Chemotherapy Induces Intratumoral Expression of Chemokines in Cutaneous Melanoma, Favoring T-cell Infiltration and Tumor Control

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Abstract

T-cell infiltration is known to impact tumor growth and is associated with cancer patient survival. However, the molecular cues that favor T-cell infiltration remain largely undefined. Here, using a genetically engineered mouse model of melanoma, we show that CXCR3 ligands and CCL5 synergize to attract effector T cells into cutaneous metastases, and their expression inhibits tumor growth. Treatment of tumor-bearing mice with chemotherapy induced intratumoral expression of these chemokines and favored T-cell infiltration into cutaneous tumors. In patients with melanoma, these chemokines were also upregulated in chemotherapy-sensitive lesions following chemotherapy, and correlated with T-cell infiltration, tumor control, and patient survival. We found that dacarbazine, temozolomide, and cisplatin induced expression of T-cell-attracting chemokines in several human melanoma cell lines in vitro. These data identify the induction of intratumoral expression of chemokines as a novel mechanism of action of chemotherapy that results in the recruitment of immune cells with antitumor activity. Therefore, identifying chemotherapeutic drugs able to induce the expression of T-cell-attracting chemokines in cancer cells may represent a novel strategy to improve the efficacy of cancer immunotherapy. Cancer Res; 71(22); 6997–7009. ©2011 AACR.

Introduction

T-cell infiltration is a known predictor of patient survival in several cancers, including colorectal and ovarian cancers, non–small cell lung carcinomas, and melanomas (1–5). T-cell–adoptive therapies represent an attractive approach to treating cancers and have yielded some promising results in melanoma, even though complete clinical responses are only observed in a minority of patients (6). Recently, the U.S. Food and Drug Administration approved the first therapeutic cancer vaccine (sipuleucel-T) for advanced prostate cancer (7). However, even when cancer vaccines induce immune responses in the majority of patients, only a few benefit from the treatment (8, 9). This continuing growth of tumors in the presence of functional antitumor immune responses, whether spontaneous or induced, is the most disturbing paradox of tumor immunology (10). The so far limited success of therapeutic cancer vaccines is largely due to our incomplete understanding of the mechanisms preventing the action of T cells locally. T-cell recruitment to the tumor is one of the potential rate-limiting steps in immunotherapy, and thus, intratumoral chemokines are likely to have a major impact (11, 12). Gene expression profiling studies have shown that intratumoral expression of chemokines, indeed, correlate with T-cell infiltration (13). Therefore, identifying drugs that favor T-cell trafficking to the tumors is essential to improve cancer vaccines.

Chemotherapy acts, in part, by direct induction of apoptosis in cancer cells. In addition, selected chemotherapies may promote immunogenic cell death, which stimulates the antitumor immune response (14). Chemotherapy can also induce stress signals leading to increased susceptibility of cancer cells to immune attack (15). In melanoma, mixed responses to chemotherapy are frequently observed (16). Therefore, we sought to understand the signals responsible for T-cell trafficking to cutaneous tumors in melanoma and to determine whether they are altered by chemotherapy.

We recently described the RETAAD model of melanoma (17). RETAAD mice develop spontaneous uveal melanomas that metastasize to the skin and visceral organs (18). Tumor-bearing animals mount a strong antitumor T-cell response, but although this response controls the outgrowth of visceral metastases, they have no effect on cutaneous tumors. We

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suspected that differential T-cell trafficking might explain this apparent paradox. Using global transcriptome analysis, we also analyzed cutaneous metastases resected from patients with melanoma before and after chemotherapy and found increased T-cell infiltration into the chemotherapy-sensitive tumors (19).

The aim of this study is to identify molecular cues controlling T-cell infiltration into cutaneous tumors and to find treatments promoting T-cell infiltration. We address this question in the RETAAD model and in patients with melanoma treated with chemotherapy. Our findings indicate that chemotherapy works, in part, through the induction of chemokine expression in cancer cells and the subsequent recruitment of T cells into the tumors.

