Regulation of CXCR4 conformation by the small GTPase Rac1: implications for HIV infection

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Short title: Rac1 regulates CXCR4 conformation
Abstract

The chemokine receptor CXCR4 is a critical regulator of cell migration and serves as a co-receptor for HIV-1. The chemokine Stromal Cell Derived Factor-1, also known as CXCL12, binds to CXCR4 and exerts its biological functions partly through the small guanosine triphosphate hydrolase (GTPase) Rac1 (ras-related C3 botulinum toxin substrate 1). We show in different cell types including CD34+ hematopoietic stem and progenitor cells that inhibition of Rac1 causes a reversible conformational change in CXCR4, but not in the related receptors CXCR7 or CCR5. Biochemical experiments showed that Rac1 associates with CXCR4. The conformational change of CXCR4 upon Rac1 inhibition blocked receptor internalization and impaired CXCL12-induced Gαi protein activation. Importantly, we found that the conformation adopted by CXCR4 after Rac1 inhibition prevents HIV-1 infection of both the U87-CD4-CXCR4 cell line and of primary peripheral blood mononuclear cells. In conclusion, our data show that Rac1 activity is required to maintain CXCR4 in the responsive conformation that allows receptor signaling and facilitates HIV-1 infection. This implies that Rac1 positively regulates CXCR4 function and identifies the Rac1-CXCR4 axis as a new target for preventing HIV-1 infection.
Introduction

The seven transmembrane-spanning G\(_i\) protein-coupled chemokine receptor CXCR4 and its ligand CXCL12 are involved in the regulation of vital processes involving cellular migration, such as angiogenesis, neuronal development, hematopoietic stem cell (HSC) and immune cell trafficking. CXCL12 or CXCR4 deficiency in mice leads to embryonic lethality, underscoring the importance of this chemokine/receptor pair\(^1\).\(^2\). CXCR4 is also implicated in pathological conditions, including tumor cell proliferation and metastasis\(^3\), and, notably, serves as a co-receptor for T-cell tropic HIV-1 strains\(^4\).

Ligand binding to CXCR4 induces a conformational change of the receptor, which then can act as a guanine nucleotide exchange factor for the heterotrimeric G\(_i\) protein, facilitating the exchange of guanosine diphosphate (GDP) for guanosine triphosphate (GTP) on the G\(_i\) subunit\(^5\). These events initiate the activation of multiple signaling pathways leading to the generation of a chemotactic response towards a CXCL12 gradient in various types of cells\(^6\).

Cellular motility, mediated by CXCR4, relies on the activation and signaling by the Rho family of GTPases, which control cytoskeletal dynamics, providing both protrusive force at the front and contraction at the rear of the cell. The best known members of the Rho family are RhoA (Ras homologue gene family member A), that stimulates myosin-based contractility, and CDC42 (cell division cycle 42) and Rac1 (ras-related C3 botulinum toxin substrate 1), that induce actin polymerization and membrane protrusions at the leading edge\(^7\). Rho GTPases are thus at the center of actin regulation in migrating cells and act as molecular switches, cycling between an active GTP-bound state and an inactive GDP-bound state. This cycle is regulated by guanine nucleotide exchange factors and GTPase activating proteins\(^8\).

The initiation of directional migration in response to CXCL12 is dependent on the level of cell surface expression of the chemokine receptor CXCR4, as well as the cells’ ability to
properly initiate signaling upon ligand binding. Similarly, T-cell tropic HIV-1 infection depends on the surface expression of CXCR4. Initial binding of the viral envelope glycoprotein 120 (gp120) is mediated by CD4. This step induces a structural rearrangement of gp120, which exposes a binding site for CXCR4. Subsequently, gp120 binding to CXCR4 induces viral fusion and entry into host cells. In vitro studies have shown that gp120 binding triggers CXCR4 signaling and presumably creates an intracellular environment that facilitates post-entry HIV-1 infection events.

It is known that cells display a heterogeneous set of CXCR4 conformations that have been associated with different Gαi activation patterns. Moreover, certain conformations generated inactive receptors. Thus, the conformation adopted by CXCR4 determines ligand binding and/or signaling capacity and possibly affects co-receptor function.

The molecular mechanisms regulating CXCR4 conformation at steady state conditions are unknown. Here, we demonstrate that Rac1 is specifically involved in regulating the conformation of CXCR4 in several human cell types, including CD34+ hematopoietic stem and progenitor cells (HSPCs), thereby controlling signaling efficiency of the receptor. Furthermore, the conformation adopted by CXCR4 after Rac1 inhibition blocked HIV-1 infection, most probably by interfering with virus binding and subsequent entry into host cells. Our findings are the first to describe the involvement of a GTPase in the regulation of the CXCR4 responsive conformation, which represents a previously unrecognized role for Rac1 in Gαi protein-coupled receptor homeostasis.
Materials and methods

Dominant negative peptides for and pharmacological inhibition of Rac1

Cell permeable peptides containing the amino acid sequence of the C-terminal region of Rac1 (CPPPVKKKRK) and CDC42 (LEPPEPKKSRR) fused to a protein transduction domain (PTD) or a control peptide that only encodes the PTD (control) were produced by F-moc protein synthesis (Department of Peptide Synthesis, Netherlands Cancer Institute, Amsterdam, The Netherlands). Rac1 C-terminal mutant peptides were produced by replacing the three prolines, i.e. aa 179-181 (CAAVKKRK), or the RKR sequence, i.e. aa 185-187 (CPPPVKKAAK), by alanine residues (Figure 1).

