Investigation of fascin1, a marker of mature dendritic cells, reveals a New role for IL-6 signaling in CCR7-mediated chemotaxis.

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Abstract

Migration of mature dendritic cells (DCs) to lymph nodes is critical for the initiation of adaptive immunity. CCR7, a G-protein-coupled receptor for CCL19/21 chemokines, is known to be essential for chemotaxis of mature DCs, but the molecular mechanism linking inflammation to chemotaxis remains unclear. We previously demonstrated that fascin1, an actin-bundling protein, increases chemotaxis of mature mouse DCs. In this paper we demonstrated that fascin1 enhanced Interleukin (IL)-6 secretion and signaling of mature mouse DCs. Furthermore, we demonstrated that IL-6 signaling is required for chemotaxis. Blockage of IL-6 signaling in WT DCs with an anti-IL-6 receptorα (IL-6Rα) antibody inhibited chemotaxis toward CCL19. Likewise, knockout (KO) of IL-6Rα inhibited chemotaxis of bone marrow-derived DCs (BMDCs). The addition of soluble IL-6Rα and IL-6 rescued chemotaxis of IL-6Rα KO BMDCs, underscoring the role of IL-6 signaling in chemotaxis. We found that IL-6 signaling is required for internalization of CCR7, the initial step of CCR7 recycling. CCR7 recycling is essential for CCR7-mediated chemotaxis, explaining why IL-6 signaling is required for chemotaxis of mature DCs. Our results have identified IL-6 signaling as a new regulatory pathway for CCR7/CCL19-mediated chemotaxis, and suggest that rapid migration of mature DCs to lymph nodes depends on inflammation-associated IL-6 signaling.

Keywords

IL-6; IL-6Rα; fascin; dendritic cells; chemotaxis; CCR7 internalization

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Introduction

Dendritic cells (DCs) are professional antigen presenting cells, playing central roles in adaptive immunity(1, 2). When DCs encounter pathogens, they undergo terminal differentiation, called maturation. Maturation causes massive changes in gene expression as well as morphology and motility, altering the function of DCs from antigen sampling to antigen presentation. While immature DCs move around the peripheral tissues to function as a sentinel, mature DCs respond to chemoattractant stimuli and migrate into lymph nodes as quickly as possible in order to present antigen information to T-cells. Thus, chemotactic migration of mature DCs to lymph nodes is essential for initiating adaptive immunity(3, 4).

Directed migration of mature DCs to lymph nodes requires induction of CCR7, a G-protein coupled receptor, in mature DCs(5–10). CCR7 senses its ligand chemokines (CCL19/21) expressed in lymph nodes(9–11). A gradient of CCL19/21 allows mature DC to migrate from the cell periphery to lymph nodes. The binding of CCL19/21 to CCR7 induces several signal transduction events including activation of MAPKs (ERK1/2 and P38MAPK), PI3K/ AKT, tyrosine kinases, Rac, Cdc42 and Rho GTPases(11–16). These downstream signaling events are suggested to be involved in chemotactic migration and survival of mature DCs(12, 13, 17). However, the molecular mechanism linking inflammation to chemotaxis of mature DCs remains unclear.

Fascin1, an actin-bundling protein, is induced to a great extent upon DC maturation(18, 19). Fascin1 is known to promote assembly of filopodia and cell migration(20–22). However, fascin1 is curiously absent in immature DCs or other blood cells including B- and T-lymphocytes, macrophages and neutrophils(23). This unique expression pattern suggests that fascin1 plays a unique role in the motility of mature DCs. We found, by analyses of fascin1 KO mice, that fascin1 promotes *in vivo* migration of ear skin DCs into draining lymph nodes after FITC ear painting(24). Fascin1 also increases *in vitro* cell motility and chemotaxis of mature, bone marrow-derived DCs (BMDCs) toward CCL19(24). The importance of fascin1 in cell motility is also observed with other types of cells including normal and transformed cultured cells(25–30).

We previously found that fascin1 KO mature DCs were more susceptible to *Listeria* infection than WT mature DCs(31). Because maturation of DCs triggers secretion of several proinflammatory cytokines including IL-1, IL-6, IL-12 and TNF, the finding has prompted us to examine whether *Listeria* infection alters serum cytokine profiles between WT and fascin1 KO mice. We found that the serum level of IL-6 cytokine is specifically reduced in fascin1 KO mice than in WT mice after *Listeria* infection. We also found that fascin1 KO BMDCs matured by lipopolysaccharide (LPS) showed reduced secretion of inflammatory cytokines including IL-6 and TNFα. Because IL-6 is shown to promote cell motility in a variety of tumor cell lines(32–36), we examined whether fascin1-mediated increase in IL-6 is involved in chemotactic migration of DCs. We found that IL-6 signaling is required for effective chemotaxis of mature DCs toward CCL19, thereby linking IL-6 mediated inflammation to chemotaxis of mature DCs.

Methods and Materials:

Reagents, antibodies and mice:

The primary antibodies used were: APC- (cat #,17–0862-81) and FITC-conjugated rat anti-CD86 (11–0862-81), AF647-labeled rat anti-mouse IL-6 (11–7061-81) and unconjugated rat anti-mouse CCR7 antibody (16–1971-85, clone 4B12, all from eBioscience, San Diego, CA); FITC-labeled MHC-II (107605), FITC-labeled CD80 (104705), and unconjugated anti-mouse IL-6Rα (115807, all from Biolegend, San Diego, CA); goat anti-mouse IL-6Rα (AF1830, R&D systems, Minneapolis, MN); normal goat IgG antibody (AB-108-C, R&D systems); rabbit anti-gp130 (sc-9045, Santa Cruz Biotech, Dallas, TX); and rabbit anti-CCR7 polyclonal antibody (TA310252, Origene, Rockville, MD). The secondary antibodies were FITC-, Cy3-, or AF647-labeled anti-rat Fab fragment and FITC- or Cy3-labeled anti-goat or anti-rabbit antibodies (Jackson ImmunoResearch, West Grove, PA). GM-CSF and CCL19 (MIP3β) were purchased from Invitrogen (Carlsbad, CA) and Miltenyi Biotec (Auburn, CA).

Fascin1 KO mice were prepared as previously reported[37]. For each experiment with homozygous mice, their WT littermates were used as a control whenever possible. IL-6Rα KO mice[38] were obtained from Jackson Laboratory and maintained at Heinrich-Heine University of Düsseldorf. WT or heterozygous littermate mice were used as a control. No phenotypic differences were detected between WT and heterozygous mice. Legs of these mice were shipped to USA, and used for the preparation of BMDCs within 24–48hr. All experimental procedures and protocols for mice are approved by the Animal Care and Facilities Committee at both Rutgers and University of Düsseldorf.

Preparation of bone marrow-derived DCs (BMDCs) and spleen DCs:

Preparation of mouse BMDCs was according to the method described in Inaba *et al*[39] with slight modification[24]. Briefly, single cell suspension was prepared from bone marrow of femurs and tibias, and plated on 65mm dishes in Iscove's modified Dulbecco's Medium containing 10% fetal calf serum and 10ng/ml of GM-CSF for 7–8 days. Non-adherent cells were collected and DCs were purified by centrifugation over a 13.7% (w/v) metrizamide discontinuous gradient. More than 85% of cells collected at the interface of the gradient were positive for CD11c. Cells were matured by overnight culture by the addition of 100ng/ml of lipopolysaccharide (LPS, Sigma).

Spleen DCs were prepared essentially according to the protocol described in [40] with slight modifications. Briefly, a single cell suspension was prepared by treating spleens with collagenase. After overnight culture, dendritic cells were purified with two rounds of MACS magnetic separation using mouse CD11c microbeads (Miltenyi Biotec) according to the manufacturer's instructions, followed by metrizamide discontinuous gradient centrifugation. More than 85% of cells are CD11c and MHC-II positive.

Cytokine profiling:

For *in vivo* cytokine profiling, WT and fascin1 KO mice were intravenously infected with *Listeria* monocytogenes (10403S, 1×10^4 cfu/mouse). Two days later, sera were taken

from euthanized mice and used for cytokine profiling with Mouse Cytokine Antibody Array C series 2000 (spanning 144 unique mouse cytokines/chemokines) according to the manufacturer's instructions (RayBiotech). For analyses of cytokines in culture supernatants of BMDCs, WT and fascin1 KO BMDCs were cultured overnight after addition of LPS (100ng/ml). Culture supernatants were then used for profiling of inflammatory cytokines using a RayBio Quantibody mouse Th17 array1 according to the manufacturer's instructions (RayBiotech). The Quantibody array allows us to quantitatively determine the concentrations of 18 cytokines/chemokines (IL-1β, IL-2, IL-4, IL-5, IL-6, IL-10, IL-12 p70, IL-17, IL17F, IL-21 IL-22, IL-23, IL-28, IFNγ, MIP-3α, TGFβ1, and TNFα. The data have been deposited in NCBI's Gene Experssion Omnibus(41) and are accessible through GEO Series accession number GSE174285, https://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE174285). ELISA to determine IL-6 was performed using an ELISA kit from BD biosciences according to the manufacturer's instructions.

