC6<sup>2/2</sup> neutrophils, the elevation of [Ca<sup>2+</sup>]<sub>i</sub> was attenuated. As expected from the behavior in chemotaxis experiments, 1 μM fMLF elicited the same response in WT and TRPC6<sup>2/2</sup> neutrophils (Fig. 6C<sub>i</sub>, 6C<sub>ii</sub>). Thus, the defect of TRPC6<sup>2/2</sup> neutrophils in intermediary chemotaxis is accompanied by a depression of intracellular Ca<sup>2+</sup> signaling after CXCR2 activation by its specific agonists.

To identify the source of the mobilized Ca<sup>2+</sup>, we measured the [Ca<sup>2+</sup>]<sub>i</sub> in response to 1 μM fMLF or 0.13 μM KC without Ca<sup>2+</sup> in the extracellular medium or by adding manganese to the extracellular medium. By omitting Ca<sup>2+</sup> from the extracellular medium, the mobilization of Ca<sup>2+</sup> from internal stores can be analyzed.
separately after chemoattractant receptor activation. Similar to the first set of experiments, fMLF and KC elicited a transient rise of [Ca\(^{2+}\)]\(_i\) in WT and TRPC6\(^{-/-}\) neutrophils also in the absence of extracellular Ca\(^{2+}\) (Fig. 7A, 7B). Stimulation with both chemokine agonists induced a similar response in WT and TRPC6\(^{-/-}\) neutrophils (Fig. 7A\(_i\), 7B\(_i\)). Thus, the depression in CXCR2-mediated Ca\(^{2+}\) signaling in TRPC6\(^{-/-}\) neutrophils is not based on an attenuated Ca\(^{2+}\) mobilization from intracellular stores.

Using the manganese-quenching method, we determined the role of TRPC6 in chemoattractant receptor mediated Ca\(^{2+}\) influx. The decrease of the Fura-2 fluorescence following the addition of Mn\(^{2+}\) is an indirect measure of Ca\(^{2+}\) influx Fig. 7C\(_i\) and 7D\(_i\) depict the percentage decrease of the fura-2 fluorescence intensity after chemoattractant receptor activation, and Fig. 7C\(_{ii}\) and D\(_{ii}\) describe the δ of slope Δ m (m\(_1\) – m\(_2\)) directly before (m\(_1\)) and after agonist application (m\(_2\)). KC elicited a higher quenching rate of the chemokine receptor activation, and Fig. 7C\(_{ii}\) and D\(_{ii}\) describe the percentage decrease of the fura-2 fluorescence intensity after chemokine receptor activation. Similar to the first set of experiments, fMLF and KC elicited a transient rise of [Ca\(^{2+}\)]\(_i\) in WT compared with TRPC6\(^{-/-}\) neutrophils after chemoattractant receptor activation. For this purpose, neutrophils were stimulated for 40 or 60 s with the respective chemoattractant and fixed and afterward stained with fluorescently labeled phalloidin. Unstimulated neutrophils of both genotypes showed a similar uniform distribution of F-actin staining (Fig. 8A). After stimulation with the respective chemoattractant, the cells of both genotypes developed a polarized distribution of F-actin. However, in TRPC6\(^{-/-}\) neutrophils, this polarization was less pronounced than in WT cells when they were stimulated with KC. Consequently, phalloidin staining after CXCR2 activation via KC was lower than in WT cells (Fig. 8B). In contrast, this defect in actin polymerization is not present when TRPC6\(^{-/-}\) neutrophils are stimulated with fMLF. TRPC6\(^{-/-}\) neutrophils exhibited the slightly increased fluorescence intensity of phalloidin after fMLF stimulation, which was accompanied by a slightly enhanced cell area.

**FIGURE 7.** Loss of TRPC6 reduces CXCR2-induced Ca\(^{2+}\) influx but not Ca\(^{2+}\) mobilization from internal stores. Mean [Ca\(^{2+}\)]\(_i\) response of WT and TRPC6\(^{-/-}\) neutrophils in the absence of extracellular Ca\(^{2+}\) after chemoattractant receptor activation. For this purpose, neutrophils were stimulated for 40 or 60 s with the respective chemoattractant and fixed and afterward stained with fluorescently labeled phalloidin. Unstimulated neutrophils of both genotypes showed a similar uniform distribution of F-actin staining (Fig. 8A). After stimulation with the respective chemoattractant, the cells of both genotypes developed a polarized distribution of F-actin. However, in TRPC6\(^{-/-}\) neutrophils, this polarization was less pronounced than in WT cells when they were stimulated with KC. Consequently, phalloidin staining after CXCR2 activation via KC was lower than in WT cells (Fig. 8B). In contrast, this defect in actin polymerization is not present when TRPC6\(^{-/-}\) neutrophils are stimulated with fMLF. TRPC6\(^{-/-}\) neutrophils exhibited the slightly increased fluorescence intensity of phalloidin after fMLF stimulation, which was accompanied by a slightly enhanced cell area.

