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Proline-Rich Tyrosine Kinase 2 and Rac Activation by Chemokine and Integrin Receptors Controls NK Cell Transendothelial Migration

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Protein tyrosine kinase activation is an important requisite for leukocyte migration. Herein we demonstrate that NK cell binding to endothelium activates proline-rich tyrosine kinase 2 (Pyk-2) and the small GTP binding protein Rac that are coupled to integrin and chemokine receptors. Chemokine-mediated, but not integrin-mediated, Pyk-2 and Rac activation was sensitive to pretreatment of NK cells with pertussis toxin, a pharmacological inhibitor of G_i protein-coupled receptors. Both Pyk-2 and Rac are functionally involved in chemokine-induced NK cell migration through endothelium or ICAM-1 or VCAM-1 adhesive proteins, as shown by the use of recombinant vaccinia viruses encoding dominant negative mutants of Pyk-2 and Rac. Moreover, we found that Pyk-2 is associated with the Rac guanine nucleotide exchange factor Vav, which undergoes tyrosine phosphorylation upon integrin triggering. Finally, we provide direct evidence for the involvement of Pyk-2 in the control of both chemokine- and integrin-mediated Rac activation. Collectively, our results indicate that Pyk-2 acts as a receptor-proximal link between integrin and chemokine receptor signaling, and the Pyk-2/Rac pathway plays a pivotal role in the control of NK cell transendothelial migration. The Journal of Immunology, 2003, 170: 3065–3073.

The ability of leukocytes to traffic coordinately throughout the body is an essential requirement for the maintenance of immunosurveillance. Leukocyte migration across the endothelium is a spatially and temporally integrated multistep process regulated by a plethora of chemokine receptors and adhesive molecules (1, 2).

Among adhesion molecules, integrins contribute to the initial leukocyte tethering and rolling along vessel endothelium and mediate firm adhesion of the leukocyte to vascular endothelium and subsequent diapedesis into the extravascular tissue. Chemokines are a superfamiliy of inflammatory mediators that properly guide leukocyte recruitment and positioning into healthy or diseased tissues by interacting with seven-transmembrane domain receptors and initiating a cascade of intracellular signaling events leading to the activation of protein tyrosine kinases (PTK), phosphoinositide-3 kinase (PI-3K), small GTP-binding proteins, and mitogen-activated protein kinases (MAPKs) (3–6). In addition, chemokines can govern leukocyte migration through a dynamic regulation of integrin adhesiveness for endothelial and extracellular matrix ligands (7, 8). Integrins too can regulate cell migration and initiate similar intracellular signal transduction pathways (9–11). Thus, leukocyte migration depends on a highly integrated signaling network culminating in coordinate activation and functional cooperation between different pathways triggered by integrin and chemokine receptors.

Activation of PTKs is a prerequisite event for leukocyte migration, controlling both integrin adhesiveness and chemotactic response. Proline-rich tyrosine kinase 2 (Pyk-2), also known as cell adhesion kinase-β, or related adhesion focal tyrosine kinase, is a nonreceptor PTK closely related to p125 focal adhesion kinase (FAK), coupling several receptors, including integrin and chemokine receptors, with a variety of downstream effectors, such as small G proteins belonging to the Ras and Rho families, MAPKs, protein kinase C, and inositol phosphate metabolism (12–16).

Recently, Pyk-2-deficient mice have been shown to exhibit a lack of splenic marginal zone B cells associated with a decreased motility of B lymphocytes in response to a variety of chemokines (17). Our previous evidence indicates that human peripheral blood NK cells express Pyk-2 that is constitutively associated with the cytoskeletal protein paxillin, but not p125 FAK. Engagement of β1 or β2 integrins on human NK cells results in the rapid tyrosine phosphorylation of both Pyk-2 and paxillin. Moreover, we found that Pyk-2 acts as an upstream mediator of β1 and β2 integrin-triggered MAPK cascades and controls the development of NK cell-mediated natural cytotoxicity (18, 19).

NK cells belong to a distinct lineage of lymphocytes that play an important role in the early phase of immune responses against certain viruses, parasites, and microbial pathogens by exhibiting cytotoxic functions and secreting a number of cytokines. NK cells mainly circulate in the peripheral blood; are resident in the spleen, liver, lungs, and intestine; and are rapidly recruited from blood to the parenchymas of several organs during viral infections, tumor growth and invasion, and inflammation (20–22). Previous evidence indicates that adhesion and migration of human NK cells...
across endothelial cells is mainly supported by leukocyte function-associated Ag (LFA-1) and αβ integrins (23–25), and that several chemokines can elicit a NK cell chemotactic response in vitro and in vivo (26–29).

