Metastatic Growth Progression Caused by PSGL-1–Mediated Recruitment of Monocytes to Metastatic Sites

Alexandra Hoos, Darya Protsyuk, and Lubor Borsig

Abstract

Tumor cell–derived selectin ligands mediate contact to the endothelium, platelets, and leukocytes through binding to selectins that facilitates metastasis. Here, we describe the mechanism of how endogenous (non–tumor derived) selectin ligands contribute to metastasis using α(1,3)fucosyltransferase 7 (Fuc-TVII−/−)–deficient mice. Experimental metastasis of MC-38GFP and Lewis lung (3LL) carcinoma cells was attenuated in Fuc-TVII−/− mice, which express minimal amount of selectin ligands. We show that metastasis is dependent on selectin ligands carried on hematopoietic cells. P-selectin glycoprotein ligand-1 (PSGL-1) was identified as the major ligand facilitating monocyte accumulation at metastatic sites. Reduced recruitment of monocytes to metastasizing tumor cells in Fuc-TVII−/− mice correlated with attenuated metastasis. Adoptive transfer of Fuc-T7+ monocytes rescued metastasis in Fuc-TVII−/− mice, indicating that selectin ligand–dependent recruitment of monocytes is required for cancer progression. Cytokine analysis in metastatic lungs revealed high expression of CCL2 in C57BL/6 mice that was significantly lower in Fuc-TVII−/− mice. The absence of monocyte recruitment in Fuc-TVII−/− mice correlated with increased apoptosis of tumor cells. Thus, the recruitment of monocytes to metastasizing tumor cells is facilitated by endogenous selectin ligands on monocytes that enable efficient tumor cell survival, extravasation, and metastasis. Cancer Res; 74(3); 695–704.

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Introduction

During hematogenous metastasis circulating tumor cells interact with blood constituents (platelets and leukocytes), which modulate their capacity to adhere to endothelium and to leave blood circulation. Malignant transformation is associated with alteration of cell surface glycosylation and presentation of altered glycan structures (1, 2). Furthermore, the enhanced expression of sialyl-Lewisx (sLex) and/or sialyl-Lewisα (sLeα) is frequently associated with poor prognosis of patients with carcinoma due to metastasis (3–5).

There is substantial evidence that selectins contribute to metastatic spread through mediation of tumor cell interaction within the circulation (reviewed in refs. 1, 6, 7). Selectins are a family of cell adhesion molecules, expressed on activated endothelium (E- and P-selectin), leukocytes (L-selectin) and on activated platelets (P-selectin), which are involved in different physiologic situations ranging from thrombosis, inflammation, hemostasis to cancer (1, 8). In the context of cancer progression, P-selectin facilitates platelet-tumor cell thrombi formation (9). L-selectin mediates leukocyte recruitment (10), and E- and P-selectin are required for adhesion of tumor cells to endothelium (11–13). The direct involvement of tumor cell–derived selectin ligands in metastasis has been shown both in vitro and in vivo (14–17). Enzymatic removal of selectin ligands, carcinoma mucins, resulted in reduced selectin ligand interactions and subsequently attenuation of metastasis (17). However, there are limited data on the involvement of endogenous (non–tumor derived) selectin ligands during cancer development and metastasis.

Selectins mediate the recruitment of leukocytes to inflammatory sites through binding to endogenous selectin ligands, expressed both on leukocytes, in high endothelial venules or on the activated endothelium (18). There are two major glycoproteins, P-selectin glycoprotein ligand-1 (PSGL-1) and E-selectin ligand-1 (ESL-1), which have been identified to mediate leukocyte rolling and adhesion during inflammation (19, 20). Selectin-mediated leukocyte trafficking is controlled prominently but not exclusively by α(1,3)fucosyltransferase Fuc-T7–dependent fucosylation, which is further complemented by α(1,3)fucosyltransferase Fuc-T4 activity (21, 22). In addition to homeostasis, leukocyte infiltration is also closely linked to cancer development. However, the mechanism of leukocyte recruitment is not unique for cancer progression and has many parallels with inflammation (8, 23). In particular, initiation of metastasis is dependent on the recruitment of leukocytes that is mediated by chemokines (24, 25). Tumor-derived CCL2 expression drives the recruitment of inflammatory monocytes that facilitates tumor cell extravasation and metastasis.
The Jackson Laboratory. Fucosyltransferase 7 mice (Fuc-TVII) of the Swiss Animal Protection Law, and approved by Veterinary Conditions, and experiments were according to the guidelines of the active role of selectin in cancer progression (10). Furthermore, increased 1-selectin ligand expression was detected in the vicinity of metastasizing tumor cells, but the identity of cells and the nature of the ligands remained unclear. The present study aims to identify selectin ligand–expressing cells and to elucidate their role in metastasis using fucosyltransferase 7–deficient mice that are lacking the majority of selectin ligands.

