CCL2-induced chemokine cascade promotes breast cancer metastasis by enhancing retention of metastasis-associated macrophages

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Breast cancer is a leading cause of cancer death, largely because of metastatic disease (Jemal et al., 2011). There are a large numbers of clinical studies that indicate a strong correlation between poor prognosis of the disease and high infiltration of macrophages in the tumor (Bingle et al., 2002; Knowles and Harris, 2007). For example, high macrophage infiltration strongly associates with reduced relapse-free and overall survival of breast cancer patients (Leek et al., 2002; Knowles and Harris, 2007). Pulmonary metastasis of breast cancer cells is promoted by a distinct population of macrophages, metastasis-associated macrophages (MAMs), which originate from inflammatory monocytes (IMs) recruited by the CC-chemokine ligand 2 (CCL2). We demonstrate here that, through activation of the CCL2 receptor CCR2, the recruited MAMs secrete another chemokine ligand CCL3. Genetic deletion of CCL3 or its receptor CCR1 in macrophages reduces the number of lung metastasis foci, as well as the number of MAMs accumulated in tumor-challenged lung in mice. Adoptive transfer of WT IMs increases the reduced number of lung metastasis foci in Ccl3 deficient mice. Mechanistically, Ccr1 deficiency prevents MAM retention in the lung by reducing MAM–cancer cell interactions. These findings collectively indicate that the CCL2-triggered chemokine cascade in macrophages promotes metastatic seeding of breast cancer cells thereby amplifying the pathology already extant in the system. These data suggest that inhibition of CCR1, the distal part of this signaling relay, may have a therapeutic impact in metastatic disease with lower toxicity than blocking upstream targets.

Pulmonary metastasis of breast cancer cells is promoted by a distinct population of macrophages, metastasis–associated macrophages (MAMs), which originate from inflammatory monocytes (IMs) recruited by the CC-chemokine ligand 2 (CCL2). We demonstrate here that, through activation of the CCL2 receptor CCR2, the recruited MAMs secrete another chemokine ligand CCL3. Genetic deletion of CCL3 or its receptor CCR1 in macrophages reduces the number of lung metastasis foci, as well as the number of MAMs accumulated in tumor-challenged lung in mice. Adoptive transfer of WT IMs increases the reduced number of lung metastasis foci in Ccl3 deficient mice. Mechanistically, Ccr1 deficiency prevents MAM retention in the lung by reducing MAM–cancer cell interactions. These findings collectively indicate that the CCL2-triggered chemokine cascade in macrophages promotes metastatic seeding of breast cancer cells thereby amplifying the pathology already extant in the system. These data suggest that inhibition of CCR1, the distal part of this signaling relay, may have a therapeutic impact in metastatic disease with lower toxicity than blocking upstream targets.

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and Bell, 2014), they are not involved in breast cancer metastasis (Qian et al., 2009). In contrast, the CD11b+ macrophages are recruited by metastasizing cancer cells but are few in number in normal lung. In an experimental metastasis model of breast cancer, these CD11b+ macrophages are recruited and in direct contact with disseminating cancer cells within 48 h after tumor injection, which promotes extravasation of cancer cells. Because depletion of the CD11b+ macrophages reduces the number and size of metastatic foci in the lung (Qian et al., 2009), the recruitment of these metastasis-associated macrophages (MAMs) is essential for extravasation and persistent growth of breast cancer cells.

We have recently reported that adoptively transferred inflammatory monocytes (IMs) characterized as CD11b+Ly6C<sup>high</sup> preferentially migrate to the lung with metastatic tumors than the primary tumor (Qian et al., 2011). We have also found that treatment with antibodies against the CC-chemokine ligand 2 (CCL2) suppresses the recruitment of IMs and reduces the number of MAMs in the lung, indicating that MAMs originate from circulating IMs. Because IMs express the CCL2 receptor CCR2 at high levels and anti-CCL2 antibody treatments reduce the number of metastatic foci, the CCL2–CCR2 axis plays an important role in metastatic seeding of breast cancer cells via recruitment of IMs. Our results thus suggest CCL2 as a potential therapeutic target to prevent the MAM-mediated tumor metastasis. However, anti–CCL2 antibody is ineffective at suppressing free CCL2 in humans (Sandu et al., 2013). Moreover, loss of CCL2 signaling severely depresses numbers of circulating monocytes that increases susceptibility to infection in mouse models (Serbina et al., 2008), suggesting the requirement for alternative targets to suppress prometastatic function of MAMs.

Although CCL2 is known as a monocyte chemoattractant (Matsushima et al., 1989), it also promotes phagocytosis, survival, and polarization of myeloid cells (Roca et al., 2009; Tanaka et al., 2010). We thus hypothesized that the CCL2–CCR2 axis may regulate functions of MAMs, and could be another mechanism underlying MAM-mediated metastatic seeding of cancer cells. Accordingly, we have found that the recruited MAMs also express CCR2 (Qian et al., 2009), and loss of Ccr2 reduces ability of macrophages to support cancer cell extravasation in vitro (Qian et al., 2011). Here, we demonstrate a novel role of the CCL2–CCR2 axis in breast cancer metastasis. We show that activation of CCR2 signaling prompts MAMs to secrete another chemokine, CCL3. The increased CCL3 secretion results in enhanced MAM–cancer cell interaction and prolonged retention of MAMs in the metastasis sites, which promotes extravasation of cancer cells. These data identify a novel prometastatic chemokine cascade that promotes lung metastasis.

RESULTS

Activation of CCL2–CCR2 axis increases CCL3 secretion from MAMs

To test our hypothesis that CCR2 acts as a signaling receptor in MAMs, we first identified potential downstream targets of CCR2 signaling in the MAMs. Previously, we reported that CD11b+ MAMs express a much higher level of CCR2 compared with CD11c+ pulmonary resident macrophages (Qian et al., 2009), suggesting that MAMs receive more CCR2 signal than resident macrophages. We therefore compared the gene expression profile of MAMs (F4/80<sup>–</sup>CD11b<sup>+</sup>) with those of resident macrophages in normal lung (Lng MΦ; F4/80<sup>–</sup>CD11c<sup>+</sup>) and similarly isolated splenic (Spl MΦ; F4/80<sup>–</sup>CD11b<sup>+</sup>) macrophages. Hierarchical clustering clearly separated MAMs from other resident macrophages, and identified 37 genes whose expression was significantly higher in MAMs (Fig. 1, A and B). To narrow down the candidates, we compared mRNA levels of these genes between WT and Ccr2-deficient macrophages and found eight genes whose expression was significantly reduced in Ccr2-deficient macrophages (Fig. 1 C). Notably, one of these genes encodes the CC-chemokine ligand 3 (CCL3), a high-affinity ligand for CCR1 (Neote et al., 1993) whose expression in myeloid cells is associated with metastasis of colon cancer and lymphoma cells (Kitamura et al., 2010; Rodero et al., 2013). It is also reported that CCL3 enhances intracellular calcium flux in human macrophages but not monocytes (Kaufmann et al., 2001), suggesting that CCL3 might possess specific roles in macrophage functions. We thus hypothesized that activation of CCL2–CCR2 signaling prompts macrophages to secrete CCL3, which regulates prometastatic functions of MAMs.