Proximity Ligation Assay (PLA) to determine IL-6Rα-gp130 association:

PLA was performed according to the manufacturer's instruction (O-link Bioscience, Uppsala, Sweden) with slight modification as described before(31). Briefly, BMDCs were fixed with 3.7% formaldehyde for 10min. Fixed BMDCs were incubated with anti-gp130 rabbit polyclonal and anti-IL-6Rα goat polyclonal antibodies. The rabbit and goat antibodies were labeled with anti-rabbit and anti-goat PLA probes, respectively, each of which was conjugated with oligonucleotides. If they were within ~40nm, these nucleotides could be ligated to form a closed circle, which was amplified with DNA polymerase and detected with fluorescently labeled oligonucleotides.

Modified Boyden chamber:

Twelve-well tissue culture inserts (3μm hole, Greiner Bio-One, Monroe, NC) were coated with collagen (50μg/ml) as described(42) and used for modified Boyden chamber assays. Equal number of WT or fascin1 KO BMDCs were matured in the presence of LPS (100ng/ml) overnight. Mature WT, fascin1 KO BMDCs or IL-6Rα-blocked BMDCs (2×10^5 cells) were placed on top wells. CCL19 (MIP3β), a chemokine for mature DCs, was added in bottom wells at the concentration of 0.6μg/ml. To determine basal cell migration without chemokine, CCL19 was omitted from the bottom wells. After 2.5hr incubation, cells migrated into the bottom wells were counted. Chemotaxis indexes were determined by dividing the number of cells migrated in the presence of CCL19 with the number of cells migrated in the absence of CCL19. To block IL-6 signaling, a neutralizing IL-6Rα antibody (AF1830, Goat polyclonal, R&D Systems) was added to mature DCs at a final concentration of 1μg/ml. The same concentration of normal goat IgG antibody (AB-108-C, R&D systems) was used as a control.

Modified Boyden chamber assays of IL-6Rα KO and WT (or heterozygous) BMDCs toward CCL19 were performed as described above. To restore IL-6 signaling of IL-6Rα KO DCs, human IL-6 (15ng/ml, 206-IL, R&D Systems) and soluble IL-6Rα (sIL-6Rα, 25ng/ml, 227-SR, R&D Systems) were added. In some experiments, collagen-coated, Transwell plates from Corning (3μm hole, Corning, Lowell, MA) were used. Because cells migrated

much more slowly with Corning's collagen-coated Transwells, the assays with Corning's Transwells were performed overnight.

Live cell imaging and chemotaxis analyses:

Chemotaxis of BMDCs toward CCL19 gradient in collagen gel was assayed according to Sixt and Lammermann(43). Briefly, BMDCs were mixed with rat tail collagen, Type I (unpepsinized native collagen, final concentration, 1.5mg/ml, ibidi, Fitchburg, WI) and the mixture was polymerized in a chamber. After addition of CCL19 (0.6μg/ml) at the top of the collagen gel, migration of BMDCs was observed by time-lapse microscopy at 2min intervals for 60–90min. Migration tracks were obtained by MTrackJ (imageJ)(44), and migration tracks, rose plot diagrams (with an interior angle of 66 degrees and an interval angle of 10 degrees), directness and migration speeds were obtained by Chemotaxis and Migration Tool software (ibidi USA Wisconsin). Twenty to ninety migrating cells were analyzed for each experiment. Migration speeds and directness were determined from migration tracks during 60min. Immovable DCs trapped in a collagen gel were not included for analyses.

Migration of BMDCs was also examined in the absence of CCL19 chemokine or in the presence of a uniform concentration of CCL19 (0.6μg/ml). For experiments without CCL19, CCL19 was not added on top of the collagen gel. For experiments with CCL19, CCL19 was added to both the collagen gel and its surrounding medium.

In vivo migration assays of BMDCs:

BMDCs (1×10^6 cells) were labeled with a cell Trace-CSFE dye (Thermo Fisher, final concentration, 2.5μM) according to the manufacturer's instructions. CSFE-labeled BMDCs (total 100 μl) with 3μg of an antibody against IL-6Rα or a control normal goat antibody were injected subcutaneously into a dorsal aspect of a foot. One day later, lymph node cells were isolated from both popliteal and inguinal lymph nodes and CSFE-labeled DCs migrated into these lymph nodes were counted by flow cytometry. Total cell numbers of lymph nodes were also counted to determine the cellularity.

Immunofluorescence & Western blots:

Immunofluorescence of surface proteins including CCR7, IL-6Rα and gp130 was performed after fixation of 4% formaldehyde without permeabilization. Images were taken as Z-stacks (0.2μm spacing) with a DeltaVision Image Restoration Microscope system, deconvolved with the softWoRx software (Applied Precision Instruments). Projected images were generated with SoftWoRx or ImageJ (http://rsb.info.nih.gov/ij/). In some experiments, images were taken on a Nikon TE300 microscope with a 60x objective lens (NA 1.4) and presented without deconvolution. Exposure times for imaging, as well as the settings for deconvolution, were constant for all samples to be compared within any given experiment. For presentation, contrast and brightness of all images in a given figure were adjusted in the same way with Photoshop (Adobe).

To determine the levels of phospho-ERK1/2, as well as those of total ERK1/2, BMDCs before and after CCL19 treatment were homogenized in a lysis buffer containing 0.5% Triton-100X as described(45). After centrifugation, the supernatants were used for Western

blotting with antibodies against phospho ERK1/2 and total ERK1/2 (Cell Signaling Technology).

Flow cytometry analyses:

For surface labeling of CCR7, gp130 and IL-6Rα, BMDCs were fixed with 3.7% formalin and incubated with a primary antibody to each protein. The primary antibodies were labeled with a FITC- or AF647-labeled second antibody. For other surface proteins including MHC-II, CD80, CD86, formalin-fixed BMDCs were labeled with a fluorescently-conjugated antibody to each protein. CD86-positive BMDCs were gated for flow cytometry analyses. Flow cytometry was performed with a BD FACSCalibur or Coulter Cytomics FC500 flow cytometer. We found that CCR7 staining of BMDCs is sometimes associated with cytoplasmic staining probably due to breakage of the dendritic membrane structure during staining procedures. To confirm membrane staining of CCR7, we also performed AMNIS imaging cytometry, which can specifically measure surface staining of CCR7.

CCR7 internalization assay:

To determine effects of IL-6 signaling on ligand-induced CCR7 internalization, BMDCs matured overnight with LPS were incubated with a neutralizing IL-6Rα antibody or control goat antibody for 10min. BMDCs were then treated with 0.6μg/ml of CCL19. BMDCs before and 5min after CCL19 activation were fixed with formalin, and labeled with anti-CCR7 and anti-CD86 antibodies. Flow cytometry was performed to determine changes in CCR7 surface expression upon CCL19 treatment.

Internalization of CCR7 was also examined with HEK293T cells stably expressing a mouse CCR7-GFP fusion construct (pCMV3-mCCR7-GFPSpark, Sino Biological Inc.). HEK293T cells were transfected with CCR7-GFP with Lipofectamin 2000 (Gibco). After selection with hygromycin, stable cell lines expressing a uniform level of CCR7-GFP were picked up with a small piece of a filter paper under a fluorescent microscope, and propagated in the presence hygromycin. To determine CCR7 internalization, CCR7-GFP-expressing HEC293T cells were incubated with or without a neutralizing antibody for 10min, then CCL19 (0.6μg/ml) was added for 5min. After fixing with 3.7% formaldehyde, cells were incubated with an anti-mouse CCR7 antibody premixed with a Cy3-labeled Fab fragment of the secondary antibody. Both GFP and Cy3 fluorescent images were taken by a Nikon TE300 or DeltaVision Image Restoration Microscope system. Cy3 fluorescent images represent surface expression of exogenously expressed mouse CCR7, which was quantitated by ImageJ.

Statistical analysis:

Statistical analyses were performed using a Student t test for two groups (http://www.physics.csbsju.edu/stats/t-test.html) or using ANOVA for more than 3 groups (Excel and StatPlus).

Results:

Fascin1 alters chemokine secretion including IL-6.

We analyzed whether infection with *Listeria monocytogenes* alters cytokine secretion profiles in mouse sera. Cytokine profiling was performed using RayBiotech cytokine array analyses (Array C series 2000; see supplemental Fig. 1 for the assignment of 144 unique mouse cytokines of the array 3–5). The analyses revealed a specific reduction in IL-6 levels of fascin1 KO mice in comparison with WT mice (Fig. 1A-a). Other inflammatory cytokines including IL-10, IL-12, and TGF-β showed no differences between WT and fascin1 KO mice. ELISA assays confirmed that the serum IL-6 level was reduced in fascin1 KO mice (220pg/ml for WT, 50pg/ml for KO) (Fig. 1B). Before infection, no differences in cytokine secretion were observed in sera between WT and fascin1 KO mice (Fig. 1A-b), suggesting that the change in the serum IL-6 level is associated with immunity.