Materials and Methods

Mice

Animals were maintained under specific pathogen-free conditions, and experiments were according to the guidelines of the Swiss Animal Protection Law, and approved by Veterinary Office of Kanton Zurich. C57BL/6 mice were purchased from The Jackson Laboratory. Fucosyltransferase 7–deficient mice (Fuc-TVII–/–) and fucosyltransferase 4 and 7 double–deficient mice (Fuc-TVII–/–/Fuc-TVII–/–) in a C57BL/6 background were kindly provided by Dr. J.B. Lowe (University of Michigan, Ann Arbor, MI) and bred in house.

Cell culture

Mouse colon carcinoma cell line MC-38 stably expressing green fluorescent protein (GFP; MC-38GFP) was grown in Dulbecco’s Modified Eagle Medium (DMEM) with 10% fetal calf serum (FCS; ref. 31). Lewis lung carcinoma (3LL) cells were grown in RPMI medium with 10% FCS (30). B16-BL6 melanoma cells were grown in DMEM with 10% FCS as described previously by Hostettler and colleagues (32).

Quantification of metastasis

Mice were intravenously (i.v.) injected with MC-38GFP cells (3 × 10^5) and euthanized after 28 days. Metastatic foci were counted and macroscopic pictures of lungs were documented. 3LL cells (1.5 × 10^5) were i.v. injected and tumor nodules were counted on day 14.

Histology and immunohistochemistry

Lungs fixed in 4% paraformaldehyde were embedded in paraffin blocks. Lungs sections (2 μm) were stained with hematoxylin and eosin (H&E) or various antibodies: Ki67 (Cl. SP6; NeoMarkers), anti-CD3 (Cl. SP7; NeoMarkers), anti-F4/80 (Serotec), anti-Ly6G (Becton Dickinson), anti-F4/80 (Becton Dickinson). For apoptosis assay anti-caspase-3 (Cell Signaling Technology) and anti-GFP (Fitzgerald Industries International) antibodies were used. Staining was performed on a NEXES immunohistochemistry robot (Ventana instruments) using an IVIEW DAB Detection Kit (Ventana) or on a Bond MAX (Leica). Images were digitalized on the Zeiss Mirax Midi Slide Scanner and analyzed with the Mirax Viewer 1.12. software.

Bone marrow reconstitutions

C57BL/6 and Fuc-TVII–/– mice were used for generation of bone marrow chimeras. Recipient animals were irradiated with 9 Gy in one dose and reconstituted by i.v. injection of 1 × 10^7 bone marrow cells (isolated from femur and tibia). Reconstitution efficiency was analyzed by the presence of selectin ligands in the peripheral blood leukocytes and the amount of Ly6G^+ cells in the blood 6 to 7 weeks after reconstitution.

Flow cytometry

Mice were perfused with PBS. Lungs were minced and digested with 2 mg/ml Collagenase D (Roche) and 2 mg/ml Collagenase A (Roche) for 1 hour at 37°C. Cells were separated using 40-μm cell strainers. Red blood cells were lysed using PharmLyse (Becton Dickinson). Cells were incubated with anti-mouse CD16/32 mAb (Becton Dickinson) and stained with fluorophore-conjugated antibodies against CD45, CD11b, F4/80, Ly6G, Ly6C, and PSGL-1 (Becton Dickinson). Rabbit anti-ESL-1 serum VE12 (a generous gift from Dietmar Vestweber, Max Planck Institute, Münster, Germany) was used together with donkey anti-rabbit-phycocerythrin (PE; eBioscience). Anti-CD31-FITC antibody (Invitrogen) was used as an internal control for lung digestion. Blood samples were treated with PharmLyse (Becton Dickinson) and stained as described above. Selectin ligands were detected with mouse selectin-Fc chimeras (L-, P-, and E-selectin; 10 μg/ml) that were precomplexed with biotinylated goat anti-human antibody (1:100; Sigma-Aldrich). Selectin binding was detected with Streptavidin-CyChrome (Becton Dickinson). Control samples were incubated with selectin chimera in the presence of 10 mmol/L EDTA. Data were acquired on a BD FACS acknowledging II flow cytometer (Becton Dickinson) and analyzed using the Flowjo software (Tree Star).