Cells were harvested in Iscove's Modified Dulbecco's Medium (IMDM; Lonza, Basel, Switzerland) containing 0.25% w/v bovine serum albumin (BSA; Sigma-Aldrich, Steinheim, Germany) named assay medium and treated with 100 µg/ml or 200 µg/ml peptide for 30 minutes. Pharmacological inhibition of Rac1 was performed with NSC23766 (Calbiochem, Nottingham, United Kingdom) or EHT1864 (Sigma-Aldrich) for 1 hour at concentrations of 25 µM or 50 µM in assay medium. Subsequently, cells were washed with phosphate-buffered saline (PBS; Fresenius Kabi, 's Hertogenbosch, The Netherlands) containing 0.5% w/v BSA named FACS medium. The DNA-binding dye, ToPro3 (Invitrogen, Carlsbad, CA, USA), was used to determine cytotoxicity. CXCL12 (PeproTech, Rocky Hill, USA) was used at a final concentration of 100 ng/ml for 30 minutes as a positive control for responsiveness of the CXCR4 receptor on the cell surface.

Peptide washout experiment

Cells were treated with the Rac1 C-terminal peptide as described above and subsequently washed twice with assay medium to remove the peptide. Thereafter, the cells were placed at 37°C. At different time points (0, 15, 30 and 60 minutes) cells were
transferred to a 96 well V-bottom plate, washed with FACS medium and fixed with 2% formaldehyde for 30 minutes at RT. Subsequently, cells were washed with FACS medium and cell surface expression levels of CXCR4 were determined by using specific CXCR4 monoclonal antibodies (mAbs; see supplementary materials and methods for specifications) and flow cytometry.

All flow cytometry measurements were performed using the FACS CANTO, FACS LSR II, or FACS LSR II HTS (BD Biosciences, Breda, The Netherlands), and results were analyzed with BD FACSDiva software 6.1 (BD Biosciences).

**Antibody feeding experiment**

In antibody feeding experiments, HL60 cells were stained with specific CXCR4 mAbs at 4°C and subsequently washed with FACS medium to remove unbound antibodies. Thereafter, the cells were incubated with assay medium, the control peptide or the Rac1 peptide for periods ranging from 5 to 45 minutes at 4°C or 37°C or with NSC23766 for 1 hour at 37°C. Subsequently, the cells were washed with FACS medium and the signal of the anti-CXCR4 antibody was determined by flow cytometry.

**Peptide pull-down assay**

HeLa cells were transiently transfected with the HA-CXCR4 construct and maintained for 24 hours. The cells were washed twice with ice-cold PBS (supplemented with 1 mM CaCl2 and 0.5 mM MgCl2) and lysed in NP-40 lysis buffer (i.e. 50 mM Tris-HCl pH 7.5, 100 mM NaCl, 10 mM MgCl2, 10% glycerol and 1% NP-40) supplemented with protease inhibitors (Complete mini EDTA; Roche, Mannheim, Germany), centrifuged at 20,000 g for 10 minutes at 4°C. The supernatant was pre-cleared by incubation with streptavidin-coated beads (Sigma-Aldrich) for 1 hour at 4°C. The pre-cleared lysate was then incubated with the indicated Rho GTPase C-terminal peptides, a peptide representing
the effector domain (ED) of Rac1 (amino acids 17-32) \(^{15}\) or a control peptide (8 µg) in the presence of streptavidin-coated beads (blocked with 4% BSA) at 4°C for 1 hour with rotation. Initial lysates and pull-down samples were analyzed by SDS-PAGE and immunoblotting using mouse anti-HA (Sigma-Aldrich) and HRP-coupled secondary antibodies.

**Immunoprecipitation**

HeLa cells were transiently transfected with HA-CXCR4 and myc-Rac1Q61L or myc-Rac1T17N constructs and maintained for 24 hours. After lysing the cells as described under “peptide pull-down assay”, the supernatant of the lysate was pre-cleared by incubation with protein G-agarose beads for 1 hour at 4°C. The pre-cleared lysates were then incubated with monoclonal anti-HA antibodies and protein G-agarose beads (blocked with 4% BSA) at 4°C for 5 hours. Samples were then washed 5 times with lysis buffer. Immunoprecipitated proteins were eluted by adding SDS sample buffer and heating at 50°C for 20 minutes. Protein association was assayed by SDS-PAGE and immunoblotting using rabbit anti-HA and rabbit anti-myc antibodies (both from Sigma-Aldrich) and HRP-coupled secondary antibodies.