Materials and Methods

Cell lines and antibodies

The B16-F10 (Cat Nr CRL-6475) and HTB-71 cell lines were from American Type Culture Collection. The Melan-ret cell line was previously described (20). The 4 human melanoma cell lines (M88, M102, M131, and M134) were kindly provided by J-B Latouche and P. Musette. The anti-CXCR3 antibody was produced by immunizing CXCR3-deficient mice with L1.2 cells expressing mouse CXCR3, as described previously (21).

Mice and patients

Animal care and experimental procedures were approved by the Institutional Animal Care and Use Committee of the Biological Resource Center, A’STAR, Singapore. Human tumor samples, patient demographics, and clinical characteristics can be found in Nardin and colleagues (19).

Gene expression analysis

Expression of immune genes relative to Gapdh (for mouse) and ACTB (for human) was measured by quantitative real-time PCR (qRT-PCR) as previously described (18). ΔCt and primer efficiency were used to calculate the relative expression.

Expression of chemokine and chemokine receptor genes was determined by qRT-PCR with the Mouse Inflammatory Cytokines and Receptors RT² profiler PCR array system (SABiosciences), and data analysis was conducted according to the manufacturer’s instructions.

Immunofluorescence

Formalin-fixed paraffin-embedded sections (5 μm) were immunolabeled for CD3 (Acris SM1754P; 1:50) using the protocol previously described (18).

Flow cytometry analyses

Single-cell suspensions were obtained by digestion with Collagenase A (1 mg/mL) and DNase I (0.1 mg/mL; Roche) in RPMI for 20 minutes. After red blood cell lysis, Fc receptors were blocked with anti-mouse CD16/CD32 for 30 minutes before incubation with antigen-specific antibodies at 1:50 dilution for 20 minutes. All antibodies were from Biolegend, except those specific for CCR1, CCR2, and CCR5 which were from R&D Systems.

Construction of expression plasmids

CCL5- and CXCL9-expressing plasmids are described in Supplementary Fig. S3. Briefly, RNA from lipopolysaccharide-activated macrophages was reverse transcribed, PCR amplified using specific primers for Ccl5 (5’-primer TACCCAGCTGGATCCATGAGATCCTGCACTG; 3’-primer AACCCGGCCCTCTAGAGCAGGGTCAGAATCAAGAAACC), and Cxcl9 (5’-primer TACCCAGCTGGATCCACCATGAA-GTCCGCTGTTCC; 3’-primer GCCCTCTAGACTGAGCTCTT-TATGTCAGTCTTCCGCT). PCR products were cloned into pcDNA3.1 Hygro(++; Invitrogen) at BamHI/XbaI sites (for Ccl5) and at BamHI/Xhol sites (for Cxcl9). Chemokine-expressing and control plasmid preparations were tested for endotoxin using Limulus amebocyte lysate assay (Lonza, 50-647U).

In vivo experiments

RETAAD T-cell migration to skin tumors. Tumor-bearing RETAAD mice (aged between 30 and 50 weeks) were injected subcutaneously in the right flank with 2 × 10⁵ B16-F10 luc cells (Xenogen). Mice were euthanized when the tumor diameter reached 1 cm. The B16 transplanted skin tumor and 1 or 2 RETAAD skin tumors were collected from the same mouse. T-cell infiltration into tumors was measured by flow cytometry.

In vivo transfection of cutaneous tumors

Tumor-bearing RETAAD mice (30–50 weeks) were used. For each mouse, 2 to 7 cutaneous tumors were transfected with 5 μg of pcDNA3.1(++;CCL5 or pcDNA3.1(++;CXCL9 or empty plasmid using in vivo JetPEI transfecting reagent (Polyplus Transfection). The mice were injected 3 times on alternate days for 5 days. On day 6, the mice were euthanized and the tumors excised, weighed, and divided into 2 parts. One part was used for intratumoral miRNA expression of Ccl5, Cxcl9, Cxcl10, Ifng, Gzma, and Gzmb by qRT-PCR; the other was dissociated and analyzed for immune cell infiltration by flow cytometry. For Ccl5 and Cxcl9 coinjection studies, 2.5 μg of pcDNA3.1(++;CCL5, pcDNA3.1(++;CXCL9, empty plasmid, or a combination of 5 μg of pcDNA3.1(++;CCL5 and pcDNA3.1(++;CXCL9 were injected into cutaneous RETAAD tumors using the protocol described previously. T-cell infiltration and intratumoral chemokine expression were measured as previously described.