Selectin immunoprecipitation and Western blot analysis

Bone marrow was isolated from femurs and tibia of 6- to 8-week-old C57BL/6 and Fuc-TVII–/– mice. Cells were stained with CD11b, Ly6G, and Ly6C antibodies (all Becton Dickinson) and sorted on a FACS Aria III (Becton Dickinson). The equal amount of CD11b^+Ly6C^+ monocytes (15 × 10^6 cells) and CD11b^+Ly6G^+ granulocytes (23 × 10^6 cells) was lysed in a buffer containing 20 mmol/L Tris pH 7.8, 150 mmol/L NaCl, 1 × complete protease inhibitor cocktail (Roche), and 0.5% Triton X-100. Mouse E-selectin-Fc chimera was precomplexed with Protein A Sepharose 4 Fast Flow beads (GE Healthcare) for 1 hour. Cell lysates were incubated with E-selectin/beads complex in the presence of 3 mmol/L CaCl2 overnight at +4°C. Beads were washed 3 times with PBS and bound ligands were eluted in Laemmli loading buffer, boiled for 10 minutes at 95°C, and separated on 7.5% SDS–PAGE gel. After a transfer, the polyvinylidene fluoride membrane was incubated with the rat anti-mouse PSGL-1 (Becton Dickinson) or rabbit anti-ESL-1 serum VE12 and developed with the enhanced chemiluminescence method (GE Healthcare).

Analysis of leukocyte–tumor cell association

Frozen lung sections (8–10 μm) prepared from C57BL/6 and Fuc-TVII–/– mice injected with MC-38GFP cells were stained with the following antibodies: CD11b (Becton Dickinson), Ly6G (Becton Dickinson), and F4/80 (AbD Serotec). Goat anti-rat-Alexa568 Ab (Invitrogen) was used to visualize signals with a fluorescence microscope. Tumor cells were counted and the...
percentage of tumor cells associated with leukocytes was determined. Images were acquired with a SP2 confocal microscope (Leica) of a total 5 μm in a z-axis and analyzed with the Imaris Software (Bitplane).

**Real-time PCR**

Total RNA was isolated from PBS-perfused and flash-frozen lungs or sorted cells (monocytes and granulocytes) from lungs using the RNeasy Mini Kit (Qiagen). The quantity and quality of the RNA was determined using a Nanodrop 2000 (Thermo Scientific). Purified RNA was reversely transcribed into single stranded cDNA using the Omniscript RT Kit (Qiagen) according to the manufacturer’s instructions. PCR was performed in CFX-96 thermocycler (Bio Rad) using a SYBR Green JumpStart Taq Ready Mix (Sigma-Aldrich) and primers specific for murine glyceraldehyde-3-phosphate dehydrogenase (GAPDH), CCL2, CCL5, IL1. Primers (Microsynth) and the SYBR Green JumpStart Taq Ready Mix (Sigma-Aldrich) and primers specific for murine glyceraldehyde-3-phosphate dehydrogenase (GAPDH), CCL2, CCL5, IL1 were amplified using the RNeasy Mini Kit (Qiagen). The quantity and quality of the RNA was determined using a Nanodrop 2000 (Thermo Scientific). Purified RNA was reversely transcribed into single stranded cDNA.