Consistent with the results from the microarray and realtime PCR, we found 40–50% reduction in CCL3 protein secretion from Ccr2-deficient macrophages compared with that from WT macrophages (Fig. 2, A and B). In the WT macrophages, stimulation with recombinant CCL2 significantly increased CCL3 mRNA and protein expression (Fig. 2 B). Because such an increase in CCL3 secretion was not found in Ccr2-deficient macrophages (Fig. 2 B), these results indicate that CCL2 signaling via CCR2 can increase CCL3 secretion from macrophages. Recombinant CCL2 failed to increase CCL3 secretion in Ccr2<sup>−/−</sup> BMDCs, and thus it is unlikely that any increase in CCL3 secretion is induced by contaminating endotoxin. Indeed, endotoxin contamination is reported as <0.01 ng/ml in our culture conditions and this is much less than is needed to increase CCL3 secretion from alveolar and peritoneal macrophages (Wang et al., 2000). To investigate whether CCL2 promotes Cd3 expression in MAMs in vivo, we injected anti–CCL2 neutralizing antibody into WT mice having a similar load of lung metastases. After 2 d of antibody treatment, we isolated MAMs (F4/80<sup>–</sup>CD11b<sup>–</sup>CD11c<sup>−/−</sup>Ly6C<sup>+</sup>) and resident pulmonary macrophages (F4/80<sup>–</sup>CD11b<sup>–</sup>CD11c<sup>−</sup>Ly6C<sup>+</sup>) from tumor-bearing lung and inflammatory monocytes (IM; CD115<sup>+</sup>CD11b<sup>–</sup>Ly6C<sup>+</sup>) and resident monocytes (RM; CD115<sup>+</sup>CD11b<sup>–</sup>Ly6C<sup>+</sup>) from peripheral blood (Fig. S1). The treatment with anti–CCL2 antibody significantly suppressed Cd3 transcript levels in MAMs (Fig. 2 C), indicating that CCL2 can increase CCL3 expression in macrophages at the metastasis sites as well. Interestingly, MAMs expressed 10-fold higher Cd3 mRNA compared with either circulating IMs or RMs, or resident macrophages in the lung. It is notable that other major leukocyte populations in the
they differentiate from IMs, and it is regulated, at least in part, by the CCL2–CCR2 signaling pathway. Our results, however, do not exclude the contribution of other pathways in the regulation of CCL3 synthesis.

CCL3 secretion from MAMs promotes metastatic seeding of breast cancer cells

Although the role of CCL3 in breast cancer metastasis remains unclear, oncomine search results (Farmer et al., 2005; Finak et al., 2008) indicated that CCL3 was up-regulated in breast cancer stroma and in basal-like invasive breast carcinoma that are predicted to have poor prognoses (Fig. 3A). These results suggest that stromal expression of CCL3 is involved in breast cancer progression. To investigate the role of CCL3 in breast cancer metastasis, we injected MDA-MB-231:4175 cells expressing luciferase (Minn et al., 2005) into the mammary fat pad of nude mice as a model for human triple negative breast cancer. The recipient nude mice were irradiated and transplanted with BM cells from immunodeficient mice (n = 3) before tumor implantation so that we could investigate the role of CCL3 from BM cells. 4 wk after tumor injection, we resected the primary tumor-bearing lung expressed low levels of Ccl3 mRNA comparable with resident macrophages, suggesting MAMs are the major source of CCL3 in the metastasis site (Fig. 2D). Consistent with these data, CCL3 mRNA level in human monocyte-derived macrophages (hMDMs) was significantly higher than freshly isolated monocytes, and this level was increased by recombinant human CCL2 (Fig. 2, E and F). We have reported that CCL3 secretion from cultured macrophages is increased by conditioned medium from mouse mammary tumor cells (Ojalvo et al., 2009). Likewise, conditioned medium from various subtypes of human breast cancer cells increased CCL3 levels in hMDMs (Fig. 2G). The conditioned medium contained CCL2 (MDA435, 56.5 ± 3.7; MDA231, 37.8 ± 5.2; T47D, 13.0 ± 0.6; MCF7, 59.4 ± 3.5 pg/ml), and the increase in CCL3 by the conditioned medium from MDA231 cells that induced highest amount of CCL3 was suppressed by anti-human CCL2 antibody treatment (67% compared with control IgG treatment; Fig. 2H). The anti-CCL2 antibody treatment also suppressed CCL3 expression induced by conditioned medium from MDA435 (78% compared with control IgG treatment) but not from T47D and MCF7 cells (unpublished data). Collectively, these results indicate that MAMs secrete high level of CCL3 once
PyMT:Cld3+/− mice (Fig. 3, C and D). As we could not find significant differences in the size of foci or weight of primary tumors (Fig. 3 D), CCL3 appears to be required for metastatic seeding of cancer cells rather than their growth at the primary and metastatic sites.

We thus investigated the role of CCL3 in extravasation, one of the rate-limiting steps of metastasis, using an experimental metastasis model that enables cancer cells to determine tumor loads in the lung by in vivo bioluminescence imaging. In support of our hypothesis, the spontaneous pulmonary metastases from the orthotopic 4175 tumors were markedly suppressed by Ccl3 deficiency (Fig. 3 B). To confirm this result in a spontaneous tumor-developing GEM model, we introduced the Ccl3-null allele to the PyMT mice on a BL6 background and found that the number of lung metastasis foci was significantly lower in PyMT:Cld3−/− than PyMT:Cld3+/− mice (Fig. 3, C and D).
avoid the early metastatic steps from the primary tumor such as local invasion and intravasation. Namely, we injected E0771-LG cells into the tail vein of mice that received BM transplantation (BMT) from WT, Cdl3−/−, or Ccr2−/− mice. Consistent with our other experimental models, transplantation of Cdl3−/− BM cells reduced number of foci without affecting the size of foci (Fig. 4 A). The suppressive effect of Cdl3 gene ablation was comparable with that of Ccr2 knockout. To investigate the requirement of CCL3 in lung metastasis of another cell line, we performed experimental metastasis assays with Met-1 mouse mammary tumor cells. Because the cells are derived from the PyMT tumor in FVB mice (Borowsky et al., 2005), we used anti-CCL3 neutralizing antibody instead of Ccl3−/− mice (C57BL/6). Consistent with the genetic model, pretreatment with anti-CCL3 antibody significantly suppressed the number of foci (Fig. 4 B). Although the suppressive effect of the antibody treatment was smaller than that of genetic Cdl3 deletion, we are unable to compare the two models (Met-1 and E0771) in the null mutant because of the genetic background. The lower effect caused by the antibody treatment may also due to the very high dose of the antibody (ND50 = 5–25 µg/ml) required to achieve complete neutralization of CCL3 in mice that is greater than the amount of antibody available to us for this experiment. Nevertheless the effects were highly significant compared with the control antibody.