Chemotherapy and adoptive transfer

Rag1−/− mice were injected subcutaneously with 10⁶ Melan-ret cells. When tumors became palpable, mice were treated for 2 consecutive days with 2 mg temozolomide or vehicle [dimethyl sulfoxide (DMSO)] only. On the following day, mice were injected intravenously with 10⁶ in vitro activated T cells purified from C57BL/6 with or without 2 μg anti-CXCR3 antibody. T-cell infiltration and intratumoral expression of chemokines were measured 24 hours after transfer.

Chemotherapeutic drug treatment and chemokine gene expression

Human melanoma cells were seeded into 12-well plates (4 × 10⁵ per well). Forty-eight hours later, drugs were added
at indicated concentrations. RNA extraction was conducted as described previously, and the expression of CCL5, CXCL9, and CXCL10 was analyzed by qRT-PCR.

**Multiplex analysis of chemokine/cytokine production by tumor cells**

Concentrations of various cytokines/chemokines in the supernatant of drug-treated cells were analyzed using multiplex bead-based assays based on xMAP technology, combining both the 21-plex (MF0-005KMII) and 27-plex (M50-0KCAF0Y) kits from Bio-Rad and according to the manufacturer’s protocol.

**Statistical analyses**

Normalized gene expression data were log-transformed and initially compared using a manova multivariate analysis. This was followed by post-hoc testing using Student t test or ANOVA. P values for multiple comparisons were adjusted using Bonferroni correction. Other parameters (tumor weight, tumor area, and percentage of tumor-infiltrating cells) were compared using nonparametric tests (Mann–Whitney or Kruskal–Wallis). Patient survival was analyzed by the Kaplan–Meier method using log-rank (Mantel–Cox) test. Statistical analyses were done using Graphpad or Bioconductor/R.

**Results**

**Limited T-cell infiltration of cutaneous tumors**

In RETAAD mice, CD8+ T cells control the outgrowth of visceral metastases but have no effect on cutaneous tumors (Lengagne and colleagues, 2008 and Supplementary Fig. S1). We hypothesized that the lack of control of skin tumors by T cells results from the absence of T-cell infiltration or from the loss of function of infiltrating T cells. To measure T-cell infiltration, we collected 22 cutaneous and 4 visceral metastases from RETAAD mice and compared the density of CD3+ T cells by flow cytometry. As shown in Fig. 1A, the median percentage of CD3+ T cells was 2.7 times higher in visceral tumors than in cutaneous tumors (2-tailed Mann–Whitney, P = 0.04). Immunofluorescent staining of tumor sections confirmed that T cells were more abundant in visceral tumors.
(14.5 vs. 4.5 cells/field of view; 2-tailed Mann–Whitney, \(P = 0.0007\); Fig. 1B, right). Using qRT-PCR, we were able to analyze a greater number of tumors, especially smaller ones. In a preliminary experiment, we verified that intratumoral expression of \(Cd3g\) faithfully reflected T-cell infiltration (Pearson’s \(r = 0.75, P < 0.0001\), linear regression slope = 0.927; Supplementary Fig. S6A). qRT-PCR analysis revealed that markers of T cells (\(Cd3g, Cd4, Cd8a, Ifng, Prf1b,\) and \(Gzm\)) were less expressed in cutaneous metastases (\(n = 20\)), confirming that there were fewer infiltrating T cells compared with visceral metastases (\(n = 10\); 1-tailed \(t\) test, \(P = 0.0011\); Fig. 1C). Expression of both \(Cd4\) and \(Cd8a\) was lower in cutaneous tumors, suggesting that both compartments were affected (\(P = 0.026\) and 0.023, respectively). Tumor weights were inversely correlated with the percentages of \(Cd3^+\), \(Cd4^+\), and \(Cd8^+\) infiltrating cells (Pearson’s \(r = -0.67, -0.58,\) and \(-0.64\) and \(P = 0.009, 0.02,\) and 0.01, respectively), suggesting that the few infiltrating T cells were able to control tumor growth (Fig. 1D).