**Isolation of monocytes**

Bone marrow cell were harvested from 6- to 8-week-old mice by flushing femur and tibia with PBS containing 2% FCS and 2.5 mmol/L EDTA. Red blood cells were lysed using ammonium chloride solution. Bone marrow nucleated cells were pre-enriched using the magnetic activated cell sorting (MACS) system. Briefly, cells were stained with biotinylated macrophage colony-stimulating factor receptor (M-CSFR) antibody (Cl. AFS98; Biolegend) and incubated with streptavidin-conjugated magnetic beads (Miltenyi Biotec). After MACS enrichment, cells were stained with Gr-1-PE mAb (Cl. RB6-8C5; eBioscience) and M-CSFR+ cells were stained with streptavidin-APC (eBioscience). Bone marrow monocytes were sorted as M-CSFR+Gr-1+med cells using a FACSAria III cell sorter (Becton Dickinson).

**Adoptive transfer**

*Fuc-TVII−/−* mice were i.v. injected with 2 × 10^5 bone marrow monocytes isolated from C57BL/6 or *Fuc-TVII−/−* mice, 6 hours after tumor cell injection (MC-38GFP or 3LL). Mice were euthanized after 28 days and metastasis was quantified as described above.

**Statistical analysis**

Statistical analysis was performed with the GraphPad Prism software (version 4.0). Data are presented as mean ± SEM and were analyzed using the two-tailed Student t test.

**Results**

**Endogenous selectin ligands facilitate metastasis**

Fucosyltransferase-7 (Fuc-T7) is the major enzyme finalizing the synthesis of endogenous selectin ligands based on the core structure of sLex in mice (21, 22). To assess the role of selectin ligands during metastasis, we i.v. injected mouse colon carcinoma cells expressing GFP (MC-38GFP) in *Fuc-TVII−/−* mice, and metastasis was analyzed 28 days later. Significant reduction in the number of metastatic foci was observed in the lungs of *Fuc-TVII−/−* mice compared with C57BL/6 mice (Fig. 1A and B). Immunohistologic examination revealed no obvious differences in composition of Ki67+ (proliferating cells), F4/80+ (macrophages/monocytes), and Ly6G+ (neutrophils) cells within the tumors between *Fuc-TVII−/−* and C57BL/6 lungs (Fig. 1C). However, tumors in *Fuc-TVII−/−* mice showed an enhanced infiltration of B220+ (B cells) and CD3+ T-cells. Of note, increased number of Ly6G+ cells was found in lung tissues of *Fuc-TVII−/−* mice compared with C57BL/6 mice. The significantly reduced number of metastatic nodules in *Fuc-TVII−/−* mice indicated that the presence of endogenous (non–tumor derived) selectin ligands is required for metastasis.

To test whether other tumor cells metastasize in endogenous selectin ligand–dependent manner, we injected 3LL cells and melanoma cells (B16-BL6) into *Fuc-TVII−/−* mice. Similar to MC-38GFP cells, 3LL and B16-BL6 cells formed less metastatic nodules in *Fuc-TVII−/−* mice compared with C57BL/6 mice (Fig. 1D and E and Supplementary Fig. S1). There was no obvious difference in the composition of metastatic nodules as determined by immunohistochimerism (Supplementary Fig. S1C).

**Selectin ligands on hematopoietic cells promote metastasis**

To determine which selectin ligand–expressing cells promote metastasis, we generated chimeric mice. Reciprocal bone marrow reconstitutions (C57BL/6 → *Fuc-TVII−/−*; *Fuc-TVII−/−* → C57BL/6) were performed and circulating myeloid cells (CD11b+ cells) were analyzed for the presence of selectin ligands 5 weeks later (Fig. 2A and B and Supplementary Fig. S2). We also confirmed increased levels of Ly6G+ cells in chimeric mice *Fuc-TVII−/−* → C57BL/6 (Supplementary Fig. S2B and S2C) that was in line with the phenotype of *Fuc-TVII−/−* mice (21). Chimeric mice were i.v. injected with MC-38GFP cells and the extent of metastasis was analyzed after 28 days (Fig. 2C and D). *Fuc-TVII−/−* mice expressing selectin ligands in the hematopoietic compartment (C57BL/6 → *Fuc-TVII−/−*) showed metastasis comparable with controls (C57BL/6 → C57BL/6). On the contrary, minimal metastasis was observed in chimeric mice expressing selectin ligands on the radio-resistant stromal compartment (*Fuc-TVII−/−* → C57BL/6). These data demonstrate that selectin ligands on hematopoietic cells facilitate metastasis.