**Loss of TRPC6 influences CXCR2-mediated actin polymerization**

To identify an impact of TRPC6 in chemoattractant-induced polymerization of actin, we performed fluorescence stainings of WT and TRPC6\(^{-/-}\) neutrophils after CXCR2 or N-formyl-methionine-leucine-phenylalanine receptor activation. For this purpose, neutrophils were stimulated for 40 or 60 s with the respective chemoattractant and fixed and afterward stained with fluorescently labeled phalloidin. Unstimulated neutrophils of both genotypes showed a similar uniform distribution of F-actin staining (Fig. 8A). After stimulation with the respective chemoattractant, the cells of both genotypes developed a polarized distribution of F-actin. However, in TRPC6\(^{-/-}\) neutrophils, this polarization was less pronounced than in WT cells when they were stimulated with KC. Consequently, phalloidin staining after CXCR2 activation via KC was lower than in WT cells (Fig. 8B). In contrast, this defect in actin polymerization is not present when TRPC6\(^{-/-}\) neutrophils are stimulated with fMLF. TRPC6\(^{-/-}\) neutrophils exhibited the slightly increased fluorescence intensity of phalloidin after fMLF stimulation, which was accompanied by a slightly enhanced cell area.
Discussion

Chemotaxis is based on the translation of an extracellular chemotactant signal into intracellular signaling cascades. On a cellular level, this involves the activation of G protein–coupled receptors, which leads to the activation of PI3K, MAPK, PLC, as well as Rho-GTPases and induces the reorganization of the actin cytoskeleton (for review see Refs. 40 and 41). It is generally accepted that the activation of chemotactant receptors leads to a rise of cytosolic Ca\(^{2+}\) (13, 42, 43). However, the contribution of molecularly identified Ca\(^{2+}\) transport proteins to chemotactic signaling and their physiological significance have not yet been clarified in detail. Evans and Falke (10) showed that Ca\(^{2+}\) influx is essential for actin polymerization, and PI3K activity in chemokinetically stimulated RAW macrophages and speculated about a contribution of TRPC channels. In recent years, several groups have verified the influence of different members of the TRPC channel family in chemotaxis. We could demonstrate the involvement of TRPC1 in fibroblast growth factor 2–induced chemotaxis of epithelial cells and Damann et al. (21) revealed a role of TRPC6 in neutrophil chemokinesis (23). On our way to identify the physiological role of molecularly identified Ca\(^{2+}\) channels in chemotactant receptor induced Ca\(^{2+}\) signaling, we focused on TRPC6 channels in neutrophil chemotaxis.

In this study, we demonstrated that TRPC6 channels are essential signaling components in neutrophil chemotaxis triggered by CXCR2 activation. This conclusion is based on the following observations: 1) chemotaxis of TRPC6\(^{-/-}\) neutrophils in a gradient of an ex vivo chemokine mixture is strongly impaired; 2) this defect was not further reinforced by CXCR2 blockade; 3) the CXCR2 activator KC almost completely failed to induce chemotaxis in TRPC6\(^{-/-}\) neutrophils; 4) Ca\(^{2+}\) influx in response to CXCR2 ligands is attenuated in TRPC6\(^{-/-}\) cells; and 5) TRPC6 knockout also impacts on the phosphorylation of intracellular signaling modules of CXCR2 and CXCR2-mediated actin polymerization. The physiological significance of these findings is underscored by our in vivo experiments. Using a nonseptic peritonitis model, we could show that less neutrophils emigrated into the peritoneal cavity of TRPC6\(^{-/-}\) mice. This is in line with the observations made in an allergic airway model, which revealed an attenuated recruitment of eosinophils into the alveolar space (44). Our data indicate that TRPC6 channels are not only required for CXCR2-mediated chemotaxis but also for PAFR-mediated chemotaxis. A PAFR-mediated activation of TRPC6 was shown before in human neutrophils (45). Thus, TRPC6 channel blockade could constitute a new anti-inflammatory therapeutic approach.