To investigate the contribution of MAMs to this CCL3-promoting metastasis, we performed adoptive transfer of IMs. We have reported that transferred IMs (CD11b+Ly6Chigh) are readily detectable in the tumor-challenged lung at least 5 d after transfer, and a significant portion of them have differentiated into MAMs (CD11b+Ly6Clo) within 2 d (Qian et al., 2011). We have also shown that intravenously injected cancer cells extravasate within 2 d after injection and this seeding is suppressed by macrophage depletion (Qian et al., 2009), suggesting that IMs injected with cancer cells can differentiate to MAMs and support tumor metastasis. We thus injected IMs isolated from WT (Ccl3+/+) or Ccl3−/− mice in combination with cancer cells to the mice transplanted with Ccl3−/− BM cells (BMT:Ccl3−/−). Importantly, the suppressive effect on foci numbers in the BMT:Ccl3−/− mice was significantly rescued by the one-time injection of Ccl3+/+ IMs (Fig. 4 C). In contrast, adoptive transfer of Ccl3−/− IMs did not change the number of foci. Because MAMs originate from IMs (Qian...
et al., 2011) and are the major source of CCL3 in the metastasis sites (Fig. 2 D), these results collectively indicate that CCL3 from MAMs can promote metastatic seeding of breast cancer cells. Supporting this interpretation, in vitro extravasation of cancer cells, which was promoted by WT macrophages, was significantly suppressed by Ccl3 deficiency (Fig. 4 D).

Figure 4. Expression of CCL3 in MAMs promotes metastatic seeding of cancer cells. (A) Number and size of lung foci were assessed in WT irradiated mice transplanted with BM cells from C57BL/6 (WT, n = 13), Ccl3<sup>−/−</sup> (n = 14), or Ccr2<sup>−/−</sup> (n = 15) mice (three independent experiments). After reconstitution of their BM, mice were injected with E0771-LG cells and euthanized after 11 d. Data are means ± SEM. *P < 0.01 versus WT. (B) Number and size of lung foci were assessed in FVB mice injected with Met-1 cells (three independent experiments). Mice were treated with IgG (n = 9) or anti-CCL3 antibodies (n = 6) 24 and 2 h before tumor injection. Data are means ± SEM. *P < 0.01. (C) Number and size of lung foci were assessed at day 11 after E0771-LG tumor cell injection in mice transplanted with WT (n = 8) or Ccl3<sup>−/−</sup> (n = 7) BM. The Ccl3<sup>−/−</sup> BM transplanted mice were also injected with WT (Ccl3<sup>+/+</sup>, n = 7) or Ccl3<sup>−/−</sup> (n = 6) inflammatory monocytes (IMs). Data are means ± SEM from four independent experiments. *P < 0.01 versus WT, †P < 0.05 versus Ccl3<sup>−/−</sup>. (D) Number of transmigrated E0771-LG cells was measured in the transendothelial migration assay in the absence (−) or presence of BMM from C57BL/6 or Ccl3<sup>−/−</sup> mice (n = 3, 2 independent experiments). Mean cell number in each insert was determined by the counts from five fields. Data are means ± SEM. *P < 0.05 versus BM (−); †P < 0.01 versus WT. (E) mRNA expression of CC-chemokine ligands and their receptors in cultured mouse macrophages (BMDM), cancer cells (Met-1 and E0771), and endothelial cells (3B-11), as indicated (two independent experiments). PCR product size (bp) is shown on the right. (F) Secretion of CCL3 protein was assessed by ELISA in cultured mouse macrophages (BMDM), cancer cells (Met-1 and E0771), and endothelial cells (3B-11), as indicated (n = 3, three independent experiments). ND, not detected. (G) mRNA expression of CCL3 and its receptors in cultured human macrophages (MDM) and breast cancer cell lines (two independent experiments). PCR product size (bp) is shown on the right.
noteworthy that only the macrophages expressed Ccr2 and Ccl3 in this in vitro system (Fig. 4, E–G), suggesting that macrophages are the cells that respond to CCL2 signaling and produce CCL3.