**Reduced tumor cell survival in lungs of *Fuc-TVII−/−* deficient mice**

We next analyzed whether tumor cell seeding to the lungs is affected by endogenous selectin ligands. MC-38GFP–injected C57BL/6 and *Fuc-TVII−/−* mice were terminated at various time points and perfused lungs were evaluated for the presence of GFP+ tumor cells (Fig. 3A and B). Similar amounts of MC-38GFP cells were observed at 30 minutes post-injection and their number decreased at 14 and 24 hours post-injection in both genotypes (Fig. 3B). However, a pronounced decrease of GFP+ cells was detected in lungs of *Fuc-TVII−/−* mice compared with C57BL/6 mice. Because the initial seeding/retenion of tumor cells in the lungs was comparable and the
difference in number of GFP⁺ tumor cells was detected first 14 hours later, we tested the possibility that the endogenous selectin ligands might be required for tumor cell survival. We analyzed lungs of mice 24 hours after tumor cell injection using caspase-3 staining for detection of apoptotic cells, and GFP staining for living tumor cells (Fig. 3C and D). We observed higher apoptosis of tumor cells in lungs of Fuc-TVII⁻/⁻ mice compared with C57BL/6 mice, indicating that the absence of endogenous selectin ligands leads to a reduced tumor cell survival.

**Endogenous selectin ligands facilitate monocyte recruitment and interactions with tumor cells**

To test whether the observed enhanced tumor cell apoptosis in the absence of selectin ligands is due to the altered recruitment of leukocytes, we analyzed lungs of C57BL/6 and Fuc-TVII⁻/⁻ mice injected with MC-38GFP cells for leukocyte infiltration at 14 and 24 hours post-injection (Fig. 4 and Supplementary Fig. S3A). Interestingly, significantly higher number of leukocytes (CD45⁺ cells) was detected in lungs of untreated Fuc-TVII⁻/⁻ mice compared with C57BL/6 mice. The analysis of leukocyte subpopulations revealed a 5-fold higher presence of Ly6G⁺ cells (neutrophils/granulocytes) in lungs of naïve Fuc-TVII⁻/⁻ mice compared with C57BL/6 mice that was also confirmed by immunohistochemical analysis (Supplementary Fig. S3B). Tumor cell injection increased CD45⁺ cell infiltration in both genotypes. Although there was no change in the number of Ly6G⁺ cells in C57BL/6 mice, further increase in Fuc-TVII⁻/⁻ mice 24 hours post-injection was detected. The higher numbers of Ly6G⁺ cells observed in lungs of Fuc-TVII⁻/⁻ mice seemed to be independent of selectin ligand expression. On the contrary, a 3-fold increase in inflammatory monocytes (Ly6Chi cells) was detected in lungs of C57BL/6 mice 14 hours post-injection (Fig. 4). The numbers of Ly6Chigh cells in Fuc-TVII⁻/⁻ mice remained on the same albeit higher level regardless of tumor cell injection. Accordingly, we observed significantly higher numbers of F4/80⁺ (macrophages) cells in C57BL/6 mice. These data showed that tumor cell–induced infiltration of Ly6Chigh cells to the lungs is dependent on endogenous selectin ligands.