These results indicate that the increase in serum IL-6 levels upon infection depends on immunity-mediated changes in the levels and/or activity of fascin1. DCs induces fascin1 to a great extent upon maturation. Mature DCs are also one of the major sources of IL-6. Therefore, we examined whether fascin1 deficiency altered IL-6 secretion by BMDCs. Quantitative cytokine profiling (RayBio Quantibody mouse Th17 array1) revealed that mature BMDCs from fascin1 KO mice showed reduced secretion of several cytokines including IL1β, IL-4, IL-5, IL-6, IL-21, IL-22, and TNFα (Fig. 1C). No significant changes in the secretion of IL-2, IL-12p70, IL-17 and IFNγ were observed. Among the altered cytokines, IL-6 and IL-21 showed the highest fold-difference between WT and fascin1 KO BMDCs. The reduced IL-6 and TNFα secretion by fascin1 KO BMDCs is consistent with a previous report that fascin1 knockdown by siRNA reduced the secretion of these two cytokines in both human and mouse monocytic leukemia (46) (note that, unlike primary blood cells, these transformed leukemia express fascin1).

Fascin1 increases the level of mRNA of IL-6.

We examined whether fascin1 affects IL-6 mRNA levels of BMDCs. We used PrimeFlow RNA assays (Affymetrix), in which transcript levels are quantitated by single molecule fluorescent *in situ* hybridization (FISH) following amplification. As Fig. 2A shows, IL-6 mRNA levels were higher in wild type BMDCs (panel c) than in fascin1 KO (panel d) BMDCs when they were matured with LPS overnight. Immature BMDCs from WT (panel a) or fascin1 KO (panel b) showed very low levels of IL-6 mRNA, which is consistent with the lack of IL-6 secretion by DCs before maturation(47, 48). Quantitative measurements of *in situ* mRNA signals confirmed that WT BMDCs showed higher mRNA levels than fascin1 KO counterparts (Fig. 2B). This result is not consistent with the previous report that fascin1 increased translational efficiency by favoring polysome formation without altering IL-6 mRNA levels(46): While the exact reason for this discrepancy is unknown, our finding suggests that fascin1 may enhance transcription of the IL-6 gene. Alternatively, fascin1 may stabilize IL-6 mRNA as cytokine mRNAs including IL-6 and TNFα mRNAs show regulated stability upon cellular activation(49–53).

Fascin1 increases IL-6 signaling.

The reduced IL-6 secretion is expected to attenuate IL-6 signaling in BMDCs. IL-6 binding to its receptors (IL-6Rα) results in the association between IL-6Rα and gp130, leading to the activation of IL-6 signaling(54). By quantitating the IL-6Rα/gp130 association by Proximity Ligation Assay (PLA), we compared the extents of IL-6 signaling between mature WT and fascin1 KO BMDCs. In PLA assays, the association between two molecules can be detected as a fluorescent speckle.

As Fig. 2C shows, PLA assay revealed that WT mature BMDCs (panel c) exhibit more fluorescent speckles than fascin1 KO mature BMDCs (panel d). The difference is confirmed by the quantitative analyses of fluorescent speckles (Fig. 2D). In contrast to mature BMDCs, immature BMDCs either from WT (Fig. 2C, panel a) or fascin1 KO (Fig. 2C, panel b) showed undetectable levels of PLA signals. The lack of PLA signals in immature BMDCs is consistent with the lack of IL-6 production before DC maturation(47, 48), providing a negative control for the PLA assay. The lower PLA signals in fascin1 KO BMDCs are not caused by decrease in the expression levels of IL-6Rα or gp130 (Supplemental Fig. 2): Both immunofluorescent localization and the expression levels of surface IL-6Rα and gp130 were similar between WT and fascin1 KO BMDCs. Taken together, these results indicate that fascin1 increases IL-6 secretion, leading to higher IL-6 signaling in mature BMDCs.

IL-6 signaling is critical for chemotaxis of mature DCs.

IL-6 signaling has been reported to increase cell motility of a variety of tumor cell lines(32–36). We thus hypothesized that fascin1-mediated, higher IL-6 signaling may account for higher chemotaxis of WT BMDCs in comparison with fascin1 KO BMDCs. To test this hypothesis, we examined, by modified Boyden chamber assays, whether the blockage of IL-6 signaling affects chemotaxis. We used a neutralizing IL-6Rα-antibody to block IL-6signaling. Normal goat IgG antibody was used as a control of a neutralizing IL-6Rα antibody. We determined a chemotaxis index (C.I.) by dividing the number of migrated cells with CCL19 gradient (chemotactic migration) with the number of migrated cells without CCL19 gradient (basal migration).

We found that IL-6 signaling is required for effective chemotaxis of mature BMDCs (Fig. 3A). The addition of a neutralizing IL-6Rα-antibody greatly reduced chemotaxis index (C. I.) of WT BMDCs to less than one-third of that of WT BMDCs with a control antibody. Consistent with the previous result(24), fascin1 KO similarly reduced C.I. to one-third of that shown by WT BMDCs. The addition of an IL-6Rα antibody to fascin1 KO BMDCs did not further reduce chemotaxis. The inhibition of chemotaxis by an IL-6Rα neutralizing antibody is not due to a change in the state of maturation of WT BMDCs: The addition of the neutralizing antibody did not significantly alter the expression levels of maturation markers (including CD80, DC86, MHC-II, fascin1 and CCR7) in WT BMDCs (Supplemental Fig. 3A-E): These results suggest that chemotaxis toward CCL19 depends on IL-6 signaling.

A recent study using gene expression analyses suggests that BMDCs generated in the presence of GM-CSF may not represent any subtype of *in vivo* DCs(55). While this issue is

still under debate(56–61), it is important to determine whether the effect of IL-6 signaling on chemotaxis is observed with DCs directly isolated from tissues. Therefore, we examined whether chemotaxis of spleen DCs from WT mice depends on IL-6 signaling. As Fig. 3B shows, the blockage of IL-6 signaling inhibited chemotaxis of spleen DCs. This result suggests that IL-6 signaling is generally required for chemotaxis of conventional mature DCs.

We further examined whether inhibition of IL-6 signaling affects DC chemotaxis *in vivo* in mice. Mature BMDCs were labeled with CSFE and mixed with a neutralizing IL-6Rα antibody or with a control antibody. They were then injected into a dorsal part of foot. Twenty-four hours later, CSFE-labeled BMDCs migrated into draining lymph nodes were counted by flow cytometry. As Fig. 3C shows, the number of BMDCs migrated into lymph nodes was greatly reduced when a neutralizing IL-6Rα antibody was co-injected. The total cell number of lymph nodes was also reduced in the presence of the neutralizing IL-6Rα antibody (Fig. 3D), confirming that DC did not reach to the lymph nodes for activation. These results suggest that IL-6 signaling is critical for *in vivo* migration of mature DCs toward draining lymph nodes.

Fascin1/IL-6 signaling axis controls the directionality of DC chemotaxis.

Our results indicate that fascin1 promotes IL-6 signaling, which is critical for chemotaxis of mature DCs. Chemotaxis depends on speeds and/or directness of migration. To determine which factor(s) fascin1 and IL-6 signaling affect, we performed live cell imaging of BMDCs migrating toward a CCL19 gradient in a collagen gel as described(43). We found that the lack of fascin1 and the inhibition of IL-6 signaling both reduce directionality of DC migration without altering migration speeds.

Figs 3E-a and c show the migration tracks of WT and fascin1 KO BMDCs, respectively. These tracks showed that WT BMDCs (Fig. 3E-a, see supplemental Videos 1 and 2) apparently moved more consistently along a CCL19 gradient (shown by arrows) than did fascin1 KO BMDCs (Fig 3E-c, supplemental Videos 3 and 4). Rose plot diagrams (Fig. 3E-b and -d; an angular histogram of the fractions of cells moving toward each direction with an interval angle of 10 degrees and an interior angle of 66 degrees) supports the above notion: More WT cells moved along the direction of the chemokine gradient than KO cells. The blockage of IL-6 signaling also reduced directed migration (Fig. 3E-e, supplemental Videos 5 and 6): The migration tracks of WT BMDCs in the presence of the neutralizing antibody against IL-6Rα migrated randomly, which can be observed with the Rose plot analysis (Fig. 3E-f). These analyses suggest that both the deficiency of fascin1 and the blockage of IL-6 signaling reduced directional migration.

To obtain more quantitative data for directional movements, we measured both directness and velocities of migration (Figs 3F and G). Directness is a scalar quantity that measures how straight the cells travel in a given distance though it does not necessarily indicate movements toward the chemoattractant. The analyses reveal that WT BMDCs moved straighter than fascin1 KO or IL-6Rα-blocked BMDCs (F). The median values of directness are 0.39 for WT; 0.22 for KO (p=0.0036, compared with WT) and 0.19 for IL-6Rα-inhibited

WT (p=0.0005, compared with WT). The difference between fascin1 KO and IL-6Rα-inhibited WT is not statistically significant.

In contrast, the migration speeds of WT, fascin1 KO BMDCs and IL-6Rα-blocked WT BMDCs were found to be statistically similar (Fig. 3G). This observation differs from our previous result that WT BMDCs moved faster than fascin1 KO migration on 2D surface(24). The discrepancy is most likely due to the difference in the mode of migration between 2D and 3D. While migration of BMDCs on a 2D surface depends on adhesion, DCs show adhesion-independent amoeboid movements in a 3D gel(62). Our previous study showed that mature WT BMDCs were able to disassemble adhesive structure called podosomes on a 2D surface, resulting in higher migration speeds(24). Fascin1 KO BMDCs, on the other hand, failed to disassemble podosomes, resulting in stronger adhesion to a 2D surface, leading to slower movements.