**CRE-Luciferase reporter gene assay**

HEK293T cells were transiently transfected using PEI with plasmids encoding for CXCR4 and the cyclic AMP responsive element (CRE) coupled to the luciferase gene (CRE-Luc) \(^{16}\). Briefly, 1 µg of CXCR4 and 1 µg CRE-Luc plasmids were transfected per 10^6 HEK293T cells and seeded onto a white 96-well plate (Greiner, Alphen a/d Rijn, The Netherlands). Two days post-transfection, the culture medium was discarded and cells were stimulated with DMEM supplemented with 0.5% w/v BSA, forskolin (3 µM) and a concentration range of CXCL12 varying from 1 pM to 100 nM in the absence or
presence of the Rac1 inhibitors. After 8 hours of incubation at 37°C, the stimulation medium was discarded and the cells were lysed in the presence of D-luciferin (Duchefa Biochemi BV, Haarlem, The Netherlands). Luminescence was measured on a Wallac Victor² plate reader (Perkin Elmer).

**Human immunodeficiency viruses and infection assays**

Single round luciferase reporter virus was produced by cotransfection of pNL4-3.Luc.R-E-construct and constructs expressing either BaL-26 envelop or HxB2 envelop in HEK293T cells using calcium phosphate. Infectious virus was harvested at 48 and 72 hours after transfection and filtered through a 0.22 μm filter. Virus titers were quantified by determination of the 50% tissue culture infectious dose (TCID50) on U87 cells expressing CD4 and CCR5 (U87-CD4-CCR5) or CXCR4 (U87-CD4-CXCR4). After 48 hours, luciferase substrate (0.83 mM ATP, 0.83 mM d-luciferin, 18.7 mM MgCl₂, 0.78 μM Na₂H₂P₂O₇, 38.9 mM Tris-HCl pH 7.8, 0.39% v/v glycerol, 0.03% v/v Triton X-100 and 2.6 μM dithiothreitol) was added. Luminescence was measured using the Centro LB 960 (Berthold Technologies, Bad Wildbad, Germany).

HIV-1 variant NL4-3 was produced by transfection of the full length construct in HEK293T cells using calcium phosphate. Infectious virus was harvested at 48 and 72 hours after transfection and filtered through a 0.22 μm filter. Virus titers were quantified by determination of the 50% tissue culture infectious dose on phytohemagglutinin (PHA)-stimulated peripheral blood mononuclear cells (PBMCs) using an in-house p24 ELISA. For the single round luciferase reporter HIV-1 infection assay, U87 cells expressing CD4 and CCR5 or CXCR4 were plated at a cell density of 6,000 cells per well and cultured for 24 hours. Next, the cells were inoculated with 200 TCID50 BaL-26 or HxB2 env pseudotyped single round luciferase virus and 48 hours later, the infectivity of the virus
was analyzed by the luciferase assay. During and after inoculation, the cells were treated with different concentrations of NSC23766 as indicated.

For the HIV-1 products qPCR, PHA-stimulated PBMCs (0.5x10^6) were inoculated with 250 TCID50 DNase treated NL4-3 in the presence or absence of 50 μM NSC23766. After 48 hours, cells were harvested for DNA isolation to be used in the qPCR studies.

Calculations and statistical analysis

The percentage of CXCR4 surface expression was calculated by normalizing the fluorescence intensity measurements on the mean of the untreated condition measurements. Measurements of both treated and untreated conditions were divided by the mean of the untreated conditions (x100%), giving rise to a mean of 100% ±SEM for the control. The isotype control background was not subtracted from the specific fluorescence intensity signal.

pEC50 was determined by fitting a sigmoidal dose-response curve using GraphPad Prism5.

Significance of differences was determined in all experiments with a two-sided unpaired Student’s t test. Two-sided p-values smaller than 0.05 were considered significant.

For further information on the materials and methods used see the Supplementary Material and Methods.
Results

Inhibition of Rac1 specifically decreases CXCR4 signal on the cell surface

To investigate whether Rac1 modulates CXCR4 function, we determined the effect of Rac1 inhibition on CXCR4 expression. We opted for a peptide-mediated approach and the use of pharmacological inhibitors of Rac1. Both methods ensure a rapid inhibition of Rac1, in contrast to the expression of a dominant-negative (DN) construct of Rac1. Inhibition of Rac1 with a biotinylated Rac1 C-terminal peptide (Figure 1A) 19, significantly reduced the CXCR4 cell surface signal detected by mAb clones 12G5 (Figure 1 B, left and middle panel) and 44717 in the myeloid HL60 cell line that expresses CXCR4 endogenously (Figure 1B, right panel). The results obtained with these CXCR4 mAb clones were consistent and the inhibitory peptide did not affect cell-viability (data not shown). Importantly, peptide-mediated inhibition of a related GTPase, CDC42, did not cause a significant decrease in CXCR4 surface signal, indicating the specificity of Rac1 for the regulation of steady-state CXCR4 expression (Figure 1B and 1C). The cell surface expression of the alternative CXCL12 receptor CXCR7, the related chemokine receptor CCR5 and the unrelated adhesion molecule LFA-1 were not reduced when HL60 cells were treated with the Rac1 inhibitory peptide (Figure 1C). Thus, Rac1 specifically controls CXCR4 exposure.