To assess whether overall changes in leukocyte infiltration to the lungs alter tumor cell–myeloid cell interactions during tissue colonization, we analyzed lung sections from MC-38GFP-injected mice using immunohistochemistry. Although the majority of tumor cells were associated with CD11b⁺ cells in C57BL/6 mice at 14 hours post-injection (Fig. 4E), there was
minimal contact detected in Fuc-TVII−/− mice. In addition, about 50% of tumor cells were associated with F4/80+ cells in C57BL/6 mice and the number increased at 24 hours post-injection (Fig. 4F). On the contrary, tumor cells were minimally associated with F4/80+ cells in Fuc-TVII−/−/− mice at any time point. Of note, despite the generally higher residency of Ly6G+ cells in the lungs of Fuc-TVII−/−/− mice, an increase in tumor cell association was observed only at 24 hours post-injection (Fig. 4F). The reduced recruitment of leukocytes to metastasizing tumor cells could be a result of missing local expression of vascular selectins. Therefore, we tested the expression of P- and E-selectin in the tumor microenvironment of Fuc-TVII−/− mice at 6 hours post-injection (Supplementary Fig. S3C). We observed comparable expression of both P- and E-selectins in the vicinity of tumor cells in the lungs of both mouse genotypes. Thus, the presence of endogenous selectin ligands on monocytes is required for the efficient recruitment of F4/80+ cells to tumor cells during metastatic initiation in the lungs.
E- and P-selectin binding to mouse genotype (Fig. 5A). A pronounced reduction of E- and P-selectin binding to Fuc-TVII−/− monocytes and granulocytes was observed (Fig. 5A and Supplementary Fig. S4). Interestingly, the minimal presence of E-selectin ligands Fuc-TVII in PSGL-1 and ESL-1 on granulocytes and monocytes from C57BL/6; Fuc-TVII signiﬁcantly lower levels in C57BL/6 mice (Fig. 5B). However, ESL-1 has been detected both in monocytes and granulocytes albeit at significantly lower levels in Fuc-TVII−/− cells compared with C57BL/6. Taken together, these data strongly indicate that Fuc-TVII−/− dependence fucosylation of PSGL-1 is responsible for the efﬁcient monocyte recruitment to metastatic sites.

PSGL-1 is the prominent selectin ligand on Ly6C hi monocytes

We next analyzed the presence of known selectin ligands PSGL-1 and ESL-1 on granulocytes and monocytes from C57BL/6; Fuc-TVII−/− and Fuc-TVII−/−/Fuc-TVII−/− mice and the binding of selectins. Flow cytometry analysis revealed that both cell population (monocytes and granulocytes) express PSGL-1 and ESL-1 at similar levels, irrespective of mouse genotype (Fig. 5A). A pronounced reduction of E- and P-selectin binding to Fuc-TVII−/− monocytes and granulocytes was observed (Fig. 5A and Supplementary Fig. S4). Interestingly, the minimal presence of E-selectin ligands in Fuc-TVII−/− monocytes (6%) and granulocytes (2%) was reduced to 0.7% and 0.6% in respective cell populations in Fuc-TVII−/−/Fuc-TVII−/− cells. This ﬁnding indicated the presence of ESL-1. To determine which of the selectin ligands is affected by the absence of Fuc-TVII enzyme, we immune-precipitated selectin ligands using E-selectin chimeras from monocytes and granulocytes either of C57BL/6 or Fuc-TVII−/− mice. We observed a dominant PSGL-1 precipitation in C57BL/6 monocytes and granulocytes that were completely absent in respective cell populations isolated from Fuc-TVII−/− mice (Fig. 5B). However, ESL-1 has been detected both in monocytes and granulocytes albeit at signiﬁcantly lower levels in Fuc-TVII−/− cells compared with C57BL/6. Taken together, these data strongly indicate that Fuc-TVII−/− dependent fucosylation of PSGL-1 is responsible for the efﬁcient monocyte recruitment to metastatic sites.

Monocytes carrying selectin ligands rescue metastasis in Fuc-TVII−/− mice

Next, we tested whether a single injection of monocytes carrying selectin ligands affect metastasis. Fuc-TVII−/− mice were administered MC-38GFP cells that were followed by single injection of puriﬁed monocytes isolated from C57BL/6 or Fuc-TVII−/− mice 6 hours later. Adoptive transfer of C57BL/6 monocytes restored metastasis in Fuc-TVII−/− mice to levels comparable with C57BL/6 mice (Fig. 6A and B). Similarly, adoptive transfer of monocytes rescued 3LL metastasis in Fuc-TVII−/− mice (Supplementary Fig. S5). No effect on metastasis was observed after i.v. injection of selectin ligand-deﬁcient Fuc-TVII−/− monocytes. These data show that endogenous selectin ligands on monocytes are essential for their recruitment to the lungs and therefore sufﬁcient to promote metastasis.