The above results differ from other reports that mutations or alterations of actin regulatory proteins affect the migration speeds of several types of cells(63–67). To confirm that fascin1 KO or the blockage of IL-6Rα does not affect migration speeds, we performed live cell imaging of WT, fascin1 KO and IL-6Rα-blocked BMDCs in a collagen gel in the absence of CCL19 or in the presence of a uniform concentration of CCL19. Fig. 4A shows the migration tracks of WT, fascin1 KO and IL-6Rα-blocked WT BMDCs in the absence (panel a) or presence (panel b) of CCL19. The migration speeds (Fig. 4B) are statistically similar among WT, fascin1 KO and IL-6Rα-blocked cells either in the absence (panel a) or presence (panel b) of CCL19. We noted that migration speeds in the presence of CCL19 is higher than those in the absence of CCL19, which is consistent with the previous report(68).

Directness measurements in the absence of CCL19 (Fig. 4C, panel a) also revealed no statistical difference among these three types of BMDCs. In the presence of CCL19, the directness of WT BMDCs is similar to that of fascin1 KO BMDCs while the directness of IL-6Rα-blocked WT BMDCs is statistically lower than that of WT BMDCs. The directness in the presence of CCL19 is higher than that in the absence of CCL19, which may reflect the difference in higher migration speeds in the presence CCL19 than in its absence.

Taken together, these results indicate that IL-6 signaling is critical for the directionality of chemotactic migration toward CCL19 without altering migration speeds, and suggest that the reduced IL-6 secretion by fascin1 KO is likely to explain the inhibition of chemotaxis.

BMDCs from IL-6Rα KO mice show impaired chemotaxis toward CCL19.

The above results predict that knockout of the IL-6Rα gene would reduce chemotaxis of mature DCs toward CCL19. To address this prediction, we compared chemotaxis indexes of BMDCs from IL-6Rα KO mice and their heterozygous littermate. The lack of IL-6Rα expression in IL-6Rα KO BMDCs was confirmed by immunofluorescence (Fig 5A).

Modified Boyden chamber chemotaxis assays revealed that BMDCs from IL-6Rα KO mice show much lower chemotaxis than BMDCs from heterozygous mice (Fig. 5B). To examine whether the lack of IL-6 signaling is indeed responsible for reduced chemotaxis, we performed rescue experiments by the addition of both soluble IL-6Rα (sIL-6Rα) and IL-6.

IL-6 binds to sIL-6Rα, the complex of which is associated with membrane-bound gp130, inducing IL-6 signaling (trans-signaling)(69–73). We found that the addition of IL-6 and sIL-6α completely rescued the impaired chemotaxis of IL-6Rα KO BMDCs, underscoring the critical role of IL-6 signaling in chemotaxis of mature DCs.

To address the possibility that the reduced chemotaxis of IL-6Rα KO BMDCs is due to a change in CCR7 expression, we compared surface expression of CCR7 between KO and heterozygous BMDCs. As Fig. 4C shows, immunofluorescence revealed that IL-6Rα KO did not affect CCR7 surface expression. Flow cytometry analyses (Figs 5D) confirmed that WT and IL-6Rα KO BMDCs express similar levels of CCR7.

IL-6 signaling controls ligand-induced internalization of CCR7.

Recycling of chemokine receptors including CCR7 has been shown to control chemotaxis(74, 75). Therefore, we examined whether inhibition of IL-6 signaling affects recycling of CCR7. We found that IL-6 signaling is essential for receptor internalization, the first step for receptor recycling. In control BMDCs (Fig. 6A, panel a), CCR7 showed rapid internalization when CCL19 was added. In the presence of a neutralizing IL-6Rα antibody, however, CCR7 internalization is almost completely blocked (panel b). These results suggest that IL-6Rα KO BMDCs should also show impaired CCR7 internalization. As Fig. 6B, panel a, shows, CCL19-induced, CCR7 internalization was also blocked with IL-6Rα KO BMDCs. Importantly, the addition of soluble IL-6Rα and IL-6 restored CCR7 internalization (panel b), reinforcing the notion that IL-6 signaling is critical for CCL19-induced internalization of CCR7.

The inhibition of CCR7 internalization by the blockage of IL-6 signaling was also observed with HEK293T cells that stably expressed a mouse CCR7-GFP (Fig. 6C). Before CCL19 addition, CCR7-GFP was mostly localized at cell-to-cell contacts (panel a). When CCL19 was added, CCR7-GFP at cell-to-cell contacts was greatly reduced with concomitant increase of GFP signals in the cytoplasm (panel b), indicating internalization of CCR7-GFP. In the presence of a neutralizing IL-6Rα antibody, however, CCR7-GFP signals remained at cell-to-cell contacts with much less cytoplasmic signals, indicating the blockage of the internalization of CCR7 (compare panel c with d, Fig. 6C).

The blockage of internalization could be clearly observed when surface CCR7 was visualized. To do so, the HEC293T cells were stained with mouse-specific antibody against CCR7 (clone 4B12) without permeabilization. This antibody and treatment allowed the detection of only surface CCR7 at cell-to-cell contacts. CCR7 staining at the cell-to-cell contacts is largely lost by the addition of CCL19 due to the internalization (compare panel e, -CCL19; with f, +CCL19). In the presence of an anti-IL-6Rα neutralizing antibody, on the other hand, the staining at the cell-to-cell contacts remained largely unchanged (compare panel g, -CCL19; with h, +CCL19). Quantitative measurements of fluorescence intensities at the cell-to-cell contacts supported this notion (Fig. 6D).

Internalization of CCR7 occurs via clathrin-coated endocytosis, which are known to be coupled with the activation of ERK1/2 signaling(76). We thus examined whether an IL-6Rα neutralizing antibody affects ERK1/2 phosphorylation. Fig. 6E shows the time courses of

ERK1/2 phosphorylation in BMDCs in the presence of a control or a neutralizing IL-6Rα antibody before and 5, 15 and 30min after the addition of CCL19. The ratios of phospho-ERK1/2 to total ERK1/2 at each time point were presented at the bottom of the figure. The neutralizing antibody reduced ERK1/2 phosphorylation throughout the entire time course: the level of ERK1/2 phosphorylation was reduced to one-third at 5min, and to about half at both 15 and 30min time points. Taken together, these results suggest that IL-6 signaling is required for CCR7 internalization, resulting in lowering ERK1/2 phosphorylation, one of the CCL19-mediated CCR7 downstream events.

The inhibition of CCR7 internalization by the blockage of IL-6 signaling could be due to lower binding between CCR7 and CCL19. To examine whether inhibition of IL-6 signaling interferes with binding of CCR7 to CCL19, we used a CCL19-human IgG Fc fusion protein as a ligand(77, 78) and the binding was detected by labeling with fluorescently-labeled anti-human IgG. The levels of the CCL19 association were not altered with or without the addition of the neutralizing IL-6Rα antibody (supplemental Fig. 3F). These results indicate that inhibition of IL-6 signaling did not alter binding of CCL19 to CCR7.

Discussion:

Critical roles of IL-6 signaling in CCR7 internalization and chemotaxis of mature DCs.

We have found that fascin1 enhances IL-6 secretion and signaling and that IL-6 signaling is necessary for CCL19-induced internalization of CCR7. This finding could explain why IL-6 signaling is required for directional migration of DCs along a CCL19 chemoattractant gradient. The binding of CCL19 to CCR7 initiates ligand-induced internalization of CCR7 via clathrin-dependent recycling endocytosis(79). The internalized CCR7-CCL19 complexes are then dissociated in the endosomes where these two molecules take two endocytic pathways(79): Whereas CCL19 is degraded in lysosomes, CCR7 is recycled back to the plasma membrane, allowing recycled CCR7 ready for "second round" signaling with a new CCL19 ligand. Therefore, the blockage of CCR7 internalization would greatly decrease CCR7 signaling for sensing CCL19 gradient, resulting in lower chemotaxis. Fig. 7 shows our current model for the role of the fascin1/IL-6 signaling axis in chemotaxis of mature DCs toward CCL19.

The role of CCR7 internalization in chemotaxis is consistent with a previous report(75). A ubiquitination-deficient mutant of CCR7 showed impaired internalization in a steady state, reducing an intracellular pool of CCR7. This led to impaired recycling upon CCL19 binding, resulting in the inhibition of chemotaxis toward CCL19(75). A similar role of receptor internalization on chemotaxis was also observed with CXCR2(74): A CXCR2 mutant with a mutation in its LLKIL motif at the C-terminus is unable to undergo ligand-induced internalization and show impaired chemotaxis(74). It should be noted, however, that ligand-induced receptor internalization is not required for all types of GPCR-mediated chemotaxis: An internalization-deficient mutant of CCR2B has been shown to support chemotaxis toward a MCP-1 gradient(80).

What could be a mechanism by which IL-6 signaling controls CCR7 internalization? Internalization of CCR7 starts when CCR7 is associated with β-arrestin(81, 82). This

association depends on the phosphorylation of the cytoplasmic C-terminus of CCR7 by a kinase like GRKs (G protein-coupled receptor kinases) (82, 83). CCR7-β-arrestin complexes bind to adaptin, leading to the assembly of clathrin-coated pits for endocytosis of CCR7. IL-6 signaling may affect any of these events. Depending on which step IL-6 signaling controls, the blockage of IL-6 signaling could have distinct effects on CCR7 desensitization. For example, if IL-6 signaling is required for the CCR7-β-arrestin association, then the blockage of IL-6 signaling would inhibit desensitization of CCR7. On the other hand, if IL-6 signaling control the β-arrestin-adaptin association, then the blockage of IL-6 signaling would keep CCR7 desensitized. We are in the process of determining these possibilities.