However, despite increasing evidence of the prominent role of chemokines and integrins in the dynamic regulation of leukocyte adhesion and migration, the signaling pathways responsible for the integrin-supported leukocyte migration elicited by chemokines are still poorly documented.

Pyk-2 is a good candidate for integrating signals that control leukocyte migration, as this tyrosine kinase is activated by both integrins and chemokines. NK cells are especially suitable for this purpose as, unlike T cells, they express Pyk-2, but not p125 FAK, that can be also involved in cell motility.

Here we report that Pyk-2 regulates NK cell transendothelial migration in response to chemokines by controlling Rac activation and thus acts as an important receptor-proximal link between integrin and chemokine receptor signaling.

Materials and Methods

Abs and reagents

The following mouse mAbs were used: anti-CD16 (B73.1) was provided by Dr. G. Trinchieri (Schering Plough, Dardilly, France); anti-CD56 (C218) was provided by Dr. A. Moretta (University of Genoa, Genoa, Italy); anti-αβ (HP2/1) integrin subunit was purchased from Immunotech (Marseille, France); anti-β2 (TS1/18) was a gift from Dr. F. Sanchez-Madrid (La Princesa Hospital, University of Madrid, Madrid, Spain); anti-phosphotyrosine (anti-pTyr; 4G10), anti-Vav1, and anti-Rac (23A8) were purchased from Upstate Biotechnology (Lake Placid, NY); anti-paxillin (clone 349) and anti-paxillin kinase linker (p95PKL; clone 13) were purchased from Transduction Laboratories (Lexington, KY). Rabbit antiserum anti-Rac 600, directed against a synthetic peptide corresponding to residues 684–762 of the C-terminal portion of Pyk-2, was provided by Dr. J. Schlessinger (Department of Pharmacology, Yale University School of Medicine, New Haven, CT); goat antiserum against Pyk-2 (N-19 and C-19) and the affinity-purified rabbit antiserum against Rac-1 were purchased from Santa Cruz Biotechnology (Santa Cruz, CA); affinity-purified rabbit antiserum against mouse Ig or goat Ig was purchased from Zymed Laboratories (San Francisco, CA). Affinity-purified (Fab'), of anti-mouse Ig (GAM) was purchased from Cappell Laboratories (Cooper Biomedical, Malverna, PA).

ICAM-1 and VCAM-1 adhesive proteins were purchased from Bender MedSystems (Vienna, Austria) and R&D Systems (Minneapolis, MN), respectively. Monoclonal chemotactic protein 1 (MCP-1)-CCL2, macrophage inflammatory protein 1β (MIP-1β)-CCL4, fractalkine/CX3CL1, and TNF-α were purchased from R & D Systems. Pertussis toxin (PTX) was purchased from Sigma-Aldrich (St. Louis, MO).

Cells

Highly purified (>95%) cultured human NK cells were obtained by incubating for 10 days nylon-nonadherent PBMC (4 × 10^5 cells) with irradiated (3000 rad) EBV-transformed B cell line RPMI 8866 (1 × 10^6 cells) as previously described (19). The human endothelial cell line EA.Hy 926 was obtained from ATCC (Manassas, VA). A functional endothelial cell layer was grown in a 12-mm well plate (pore size, 3μm; pore size, 3μm; pore size, 3μm; pore size, 3μm) in endothelial cell medium (Life Technologies, Gaithersburg, MD) supplemented with 0.1% phosphate-free FCS. After stimulation, the cells were lysed, and immunoprecipitated samples were subjected to Rac-GTP loading assay, the results were evaluated as the Rac-GTP/Rac-GTP plus Rac-GDP ratio, as previously described (31). In some experiments Rac activation was evaluated by labeling cell lysates with the GST-p21-activated kinase (GAP) fusion protein (provided by Dr. J. G. Collard, The Netherlands Cancer Institute, Amsterdam, The Netherlands) bound to glutathione-coupled Sepharose beads at 4°C for 30 min, and bound active GTP-Rac molecules were analyzed by Western blotting using an anti-Rac mAb (32).

Recombinant vaccinia virus infection

cDNAs encoding wild-type Pyk-2 and the kinase-dead mutant of Pyk-2 (Pyk-M), were provided by Dr. J. Schlessinger (Department of Pharmacology, Yale University School of Medicine, New Haven, CT, Recombinant vaccinia virus encoding wild-type Pyk-2 or Pyk-M were generated in our laboratory as previously described (19).