CCL3–CCR1 axis enhances MAM accumulation and promotes tumor metastasis

Because mRNA of the CCL3 receptors CCR1 and CCR5 are expressed predominantly by human and mouse macrophages rather than breast cancer cells or endothelial cells (Fig. 4, E–G; see also Fig. 6 H), the MAM–derived CCL3 is likely to act as an autocrine mediator for MAMs rather than increasing cancer cell motility/invasiveness or vascular permeability. In the experimental metastasis model, we have shown that the MAMs (CD11b+) are recruited to the lung as early as 36 h after introduction of cancer cells into circulation. Using an ex vivo imaging system, we have also shown that majority of the i.v. injected cancer cells directly contact with the MAMs and extravasate within 48 h. In this system, macrophage deple-
enhance MAM retention through regulating the interaction between cancer cells and MAMs. Supporting this hypothesis, loss of *Ccl3* or *Ccr1* reduced the numbers of CD11b+ cells interacting with disseminating cancer cells in the lung (Fig. 7, C and D). We then determined the duration of interaction between macrophages and E0771-LG cancer cells in vitro. We cultured macrophages labeled with CMTMR fluorescent dye on Matrigel with cancer cells and tracked them for enhance MAM retention through regulating the interaction between cancer cells and MAMs. Supporting this hypothesis, loss of *Ccl3* or *Ccr1* reduced the numbers of CD11b+ cells interacting with disseminating cancer cells in the lung (Fig. 7, C and D). We then determined the duration of interaction between macrophages and E0771-LG cancer cells in vitro. We cultured macrophages labeled with CMTMR fluorescent dye on Matrigel with cancer cells and tracked them for
Figure 6. The CCL3–CCR1 axis is required for accumulation of MAMs and after extravasation of cancer cells. (A) Levels of chemokine receptors were assessed by flow cytometry in circulating inflammatory monocytes (IMs) and lung MAMs, as indicated. Cells were isolated from WT mice 24 h after E0771-LG tumor cell injection (n = 3). Dotted lines and shaded areas show control isotype matched IgG for each cell type. Representative histograms from three independent experiments are shown. (B) Levels of Ccr1 and Ccr5 mRNA were assessed in IMs, MAMs, and E0771-LG cancer cells. Cells were isolated from WT mice 24 h after E0771-LG tumor cell injection (n = 4). Data are means ± SEM. *, P < 0.05 versus IM. (C) Levels of chemokine receptors were assessed in CD45–CD31+ endothelial cells from the tumor cell–challenged lung. Cells were isolated from WT mice 24 h after E0771-LG tumor cell injection (n = 3). Dotted lines and shaded area show control isotype matched IgG for each receptor. A representative histogram from two independent experiments is shown. (D) Levels of chemokine receptors on cultured E0771-LG tumor cells were assessed by flow cytometry. Dotted lines and shaded areas show control isotype matched IgG for each receptor. A representative histogram from two independent experiments is shown (n = 2). (E) Relative numbers of lung CD11b+ macrophages (top) and circulating CD11b+CD115+ monocytes (bottom) were assessed by flow cytometry in C57BL/6 (WT; n = 14), Ccl3−/− (n = 4), Ccr1−/− (n = 7), and Ccr5−/− (n = 7) mice challenged with E0771-LG cells 24 h before measurement (at least two independent experiments/genotype). Data are means ± SEM. *, P < 0.05 versus WT. (F) Number and size of lung foci were assessed in mice transplanted with BM cells from C57BL/6 (WT, n = 14), Ccl3−/− (n = 11), or Ccr1−/− (n = 9) mice. Mice were injected with E0771-LG cells (two independent experiments). Data are means ± SEM. *, P < 0.01. (G) Number of transmigrated E0771-LG cells was measured in the transendothelial migration assay in the presence of BMDMs from C57BL/6 or Ccr1−/− mice (n = 6, three independent experiments). Mean cell number in each insert was determined by the counts from five fields. Data are means ± SEM. *, P < 0.01. (H) CCR1 protein expression was assessed by flow cytometry in BMDMs, 3B-11 endothelial cells, and Met-1 tumor cells. A representative histogram from two independent experiments is shown (n = 2).
Figure 7. CCR1 signaling enhances attachment of macrophages to cancer cells and promotes their retention in tumor-bearing lung. (A) The fate of transferred CMFDA-labeled IMs in mouse lung metastases were followed. CD11b+CD115-Ly6C- inflammatory monocytes (IMs) isolated from WT or Ccr1−/− mice were labeled with CMFDA and transferred to WT mice that received i.v. injection of E0771-LG cells expressing luciferase. Pulmonary tumor burdens in the recipients were determined by in vivo bioluminescence imaging 1 d before monocyte transfer (10 d after tumor injection). Relative numbers of CMFDA-labeled cells in CD45+CD11b+ cells from tumor-bearing lungs were assessed 18 or 42 h after IM transfer (n = 4, 4 independent experiments). Data are means ± SEM. *, P < 0.01. (B) Data show percentage of F4/80+CD11b+Ly6C− cells (MAMs) in CMFDA+ cells from tumor-bearing lung (n = 4, 4 independent experiments). Data are means ± SEM. *, P < 0.01 versus 18 h. n.s., not significant. (C) Number of CD11b+ cells associated with cancer cells in the lung were counted in WT Ccl3−/−, and Ccr1−/− mice from images in D (n = 4, 4 independent experiments). Interaction between cancer cells and CD11b+ myeloid cells were detected by immunostaining 24 h after intravenous injection of CMFDA-labeled E0771-LG cells. Data are means ± SEM. *, P < 0.05. (D) Representative fluorescence microscopy images of lung 24 h after E0771-LG injection. Green, CMFDA-labeled E0771-LG cells; Red, CD11b; Blue, nuclei; Arrow head, interaction between myeloid cells and cancer cells. Dotted line indicates the interaction between macrophage and tumor cell. Bars, 10 µm. See Videos 1 and 2. (F) Mean duration of interactions between macrophages and cancer cells (n = 3, three independent experiments) were assessed from images in (E; 10 fields/group in each experiment). Data are means ± SEM. *, P < 0.01 versus PBS; †, P < 0.05 versus CCL3. (H) Interactions between macrophages and cancer cells were assessed by flow cytometry (n = 4, four independent experiments). Macrophages were pretreated with anti-integrin α4 neutralizing antibody (α4 Ab: +) or control isotype matched IgG (α4 Ab: −). Data are means ± SEM. *, P < 0.01 versus PBS; †, P < 0.05 versus CCL3. (J) The effect of integrin α4 inhibition on the fate of transferred IMs in mouse lung metastases was assessed by flow cytometry following the experimental procedure in A. Anti-integrin α4 neutralizing antibody (α4) was injected 18 h after IM transfer. Relative numbers of CMFDA-labeled cells in CD45+CD11b+ cells from tumor-bearing lung were assessed 42 h after IM transfer (n = 5, five independent experiments). Data are means ± SEM. *, P < 0.05.
24 h by microscopy. The majority of WT macrophages were retained at the same position once they attached to cancer cells, and the mean interaction time was 353 ± 21 min (Fig. 7, E and F). In contrast, Cld3−/− or Ccr1−/− macrophages interacted with cancer cells for a significantly shorter time than WT macrophages (252 ± 16 or 204 ± 14 min, respectively; Fig. 7 F). We also found that Cld3−/− or Ccr1−/− macrophages more frequently detached from cancer cells and moved around the dish (Fig. 7 E and Videos 1 and 2), suggesting that the CCL3–CCR1 axis can enhance macrophage–cancer cell interaction, which arrests the macrophages. To confirm these results, we cultured macrophages with E0771-LG cancer cells together in suspension for 1 h, and determined the ratio of macrophages interacting with cancer cells by flow cytometry. Consistent with our findings (Fig. 7, E and F), we found a lower number of Cld3−/− or Ccr1−/− macrophages bound to cancer cells compared with WT macrophages (Fig. 7 G).