IL-6 signaling induces several downstream events including activation of JAK/STAT3, MAPK, and PI3K/AKT. We have shown that a neutralizing IL-6Rα antibody inhibited MAPK activation (Fig.6E). This data, however, cannot identify whether MAPK activation is involved in IL-6-dependent migration of mature DCs, because both IL-6 signaling and CCR7 signaling activate MAPK. Further study is required to determine which of the downstream events of IL-6 signaling is involved in migration of mature DCs.

Inflammation-dependent and independent migration of CCR7-mediated chemotaxis

We have demonstrated that chemotaxis of mature DCs toward CCL19 depends on IL-6 signaling, which is associated with inflammation. However, this dependence on IL-6 signaling does not apply for all types of CCR7-mediated chemotaxis. For example, naïve T-cells express CCR7, which is critical for their homing to lymph nodes. Their migration occurs without inflammation, and therefore should not require IL-6 signaling. This IL-6-independent migration of T-cells is consistent with the lack of fascin1 in T-cells. Thus, the mechanism of T-cell homing to lymph nodes must be very different from chemotaxis of mature DCs.

The inflammation-independent chemotactic migration may also explain why more DCs were found in lymph nodes of IL-6 KO mice than in those of WT counterparts(84). The increase of DCs in IL-6 KO mice was observed at a steady-state condition without inflammation. Migrating DCs in the steady state may, at least in part, represent DCs "semi-matured" by a self-antigen: It has been reported that these "semi-matured" DCs express CCR7 and migrate into lymph nodes, establishing peripheral tolerance(11). Such migration may not require rapid migration as observed with "fully-matured" DCs during pathogen-induced inflammation. "Fully matured" DCs, on the other hand, need to migrate into lymph nodes as quickly as possible for the initiation of adaptive immune responses against invading pathogens. We suggest that IL-6 signaling is required to ensure that migration of "fully-matured" DCs is inflammation-dependent.

Possible role of the fascin1/IL-6 axis in cancer cell metastasis

Several studies showed that fascin1 promotes metastasis of many cancers including breast, colorectal and gastric carcinoma(28, 29, 85–90). Fascin1 siRNA or fascin1 inhibitors have been reported to inhibit cancer cell migration *in vitro*, as well as metastasis in an *in vivo* mouse model(26–30). These results have been interpreted in the following way: Fascin1 promotes filopodia assembly, thereby accelerating cancer cell migration(20, 24, 25, 91).

Our current results suggest a new role of fascin1 in enhancing IL-6 signaling in cancer cells. Both fascin1 and IL-6 are upregulated in many cancer cells, both of which are shown to increase migration of several types of cancer cells(36, 92–98). Because IL-6 itself is shown to increase fascin1 expression(99), increased expression of fascin1 could create a positive feedback loop for IL-6 signaling in cancer cells. One possible scenario is that fascin1/IL-6 signaling may promote lymphatic metastasis because CCR7 is often expressed in cancer cells with lymphatic metastasis(100). Fascin1/IL-6 signaling may also be involved in CCR7-independent cell migration because IL-6 can increase chemotaxis of monocytes and T-cells in a CCR7-independent manner(101, 102). In addition, IL-6 exerts multiple effects on tumor cell proliferation and survival, angiogenesis, and inflammation, all of which globally favor cancer cell metastasis. Thus, the fascin1/IL-6 signaling axis could be a target of therapeutic treatments for cancer metastasis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments:

Abbreviations:

WT	wild type
KO	knockout
DCs	Dendritic cells
BM-DCs	Bone marrow-derived dendritic cells

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Key points:

- Fascin1 enhances IL-6 secretion and IL-6 signaling in mature dendritic cells.

- IL-6 signaling is critical for chemotaxis toward CCL19.

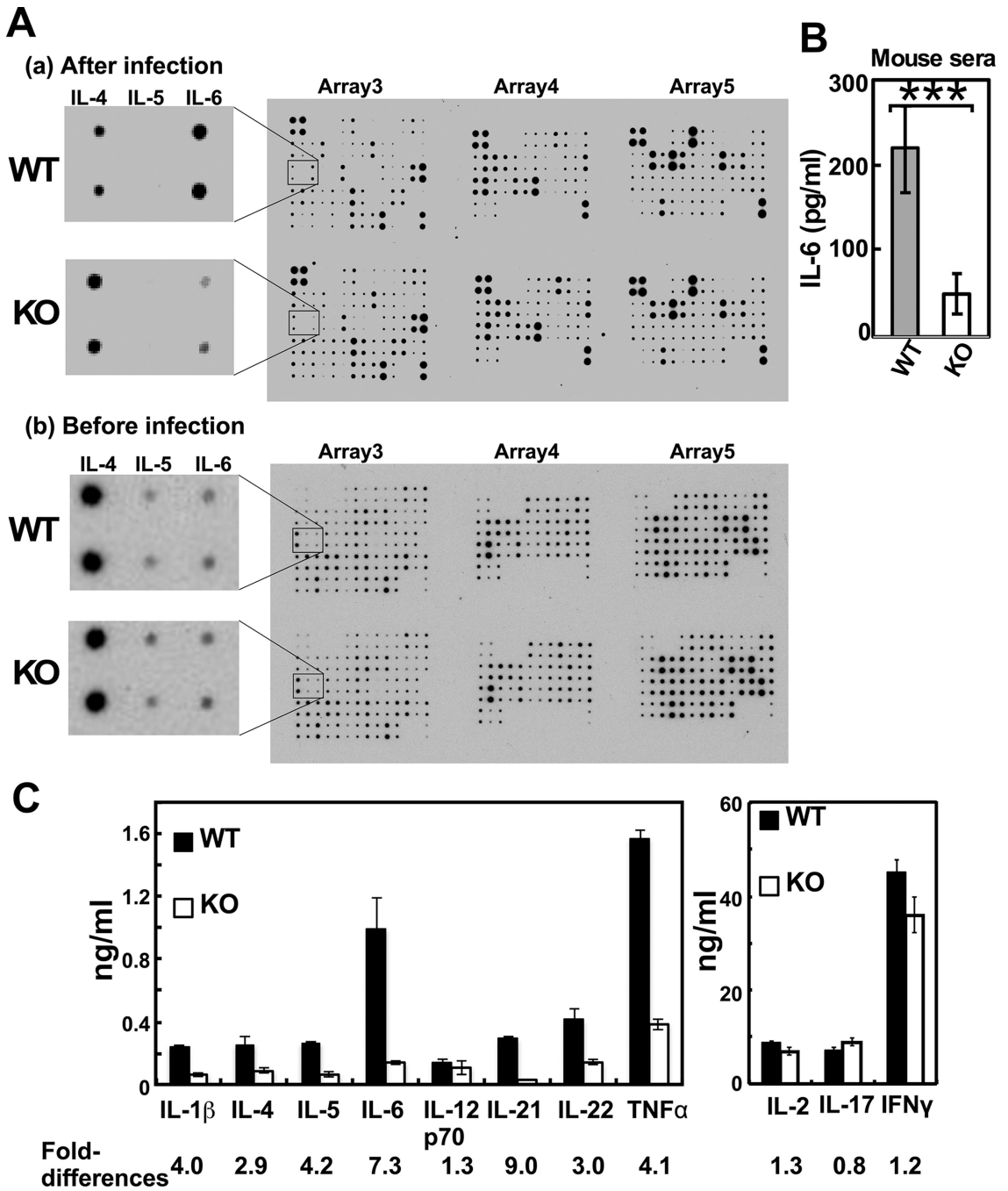- IL-6 signaling is required for CCR7 internalization of CCR7, GPCR of CCL19.

Figure 1.