Recombinant vaccinia virus infection encoding wild-type (WT) Rac-1, dominant-negative N17-Rac-1, or wild-type vaccinia virus alone (WR) were provided by Dr. P. Leibson (Mayo Clinic and Foundation, Rochester, MN). Semipurified recombinant vaccinia virus preparations were used to infect human NK cells for 1 h in serum-free medium at a multiplicity of infection of 20:1. The remainder of the infection (4 h) was conducted in RPMI 1640 with 10% FCS. Cellular debris were removed from infected NK cells by Lymphoprep (Nycomed, Oslo, Norway) gradient centrifugation, and viability was >95% before biochemical and functional assays.

[^2P]Orthophosphate labeling, cell stimulation, and lystate preparation

Human NK cells were labeled (2 × 10^5 cells/ml) for 4 h at 37°C with[^2P]Orthophosphate (0.2 mCi/ml, 4500 Ci/mmol; Amersham International, Little Chalfont, U.K.) in phosphate-free RPMI 1640 (Life Technologies, Gaithersburg, MD) supplemented with 0.1% phosphate-free FCS. Three × 10^7[^2P]-labeled NK cells were allowed to bind to untreated or TNF-α-treated EA.Hy endothelial cells at 37°C for 15 min. Incorporated radioactivity was quantified in cell lysates after cold 10% TCA precipitation, and equal amounts of[^2P]-labeled proteins from each cell lysate were immunoprecipitated with anti-Pyk-2 Abs.

As both NK and endothelial cells express Pyk-2, we evaluated the tyrosine phosphorylation status of NK cell-derived Pyk-2 by performing binding experiments using unlabeled NK cells and paraformaldehyde-fixed EA.Hy endothelial cells as previously reported (19). This treatment prevents a possible activation of kinases expressed by target cells and has no effect on their binding to NK cells.

In experiments involving Ab-mediated cell surface receptor engagement, NK cells (4 × 10^5 cells/300 μl/tube) incubated with saturating doses of the appropriate mAb for 30 min at 4°C were stimulated for different lengths of time with soluble GAG (1.5 μg/10^6 cells), GAG-coated polystyrene beads, or ICAM-1- or VCAM-1- precoated polystyrene beads at 37°C (19). NK cell (20 × 10^6 cells) stimulation was also performed using MCP-1/CCL2 (20 nM), MIP-1β/CCL4 (20 nM), or fractalkine/CX3CL1 (4 nM) for the indicated time periods at 37°C. Cell lysates, immunoprecipitation, and immunoblotting analysis were performed as previously described (18).

Rac activation assay

To estimate Rac-1 activation, human NK cells were starved for 3 h in phosphate-free RPMI and labeled for 3 h with[^2P]Orthophosphate (0.5 mCi/ml, 4500 Ci/mmol; Amersham International, Little Chalfont, U.K.) in phosphate-free RPMI 1640 (Life Technologies, Gaithersburg, MD) supplemented with 0.1% phosphate-free FCS. After stimulation, the cells were lysed, the immunoprecipitated samples were subjected to Rac-GTP loading assay, and the results were evaluated as the Rac-GTP/Rac-GTP plus Rac-GDP ratio, as previously described (31). In some experiments Rac activation was evaluated by incubating cell lysates with the GST-p21-activated kinase (GAP) fusion protein (provided by Dr. J. G. Collard, The Netherlands Cancer Institute, Amsterdam, The Netherlands) bound to glutathione-coupled Sepharose beads at 4°C for 30 min, and bound active GTP-Rac molecules were analyzed by Western blotting using an anti-Rac mAb (32).

Migration assay

Cell migration was measured using a Transwell migration chamber (diameter, 24 mm; pore size, 3 μm; Costar, Cambridge, MA). NK cells were infected for 5 h with recombinant vaccinia viruses encoding wild-type Pyk-2, Pyk-M, WT Rac-1, dominant-negative N17-Rac-1, or vaccinia virus alone (WR). Infected cells (4 × 10^5 cells/well) were then assayed for their ability to migrate through a monolayer of TNF-α (10 ng/ml)-pretreated endothelial cells or through ICAM-1 (5 μg/ml)-, VCAM-1 (1 μg/ml)-, or BSA (5 μg/ml)-coated filters. For the migration on ICAM-1 or VCAM-1, 5 nM MCP-1/CCL2 was added in the lower compartment. After 60 min at 37°C, the number of migrated cells was counted using an inverted microscope with ×100 magnification. Data are expressed as the mean ± SD, obtained from three independent experiments.

Infection with WT virus alone (WR) or only significantly reduced (10–20%) NK cell migration (data not shown).