To confirm these results, we used the pharmacological Rac1-guanine nucleotide exchange factor inhibitor, NSC23766, which does not affect the function of CDC42 or RhoA 20. This inhibitor did not induce cellular toxicity in our experimental conditions (data not shown). In accordance with the previous findings, NSC23766-mediated Rac1 inhibition significantly reduced CXCR4 cell surface signal on U937 cells (Figure 1D, left panel) and HL60 cells (data not shown). CXCR7 expression on these cells was not affected, again showing the specificity of Rac1 for CXCR4 regulation (Figure 1D, right panel). The effect of Rac1 inhibition on CXCR4 surface signal was further confirmed on
human cord blood (CB)-derived CD34+ cells (Figure 1E). The same results were also observed with the pharmacological Rac1 inhibitor EHT1864 (data not shown). These results indicate that Rac1 specifically regulates the CXCR4 signal on resting cells.

The Rac1 C-terminus contains a proline-rich domain and a polybasic domain, which are both involved in the binding of specific effector proteins. To examine whether these domains are involved in regulating CXCR4 expression, we used the same Rac1 peptide, but now with substitutional mutations of the proline-rich amino acid sequence or the polybasic amino acid sequence in HEK293T cells transiently expressing CXCR4. The Rac1 peptide with a mutated proline-rich sequence decreased the CXCR4 signal to the same extent as the wild-type Rac1 peptide. The Rac1 peptide with a mutated polybasic region resulted in a less prominent decrease of CXCR4 signal suggesting the involvement of the polybasic binding motif. As observed in other cell types, peptide-mediated inhibition of CDC42 in HEK293T cells exogenously expressing CXCR4 did not cause a significant decrease in CXCR4 surface expression (Figure 1F). Overall, these data show that Rac1 specifically regulates CXCR4 expression in distinct cell types and that the polybasic region of the Rac1 C-terminus is at least partially required for Rac1 to exert this function.

To assess whether Rac1 and CXCR4 associate, we performed a streptavidin-based pull-down assay using the different biotinylated peptides described above or the Rac1 peptide representing part of the ED (aa 17-32) in lysates of HeLa cells expressing hemagglutinin (HA)-tagged CXCR4. We found that CXCR4 clearly interacts with the Rac1 C-terminal peptide independently of the proline rich domain. Binding was partially abolished when the polybasic region is mutated and we did not observe an interaction between HA-CXCR4 and the CDC42 C-terminal peptide or the Rac1 ED peptide (Figure 1G). These results correlate with the reduced effect of the polybasic mutant Rac1 C-terminal peptide on the CXCR4 surface signal as compared to the wild-type or the...
proline mutant Rac1 C-terminal peptide as observed in figure 1F. Next, to investigate the interaction between CXCR4 and full-length Rac1, we performed immunoprecipitation experiments in HeLa cells transfected with HA-CXCR4 and the myc-tagged active mutant of Rac1 (Q61L) or the myc-tagged DN mutant of Rac1 (T17N). Our results show that both myc-Rac1Q61L and myc-Rac1T17N co-immunoprecipitated with CXCR4 (Figure 1H). Together, these data show that Rac1, via its C-terminus, associates with CXCR4 independently of the GDP-GTP loading state of the GTPase and of agonist stimulation of the receptor.

**Rac1 inhibition causes a conformational change of CXCR4**

To investigate the fate of CXCR4 after inhibition of Rac1, HL60 cells were treated with the inhibitory Rac1 peptide after which surface and total CXCR4 expression were measured. Inhibition of Rac1 caused a significant decrease of CXCR4 detected on the cell surface (Figure 2A, left panel), while the total levels remained unaffected as compared to control cells (Figure 2A, right panel). To determine whether the effect of Rac1 inhibition on CXCR4 expression was reversible, HL60 cells were first treated with the Rac1 inhibitory peptide, which was subsequently removed by washing the cells. Thereafter, surface levels of CXCR4 were measured after various time intervals during 60 minutes. The CXCR4 signal on the cell surface was still significantly decreased at fifteen minutes following peptide removal, but returned to baseline levels as compared to untreated cells after 60 minutes (Figure 2B). Moreover, at this time-point CXCR4 was responsive, as shown by CXCL12-induced receptor internalization measured by a decrease in receptor surface expression. In addition, treating the cells again with the Rac1 inhibitory peptide resulted once more in a decrease of CXCR4 surface signal (Figure 2C). Together these results show that inhibition of Rac1 causes a reversible decrease of CXCR4 surface signal, which is not due to CXCR4 degradation.
To determine whether Rac1 inhibition enhances CXCR4 internalization, HL60 cells were incubated with the Rac1 inhibitory peptide or NSC23766 at 4°C, at which temperature vesicular trafficking, including internalization of membrane proteins, is abrogated. As a control, cells were treated with CXCL12. CXCL12-induced internalization of CXCR4 was severely impaired at 4°C as compared to 37°C, indicating that receptor internalization is indeed abolished at low temperature (Figure 3A). Peptide-mediated inhibition of Rac1 at 4°C, however, resulted in the same CXCR4 surface signal decrease as observed at 37°C (Figure 3A). Incubation of the cells with NSC23766 at 4°C also resulted in a significant decrease of CXCR4 surface signal (data not shown). Therefore, it is unlikely that the decrease of CXCR4 surface signal upon Rac1 inhibition is due to enhanced endocytosis.