A recent report indicates that human breast cancer cells expressing VCAM-1 can bind to leukocytes that express α4 integrin, a VCAM-1 receptor (Chen et al., 2011). Because E0771-LG mouse breast cancer cells also expressed VCAM-1 and MAMs accumulated in the tumor-bearing lung expressing α4 integrin (Fig. 7 H), we investigated the possibility that the CCL3–CCR1 axis promotes macrophages to interact with cancer cells through α4 integrin. The interaction between macrophages and cancer cells was enhanced by CCL3 in Cld3−/− macrophages, and suppressed by anti-α4 integrin antibody treatment (Fig. 7 I). The antibody treatment also suppressed macrophage–cancer cell interaction in the absence of CCL3 to the comparable level with that in the presence of CCL3, suggesting that α4 integrin is required for both basal as well as CCL3-induced macrophage attachment to cancer cells. Furthermore, treatment of tumor-bearing mice with anti-α4 integrin antibody 18 h after IM transfer, a time point when the highest number of IMs had infiltrated into the lung (Fig. 7 A), resulted in significantly reduced numbers of transferred cells after 42 h (Fig. 7 J). This result indicates that α4 integrin contributes to MAM retention in vivo.

Collectively, our results in several models of metastasis including spontaneous GEM ones revealed the existence of a chemokine cascade that promotes breast cancer metastasis. Activation of CCL2–CCR2 signaling promotes CCL3 secretion that activates CCR1 signaling in MAMs. Activation of CCR1 in turn enhances interaction of MAMs with metastasizing cancer cells at least in part through integrin α4. As a result, prolonged MAM retention enhances extravasation of cancer cells and therefore metastasis.

**DISCUSSION**

Previously, we showed that a chemokine CCL2 recruits IMs to metastatic sites where they differentiate to MAMs (Qian et al., 2011). In this study, we revealed a novel role for CCL2 as a trigger of a prometastatic chemokine cascade involving CCL3 signaling via CCR1 that is required for efficient metastasis. These data illustrate a signaling relay that amplifies the pathology already in the system by promoting retention of recruited monocytes that stimulate tumor cell establishment at the metastatic site.

Our in vivo and in vitro results indicate that CCL2 can increase CCL3 expression in MAMs at the metastasis site. The CCL2-induced CCL3 expression is likely to be specific to the prometastatic macrophage lineage, as neutralization of CCL2 by antibodies significantly reduced Cld3 expression in IMs and MAMs, but not in resident monocytes or macrophages. Consistent with this interpretation, expression of Cld3 was highest in MAMs compared with other leukocytes in the tumor-bearing lung. Importantly, a single injection of Cld3−/− IMs but not IMs lacking CCL3 was sufficient to rescue the suppressive effect of Cld3−/− on experimental metastasis. Furthermore, in our in vitro extravasation assay, macrophages but not cancer cells or endothelial cells secrete CCL3 protein. These findings strongly suggest that MAMs are the main cell type in the metastasis site that produces CCL3 in response to CCL2 signaling. In cultured macrophages, basal CCL3 secretion is suppressed by Cgr2 deficiency, suggesting that CCL2 from macrophages cell autonomously regulates their CCL3 expression. Furthermore, CCL3 expression is increased by conditioned medium from cancer cells in part through a CCL2-mediated mechanism. These results suggest that CCL2 secreted by both cancer cells and macrophages can promote secretion of CCL3 that is required for tumor metastasis. Consistent with this, we have reported that both cancer cells and macrophages express Cld2 mRNA, and that CCL2 from both tumor cells and stromal cells contribute to metastatic seeding of cancer cells (Qian et al., 2011). Our results, however, do not exclude the involvement of other factors in regulation of CCL3 secretion. However, identification of such molecules is beyond a scope of this study and requires further experimentation.

A recent study demonstrates that tumor-associated macrophages (TAMs) in the PyMT mammary tumors also express CCR2 and are differentiated from the IMs (Franklin et al., 2014). We have reported that the TAMs in the PyMT tumors also express high level of CCL3 (Qjalvo et al., 2009), suggesting that CCL2 regulates CCL3 expression in the TAMs as well. However, it will not affect the recruitment of MAMs to the lung as they originate from circulating monocytes (IMs) that preferentially migrate to the lung with metastatic tumors than to the primary mammary tumors through CCL2-mediated mechanism (Qian et al., 2011). Indeed, in the current study, we found only an inhibition of metastasis but no deficit in PyMT primary tumor growth in the absence of Cld3. In contrast to our results, i.e. injected B16 melanoma cells develop more lung metastatic foci in Cld2−/− or Cld3−/− mice than WT mice (Nakasone et al., 2012). This discrepancy can be explained by a difference in the immune cell profile in particular cancer models. Namely, stromal loss of Cld3 or Cld2 reduces numbers of antitumorigenic immune cells such as CD4+ T, CD8+ T, and NK cells in the lung of melanoma metastasis model, but their numbers were not altered in the lung of our breast cancer metastasis model (Fig. 5 B). In contrast,
recruitment of prometastatic CD11b+ MAMs is reduced by lack of stromal CCL2 or CCL3 in breast cancer models (Fig. 5 A; Qian et al., 2011) but not in the melanoma model. It remains to be clarified how different metastatic environments regulate the response of immune cells to CCL2/CCL3.

To our knowledge, this is the first report demonstrating the involvement of a chemokine cascade in metastasis. Although chemokine-induced chemokine expression is reported in cultured mouse dendritic cells (Fischer et al., 2001) and astrocytes (Luo et al., 2000), its contribution to tumor progression remains unknown. In our metastasis models using mouse and human cells, loss of CCL3 reduced early accumulation of MAMs in the tumor-challenged lung without affecting recruitments of neutrophils or lymphocytes. Interestingly, pulmonary infection with C. neoformans can induce CCL3 expression, and neutralization of CCL2 significantly decreases its levels in the lung of infected mice (Huffnagle et al., 1997). In this model, neutralization of CCL3 attenuated the accumulation of macrophages but not lymphocytes, suggesting that CCL2-induced CCL3 expression may be a common mechanism for macrophages to accumulate in the lung under pathological situations. Our results suggest that accumulation of macrophages (MAMs) via CCL2-induced CCL3 is required for the efficient metastatic seeding of cancer cells. Although we also found the early recruitment of neutrophils to the tumor-challenged lung by CCL3-independent mechanisms, they play a minor role in metastatic seeding, at least in our model. However, our results do not exclude their contributions to the establishment of metastatic foci as we treated the animals with neutralizing antibodies for a short time and did not assess the effects of prolonged treatment. In addition, neutrophils may well be important in cancer models other than breast cancer.