Results

Binding of cultured NK cells to endothelium results in tyrosine phosphorylation of NK cell-derived Pyk-2

To understand the signaling pathways involved in leukocyte migration across endothelium, we first investigated whether Pyk-2, a nonreceptor PTK belonging to the FAK family, could be phosphorylated upon binding of NK cells to endothelium. To analyze NK cell-derived, but not target cell-derived, Pyk-2, human NK cells were labeled with[^2P]Orthophosphate and then allowed to bind to untreated or TNF-α-treated EA.Hy endothelial cells for different periods of time. As shown in Fig. 1A, binding of NK cells
FIGURE 1. Binding of human NK cells to endothelial cells induces Pyk-2 tyrosine phosphorylation: involvement of integrin and chemokine receptors. A, [32P]orthophosphate-labeled human NK cells were incubated for 15 min at 37°C with endothelial cells (E.C.) and were left untreated or were treated with TNF-α (10 ng/ml). Cell lysates were immunoprecipitated with anti-Pyk-2 (600) Ab. The radioactive protein complexes were resolved by 7% SDS-PAGE, followed by autoradiography (top panel) or were transferred to nitrocellulose and immunoblotted with anti-Pyk-2 Ab (bottom panel). Sizes are indicated in kDa and the position of Pyk-2 is indicated with an arrow. B, Human NK cells were incubated with paraformaldehyde-fixed endothelial cells (E.C.), untreated or treated with TNF-α (10 ng/ml), for the indicated time periods at 37°C. Cell lysates were immunoprecipitated with anti-Pyk-2 (C19) Ab. The resulting protein complexes were resolved by 7% SDS-PAGE, transferred to nitrocellulose, and immunoblotted with anti-pTyr (4G10; top panel) or anti-Pyk-2 (N19; bottom panel) Ab. C, Human NK cells pretreated with vehicle (DMSO) or PTX (100 ng/ml) for 90 min at 37°C were allowed to bind for 15 min at 37°C to TNF-α (10 ng/ml)-pretreated endothelial cells fixed with paraformaldehyde. Cell lysates were analyzed as described in B. D, Human NK cells pretreated with vehicle (DMSO) or PTX, as described in C, were first incubated with control medium (−), anti–β2 (TS1/18), anti–α4 (HP2/1), or anti-CD56 (C218) mAb for 30 min at 4°C and then cross-linked with GAM for 5 min at 37°C. Cell lysates were analyzed as described in B. E, Human NK cells pretreated with vehicle (DMSO) or PTX, as indicated in C, were stimulated with control medium (−), MCP-1/CCL2 (20 nM), or fractalkine/CX3CL1 (FLK; 4 nM) for 5 min at 37°C. Cell lysates were immunoprecipitated with anti-Pyk-2 (C19) Ab and analyzed as indicated in B. F, Human NK cells were stimulated with control medium (−) or ICAM-1-, VCAM-1-, or BSA-coated polystyrene beads for the indicated time periods at 37°C. Cell lysates were immunoprecipitated with anti-Pyk-2 (C19) Ab and analyzed as indicated in B. The results shown are representative of one of three independent experiments.
to endothelial cells resulted in Pyk-2 phosphorylation, which was higher when endothelial cells were pretreated with TNF-α. This event correlated with increased Pyk-2 tyrosine phosphorylation, as demonstrated by immunoblotting analysis with anti-pTyr mAb of Pyk-2 immunoprecipitates from NK cells stimulated with prefixed endothelial cells (Fig. 1B). In response to untreated endothelial cells, Pyk-2 tyrosine phosphorylation was evident at 15 min and was further increased at 30 min upon stimulation, whereas when NK cells were allowed to bind to TNF-α-treated endothelial cells, maximal tyrosine phosphorylation was already observed at 15 min. In addition to Pyk-2, other proteins migrating at ~97 and ~65–68 kDa were present in the anti-Pyk-2 immunoprecipitates, and their tyrosine phosphorylation status was enhanced with the same kinetics of Pyk-2 (data not shown). No phosphorylated proteins were detected in rabbit anti-mouse Ig immunoprecipitates used as a control (data not shown).

The increased level of Pyk-2 phosphorylation in response to TNF-α-treated endothelial cells was associated with increased NK cell binding, which can be attributable to an enhanced expression of ICAM-1 and VCAM-1 integrin ligands on TNF-α-treated cells (data not shown). Moreover, TNF-α can induce the expression of chemokines on endothelial cells, which may also promote NK cell binding to endothelial cells by regulating integrin avidity (7, 8) and/or activating Pyk-2 (14–16).