Inflammatory monocytes support tumor cell survival, growth, and metastasis through secretion of cytokines and growth factors (23). To test whether reduced monocyte recruitment in Fuc-TVII−/− mice alters the microenvironment of metastasizing tumor, we examined cytokines in the lungs of MC-38GFP-injected mice after 24 hours (Fig. 6C and Supplementary Fig. S6). No signiﬁcant changes in expression levels of IL1β, TNF-α, and CCL5 were observed in both genotypes (C57BL/6 and Fuc-TVII−/− mice). The analysis of neutrophil-speciﬁc chemokines, CXCL1, CXCL2, and CXCL5, showed minimal changes in mice of both genotypes (data not shown), indicating that the general increase in lung neutrophils...
observed in Fuc-TVII/C0/C0 mice is based on a different mechanism. Interestingly, the expression of CCL2 was 6-fold higher in C57BL/6 mice 14 hours p.i. that remained 2-fold above the basal levels also at 24 hours p.i. (Fig. 6C). In comparison, CCL2 expression levels were always reduced in Fuc-TVII/C0/C0 mice albeit some induction after tumor cell injection has been detected. Of note, TGF-β expression was slightly decreased in lungs of C57BL/6 mice injected with tumor cells 24 hours post-injection compared with naive lungs (Supplementary Fig. S6).

It was previously shown that CCL2 promotes tumor cell extravasation through the recruitment of mononuclear cells (27, 28) and mediates a direct endothelial activation resulting in increased vascular permeability (28). Because we observed reduced CCL2 expression levels in lungs of Fuc-TVII/C0/C0 mice, we tested the lungs vascular permeability upon tumor cell injection. A comparable vascular leakage was detected in C57BL/6 and Fuc-TVII/C0/C0 mice (Supplementary Fig. S7). This observation is in line with previous data showing that tumor cell–derived CCL2 is mainly responsible for induction of vascular permeability (28). Thus, lower levels of CCL2 in tumor cell–injected Fuc-TVII/C0/C0 mice are likely the consequence of reduced monocyte recruitment to the lungs. To test this hypothesis, we isolated monocytes and granulocytes from lungs of tumor cell–injected mice and analyzed CCL2 expression. Monocytes (CD11b+/Ly6Chi) isolated from both genotypes had comparable levels of CCL2 expression that was about 4-fold higher than in circulating monocytes (Fig. 6D). This finding indicated that monocytes recruited to the lungs express higher levels of CCL2. Of note, we detected minimal expression of CCL2 in granulocytes (CD11b+/Ly6G+Ly6Cmedium) from both genotypes, indicating that neutrophils do not significantly contribute to CCL2 presence in the lungs. These data provided evidence that the absence of selectin ligands reduced the ability of monocytes to migrate to the metastatic lungs and resulted in attenuation of metastasis due to inefficient tumor cell extravasation.

Figure 5. PSGL-1 on monocytes is the prominent ligand for selectin–mediated recruitment of Ly6CChi monocytes. A, the gating strategy and the analysis of PSGL-1 and ESL-1 expression in the peripheral blood cells. Ly6CChi monocytes and Ly6C– granulocytes derived from C57BL/6, Fuc-TVII/C0/C0 and Fuc-TVII/C0/C0/Fuc-TVII/C0/C0 double–deficient mice were stained with E-selectin. B, immunoprecipitation of E-selectin ligands on Ly6CChi monocytes and Ly6C– granulocytes. E-selectin–bound proteins were separated on SDS–PAGE gel and blotted with either anti-PSGL-1 or ESL-1 antibodies. Splenocytes were used as a positive control.
Discussion

Inflammatory leukocytes at primary tumor and metastatic sites contribute to formation of the protumorigenic microenvironment through production of cytokines, growth factors, and matrix-degrading enzymes (23, 34). Increased recruitment of myeloid cells and inflammatory monocytes is associated with enhanced tumor cell extravasation and malignant outgrowth of breast and colon cancers (26, 28, 35). In addition, leukocyte recruitment is dependent on the capacity of leukocytes to adhere to activated endothelium through L-selectin (10). Here, we provide evidence that endogenous selectin ligands on monocytes are required for their specific recruitment to metastatic sites. Furthermore, PSGL-1 was identified as the major selectin ligand responsible for the selectin-mediated recruitment of monocytes to metastatic sites. This is in agreement with previous published results that Fuc-T7 is the major fucosyltransferase responsible for the synthesis of selectin ligands on PSGL-1, whereas its activity is critical for the formation of selectin ligands on PSGL-1 (38). Nevertheless, we provided evidence that Fuc-T7 enzyme activity is critical for the formation of selectin ligands on PSGL-1 that mediates recruitment of inflammatory monocytes (Ly6C<sup>hi</sup>) to early metastatic sites. This finding is in agreement with a recent identification of PSGL-1 ligands as mediators of leukocyte recruitment to atherosclerotic lesions (39). Thus, similarly to inflammation, leukocyte recruitment to metastatic microenvironment is also determined by selectin ligands on leukocytes (40). Whether leukocytes are recruited through vascular selectins, P- and/or E-selectin, or through binding to L-selectin on already adherent leukocytes remain to be determined.