Importantly, our experiments clearly show a specificity of TRPC6 channels in chemotaxis. First, TRPC6 channels are not involved in signaling of all chemotactants. They play no role at all in chemotaxis toward the end-target chemotactant fMLF. Moreover, TRPC6 channels almost exclusively affect the “compass mechanism” of chemotacting neutrophils. The “engine mechanism” appears to be unaffected because TRPC6\(^{-/-}\) neutrophils migrate almost with the identical speed as WT cells. TRPC6 deficiency leads to impaired Ca\(^{2+}\) signaling after stimulation of the neutrophils with the chemokine mixture or single CXCR2 activation with KC. The Ca\(^{2+}\) measurements in the absence of extracellular Ca\(^{2+}\) and the Mn\(^{2+}\) quench experiments indicate that the remaining increase in [Ca\(^{2+}\)]\(_i\) in TRPC6-deficient cells may be induced by Ca\(^{2+}\) release from intracellular stores and by store-operated calcium entry through recently described STIM and Orai proteins in PMNs (46, 47), whereas ROCE through TRPC6 is lost. Expectedly, the rise of the [Ca\(^{2+}\)]\(_i\) was not altered in TRPC6\(^{-/-}\) neutrophils after stimulation with fMLF and in the absence of extracellular Ca\(^{2+}\). The question remains how TRPC6 channels exclusively control the compass-mechanism in CXCR2-mediated chemotaxis. A hypothetical organization of all signal transduction components in large signaling complexes remains an intriguing possibility. DAG is the known endogenous activator of TRPC6 (17, 48). DAG is a product of PLC-mediated hydrolysis of phosphatidylinositol 4,5-bisphosphate with PLC being activated by G protein–coupled receptors like CXCR2 (49, 50). Thus, CXCR2-mediated ROCE via TRPC6 channels is likely to be induced via DAG generated by PLC (Fig. 9). PI3K/Akt signaling is reported to play a central role in chemotaxis toward intermediary chemotactants, whereas p38 MAPK signaling plays a subordinate role therein (4). We could support this hypothesis with our chemotaxis data. Blocking of PI3K or p38 MAPK affected chemotaxis of WT neutrophils, whereas there was no additive effect on chemotaxis in TRPC6\(^{-/-}\) cells. The TRPC6\(^{-/-}\)-dependent chemotaxis defect was accompanied by impaired Ca\(^{2+}\) signaling, reduced Akt phosphorylation, and diminished F-actin formation. This would be consistent with observations made in LPS-stimulated RAW macrophages. In these cells, Evans and Falke (10) described a Ca\(^{2+}\) dependence for maintaining PI3K activity at the leading edge. The loss of Ca\(^{2+}\) influx led to reduced F-actin dynamics in migrating cells (10, 21), which is supported by our observation that the loss of TRPC6 leads to a reduced F-actin formation after CXCR2 stimulation. Although the PI3K signaling element Akt is known to regulate actin dynamics via cofilin and girdin (51), no direct Ca\(^{2+}\) dependence is known for activation of PI3K. Thus, other regulators of actin dynamics such as Rac and Cdc42 are likely to be involved (52). Both are known to be tightly regulated by guanine-nucleotide-exchange factors, which are activated by PI3K-mediated phosphatidylinositol (3,4,5)-trisphosphate production and via Ca\(^{2+}\) (53–55). Furthermore, Rac activation and actin polymerization stimulates PI3K-mediated phosphatidylinositol (3,4,5)-trisphosphate production, which loops PI3K and Rac activation in a positive way (56–59). Thus, a reduced Rac activation based on diminished Ca\(^{2+}\) mobilization after CXCR2 stimulation in TRPC6\(^{-/-}\) neutrophils could disrupt the positive feedback loop involving PI3K and Rac. This would result in an incomplete amplification of chemotactant receptor–mediated signaling cascades and thereby cause a defect in chemotaxis.
In conclusion, our data show a receptor-specific role for TRPC6 in neutrophil chemotaxis. CXCR2-mediated intermediary chemotaxis is tightly regulated by TRPC6 channels, whereas 1MLF-mediated end-target chemotaxis is unaffected in TRPC6-deficient neutrophils. We thereby identified a second TRP channel that is intimately linked to a specific chemooatractive receptor pathway. Previously, TRPM2 channels could be assigned to 1MLFR signaling in neutrophils (60). We propose that TRPC6 channels support the “compass mechanism” of chemotactizing neutrophils by providing $Ca^{2+}$ to sustain a positive feedback loop involving PISK and Rac signaling. Our study shows that the well-directed pharmacological inhibition of single chemooatractive receptor–mediated signaling components could constitute potential targets to regulate specific cells of the immune system without complete downregulation of their function. $Ca^{2+}$ permeable channels like TRPC6 could thereby represent a therapeutic target for the treatment of inflammatory diseases.

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Disclosures

The authors have no financial conflicts of interest.

References

**Supplemental legends**

**Video 1. Chemokine-cocktail induced chemotaxis of WT neutrophils.** 30 min. movie of WT neutrophils in a gradient of the chemokine-cocktail. Highest concentration of the chemokine-cocktail is on the top of the movie. Pictures were taken every 5 sec., frame rate is 90 fps.

**Video 2. Chemokine-cocktail induced chemotaxis of TRPC6<sup>-/-</sup> neutrophils.** 30 min. movie of TRPC6<sup>-/-</sup> neutrophils in a gradient of the chemokine-cocktail. Highest concentration of the chemokine-cocktail is on the top of the movie. Pictures were taken every 5 sec., frame rate is 90 fps.

**Video 3. fMLP induced chemotaxis of WT neutrophils.** 30 min. movie of WT neutrophils in a gradient of the chemokine-cocktail. Highest concentration of the chemokine-cocktail is on the top of the movie. Pictures were taken every 5 sec., frame rate is 90 fps.

**Video 4. fMLP induced chemotaxis of TRPC6<sup>-/-</sup> neutrophils.** 30 min. movie of TRPC6<sup>-/-</sup> neutrophils in a gradient of the chemokine-cocktail. Highest concentration of the chemokine-cocktail is on the top of the movie. Pictures were taken every 5 sec., frame rate is 90 fps.