To examine whether Rac1 controls CXCR4 trafficking, antibody-feeding experiments were performed. Fluorescently labeled anti-CXCR4 mAb (clone 12G5 or 44717) were first allowed to bind to the receptor before addition of the Rac1 inhibitor to the cells. Using flow cytometry we found that inhibition of Rac1 for various time periods resulted in a time-dependent decrease of the fluorescence intensity of the 12G5 CXCR4 antibody signal (Figure 3B). In addition, incubation with the Rac1 inhibitory peptide for 30 minutes or NSC23766 for 1 hour also caused a major decrease in fluorescence intensity of the 44717 CXCR4 antibody signal compared to untreated or control peptide treated cells (Figure 3C). These results were obtained at 37°C, but also at 4°C (data not shown), thereby excluding the internalization of the receptor-antibody complex. These data show that the bound antibodies dissociate upon Rac1 inhibition, which is indicative for a conformational change of CXCR4 induced by Rac1 inhibition.

To substantiate this notion, we used the amino-terminus specific CXCR4 mAb, 4G10, which is a conformation-independent antibody. Interestingly, the conformation-independent CXCR4 antibody did not dissociate from its receptor following Rac1
inhibition in an antibody-feeding experiment (Figure 3D). This is in contrast to the
dissociation of the 12G5 and 44717 antibodies (Figure 3B-C), that have previously been
described to be conformation-dependent antibodies. In addition, pre-treatment of
HL60 cells (Figure 3E) or CD34+ (supplemental figure 1) with NSC23766 did not result in
a loss of CXCR4 surface signal measured by 4G10 as compared to antibody clones
12G5 and 44717. Our observations that the binding of 4G10 to CXCR4 is not affected by
Rac1 inhibition, confirm that the receptor is not internalized, but rather adopts a new
conformation upon Rac1 inhibition.

**CXCR4 conformational change upon Rac1 inhibition abrogates receptor
internalization and impairs G\(_{\text{i}}\) signaling**

To study the functional consequences of the CXCR4 conformational change, we
measured ligand-induced receptor endocytosis following Rac1 inhibition. To this end, we
used the conformation-independent antibody clone, 4G10. In Jurkat T-cells, CXCL12
stimulation induced a significant decrease of CXCR4 surface expression, which is
indicative for receptor endocytosis. However, following NSC23766 treatment, ligand
stimulation did not cause receptor internalization suggesting that the conformational
change in CXCR4 upon inhibition of Rac1 blocks CXCL12 binding (Figure 4A).
To determine CXCR4 signaling efficiency upon Rac1 inhibition in Jurkat T-cells, we
investigated the capacity of CXCR4 to inhibit cAMP production as a result of G\(_{\text{i}}\) protein
activation. Using a cAMP response element (CRE) reporter gene in transiently-
transfected HEK293T cells, CXCL12 stimulation inhibited the forskolin-induced CRE
activation \((\text{pEC}50 = 9.1 \pm 0.1, n=3)\). Inhibition of Rac1 drastically reduced CXCL12-
mediated cAMP inhibition as illustrated by a significant shift to the right of the CXCL12
concentration response curve \((\text{pEC}50 \text{ for NSC23766} = 7.7 \pm 0.1, (p<0.01)\) and \text{pEC}50
for the Rac1 inhibitory peptide = 8.7 ± 0.1, (p<0.05), n=3) (Figure 4B). This means that the conformation of CXCR4 adopted after Rac1 inhibition has a decreased capacity in initiating Gαi protein signaling. These data suggest that CXCR4 becomes less sensitive to CXCL12 upon Rac1 inhibition. Overall, the lack of receptor internalization and impaired Gαi signaling after Rac1 inhibition, demonstrate that Rac1 activity is required for the maintenance of the responsive CXCR4 conformation.

**HIV-1 infection is inhibited after CXCR4 conformational change**

Two chemokine receptors CXCR4 and CCR5 have been identified as co-receptors for HIV-1, and viral tropism is defined by the use of either CXCR4 (X4 viruses) or CCR5 (R5 viruses) 4,22. To evaluate whether the CXCR4 conformational change caused by Rac1 inhibition affects HIV-1 binding and infection, we initially performed an infection assay using a single-round, luciferase reporter HIV-1 (NL4-3.Luc.R-E-) pseudotyped with a CXCR4-using envelop (HxB2) or a CCR5-using envelop (BaL-26). U87 cells stably expressing CD4 in combination with CXCR4 or CCR5 were used as host cells in this assay. Treating these cells with NSC23766 caused a conformational change of CXCR4, as determined by the loss of conformation-dependent antibody binding without affecting the binding of the conformation-independent 4G10 antibody clone (Figure 5A, left and middle panel). The conformation of CCR5 was unaffected by NSC23766 treatment (Figure 5A, right panel). As shown in Figure 5B, NSC23766 treatment markedly reduced infection of luciferase reporter HIV-1 pseudotyped with the X4-using HxB2 envelop as compared to untreated cells. Several reports identified Rac1 and its downstream effectors, involved in actin dynamics, as crucial players in the entry of R5 viruses into host cells 23,24. However, in our system, R5 HIV-1 infection was independent of Rac1, since NSC23766 treatment did not affect the infection of luciferase reporter HIV-1
pseudotyped with the R5-using BaL-26. These data confirm the specificity of Rac1 for regulating CXCR4 conformation without interfering with CCR5.