Together, these data show that both \(Cd4^+\) and \(Cd8^+\) T cells poorly infiltrate cutaneous tumors in RETAAD mice. This observation is likely to explain the lack of T cell control over cutaneous tumors.

**T cells infiltrate exogenous skin tumors**

To determine whether the poor infiltration of T cells into cutaneous tumors was due to an intrinsic defect in T cells from RETAAD mice or a feature of the tumors themselves, we compared autochthonous RETAAD and transplanted B16 cutaneous tumors. B16 cells were injected subcutaneously into tumor-bearing RETAAD mice. Fourteen days after injection, the transplanted B16 and autochthonous RETAAD tumors were excised and T-cell infiltration was measured. As shown in Fig. 2A, \(Cd3^+, Cd4^+,\) and \(Cd8^+\) T cells were, respectively, 11-fold, 9-fold, and 11-fold more abundant in B16 than in RETAAD tumors (2-tailed Mann–Whitney, \(P < 0.01\)).

These data show that T cells from RETAAD mice have the capacity to infiltrate cutaneous tumors. Therefore, the paucity of T cells in RETAAD cutaneous tumors is most likely due to the tumor environment being poorly permissive to T-cell infiltration.

**T-cell infiltration of exogenous skin tumors correlates with high chemokine expression**

Chemokines present in tumors are likely to play a major role in T-cell recruitment. Therefore, we compared the repertoire of chemokines expressed in autochthonous RETAAD tumors and transplanted B16 tumors grown in RETAAD mice using low-density PCR arrays. Thirty-nine genes, including 26 chemokines and 13 chemokine receptors, involved in inflammation were analyzed by qRT-PCR. As shown in Fig. 2B, 14 of the 26 chemokines analyzed were differentially expressed in transplanted B16 compared with autochthonous RETAAD tumors (open squares; \(P < 0.05\), fold change > 2), with the vast majority of these chemokines (12 of 14) being more highly expressed in B16 tumors. \(Cxc9\) and \(Cxc110\) were the two most differentially expressed chemokines, with 105- and 42-fold greater expression in B16 tumors, respectively. Five additional chemokines, \(Ccl2, Ccl3, Ccl4, Ccl7,\) and \(Cxc15\) were at least 10-fold more highly expressed in B16 tumors than in autochthonous RETAAD tumors.

To gain further insight into the possible role of these differentially expressed chemokines in T-cell recruitment, we analyzed the expression of the corresponding chemokine receptors on peripheral blood T cells from RETAAD mice. \(Ccr1, Ccr2, Ccr3, Ccr5,\) and \(Cxcr3\) expressions were analyzed by flow cytometry on naive, central memory, and effector memory T cells. The chemokine receptor \(Cxcr3\) was highly expressed by several subsets of circulating T cells, whereas \(Ccr1, Ccr3,\) and \(Ccr5\) were only expressed at marginal levels (Fig. 2C). \(Ccr2\) was expressed by 25% ± 2% of effector memory \(Cd4^+\) T cells. \(Ccr1, Ccr2, Ccr3,\) and \(Ccr5\) were highly expressed on various subsets of myeloid cells (Supplementary Fig. S2). Within the \(Cd4^+\) T cells, 4% ± 1.9% of the central memory and 58% ± 10% of the effector memory cells expressed \(Cxcr3\) (Fig. 2D), whereas among the \(Cd8^+\) T-cell population, 93% ± 3.6% of the central memory and 75% ± 5.7% of the effector memory cells expressed \(Cxcr3\).

\(Cxcr3\) has only 3 known ligands: \(Cxc19, Cxcl10,\) and \(Cxcl11\). Therefore, our data strongly suggest a role for \(Cxcl9\) and \(Cxcl10\) in T-cell recruitment into cutaneous tumors.