CCL3 can bind to CCR1 and CCR5 with high affinity. In our experimental metastasis model of breast cancer, loss of CCR1 but not CCR5 reduced early accumulation of MAMs that was observed by 24 h after tumor cell injection. In a lung metastasis model of renal cancer, however, loss of CCR5 but not CCR1 reduces macrophage accumulation in the lung foci after 7 d of tumor cell injection (Wu et al., 2008). These differences might suggest specialized requirement of chemokine receptors for macrophages to accumulate in distinct microenvironments at different phases of metastasis, i.e., CCR1 in early and CCR5 in late metastatic foci. Such nonredundant roles of CCR1 and CCR5 in myeloid cell accumulation have been demonstrated in some in vivo experiments using gene-ablated mice. For example, CCR1 but not CCR5 is required for macrophages to accumulate in the kidney of mice that have received unilateral ureteral obstruction (Eis et al., 2004). Furthermore, intraperitoneal CCL3 injection increases the number of neutrophils in the peritoneal cavity within 4 h and this accumulation is suppressed in Ccr1−/− but not in Ccr5−/− mice (Ramos et al., 2005). Interestingly, an in vitro migration assay shows that CCR1 predominantly mediates the arrest of monocytes under shear flow (Weber et al., 2001), which is consistent with our finding that CCR1 predominately contributes to the retention of IMs/MAMs. Thus, tumor cells may have subverted the normal cellular physiology of mononuclear phagocytes during infection or repair to their own survival advantage.

Although some studies show that CCL3 can stimulate in vitro migration of cancer cells (Youngs et al., 1997; Prest et al., 1999), we did not find expression of CCR1 or CCR5 in cancer cells. In contrast, we found that MAMs in the metastasis sites express both receptors, and Ccr1/5 mRNA levels are much higher in the MAMs than circulating monocytes. Consistent with our results, freshly isolated human monocytes increase surface expression of CCR1 and CCR5 when they are kept in culture and differentiate to macrophages (Kaufmann et al., 2001). On the other hand, CCR2 expression is reduced in macrophages compared with monocytes. In this system, the differentiated macrophages thus show stronger responses to CCL3 than monocytes in chemotaxis and intracellular calcium flux assays, whereas responses to CCL2 are the opposite. The differential responsiveness of monocytes and macrophages to distinct sets of chemokines can explain why an impaired CCL3–CCR1 axis prolongs retention of MAMs without affecting initial recruitment of IMs (Fig. 7A).

Our results indicate that activation of the CCL3–CCR1 axis prolongs retention of MAMs in the lung at least in part through integrin α4. We also show that activation of the CCL3–CCR1 axis enhances adhesion of macrophages to VCAM-1 expressing cancer cells via integrin α4. In myeloma cells, CCL3 can increase the expression of integrin β1, which forms a heterodimer with integrin α4 and binds to the ligands such as fibronectin and VCAM-1 (Oba et al., 2005). In our metastasis model, however, the MAMs isolated from WT and Ccr1−/− mice expressed comparable levels of integrin α4 and β1 mRNA and protein (unpublished data), suggesting that the CCL3–CCR1 axis might regulate adhesive configurations of integrins rather than their expression. Similar results are reported in the in vitro T cell adhesion assay (Lloyd et al., 1996). Namely, CCL3 induces T cell adhesion to recombinant VCAM-1 that is suppressed by anti-integrin α4 neutralizing antibody, whereas CCL3 does not alter surface expression of integrins. CCL3 can also increase adhesion of hematopoietic progenitor cells to fibronectin (Suchiro et al., 1999). The effect of CCL3 on the progenitor cells is inhibited by blocking antibodies against integrins α4 and β1, although CCL3 does not alter integrin expression. Interestingly, when these progenitor cells are exposed to CCL3, the amount of F-actin in the cell cortex is increased within 60 s. Although the precise mechanism remains undefined, it is possible that the CCL3–CCR1 axis regulates conformational changes and/or clustering of integrins through the polymerization of cytoskeletal actin that is associated with the endodomain of integrins.

Breast cancer cells frequently metastasize to the bone and lung, which makes breast cancer a leading cause of cancer death. Unfortunately, current therapies are not sufficient to prevent it probably because of resistance by rapid evolution of mutation-prone cancer cells. A newly appreciated target for therapy is the tumor microenvironment (Joyce and Pollard, 2009;
Hanahan and Coussens, 2012) and particularly macrophages within it because they promote breast cancer metastasis (Qian and Pollard, 2010) and they are not prone to hypermutation. CCL2 is one target fitting this strategy as it recruits MAMs that promote metastasis (Qian et al., 2011). Indeed, anti-CCL2 antibodies suppress distant metastases and improve overall survival in preclinical models (Lu and Kang, 2009; Qian et al., 2011; Zhu et al., 2011). However, humanized anti-CCL2 antibody is ineffective at achieving biological effects in humans due to a feedback mechanism that increases CCL2 production (Sandu et al., 2013), which suggests difficulty in suppressing the IM recruitment by CCL2 deprivation. Furthermore, loss of CCL2 signaling in mouse models severely depresses the numbers of circulating monocytes and increases susceptibility to infection (Serbina et al., 2008). A recent paper also suggests a risk of anti-CCL2 therapy as there is a rebound increase of prometastatic myeloid cells after cessation of the therapy that accelerates the metastatic diseases (Bonapace et al., 2014). Here, we show that human and mouse macrophages secrete CCL3 through activation of CCL2 signaling. Deletion of CCL3 or its receptor CCR1 in macrophages reduces the number of lung metastasis foci developed by human and mouse breast cancer cells, as well as the number of MAMs accumulated in tumor-challenged lung without inhibiting circulating monocyte number. Because the suppressive effect of CCL3 gene ablation is comparable with Ccr2 knockout and antibody treatment inhibits metastasis (Fig. 4, A and B), these results suggest that inhibition of the CCL2-induced chemokine cascade is effective in preventing breast cancer metastasis and suggests that CCR1 antagonists as a better therapeutic option. Supporting this proposal, recent clinical trials in rheumatoid arthritis indicate that CCR1 antagonists show clinical activity without feedback-related increases in CCR1 ligands, suppressive effects on monocytes, or adverse events including increased risk of infections (Dairagh et al., 2011; Tak et al., 2013).