To further support that the infection of X4-using HIV-1 was inhibited at the level of virus entry, additional infection experiments were performed analyzing early steps after virus entry by qPCR. U87-CD4-CXCR4 cells were inoculated with a replicating X4-virus (NL4-3) and 48 hours later total DNA was isolated and analyzed for the presence of early (R/U5) products of reverse transcription. In agreement with the data from the HIV-1 luciferase assay, the detected levels of R/U5 were significantly lower in NSC23766-treated cells as compared to untreated conditions (Figure 5C). These results were further confirmed in X4-using HIV-1 infection experiments using PHA-stimulated PBMCs. Figure 5D shows that only low levels of R/U5 and the relatively late (pol) product of reverse transcription were detected in NSC23766-treated PBMCs as compared to untreated cells. As the presence of R/U5 proviral DNA is indicative for efficient virus entry and initiation of reverse transcription, these data demonstrate that Rac1 inhibition impairs virus entry by altering CXCR4 conformation. These data correlate with the lack of CXCR4 internalization after Rac1 inhibition as observed in Figure 4A.
Discussion

Although the conformational change of CXCR4 that follows ligand binding is established, less is known about the ligand-independent regulation of CXCR4 conformation in resting cells. Here, we show that the conformation of CXCR4 in resting conditions is of major importance as it defines the responsiveness to the CXCL12 chemotactic stimulus and susceptibility for HIV-1 binding and entry into host cells. The link between CXCR4 and Rac1 was previously established by showing that Rac1 is an important downstream signaling molecule translating the CXCL12 stimulus to cytoskeletal remodeling and cell movement. Interestingly, we found that Rac1 associates with CXCR4 via the Rac1 C-terminus independently of GDP-GTP loading of the GTPase or ligand stimulation. Furthermore, Rac1 controls CXCR4 conformation specifically, since Rac1 inhibition did not affect the conformation of the related chemokine receptors CCR5 and CXCR7. Finally, Rac1 regulation of CXCR4 conformation was not cell-type specific, since we observed similar results in different cell types, including CD34+ HSPCs. Thus, our findings identify Rac1 as a positive regulator of CXCR4.

Furthermore, the lack of receptor internalization and reduced capacity to activate Goi protein after Rac1 inhibition, demonstrates that Rac1 activity is required for the maintenance of the responsive CXCR4 conformation. This suggests that Rac1 acts as an intracellular positive allosteric modulator of CXCR4, which stabilizes the responsive conformation of the receptor.

Baribaud et al. described the presence of at least two antigenically distinct conformations of CXCR4 in resting conditions. This heterogeneity in CXCR4 populations was not due to differences in N-linked glycosylation or sulfation of the receptor. Our preliminary results identified the 3rd intracellular loop of CXCR4 as an important domain for defining the receptor’s conformation (Y.Z., unpublished data, May 1, 2011). Interestingly, we have previously shown that by modifying intracellular parts of the viral
chemokine receptor ORF74, the conformation of the receptor and binding of its ligand(s) is altered 26. Further work will unravel whether Rac1 and the 3rd intracellular loop of CXCR4 act in concordance to regulate the conformation adopted by this receptor.

It is not clear how Rac1 maintains CXCR4 in the responsive conformation. It has been shown that disruption of cholesterol rich lipid raft domains causes a conformational change of CXCR4 27. Active Rac1 is localized in lipid raft microdomains 28;29 and may preserve a pool of CXCR4 in a responsive conformation at these specific signaling platforms on the cell membrane. These CXCR4 pools would represent the receptor subset with high signal transduction capacity and HIV-1 co-receptor activity 30;31.

The fact that Rac1 inhibition impaired the binding of the two tested conformational-dependent anti-CXCR4 antibodies, which both recognize an epitope in the 2nd extracellular loop of CXCR4, implies that at least the conformation of this domain is altered upon Rac1 inhibition. Moreover, the 2nd extracellular loop plays a prominent role in HIV-1 gp-120 recognition and binding 14;32. In line with this, we found that CXCR4 conformation following Rac1 inhibition prevented CXCR4-dependent HIV-1 infection. Thus, next to a specific domain in the co-receptor, viral entry is also dependent on the conformation adopted by the co-receptor.

Our data showing that Rac1 inhibition alters the conformation of CXCR4 expressed on CD34+ HSPCs may also have important clinical implications. First, Carter et al. recently showed that CXCR4-tropic HIV-1 can infect HSCs thereby creating a latent viral reservoir which could be responsible for the disease progression of AIDS 33. Therefore, manipulating CXCR4 conformation on this cell population will contribute to the eradication of the latent HIV-1 reservoir. Next, a change of CXCR4 conformation, which no longer supports its binding to CXCL12, could improve HSC mobilization since the retention of these cells in the bone marrow depends on the CXCR4-CXCL12 axis. In line with this assumption, it has been shown that intraperitoneal administration of NSC23766
in mice caused a massive mobilization of HSCs into the circulation\textsuperscript{34}. A change of CXCR4 conformation after NSC23766 administration, which breaks the CXCR4-CXCL12 interaction, is a possible mechanism explaining the tremendous egress of HSCs from the bone marrow.