**Transfection of RETAAD skin tumors with Cxcl9 induces T-cell infiltration**

To directly show the role of \(Cxcr3\) ligands in T-cell recruitment, we transfected established RETAAD autochthonous tumors with a plasmid encoding \(Cxcl9\). RETAAD mice bearing multiple cutaneous metastases (median weight = 60 mg) were selected for this experiment. The mice received three intratumoral injections on alternate days. In each mouse, 1 or 2 tumors were injected with the \(Cxcl9\)-encoding plasmid and 1 or 2 tumors were injected with a control plasmid. On day 6, tumors were excised, weighed, and T-cell infiltration was assessed by flow cytometry. As shown in Supplementary Fig. S4A, injection of the \(Cxcl9\)-encoding plasmid induced a 60-fold increase in intratumoral expression of \(Cxcl9\) measured by qRT-PCR at day 6. Expression of \(Cxcl10\) was not affected. Importantly, \(Cxcl9\) transfection resulted in a 6-fold increase in both \(Cd4^+\) and \(Cd8^+\) T-cell infiltration into RETAAD cutaneous tumors (1-tailed Mann–Whitney, \(P = 0.0026\) and 0.0025, respectively; Fig. 3A). Injection of the control plasmid did not significantly alter the T-cell infiltrate (Supplementary Fig. S4B).

To characterize \(Cxcl9\)-recruited T cells, we analyzed the expression of several effector molecules by qRT-PCR. The expression of \(Ifng, Gzma,\) and \(Gzm\) was enhanced in \(Cxcl9\)-treated tumors compared with control tumors by 7-, 5-, and 5-fold, respectively (1-tailed \(t\) test, \(P = 0.006, 0.01,\) and 0.02, respectively; Fig. 3B). Moreover, using flow cytometry, we detected a 43% increase in tumor cell death (1-tailed Mann–Whitney, \(P = 0.03\)) in treated tumors compared with control tumors (Fig. 3C).

Taken together, these observations show that \(Cxcl9\) attracts effector T cells exhibiting type 1 polarization and cytotoxic potential.
**Cxcl9 expression inhibits exogenous tumor growth in a T-cell–dependent manner**

We next investigated whether ectopic expression of Cxcl9 could control tumor growth in vivo. Therefore, we transfected Cxcl9 into Melan-ret cells, a cell line derived from a RETAAD cutaneous tumor. Cxcl9-transfected cells were injected subcutaneously into syngeneic C57BL/6 mice. Tumor growth was monitored every 2 to 3 days for 16 days. Cxcl9-expressing tumor cells showed severely impaired growth compared with control cells; tumor formation was abolished in 2 of 5 mice (Fig. 3D). Mice were euthanized at day 16, tumors were collected and weighed, and T-cell infiltration was analyzed by qRT-PCR.
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highly correlated with Cd3g involved in T-cell infiltration. By comparing a set of 37 cutaneous or visceral tumors, we found that Cd3g expression was highly correlated with Cd3g expression (Pearson’s r = 0.65, P = 4.75e-6; Supplementary Fig. S5). Surprisingly, RETAAD circulating T cells express very low levels of the known receptors of CCL5, namely, CCR1, CCR3, and CCR5 (Fig. 2C). Therefore, secretion of CCL5 by the T cells may account for the observed correlation. Alternatively, CCL5 might play a role in T-cell attraction, for example, by synergizing with CXC3 ligands. To test the latter hypothesis, RETAAD cutaneous tumors were transfected with a plasmid encoding CCL5 alone, CXCL9 alone, or a combination of both plasmids. Suboptimal doses of the CXCL9 plasmid were used. The mice were injected 3 times on alternate days for 5 days. On day 6, the tumors were analyzed for T-cell infiltration. G and H, CXCL9 synergizes with CCL5 to recruit T cells. RETAAD cutaneous tumors were injected with 2.5 μg plasmid DNA encoding CCL5 (n = 10) or CXCL9 (n = 11), a combination of both plasmids (n = 15), or control plasmid (n = 9) on alternate days for 5 days. On day 6, tumors were analyzed for T-cell infiltration. G, the percentages of CD3+ T cells measured by flow cytometry were compared using Kruskal-Wallis test. The expression of Cd3g was compared by ANOVA and Bonferroni multiple comparison posttest. H, surface expression of CCR5 on CD4+ and CD8+ T cells in peripheral blood (n = 6) and TIL (n = 16). Mann-Whitney U test, 1-tailed. All data are representative of 3 independent experiments conducted. Statistical differences between groups are represented by ***, P < 0.001; **, P < 0.01; *, P < 0.05; ns, nonsignificant. C, control plasmid; Tr, tumors injected with the CXCL9 plasmid; Tf, Melan-ret transfected with CXCL9 plasmid.