Fascin1 increases IL-6 secretion *in vivo* and *in vitro*. A, Analysis of cytokine profiles in sera of WT and fascin1 KO mice 48hr after infection with *Listeria monocytogenes*. Sera were analyzed using RayBio Mouse cytokine antibody Arrays 3–5 (see Supplemental Figure 1 for the positions of each cytokines analyzed). IL-6 is specifically reduced in sera from fascin1 KO mice. The data is a representative of three independent experiments. B, ELISA analyses of IL-6 levels in sera confirmed decreased IL-6 secretion in fascin1 KO mice. ***, p<0.001. Error bars, standard deviation of four independent experiments. C, Cytokine profile of

culture supernatants of WT and fascin1 KO BMDCs analyzed by Quantibody Mouse Th17 Array1 (RayBiotech, Inc). Fold-differences between WT and KO BMDCs are indicated below each cytokine. The data is a representative of three independent experiments.
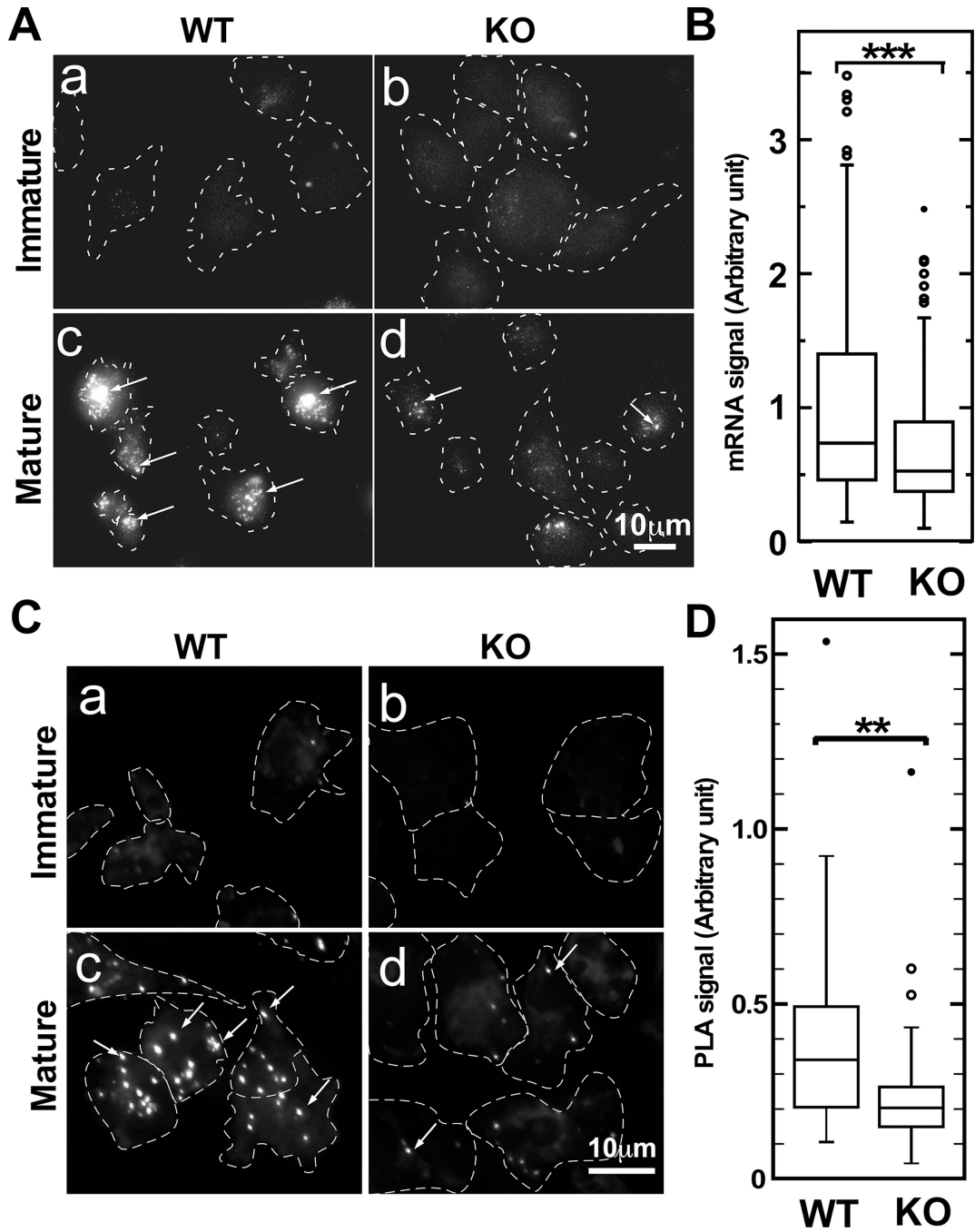
Figure 2.
Fascin1 increases IL-6 mRNA levels and IL-6 signaling. A, PrimeFlow RNA assay to determine *in situ* IL-6 mRNA levels in WT (a & c) and fascin1 KO (b & d) BMDCs. a & b, immature BMDCs; c & d, mature BMDCs. Fluorescence dots (indicated by arrows) represent *in situ* hybridized and amplified IL-6 mRNA. Mature wild type BMDCs (c) show more and higher levels of fluorescent dots than mature fascin1 KO BMDCs (d). Note that immature BMDCs either from WT (a) or KO (b) show very low mRNA levels, which is consistent with the lack of IL-6 secretion in immature BMDCs. Dashed lines,

Cell boundaries. B, Quantitative analysis of in situ mRNA signals of mature wild and KO BMDCs (>200 cells). The data are representative of three independent experiments. ***, p<0.001. C, Higher IL-6 signaling of WT BMDCs than that of fascin1 KO BMDCs. Proximity Ligation Assay (PLA) was used to determine the *in situ* association between IL-6Rα and gp130, representing the extent of IL-6 signaling. a & b, immature BMDCs; c & d, mature BMDCs. a & c, WT. b & d, fascin1 KO. Fluorescence speckles (arrows) indicate the association between IL-6Rα and gp130. Cell boundaries are indicated by dashed lines. The images are representative of three independent experiments. D, Quantitative analyses of PLA signals in WT and fascin1 KO BMDCs (n=51). **, p<0.01.
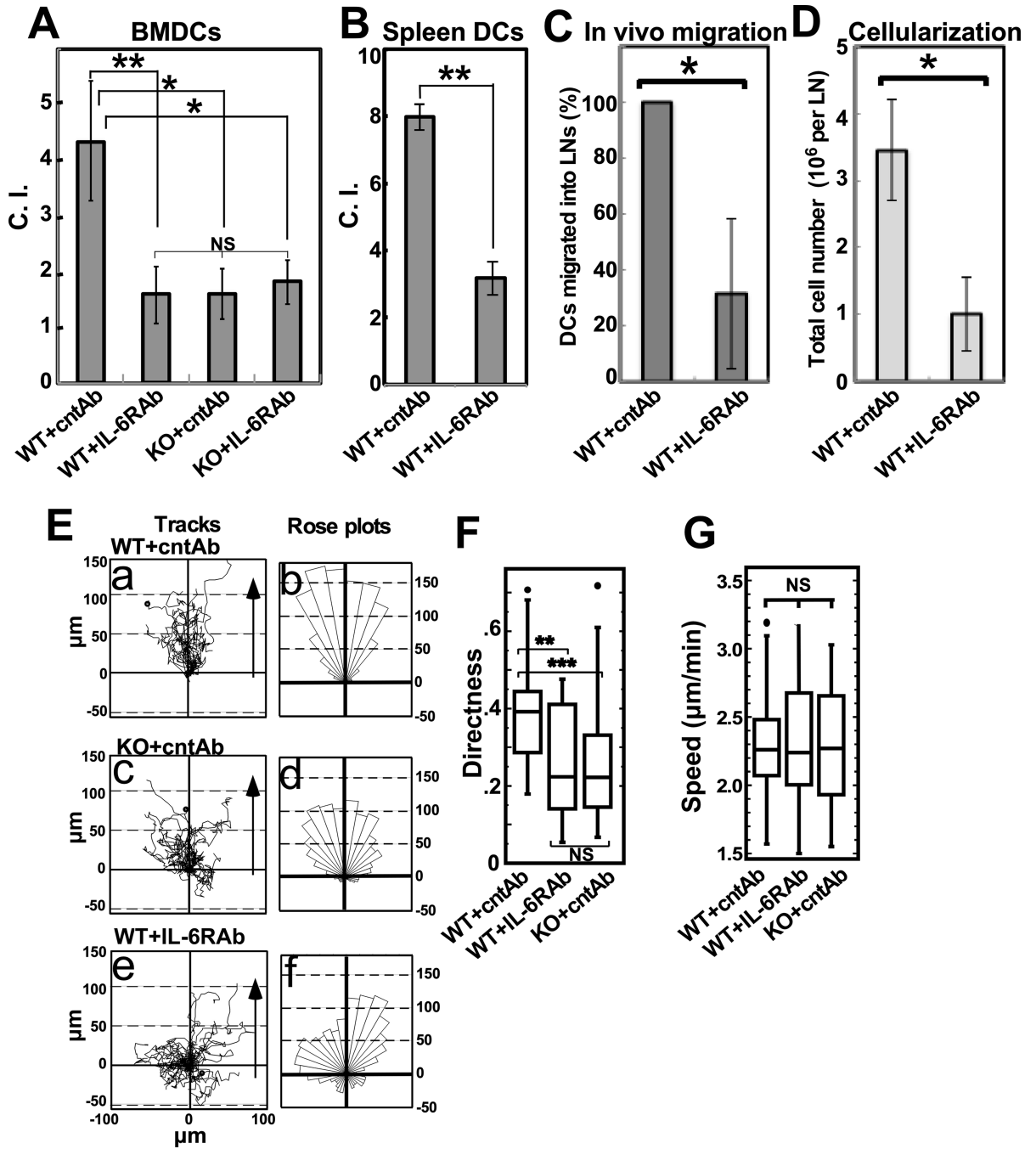
Figure 3.