We then investigated the contributions of chemokines and integrins mediating NK cell adhesion to activated endothelium, namely α5β1 and LFA-1 (23–25), in the induction of Pyk-2 tyrosine phosphorylation.

We evaluated the possible involvement of chemokine receptors belonging to the G protein-coupled receptor family in the endothelial cell-induced Pyk-2 tyrosine phosphorylation either by pretreating NK cells with PTX, a pharmacological inhibitor of G protein-coupled receptors or by NK cell stimulation with chemokines such as MCP-1/CCL2 and fractalkine/CX3CL1 produced by activated endothelial cells or with MIP-1β/CCL4 (5, 26–29). Pretreatment with PTX completely inhibited Pyk-2 tyrosine phosphorylation induced by chemokines (Fig. 1E) and only partially reduced that triggered by NK cell binding to TNF-α-activated endothelial cells (Fig. 1C), while it did not affect that triggered by integrin cross-linking (Fig. 1D). Stimulation of NK cells with chemokines resulted in a rapid induction of Pyk-2 tyrosine phosphorylation, which was already evident at 1 min and, differently from that induced by integrins (18, 19), rapidly declined between 5 and 10 min (data not shown). Moreover, stimulation of NK cells with the purified ligands for α5β1 (VCAM-1) and for LFA-1 (ICAM-1) resulted in a rapid increase in Pyk-2 tyrosine phosphorylation (Fig. 1F). Taken together these findings indicate that NK cell binding to endothelial cells triggers Pyk-2 tyrosine phosphorylation as a result of integrin and chemokine receptor stimulation.

Pyk-2 controls transendothelial migration of cultured NK cells

To provide direct evidence of the functional role of Pyk-2 in the regulation of NK cell migration across the endothelium, NK cells were infected with recombinant vaccinia viruses encoding the WT (Pyk-2) or Pyk-M, able to prevent Pyk-2 enzymatic activity (12, 19). Infected NK cells were then assayed for their ability to migrate through a monolayer of TNF-α-treated endothelial cells (Fig. 2A) or ICAM-1- or VCAM-1-coated filters in response to the chemotactant MCP-1/CCL2 (Fig. 2B). Overexpression of Pyk-M significantly inhibited NK cell transendothelial migration as well as chemokine-induced transmigration of NK cells on ICAM-1 or VCAM-1 endothelial ligands. By contrast, enhanced cell migration was observed upon overexpression of WT Pyk-2. Comparable levels of WT Pyk-2 and Pyk-M overexpression were demonstrated by Western blot of whole-cell lysates (Fig. 2, inset panel). These data indicate that Pyk-2, through its kinase activity, controls the signaling pathways leading to NK cell migration.

FIGURE 2. Pyk-2 controls NK cell transendothelial migration. NK cells infected with recombinant vaccinia virus encoding WT Pyk-2, Pyk-M, or vaccinia virus alone (WR) were assayed for their ability to migrate through a monolayer of TNF-α (10 ng/ml)-pretreated endothelial cells (A) or through ICAM-1 (5 μg/ml)-, VCAM-1 (1 μg/ml)-, or BSA (5 μg/ml)-coated filters using MCP-1/CCL2 (5 nM) as chemoattractant (B). Data are expressed as the mean ± SD percentage of migrated cells obtained from three independent experiments. The percentage of NK cell migration through ICAM-1- or VCAM-1-coated filters in the absence of chemoattractant was <1% (data not shown). The inset panel shows Pyk-2 and Pyk-M overexpression.
Binding of cultured human NK cells to endothelial cells or stimulation of cultured NK cells with ICAM-1, VCAM-1, or chemokines results in Rac-1 activation: role of Rac-1 in NK cell transendothelial migration

Rac is a member of the Rho family of small GTPases that are implicated in a wide spectrum of cellular processes, including cytoskeletal organization, cell adhesion, cell polarity, cell motility, and transcriptional activation (33, 34). It has been reported that Pyk-2 activation acts as a receptor-proximal event controlling MAPK activation in response to different stimuli, and a link between Pyk-2 and Ras in the control of ERK activation has been proposed (12, 16). However, no direct demonstration that Pyk-2 can control Rac-1 activation has been made to date.