CXCL9 synergizes with CCL5 to recruit T cells

Knowing that CXCL9 promotes T-cell recruitment and that chemokines often act in concert, we then asked whether other chemokines expressed in RETAAD tumors were also involved in T-cell infiltration. By comparing a set of 37 cutaneous or visceral tumors, we found that Cd3g expression was highly correlated with Cd3g expression (Pearson’s r = 0.65, P = 4.75e-6; Supplementary Fig. S5). Surprisingly, RETAAD circulating T cells express very low levels of the known receptors of CCL5, namely, CCR1, CCR3, and CCR5 (Fig. 2C). Therefore, secretion of CCL5 by the T cells may account for the observed correlation. Alternatively, CCL5 might play a role in T-cell attraction, for example, by synergizing with CXC3 ligands. To test the latter hypothesis, RETAAD cutaneous tumors were transfected with a plasmid encoding CCL5 alone, CXCL9 alone, or a combination of both plasmids. Suboptimal doses of the CXCL9 plasmid were used. The mice were injected 3 times on alternate days for 5 days. On day 6, the tumors were harvested, weighed, and analyzed for CD3+ T-cell infiltration by cytometry and qRT-PCR. As shown in Fig. 3G, treatment with CCL5 plasmid alone did not lead to enhanced T-cell infiltration. Similarly, treatment with suboptimal doses of CXCL9 plasmid had only a marginal effect. However, the combination of both CCL5 and CXCL9 resulted in a synergistic increase in T-cell infiltration (1-way Kruskal-Wallis, P = 0.03) and Cd3g

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expression within the tumors (1-way ANOVA, P < 0.0001). This synergistic effect was observed for both CD4⁺ and CD8⁺ T cells (Supplementary Fig. S6B).

This increased infiltration of T cells in tumors coinjected with CCL5 and CXCL9 plasmids was not due to CCL5-mediated increase in CXCL9 production (data not shown). Conversely, T cells may undergo changes in chemokine receptor expression upon infiltration into the tumor. Therefore, we compared CCR5 expression on tumor-infiltrating lymphocytes (TIL; n = 16) and blood lymphocytes (n = 6). Interestingly, we detected a small but reproducible increase in the percentage of CCR5-expressing CD4⁺ and CD8⁺ (40% and 80% increase, respectively) in TIL compared with blood lymphocytes (Fig. 3H).

Altogether, these data show a synergy between CXCL9 and CCL5 for T-cell recruitment and suggest that CCR5 upregulation in the tumor microenvironment may favor T-cell retention in CCL5-expressing tumors.

Chemotherapy induces chemokine production in human melanoma cell lines

Chemotherapy is known to alter the transcriptome of cancer cells and has been reported to modify their profile of chemokine secretion (22). Therefore, we tested 3 chemotherapeutic drugs commonly used to treat stage IV melanoma (temozolomide, cisplatin, and dacarbazine), for their ability to induce T-cell–attracting chemokines in vitro. Five human melanoma cell lines (HTB-71, M88, M102, M131, and M134) were included in the study. Transcription of the CCL5, CXCL9, and CXCL10 genes was measured by qRT-PCR 72 hours after drug treatment. As shown in Fig. 4A, each drug and each cell line displayed a unique pattern of chemokine expression; at least 2 T-cell–attracting chemokines were actively transcribed in all cell lines after treatment with at least one drug. Temozolomide strongly induced all 3 chemokines in M102 and M134, and CXCL10 in HTB-71 and M131 (>10-fold increase). Cisplatin induced all 3 chemokines in M102 but only the CXCR3 ligands in M134 and CXCL10 in M88. Dacarbazine induced all 3 chemokines in HTB-71. Dose–response relationships were observed for temozolomide and cisplatin (Fig. 4B), but no reproducible dose–response relationships were observed for dacarbazine. This is likely due to the fact that dacarbazine requires conversion into the active metabolite 5-(3-methyltriazen-1-yl)imidazole-4-carboxamide, which relies on spontaneous catalytic reaction in vitro whereas liver enzymatic activity carries out this step in vivo. Therefore, we focused on temozolomide (which shares the same active metabolite as dacarbazine) and cisplatin for the rest of the study. Figure 4C shows the kinetics of CCL5, CXCL9, and CXCL10 induction in M102 cells following treatment with 100 µg/mL temozolomide. Transcription of CXCL10 was detectable as soon as 24 hours after treatment, whereas CXCL9 and CCL5 transcription was only detected at 48 and 72 hours. Under these experimental conditions, cell death was not observed before 48 hours, showing that CXCL10 transcription preceded cell death. In fact, for lower concentrations of temozolomide, CXCL9 and CCL5 expression also preceded cell death (data not shown).