L-6 signaling is critical for chemotaxis of DCs. A, Effects of the inhibition of IL-6 signaling on chemotaxis of BMDCs. Collagen-coated, modified Boyden chamber chemotaxis assays were used to determine chemotaxis indexes (C.I) of WT BMDCs with a control antibody (WT+cntAb, n=3); WT with a neutralizing antibody against IL-6Rα (WT+IL-6RAb, n=3); fascin1 KO BMDCs with a control antibody (KO+cntAb, n=3); KO with a neutralizing antibody against IL-6Rα (KO+IL-6RAb, n=3). Error bars are standard deviations from 3 independent biological replicates. B, A neutralizing antibody against IL-6Rα also inhibits

chemotaxis of mature DCs isolated directly from spleens (n=3). Collagen-coated modified Boyden chamber chemotaxis assay was used to determine chemotaxis indexes (C.I.). Error bars are standard deviations from 3 independent biological replicates. C & D, Effects of a neutralizing antibody on *in vivo* chemotaxis (C) and cellularity (D). CSFE-labeled BMDCs together with a control (WT+cntAb) or neutralizing antibody (WT+IL-6RAb) were injected into the dorsal part of the foot. After 24hr, BMDCs migrated into draining lymph nodes were counted by flow cytometry (C). Total cell numbers of lymph nodes were also counted to show differences in cellularity (D). Error bars are standard deviations from 3 independent biological replicates. E, Analyses of migration tracks. Live cell imaging of BMDCs migrating in a collagen gel toward CCL19 was performed to obtain migration tracks (a, c & e) and rose diagram plots for directionality(b, d & f). a & b, WT with control antibody (WT+cntAb, n=19): c & d, fascin1 KO with control antibody (KO+cntAb, n=23): e & f, WT BMDCs in the presence of a neutralizing antibody against IL-6Rα (WT+IL-6RAb, n=28). WT BMDCs (a & b) showed more consistent migration toward CCL19 than fascin1 KO counterparts (c & d). Blockage of IL-6 signaling inhibits directed migration of WT BMDCs (e & f). Arrows, the direction of a CCL19 gradient. F & G, Box plot analyses of directness (F), and migration speeds (G). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; NS, not significant. The experiments were performed at least 3 times for each condition and a representative result is given.
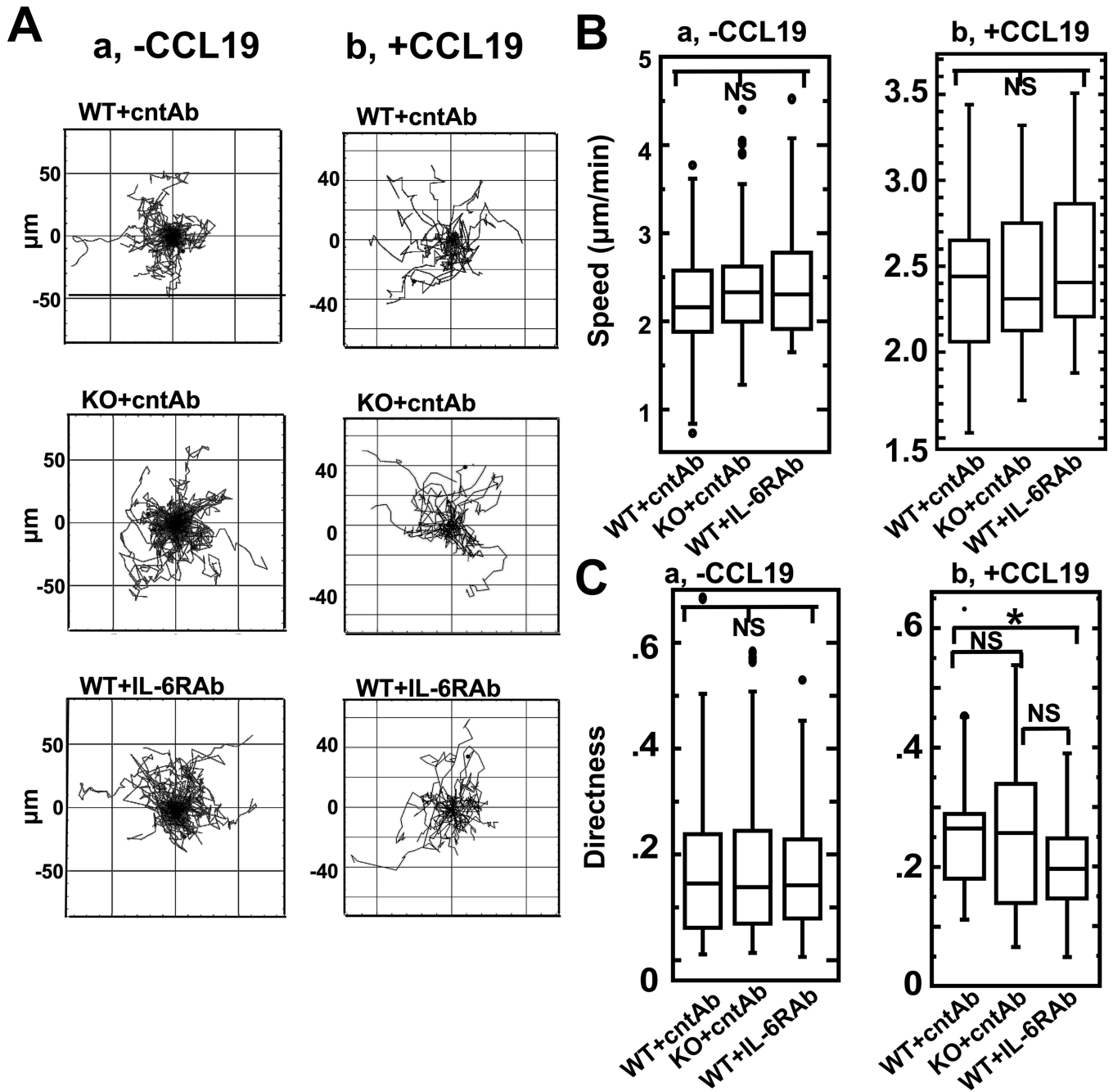
Figure 4.
Knockout of fascin1 or blockage of IL-6Rα did not alter migration speeds in a collagen gel with or without CCL19 chemokines. Live cell imaging of BMDCs migrating inside a collagen gel in the absence or presence of CCL19 (uniform concentration of 0.6μg/ml) were performed to obtain migration tracks, migration speeds and directness. A, Migration tracks. Panel a (left side), in the absence of CCL19. WT BMDCs with control antibody (WT+cntAb, n=93), fascin1 KO BMDCs with control Ab (KO+cntAb, n=157) and WT BMDCs with a neutralizing IL-6Rα antibody (WT+IL-6RAb, n=90) were analyzed. Panel b (right side), in the presence of a uniform CCL19 concentration. WT BMDCs with control