We therefore investigated whether binding of human NK cells to endothelial cells or to ICAM-1 or VCAM-1 integrin ligands or NK cell stimulation with chemokines could result in Rac-1 activation. We first performed GTP-loading experiments in human NK cells upon binding to endothelial cells pretreated or not with TNF-α for 30 min. Chromatographic analysis of nucleotides bound to Rac-1 indicates that NK cell binding to endothelial cells results in a 1.5-fold increase in the ratio of GTP-bound Rac-1, whereas a 2-fold increase was observed in response to TNF-α-treated endothelial cells (Fig. 3A). Accordingly, using a GST-PAK fusion protein that binds the active form of Rac-1, we found that stimulation of NK cells with anti-β2- or anti-α4-specific mAb or with ICAM-1 or VCAM-1 proteins resulted in Rac-1 activation. Anti-CD56 control mAb or BSA treatment did not significantly activate Rac-1 compared with untreated samples (Fig. 3B). Moreover, NK cell stimulation with chemokines resulted in a rapid induction of Rac-1 activation that was inhibited by pretreatment with PTX (Fig. 3C). Chemokine-induced Rac activation was already evident at 30 s and persisted until 10 min after stimulation (data not shown).

The activation of Rac-1 in NK cells upon binding to endothelial cells and integrin or chemokine receptor engagement prompted us to investigate whether activation of this small GTP-binding protein is required for the integrin-supported NK cell migration across endothelium. NK cells were infected with recombinant vaccinia viruses encoding the WT Rac-1 or dominant negative N17-Rac-1. Infected human NK cells were then assayed for their ability to migrate through a monolayer of TNF-α-treated endothelial cells (Fig. 4A) or on ICAM-1- or VCAM-1-coated filters in response to the chemoattractant MCP-1/CCL2 (Fig. 4B). Overexpression of dominant negative N17-Rac-1 resulted in inhibition of NK cell transendothelial migration as well as of chemokine-induced transmigration of NK cells on ICAM-1- or VCAM-1-coated filters; conversely, overexpression of WT Rac-1 significantly enhanced NK cell migration. Equal levels of overexpression of the WT Rac-1 and N17-Rac-1 constructs was demonstrated by Western blot of whole-cell lysates (Fig. 4, inset panel).

![Figure 3](http://www.jimmunol.org/)

**Figure 3.** Activation of Rac upon NK cell binding to endothelial cells or integrin or chemokine receptor engagement. A, 32Porthophosphate-labeled human NK cells were incubated for 30 min with endothelial cells (EAHY) and were left untreated or were treated with TNF-α (10 ng/ml). Cell lysates were immunoprecipitated with anti-Rac polyclonal Ab, and nucleotides were then eluted and separated by TLC. The positions at which GDP and GTP standards run are indicated. B, Human NK cells were stimulated for 5 min at 37°C with control medium (−) or polystyrene beads coated with anti-β2 (TS1/18), anti-α4 (HP2/1), or anti-CD56 (C218) mAb or with ICAM-1, VCAM-1, or BSA. Cell lysates were incubated with GST-PAK fusion protein, and bound active GTP-Rac molecules were evaluated by Western blotting using an anti-Rac mAb (top panel). Cell lysates probed for total Rac are shown as loading controls (bottom panel). C, Human NK cells pretreated with vehicle (DMSO) or PTX, as described in Fig. 1C, were stimulated with control medium (−), MCP-1/CCL2 (20 nM), or fractalkine/CX3CL1 (FLK; 4 nM) for 5 min at 37°C. Cell lysates were analyzed as indicated in B. These results represent one of three independent experiments.
These data indicate that NK cell binding to endothelial cells or integrin or chemokine receptor engagement results in Rac-1 activation, and Rac-1 is a crucial component in the signaling pathway leading to the integrin-supported transendothelial migration of NK cells elicited by chemokines.

Pyk-2 controls Rac-1 activation in cultured human NK cells

To investigate whether Rac-1 activation is dependent on Pyk-2 activity, human NK cells were infected with recombinant vaccinia viruses encoding the wild-type Pyk-2 or Pyk-M. Infected cells

**FIGURE 4.** Rac controls NK cell transendothelial migration. NK cells infected with recombinant vaccinia virus encoding WT Rac, N17-Rac, or vaccinia virus alone (WR) were assayed for their ability to migrate through a monolayer of TNF-α (10 ng/ml)-pretreated endothelial cells (A) or through ICAM-1 (5 μg/ml), VCAM-1 (1 μg/ml), or BSA (5 μg/ml)-coated filters using MCP-1/CCL2 (5 nM) as chemoattractant (B). Data are expressed as the mean ± SD percentage of migrated cells obtained from three independent experiments. The percentage of NK cell migration through ICAM-1- or VCAM-1-coated filters in the absence of chemoattractant was <1% (data not shown). The inset panel shows Rac and N17-Rac overexpression.