We confirmed that CCL5, CXCL9, and CXCL10 mRNA were translated into proteins by analyzing supernatants of M102 cells 72 hours after treatment with temozolomide (100 µg/mL) or cisplatin (10 µg/mL). Using ELISA and Luminex-based Bioplex suspension arrays, culture supernatants were tested for a variety of secreted proteins, including 28 cytokines, 7 additional chemokines, and 10 angiogenic and growth factors. As shown in Fig. 4D, temozolomide induced more than 9-fold increase in the secretion of 5 chemokines (CCL2, CCL5, CXCL8, CXCL9, and CXCL10) and 1 chemokine-like factor (MIF), whereas cisplatin induced CXCL8, CXCL10, and MIF. Importantly, none of the other factors was significantly induced (Table 1).

Altogether, these data show that 3 chemotherapeutic drugs commonly used for the treatment of human metastatic melanoma induce specific expression of chemokines involved in T-cell attraction.

Enhanced chemokine expression and T-cell infiltration in cutaneous tumors from mice treated with temozolomide

We next determined whether chemotherapy could facilitate intratumoral T-cell infiltration by inducing chemokine expression in cutaneous tumors. Rag1⁻/⁻ mice bearing subcutaneous Melan-ret tumors were first treated with temozolomide and then adoptively transferred with in vitro activated T cells. Tumors were collected and analyzed for chemokine expression by qRT-PCR and T-cell infiltration by cytometry. As shown in Fig. 5A, temozolomide treatment induced significant upregulation of Ccl5, Cxcl9, and Cxcl10 (1-tailed t test, P = 0.01, 0.02, and 0.0003, respectively). Importantly, this enhanced chemokine expression was associated with a more than 50% increase in CD3⁺ T-cell infiltration. Moreover, this increase was completely suppressed by anti-CXCR3 blocking antibody. This indicates that temozolomide-induced chemokines are functional and are able to attract T cells into cutaneous tumors.

Enhanced expression of CCL5, CXCL9, and CXCL10 after chemotherapy is associated with tumor control and superior survival of patients with melanoma