It has been reported that CCR1 can also regulate trafficking of potentially tumoricidal immune cells such as T cells (Schaller et al., 2008), NK cells (Bernardini et al., 2008), and dendritic cells (Ida et al., 2008). Although an impact of CCR1 activation in these cells on tumor metastasis is largely unknown, it seems to play a minor role in some types of tumors because prolonged treatment with CCR1 antagonists suppresses multiple myeloma tumor burden in the bone (Dairagh et al., 2012) and colon cancer liver metastasis (Kitamura et al., 2010). These studies, as well as our current results, suggest the therapeutic potential of CCR1 antagonists in metastatic progression of certain tumor types, including breast cancer.

MATERIALS AND METHODS

Cell lines, primary samples, and cell culture. We obtained E0771 mouse mammary adenocarcinoma cells derived from a medullary cancer (Evens et al., 2005) from E. Mihich (Rosewell Park Cancer Institute, Buffalo, NY). To obtain highly metastatic populations, we injected E0771 cells i.v. into C57BL/6 mice, and cultured the cells isolated from lung metastatic foci (E0771-LG). Human breast cancer cells MDA-MB-435, MDA-MB-231, T47D, and MCF7 were provided by P. Kenny and O. Griricz (Albert Einstein College of Medicine, Bronx, NY), and MDA-MB-231:4175TGL clone was provided by J. Masaguti (Memorial Sloan-Kettering Cancer Center, New York, NY). All cancer cells were cultured in DMEM supplemented with 10% fetal bovine serum (FBS). Mouse BM derived macrophages (BMDMs) were isolated as described previously (Tushinski et al., 1982) and cultured in αMEM supplemented with 10% FBS and 104 U/ml human recombinant CSF-1. In some experiments, the BMDMs were cultured with recombinant mouse CCL2 (Peprotech; endotoxin level is <0.1 ng/µg of protein) for 12 h. Human blood (buffy coats) was obtained from New York Blood Services under informed consent, which is approved by Albert Einstein College of Medicine Institutional Review Board. Peripheral blood mononuclear cells (PBMCs) were isolated as described previously (Cassetta et al., 2013), and monocytes were isolated using the Mac Monocyte isolation kit II (Miltenyi Biotec). The isolated monocytes were cultured in αMEM supplemented with 10% FBS and 104 U/ml CSF-1 for 7 d to differentiate them into macrophages. In some experiments, the human macrophages were cultured in αMEM supplemented with 10% FBS and 104 U/ml human recombinant CSF-1 or the same medium that had been conditioned from human breast cancer cells for 24 h.

Mice. Ccr2−/−, Ccl3−/−, Ccr1−/−, ROSA-rtTA, and tetO-Cre mice on the C57BL/6 genetic background were purchased from The Jackson Laboratory. Ccr1−/− (C57BL/6) and Rag2−/− mice were purchased from Taconic. We obtained transgenic mice expressing PyMT oncogene under the control of MMTV-LTR promoter (PyMT) on the FVB background from W.J. Muller (McGill University, Montreal, Canada) and those backcrossed with C57BL/6 mice (PyMT BL6) from S.J. Gendler (Mayo Clinic, Phoenix, AZ). The PyMT BL6 or Rag2−/− mice were further crossed with C3a−/− mice to construct PyMT:C3a−/− or Rag2−/−:C3a−/− compound mutants. We have constructed a conditional knockout strain for CSF-1 receptor that is essential for survival of distinct populations of myeloid cells (Li et al., 2006). The B6.Cg-Csf1r<sup>F/F</sup>/J (Csf1r<sup>F/F</sup>) mice were crossed with ROSA-rtTA and tetO-Cre mice to construct rtTA:tetO-Cre:Csf1r<sup>F/F</sup> mice, in which inflammatory monocytes are depleted by loss of Csf1r after doxycycline treatment. 8- to 10-week-old female mice were used unless described specifically. All animals were randomly allocated by genotype. All procedures involving mice were conducted in accordance with National Institutes of Health regulations concerning the care and use of experimental animals. Experimental procedures were approved by Institutional Animal Care & Use Committee of the Albert Einstein College of Medicine.

BMT. BM cells were isolated from C57BL/6, C3a−/−, Ccr1−/−, Rag2−/−, or Rag2−/−:C3a−/− mice. BM cells were counted in a hemocytometer and resuspended at 2 × 10<sup>6</sup> cells/ml in PBS. The 4-wk-old recipient mice (C57BL/6 or nu/nu mice) were irradiated with 9 Gy γ-rays and transplanted with 4 × 10<sup>6</sup> donor cells i.v.. The recipient mice were used for experiments 6–8 wk later.

Experimental metastasis assay. 4 × 10<sup>5</sup> E0771-LG cells were injected into the tail vein of C57BL/6 or knockout mice (7-wk-old female). In cases where the mice had received BMT, the number of cells injected was reduced to 3 × 10<sup>5</sup>. To deplete CSF-1–dependent myeloid cells, we gave doxycycline in the drinking water to the rtTA:tetO-Cre:Csf1r<sup>F/F</sup> mice from 7 d before tumor injection to the endpoint. We also injected 10<sup>6</sup> Met-1 cells into the tail vein of FVB females. We euthanized the mice 11 d (E0771-LG) or 14 d (Met-1) after tumor cell injection, and dissected the lung to prepare H&E sections as described previously (Qian et al., 2011). Lung images of all five lobes were taken using a Zeiss SV11 microscope with a Retiga 1300 digital camera via 2× objective lens, and analyzed using Fiji software to determine the average number of metastasis nodules per mm<sup>2</sup> of lung area. The average size of nodules (total nodule area [mm<sup>2</sup>]/total nodule number) is also determined and converted to the average diameter (mm). 10<sup>4</sup> MDA-MB-231:4175 human breast cancer cells were injected into the mammary fat pad of nu/nu mice that received BM cells from Rag2−/− or Rag2−/−:C3a−/− mice. After 4 wk, we dissected the primary tumor and determined tumor loads in the lung area by in vivo bioluminescence imaging every week.
Antibody treatment. The mice injected with 4 × 10^5 E0771-LG cells received anti-mouse CCL2 neutralizing antibody or control isotype matched IgG (5 mg/kg body weight) via i.p. injection on days 9 and 10 after tumor injection. 24 h after the last treatment, the mice were euthanized to isolate monocytes and macrophages. To neutralize CCL3, the FVB mice injected 10^6 Met-1 cells received anti-mouse CCL3 antibody or control IgG (R&D Systems; 5 mg/kg body weight) via i.p. injection 2 h before and 24 h after tumor injection. To deplete neutrophils, anti-mouse Ly6G neutralizing antibodies or control isotype matched IgG (BioLegend) were given at 1 mg/kg body weight via i.p. injection before and 24 h and, after 16 h of tumor injection.