**FIGURE 5.** Pyk-2 controls integrin-induced Rac activation in human NK cells. A, NK cells infected with recombinant vaccinia viruses encoding WT Pyk-2, Pyk-M, or vaccinia virus alone (WR) were stimulated with control medium (−) or polystyrene beads coated with ICAM-1, VCAM-1, or BSA for 5 min at 37°C. Cell lysates were incubated with GST-PAK fusion protein, and bound active GTP-Rac molecules were analyzed by Western blotting using an anti-Rac mAb (top panel). Densitometric analysis obtained comparing active Rac in WR, Pyk-2, and Pyk-M samples shows that Pyk-M overexpression results in 65 ± 10 and 73 ± 15% inhibition of Rac activation upon ICAM-1 or VCAM-1 stimulation, respectively. Pyk-2 overexpression only marginally affected integrin-induced Rac activation. B, NK cells infected with recombinant vaccinia viruses encoding WT Pyk-2, Pyk-M, or vaccinia virus alone (WR) were stimulated with control medium (−), MCP-1/CCL2 (20 nM), or fractalkine/CX3CL1 (FLK; 4 nM) for 5 min at 37°C. Cell lysates were analyzed as indicated in A. Cell lysates probed for total Rac are shown as loading controls (middle panels). The amounts of overexpressed Pyk-2 and Pyk-M are shown in the bottom panels. These results represent one of three independent experiments.
were then left untreated or stimulated with VCAM-1, ICAM-1 or BSA, or with chemokines such as MCP-1/CCL2 and Fractalkine/CX3CL1, and Rac-1 activation was analyzed using GST-PAK fusion protein in an affinity precipitation assay followed by immunoblotting analysis with anti-Rac mAb.

Overexpression of Pyk-M almost completely inhibited integrin- (Fig. 5A) and chemokine- (Fig. 5B) induced Rac-1 activation, thus demonstrating that chemokine- and β1 and β2 integrin-mediated Rac-1 activation is under the control of Pyk-2 kinase activity.

We then investigated the molecular mechanisms by which Pyk-2 controls Rac activation. We have previously reported that β1 integrin cross-linking on human NK cells results in tyrosine phosphorylation of the exchange factor for Rac-1, p95 Vav (31). Moreover, it has been recently described that paxillin, through p95 PKL, associates with PAK-interacting exchange factor (PIX), another guanine nucleotide exchange factor for Rac and Cdc42 (35). The presence of a tyrosine-phosphorylated protein migrating at ~97 kDa in Pyk-2 immunoprecipitates upon NK cell binding to endothelial cells or integrin stimulation, prompted us to investigate whether p95 Vav and/or p95 PKL/PIX complex were involved in the Pyk-2-mediated control of Rac-1 activation.

FIGURE 6. Pyk-2 immunocomplexes contain paxillin and p95 Vav, which undergo tyrosine phosphorylation upon integrin ligation on human NK cells. Human NK cells were first incubated with control medium (−) or anti-α4 (HP2/1), anti-β2 (TS1/18), or anti-CD56 (C218) mAb for 30 min at 4°C and then cross-linked with GAM for 5 min at 37°C. Cell lysates were immunoprecipitated with anti-Pyk-2 (C19) Ab (A) and reimmunoprecipitated with anti-paxillin mAb following Pyk-2 immunodepletion (B). All the immunoprecipitates obtained were sequentially immunoblotted with anti-pTyr (4G10), anti-p95 PKL (clone 13), anti-Vav, anti-paxillin (clone 349), or anti-Pyk-2 (N19) Ab. These results represent one of three independent experiments.

Discussion

Although PTK activation has been implicated in the control of leukocyte trafficking and chemotactic response (36–38), the tyrosine kinases involved remain still largely undefined. Previous evidence indicates that PTKs belonging to the Src family, namely...
Hck, Fgr, and Lyn, regulate the migration of myeloid leukocytes into injured tissues by controlling \( \beta_1 \) integrin signaling and adhesive events (39, 40). In addition, Lck, independently of ZAP-70, has been shown to up-regulate \( \alpha_\beta_2 \) integrin affinity in response to the stromal cell-derived factor-1/CXCL12 chemokine in Jurkat T lymphoblastoid cells (41). Among Syk family PTKs, ZAP-70 is essential for LFA-1-dependent chemokine-elicted chemotaxis and in vivo metastatic invasion of tumorigenic T cell hybridomas, whereas it is not required for integrin-independent cell migration induced by high concentrations of stromal cell-derived factor-1/CXCL12 (42).

Nothing is known about the role played by PTKs belonging to the FAK family in leukocyte transmigration during inflammatory responses.