In conclusion, we established Rac1 as a key player in the regulation of CXCR4 conformation, thereby controlling the fine-tuning of CXCR4 activity and affecting HIV-1 binding and fusion. Finally, uncovering the molecular mechanisms governed by Rac1 and directed at the regulation of CXCR4 conformation, will provide novel strategies to block infection of X4 viruses which have previously been associated with an increased progression rate to AIDS.
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Authorship

Contribution: Y.Z., K.B., D.M. and K.A.V.D. performed experiments; Y.Z., C.V., N.A.K, M.J.S., D.M., P.L.H. and P.B.V.H. designed the research and analyzed the results; Y.Z. and P.B.V.H made the figures and wrote the paper.

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Reference List


Legends to the figures

Figure 1. Rac1 inhibition causes a decrease of CXCR4 surface signal and Rac1 associates with CXCR4.

(A) Schematic representation of the Rho-like GTPase C-terminal peptides fused to a protein transduction domain as used in this study. (B) HL60 cells were incubated with the Rac1 or CDC42 inhibitory peptides and CXCR4 expression was detected by flow cytometry using the fluorescently labeled mAb 12G5 or 44717. The panels show a histogram overlay (left) and bar graphs (middle and right) representing the CXCR4 surface signal. Histogram: thin solid line: isotype control mAb, long dashed line: untreated, thick solid line: control peptide, dashed line: CDC42 C-terminal peptide, dotted line: Rac1 C-terminal peptide. The CXCR4 surface signal in the untreated condition and control peptide treated condition completely overlap. (n=3) (C) HL60 cells were incubated with the Rac1 or CDC42 inhibitory peptides and CXCR7, CCR5 and LFA-1 surface signal were measured by flow cytometry. (n= 3) (D) U937 cells were treated with 50 μM NSC23766 and the CXCR4 (detected by mAbs 12G5 and 44717) and CXCR7 surface signals were measured by flow cytometry. (n=3) (E) CD34+ cells isolated from CB were treated with NSC23766 and the CXCR4 signal (detected by mAb 12G5 or 44717) was measured by flow cytometry. (n=5) (F) HEK293T cells exogenously expressing CXCR4-GFP were treated with the Rac1 (mutant) C-terminal peptides or the CDC42 C-terminal peptide and the CXCR4 surface signal (detected by mAb 12G5) was measured on the GFP-positive cells by flow cytometry. (n=3) (G) Pull-down (PD) experiment was performed using lysates from HeLa cells exogenously expressing HA-CXCR4 with beads only, a control peptide, wild-type and mutant Rac1 C-terminal peptides, the Rac1 17-32 ED peptide and the CDC42 C-terminal peptide. Association of CXCR4 was detected by immunoblotting (IB) with an HA-specific monoclonal antibody. (representative example out of two independent experiments) (H) Immunoprecipitation
assays (IP) were performed in HeLa cells transfected with an empty vector (pcDNA3) or with HA-CXCR4 and co-transfected with myc-Rac1Q61L or myc-Rac1T17N. Immunoprecipitation of the receptor was performed using an HA-specific antibody or an IgG control antibody and immunoblotting was performed with an HA-specific or a myc-specific antibody. (representative example out of two independent experiments)

ED: effector domain of Rac1, HV: hypervariable domain of Rac1, PTD: protein transduction domain, Rac1 PPP→AAA, Rac1 RKR→AAA: Rac1 C-terminal peptide mutants where the three prolines, or RKR sequence were replaced by alanine residues, respectively, Rac 17-32: effector domain, TCL: total cell lysates, EV: empty vector, HA-X4: HA-tagged CXCR4.

Bars show the median (B-C) and the mean (D-E -F) fluorescence intensity determined by flow cytometry and expressed as percentage ± SEM compared to untreated or to control conditions. *p< 0.05, **p< 0.01

**Figure 2. The effect of Rac1 inhibition on CXCR4 is reversible.**

(A) HL60 cells were incubated with the Rac1 inhibitory peptide and then surface CXCR4 (left) or total CXCR4 (right) were measured using mAb 44717 by flow cytometry. (n=3) (B) HL60 cells were incubated with the Rac1 inhibitory peptide, washed and placed at 37°C and CXCR4 surface signal (detected by mAb 12G5) was determined after different time periods by flow cytometry. (n=4) (C) One hour after wash out of the Rac1 inhibitory peptide, HL60 cells were incubated again with the inhibitory peptide or with CXCL12 and the CXCR4 surface signal (as detected by mAb 12G5) was determined by flow cytometry (n=3).

Bars show the mean (A) and median (B-C) fluorescence intensity determined by flow cytometry and expressed as percentage ± SEM compared to untreated conditions. *p< 0.05, **p< 0.01
Figure 3. Rac1 inhibition alters CXCR4 conformation.