In vivo bioluminescence imaging. We injected 100 µl of D-luciferin solution (10 mg/ml in PBS, i.v.; GoldBio) into anesthetized tumor-bearing mice. Bioluminescence from the luciferase-expressing tumor cells was determined using IVIS-SPECTRUM in vivo photon-counting device (Caliper Life Sciences). Images were quantified as photon counts using the Living Image software (Caliper Life Sciences).

Adoptive transfer of monocytes. In metastasis assay, CD11b^+Ly6C^-Ly6G^- cells were sorted from BM monocytes isolated from WT or Ccl3^-/- mice and 5 × 10^5 cells were injected with 4 × 10^5 E0771-LG cells into mice transplanted with Ccl3^-/- BM cells. To chase the cell fate, monocytes were sorted from C57BL/6 or Ccl3^-/- mice and labeled with CellTracker CMFDA (Invitrogen) following the manufacturer’s instructions. The labeled monocytes (5 × 10^5) were transferred into C57BL/6 mice bearing pulmonary metastases. Pulmonary tumor burdens in the recipients were determined by in vivo bioluminescence imaging one day before monocyte transfer. The tumor-bearing mice were allocated to each group equally by their tumor loads. Some recipients were treated with anti-integrin α4 antibodies (5 mg/kg body weight, i.p.; BioLegend) 18 h after transfer.

Flow cytometry and sorting. Single-cell suspensions were prepared from perfused lungs or blood samples as described previously (Qian et al., 2011). After blocking with anti–mouse CD16/CD32 antibody (BD), the cells were stained with DAPI and fluorescent antibodies to following antigens: Ccl3^-/- or Ccr5^-/- mice and 5 × 10^5 of E0771-LG cells into mice transplanted with Ccl3^-/- BM cells. To chase the cell fate, monocytes were sorted from C57BL/6 or Ccl3^-/- mice and labeled with CellTracker CMFDA (Invitrogen) following the manufacturer’s instructions. The labeled monocytes (5 × 10^5) were transferred into C57BL/6 mice bearing pulmonary metastases. Pulmonary tumor burdens in the recipients were determined by in vivo bioluminescence imaging one day before monocyte transfer. The tumor-bearing mice were allocated to each group equally by their tumor loads. Some recipients were treated with anti-integrin α4 antibodies (5 mg/kg body weight, i.p.; BioLegend) 18 h after transfer.

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ELISA. Mouse BM macrophages or human breast cancer cells were cultured in mMEM supplemented with 10% (vol/vol) FBS and 10^4 U/ml human recombinant CSF-1 for 12 or 24 h, respectively. Conditioned media were collected from the cultured cells, and the levels of mouse CCL3 (MIP-1α) or human CCL2 (MCP-1) were determined using the Mouse MIP-1α ELISA kit or Human CCL2 (MCP-1) ELISA kit (eBioscience). Samples were collected independently and analyzed by one assay.

In vitro extravasation assay. The extravasation assay was performed as described previously (Qian et al., 2011). In brief, 2 × 10^8 3B-11 mouse endothelial cells (American Type Culture Collection) were cultured on top of GFR α1 MEM supplemented with 10% FBS and 10^4 U/ml CSF-1. After 36 h, the chambers were fixed with 4% paraformaldehyde, and cells on top were removed. Fluorescent images of 5 randomly selected fields in each insert were captured with Olympus IX81 fluorescence microscope and numbers of cancer cells migrated through endothelial monolayer were counted using Fiji software.

In vitro interaction assay. BMDCs and E0771-LG cells were labeled with CellTracker CMTMR and CFMDF (Invitrogen), respectively. To determine dynamic interaction between BMDCs and cancer cells, single cell suspension of each labelled cells (5 × 10^5) were placed on Matrigel (5 mg/ml) and cultured for 1 h in mMEM supplemented with 10% FBS and 10^5 U/ml CSF-1. Bright-field and fluorescent images (10 randomly selected fields in each well) were acquired every 10 min by fluorescence microscopy (Axiovert 200). Movies of BMDCs were tracked in Fiji Imagej and tracks were analyzed in Mathematica (Wolfram) to determine the duration of interaction between BMDCs and cancer cells. To detect BMDC binding to cancer cells, single cell suspension of each labeled cells (5 × 10^5) were mixed in v-bottom 96-well plates and cultured for 1 h in mMEM supplemented with 10% FBS and 10^5 U/ml CSF-1. The ratio of CMFTMR/CFMDF double–positive population was determined by flow cytometry. Based on a side-scattered light (SSC), we confirmed that >80% of double–positive fraction consists double of cells whereas <10% of single positive fraction does. To maintain binding activity of integrin, the cells were kept in Hepes buffer containing CaCl_2 and MgCl_2 during the analysis.

Immunofluorescence staining. E0771-LG cells (10^6) labeled with CellTracker CMFDA (Invitrogen) were injected into the mice. After 20 h, the lungs were dissected and directly embedded in O.C.T. compound (Sakura Finetek). Sections were fixed with cold acetone, immunostained with rat monoclonal antibodies to CD11b (1:1000; BD) followed by Alexa Fluor 546.
anti-rat IgG (1:250; Molecular Probes), and mounted with VECTASHIELD with DAPI (Vector Laboratorites). Fluorescent images were captured and analyzed with Olympus IX81 fluorescence microscope and Adobe Photoshop software.

Statistical analysis. Sample size was determined based on a relative standard deviation from our previous studies. All samples were collected independently and analyzed by at least two independent experiments. Data were analyzed by Student’s t test and are expressed as mean ± SEM. P-values <0.05 were considered significant.

Online supplemental material. Fig. S1 shows the FACS gating strategy to identify myeloid cell populations quantified in Figs. 2, 5, and 6. Video 1 and Video 2 show time lapse imaging of interactions between WT (S1) or Ccr1−/− (S2) BMDMs and E0771 cancer cells. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20141836/DC1.

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J.W. Pollard has patent applications pending for macrophages synthesized molecules in the treatment of metastasis. The authors declare no additional competing financial interests.

Author contributions: T. Kitamura and J.W. Pollard designed the research and analyzed data. T. Kitamura performed and analyzed the in vitro and in vivo data. B-Z. Qian generated the microarray data. D. Soong established and performed the in vitro and in vivo assay. R. Noy and J. Li generated the PyMT:Ccl3−/− mice. L. Cassetta provided human monocytes. G. Sugano developed the analytic program. Y. Kato established the in vitro interaction assay. T. Kitamura and J.W. Pollard wrote the manuscript.

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MIP-1α during differentiation of human monocytes to macrophages.