Herein we show that Pyk-2 regulates transendothelial migration of cultured NK cells in response to chemokines by controlling Rac activation, and thus acts as an integration point between integrin and chemokine receptor stimulation.

Pyk-2 is rapidly activated by NK cell binding to endothelial cells as well as upon cross-linking of LFA-1 and \( \alpha_\beta_1 \) integrins by their respective endothelial ligands, ICAM-1 and VCAM-1, or by endothelial cell-derived chemokines mediating NK cell chemotaxis, such as MCP-1/CCL2 and fractalkine/CX3CL1. Moreover, we demonstrate a functional role for Pyk-2 in NK cell migration across activated endothelial cells or in MCP-1/CCL2 elicited migration on ICAM-1 and VCAM-1 integrin ligands by WT Pyk-2 overexpression.

The migratory response and the signaling events elicited by MCP-1/CCL2 in cultured NK cells are probably mediated by CCR2, which is the key regulator of actin cytoskeleton dynamics. To our knowledge, Rac activation is rapidly induced by NK cell interaction and chemokine receptor stimulation. Pyk-2 has been proposed to contribute to regulate cell positioning by transducing signals from a chemokine receptor to an integrin (17).

Our study also shows that Pyk-2 controls NK cell transendothelial migration by activating the Rho family small G protein Rac, a key regulator of actin cytoskeleton dynamics. To our knowledge, this is the first evidence of Pyk-2-mediated regulation of Rac activation. Rac activation is rapidly induced by NK cell interaction with endothelial cells or upon cross-linking of LFA-1 and \( \alpha_\beta_1 \) integrins by their respective ICAM-1 and VCAM-1 ligands or specific mAbs as well as upon chemokine receptor stimulation. We have also demonstrated that Rac is functionally involved in the NK cell migration across activated endothelial cells or in MCP-1/CCL2-elicited migration on ICAM-1 and VCAM-1 integrin ligands by WT Rac overexpression. Finally, we provide direct evidence that Pyk-2 activation is required for chemokine- and integrin-mediated activation of Rac by overexpression of the kinase-dead mutant of Pyk-2. Pyk-2-mediated regulation of Rac signaling involves control of the guanine exchange factor activity of Vav, but not that of PIX, an exchange factor for Rac that is associated with paxillin through p95 PKL. Indeed, Vav associates with Pyk-2 and is rapidly tyrosine-phosphorylated in response to \( \beta_1 \) and \( \beta_2 \) integrins or upon NK cell binding to endothelial cells (data not shown), and Pyk-M overexpression results in decreased Vav tyrosine phosphorylation. In addition, p95 PKL does not coprecipitate with Pyk-2, and thus it is unlikely that Pyk-2 can be part of a complex containing paxillin, PKL, and PIX.

Our findings on the critical role of Rac in the control of NK cell transendothelial migration are consistent with in vivo evidence that neutrophils from Rac-/-/- mice display a deficient chemotaxis that is accompanied by reduced generation of filamentous actin in response to chemoattractants (46). In addition, Rac-2 has been involved in the migratory responses of leukocytes to chemoattractant stimuli such as FMLP and leukotriene B4 (47–49). Furthermore, Rac-1 has been implicated in the in vivo invasiveness of T lymphoma cells (50).

Whether Rac might be also required for the chemokine-induced control of integrin avidity is presently unknown, although constitutively active Rac has been reported to up-regulate integrin-mediated T cell adhesion (51).

Transduction of the migratory signals depends on a complex interplay among molecules that regulate actin, myosin, and other cytoskeleton components and results in the formation of protrusive structures at the front of the migrating cell and retraction at the rear of the cell (52). Rac plays a pivotal role in the regulation of actin cytoskeleton both by stimulating the formation of lamellipodia and membrane ruffles and by reducing contractile forces (33, 34). Thus, Rac might control leukocyte polarization and migration by connecting integrin and chemokine receptor signaling to diverse downstream effectors that induce actin nucleation and polymerization and reduce actomyosin assembly (53).

Most studies aimed at delineating the signaling pathways responsible for leukocyte transendothelial migration deal with chemokine receptor-initiated signals. On the other hand, studies concerning the migratory behavior of adherent cells such as fibroblasts or epithelial cells mainly analyze integrin-triggered signaling cascades, even though recent evidence indicate that chemokines may also control trafficking of nonhemopoietic cells (54). Our results indicate that Pyk-2-controlled signaling pathways initiated by both integrin and chemokine receptors function in a coordinated and integrated manner for full activation of the NK cell migratory response.

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