An accelerated growth of primary tumors in selectin-deficient mice has been previously reported (41). Similarly, we observed an accelerated tumor growth of subcutaneously injected MC-38GFP cells in Fuc-TVII<sup>−/−</sup> mice compared with C57BL/6 mice (Supplementary Fig. S8). This finding indicates that endogenous selectin ligands restrict primary tumor growth but potentiate metastatic outgrowth at metastatic sites. Therefore, selectin-mediated interactions have spatially
and temporally defined diverse functions during tumorigenesis. Interestingly, the accelerated tumor growth in E, P, and L-selectin-triple–deficient mice was dependent on bone marrow–derived cells (41). Although we confirmed that selectin-dependent recruitment of monocytes facilitates metastasis, the identity and function of leukocytes recruited to primary subcutaneous tumors remain to be identified.

Neutrophils during cancer progression exert dual activities either promoting tumor cell growth or contributing to elimination of tumor cells depending on the cellular context and the polarization status of the cells (42, 43). Neutrophil–malignant tumor cell interactions promoted tumor cell retention within the lungs (42). In mesothelioma tumors, neutrophils contributed to cancer progression, whereas the blockade of TGF-β resulted in recruitment of cytotoxic neutrophils, leading to elimination of tumor cells (43). The observed higher numbers of lung-residing neutrophils and also their association with tumor cells in Fuc-TVII+/− mice also raised the question whether neutrophils affect metastasis. Depletion of Ly6G cells resulted in a partial rescue of metastasis, indicating that neutrophils also contributed to elimination of tumor cells in Fuc-TVII+/− mice (Supplementary Fig. S9). This finding was further corroborated by detection of apoptotic tumor cells in lungs of Fuc-TVII+/− mice that was increased compared with C57BL/6 mice. Apparently, neutrophil recruitment to the lungs was not dependent on selectin ligands, which is in agreement with previous reports that neutrophils are able to infiltrate some organs, including lungs, in a selectin–selectin ligand independent mechanism (44).

Several studies reported that reduced recruitment of monocytes to tumor cells resulted in increased neutrophil association (28, 45). Monocyte recruitment to metastasizing tumor cells is primarily CCL2-dependent (28, 35, 45) and is normally associated with reduced infiltration of neutrophils (45). This plasticity in leukocyte recruitment corresponds with our findings in which reduced monocyte recruitment was accompanied with lower CCL2 levels and resulted in enhanced neutrophil recruitment in Fuc-TVII+/− mice. Nevertheless, the adoptive transfer of selectin-ligand–positive monocytes rescued metastasis that underlines the active role of monocytes during tumor cell extravasation (27, 28).

Elevated levels of CCL2 at metastatic sites correlated with enhanced metastasis of breast, colon, prostate, and lung cancer cells in different mouse models (27–29). Here, we provided evidence that inflammatory monocytes express significant levels of CCL2 that possibly contribute to higher CCL2 levels in lungs during metastasis.

In conclusion, the rescue of metastasis upon adoptive transfer of inflammatory monocytes confirmed the essential role of selectin-mediated interactions during metastatic initiation. This finding provided evidence that apart from well-known involvement of tumor cell–derived selectin ligands, the presence of endogenous selectin ligands, particularly PSGL-1 on leukocytes, is required for cancer progression.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: A. Hoos, L. Borsig

Development of methodology: L. Borsig

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): A. Hoos, D. Protsyuk, L. Borsig

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): A. Hoos, D. Protsyuk, L. Borsig

Writing, review, and/or revision of the manuscript: A. Hoos, L. Borsig

Study supervision: L. Borsig

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Metastatic Growth Progression Caused by PSGL-1–Mediated Recruitment of Monocytes to Metastatic Sites

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