(A) HL60 cells were incubated with CXCL12 or the Rac1 inhibitory peptide at 4°C or 37°C and the CXCR4 surface signal (detected by mAb 44717) was measured by flow cytometry. (n=3) (B) Antibody-feeding experiments where HL60 cells were first stained with anti-CXCR4 mAb 12G5 and subsequently incubated with the Rac1 inhibitory peptide for different time periods. mAb signal was then measured by flow cytometry. (n=3) (C) Antibody-feeding experiments for which HL60 cells were first stained with anti-CXCR4 mAb 44717 and subsequently incubated with the Rac1 inhibitory peptide for 30 min or NSC23766 for 1 hour. mAb signal was subsequently measured by flow cytometry. (n=3) (D) Antibody-feeding experiments for which HL60 cells were first stained with the conformation-independent anti-CXCR4 mAb 4G10 and subsequently incubated with the Rac1 inhibitory peptide for 30 min or NSC23766 for 1 hour. mAb signal was subsequently measured by flow cytometry. (n=3) (E) HL60 cells were treated with NSC23766 and CXCR4 surface signal (detected by mAb 44717 or 4G10) was measured. (n=3)

Bars show the mean fluorescence intensity determined by flow cytometry and expressed as percentage ± SEM compared to untreated or control conditions. *p< 0.05, **p< 0.01

Figure 4. CXCR4 internalization and Gαi signaling are impaired after CXCR4 conformational change upon Rac1 inhibition.

(A) Jurkat T-cells were pretreated with or without NSC23766 and subsequently incubated with or without CXCL12. The CXCR4 (detected by mAb 4G10) surface signal was then measured. (n=3) Bars show the mean fluorescence intensity determined by flow cytometry and expressed as percentage ± SEM compared to untreated conditions. (B) HEK 293T cells expressing CXCR4 and CRE-Luc were stimulated with forskolin and different concentrations of CXCL12 (varying from 1 pM to 100 nM) in the absence or
presence of NSC23766 or the Rac1 inhibitory peptide. After 8 hours, CXCL12-mediated inhibition of cyclic AMP synthesis was analyzed by the luciferase assay as indicated in the materials and methods section. The graph shows normalized data of 3 independent experiments where 100% represents the luciferase activity of untreated cells at the lowest CXCL12 concentration. **p< 0.01

**Figure 5. HIV-1 infection is blocked after CXCR4 conformational change.**

(A) U87-CD4-CXCR4 and U87-CD4-CCR5 cells were incubated with NSC23766 and CXCR4 (detected by mAb 44717 or 4G10) and CCR5 (detected by mAb 2D7) surface signals were measured. Bars show the mean fluorescence intensity determined by flow cytometry and expressed as percentage ± SEM compared to untreated conditions. (n=3)

(B) U87-CD4-CXCR4 and U87-CD4-CCR5 cells were inoculated, in the presence or absence of NSC23766, with the single round luciferase reporter HIV-1 pseudotyped with the X4-using envelop HxB2 or the R5-using envelop BaL-26, respectively. 48 hours later, the infectivity of the virus was analyzed by the luciferase assay. Bars show the luciferase activity measured by a microplate luminometer and expressed as percentage ± SEM compared to untreated conditions. (n=3)

(C) U87-CD4-CXCR4 cells were inoculated with the X4-virus NL4-3 in the presence or absence of NSC23766. After 48 hours, DNA samples were isolated and the early reverse transcriptase product R/U5 was quantified by qPCR. Bars show the number of proviral DNA copies corrected for differences in DNA input (β-actin) and expressed as percentage ± SEM compared to untreated conditions. (n=3)

(D) PHA-stimulated PBMCs were inoculated with the X4-virus NL4-3 in the presence or absence of NSC23766. After 48 hours, DNA samples were isolated and R/U5 and pol proviral DNA were quantified by qPCR. Bars show the number of proviral DNA copies corrected for differences in DNA input (β-actin) and
expressed as percentage ± SEM compared to untreated conditions.

(n=4) *p< 0.05, **p< 0.01
Figure 1

A

Rac1 Biotin  YGRKKRRQRRR G CPPPVKKRKRK  N- C
CDC42 Biotin  YGRKKRRQRRR G LEPPEPKKSRR  N- C
PTD  GTPase C-terminus

B

mAb 12G5

C

Surface CXCR4 (%)

D

mAb 12G5  mAb 44717

E

mAb 44717  mAb 12G5

F

mAb 12G5

G

IB: HA

H

Light chain
Myc-Rac1Q61L
HA-CXCR4

Figure 2

A

Surface CXCR4 (%)

Untreated  control  Rac1 C-term

mAb 44717

B

Surface CXCR4 (%)

Untreated  0  15  30  60

mAb 12G5

C

Surface CXCR4 (%)

Untreated  control  Rac1 C-term  CXCL12

mAb 12G5
Figure 3

A

mAb 44717

Surface CXCR4 (%)

untreated CXCL12 control Rac1 C-term untreated CXCL12 control Rac1 C-term

4°C 37°C

B

mAb 12G5

Bound anti-CXCR4 (%)

untreated Rac1 C-term

0 20 40 60 80 100 120

5 min 10 min 15 min 30 min 45 min

C

mAb 44717

Bound anti-CXCR4 (%)

untreated control Rac1 C-term untreated NSC23766

D

mAb 4G10

Bound anti-CXCR4 (%)

untreated control Rac1 C-term untreated NSC23766

E

mAb 44717 mAb 4G10

Surface CXCR4 (%)

untreated NSC23766 untreated NSC23766

mAb 44717 mAb 4G10
Figure 4

A

Surface CXCR4 (%)

untreated  CXCL12  NSC23766  NSC23766 + CXCL12

**

mAb 4G10

B

CRE-Luc activation (%)

untreated  NSC23766  Rac1 C-term

log [CXCL12] (M)
Regulation of CXCR4 conformation by the small GTPase Rac1: implications for HIV infection

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