antibody (WT+cntAb, n=26), fascin1 KO BMDCs with control Ab (KO+cntAb, n=22) and WT BMDCs with a neutralizing IL-6Rα antibody (WT+IL-6RAb, n=36) were analyzed. B, analyses of speeds in the absence (panel a) or presence of CCL19 (panel b). C, Analyses of directness in the absence (panel a) or presence (panel b) of CCL19. The experiments were performed at least 2 times for each condition and a representative result is given. *, p<0.05; NS, not significant.
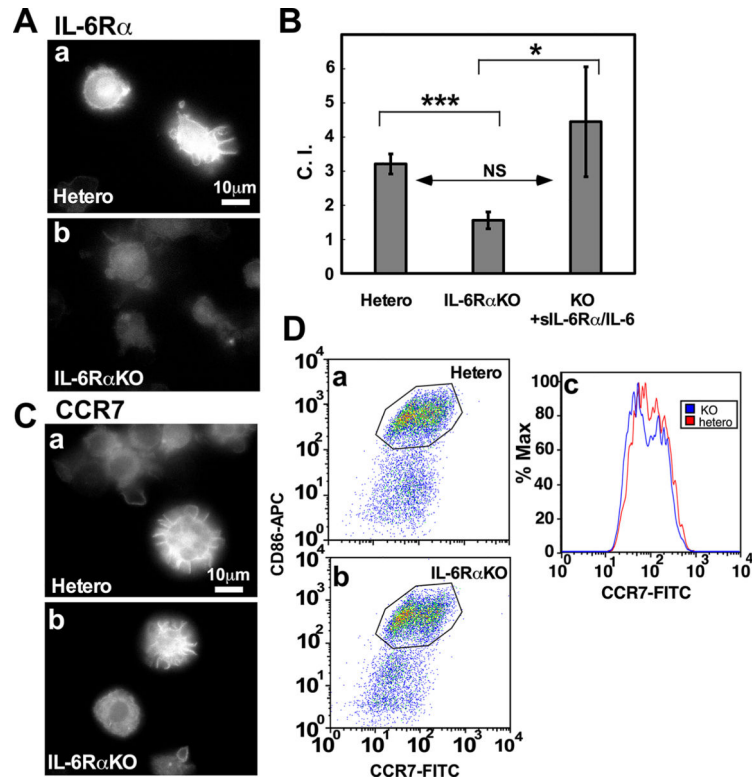
Figure 5.
Impaired chemotaxis of IL-6Rα KO BMDCs and its restoration by the addition of soluble IL-6Rα (sIL-6Rα) and IL-6. BMDCs were isolated from heterozygous (hetero) and IL-6Rα KO mice. A, Immunofluorescence of IL-6Rα in heterozygous (a) and IL-6Rα KO BMDCs (b) confirming the lack of IL-6Rα in KO BMDCs. B, Collagen-coated, modified Boyden chamber chemotaxis assays of heterozygous (hetero), IL-6Rα KO, and IL-6Rα KO in the presence of sIL-6Rα and IL-6 (KO+sIL-6R/IL-6). Note that KO BMDCs show reduced chemotaxis indexes, which were rescued by the addition of soluble IL-6Rα (sIL-6Rα) and IL-6. Error bars are standard deviations from 4 independent biological replicates. C & D, IL-6Rα KO did not alter surface expression of CCR7. Immunofluorescence (C) showing similar levels of surface CCR7 in heterozygous (a) and IL-6Rα KO BMDCs (b). Flow cytometry analyses (D) confirming that IL-6Rα KO did not affect the levels of CCR7 surface expression. After CD86-positive heterozygous (a) and IL-6Rα KO (b) BMDCs were gated, the levels of CCR7 surface expression were examined in histogram (c). *, $p < 0.05$; ***, $p < 0.001$; NS, not significant.
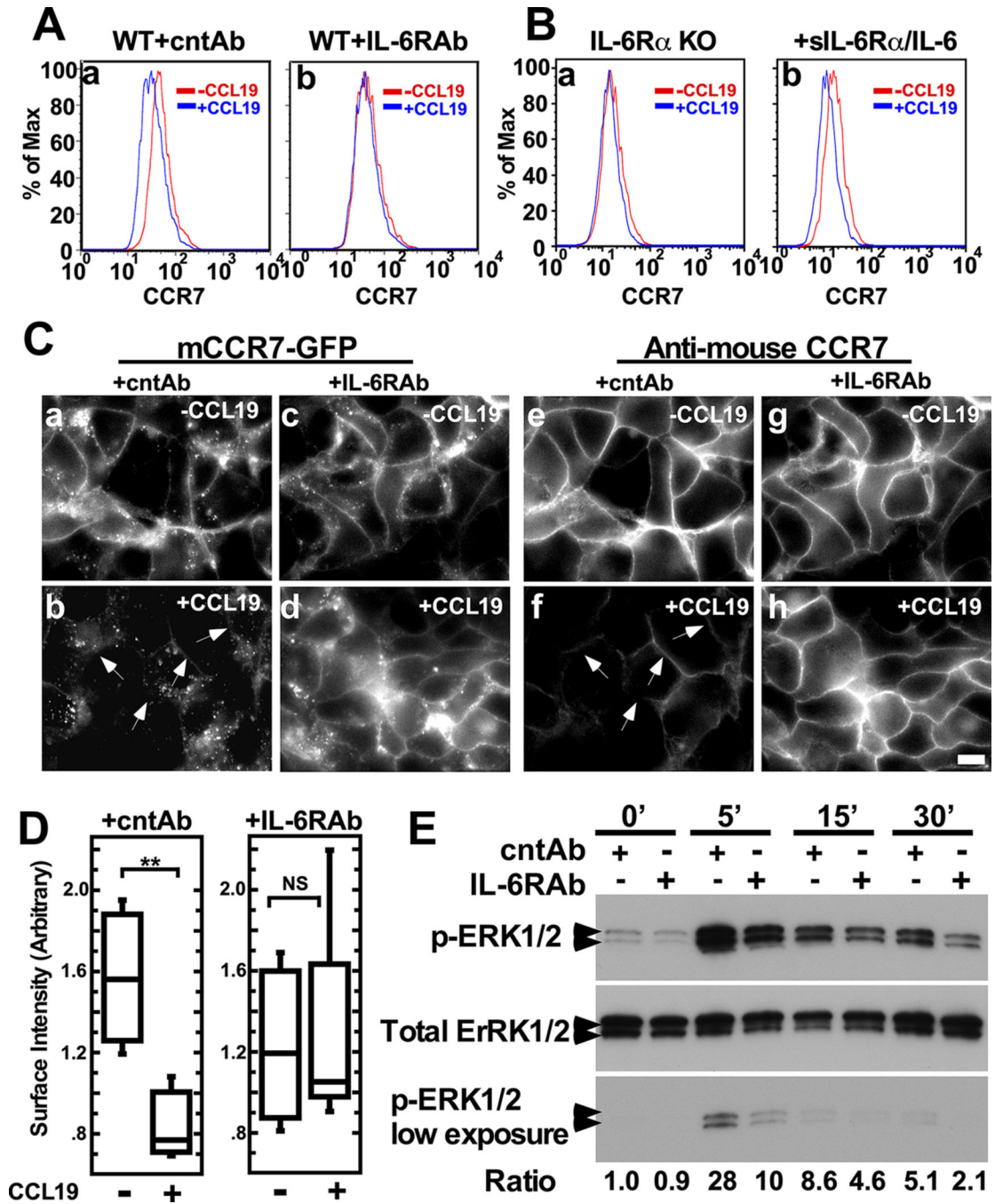
Figure 6.

IL-6Rα signaling is critical for CCR7 internalization and CCL19-induced ERK1/2 phosphorylation. A, Effects of the blockage of IL-6 signaling on CCR7 internalization. WT BMDCs were stimulated with CCL19 for 5 min in the presence of either control (a) or neutralizing antibody (b). Then surface CCR7 expression was determined by flow cytometry. Surface expression of CCR7 was examined with CD86+ BMDCs before (-CCL19) and after CCL19 addition (+CCL19). Note that CCR7 internalization was blocked by a neutralizing antibody to IL-6Rα. The data is a representative of at least

two independent experiments. B, Effects of IL-6 signaling on CCR7 internalization of IL-6Rα KO BMDCs. IL-6Rα KO BMDCs were stimulated with CCL19 in the absence (a) or presence of sIL-6Rα (soluble IL-6Rα) and IL-6 (b). Note that IL-6Rα KO BMDCs showed impaired CCR7 internalization (a), which was rescued by the addition of sIL-6Rα and IL-6 (b). The data is a representative of at least two independent experiments. C, Inhibition of CCR7 internalization by the blockage of IL-6 signaling in HEK293T epithelial cells. HEK293T cells stably expressing mouse CCR7-GFP were stimulated with CCL19 in the presence of either control or neutralizing antibody against IL-6Rα. a-d, fluorescence images of CCR7-GFP in control cells (a & b) or IL-6Rα neutralizing antibody-treated cells (c & d) before (a & c) or after addition of CCL19 (b & d). The same cells were counter stained with an antibody specific to mouse CCR7 to detect only surface CCR7 (e-h) in control (e & f) or IL-6Rα neutralizing antibody-treated cells (g & h) before (e & g) or after (f & h) addition of CCL19. The data is a representative of three independent experiments. D, Quantitative measurements of surface CCR7 immunofluorescence (panels e-h of C) at cell-to-cell contacts. In contrast to the control, the addition of a neutralizing antibody against IL-6Rα blocked internalization of CCR7. The data is a representative of 3 independent experiments. E, Effects of the blockage of IL-6 signaling on CCL19-induced ERK1/2 phosphorylation of WT BMDCs. WT BMDCs were stimulated with CCL19 in the presence of a control or neutralizing antibody, then ERK1/2 phosphorylation levels were determined at 0, 5, 15 and 30min after CCL19 addition using Western blotting with a phospho-specific ERK1/2 antibody. For normalization, the same membranes were re-blotted with a pan ERK1/2 antibody. The ratios of phosphoERK1/2 to total ERK1/2 are indicated below the figure. The data is a representative of three independent experiments. **, p<0.01; NS, not significant.
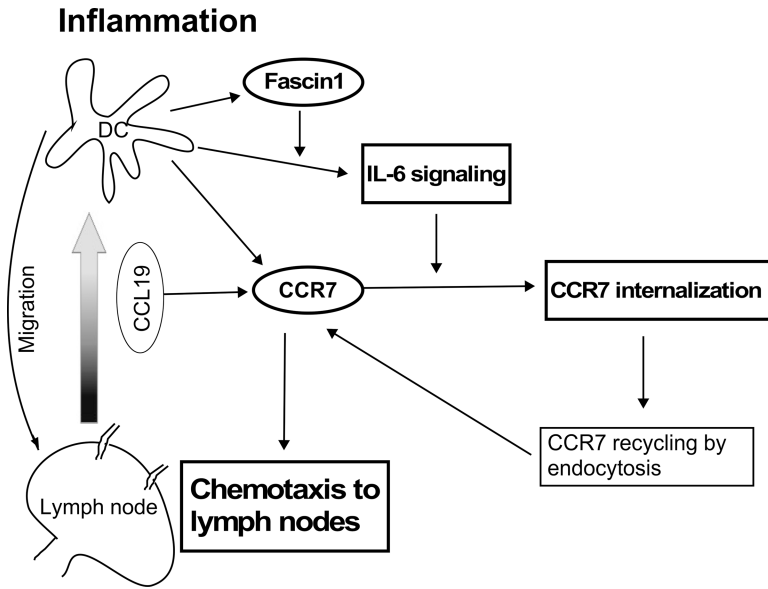
Figure 7.
Model for the role of the fascin1/IL-6 signaling axis in chemotaxis of mature DCs. Upon inflammation, mature DCs induces fascin1 and CCR7. Fascin1 enhances IL-6 secretion, as well as IL-6 signaling. IL-6 signaling is required for CCL19-mediated CCR7 internalization. Internalized CCR7 is recycled back to the cell surface, reinforcing CCL19/CCR7-mediated migration of mature DCs toward lymph nodes.