We previously showed increased T-cell infiltration in chemotherapy-sensitive tumors of patients with melanoma treated with dacarbazine (19). In the previous study, we carried out global transcriptome analysis of 33 cutaneous metastases resected before or after chemotherapy. We now reanalyzed these data, asking whether there were any chemokine whose expression correlated with T-cell infiltration. Among all the genes coding for chemokines, CCL5, CXCL9, and CXCL10 were the most significantly correlated with CD3⁺ and CD8⁺ expression, and among the most significantly correlated with CD4⁺ (Fig. 6A). We next compared CD4⁺ and CD8⁺ expression in 3 categories of tumor samples: those that expressed low levels of the 3 chemokines, those that expressed high levels of CCL5 or high levels of CXCR3 ligands, and those that expressed high levels of CCL5 and high levels of at least 1 CXCR3 ligand. This comparison revealed a clear synergy between CCL5 and CXCR3 ligands for T-cell infiltration (Fig. 6B). To determine whether chemotherapy had any impact on chemokine expression, we...
compared CCL5, CXCL9, and CXCL10 expression in tumors before and after therapy. As shown in Fig. 6C, whereas dacarbazine did not induce any significant changes in chemotherapy-resistant tumors, that is, progressing lesions, an increase in CCL5, CXCL9, and CXCL10 expression was observed after treatment in chemotherapy-sensitive tumors (1-tailed t test, \( P = 0.006, 0.017, \) and 0.041, respectively). CD4 and CD8A expression was also significantly increased in chemotherapy-sensitive tumors (\( P = 0.0004 \) and 0.0009, respectively; Fig. 6D). Manova multivariate analysis showed that chemokines and T-cell markers were significant predictors of the response to chemotherapy (Wilks test, \( P = 0.0014 \)). Post-hoc tests showed that expression levels of CXCL9, CXCL10, CCL5, CD4, and CD8A were all significant predictors of tumor response (\( P = 0.00022, 0.00024, 3.2e-5, 4.1e-5, \) and 2.7e-5, respectively). Finally, Kaplan–Meier analysis showed that patients exhibiting higher chemokine expression after chemotherapy survived longer (\( P = 0.0002; HR = 35; \) Fig. 6E).
Table 1. Multiplex analysis of soluble factors secreted by M102 cell line after chemotherapeutic drug treatment

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<th>Analyte</th>
<th>Mean ± SD (pg/mL temozolomide)</th>
<th>Mean ± SD (pg/mL, DMSO)</th>
<th>Fold increase</th>
<th>P</th>
<th>Mean ± SD (pg/mL cisplatin)</th>
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<td>Eotaxin</td>
<td>42.1 ± 16.4</td>
<td>97.3 ± 89.8</td>
<td>0.43</td>
<td>0.25</td>
<td>84.5 ± 101</td>
<td>119.3 ± 133.6</td>
<td>0.71</td>
<td>0.35</td>
</tr>
<tr>
<td>FGF basic</td>
<td>41.5 ± 12.7</td>
<td>22.3 ± 18.7</td>
<td>1.86</td>
<td>0.10</td>
<td>44.8 ± 16.7</td>
<td>42.9 ± 45</td>
<td>1.04</td>
<td>0.35</td>
</tr>
<tr>
<td>GM-CSF</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IFNα</td>
<td>254 ± 199.3</td>
<td>319.6 ± 276.4</td>
<td>0.79</td>
<td>0.35</td>
<td>83.1 ± 42.4</td>
<td>700.5 ± 776.8</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>IL-1α</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
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<tr>
<td>IL-1β</td>
<td>ND</td>
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<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IL-1ra</td>
<td>200.2 ± 162.1</td>
<td>221.4 ± 184.1</td>
<td>0.9</td>
<td>0.41</td>
<td>131.3 ± 118.1</td>
<td>298 ± 256.4</td>
<td>0.46</td>
<td>0.35</td>
</tr>
<tr>
<td>IL-2</td>
<td>ND</td>
<td>NA</td>
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<td>NA</td>
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</tr>
<tr>
<td>IL-2ra</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
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</tr>
<tr>
<td>IL-3</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
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<tr>
<td>IL-4</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>IL-5</td>
<td>ND</td>
<td>NA</td>
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<td>NA</td>
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<tr>
<td>IL-6</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>IL-7</td>
<td>ND</td>
<td>NA</td>
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<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
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<tr>
<td>IL-8/CCL8</td>
<td>83,229 ± 67,610</td>
<td>7,869 ± 2,354</td>
<td>10.58</td>
<td>0.05</td>
<td>11,343 ± 1,856</td>
<td>2,144 ± 1,243</td>
<td>5.29</td>
<td>0.05</td>
</tr>
<tr>
<td>IL-9</td>
<td>75.3 ± 50.9</td>
<td>71.5 ± 55.5</td>
<td>0.92</td>
<td>0.50</td>
<td>10.2 ± 1.5</td>
<td>113 ± 117.1</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>IL-10</td>
<td>19.4 ± 16.2</td>
<td>48.1 ± 29.4</td>
<td>0.4</td>
<td>0.10</td>
<td>10.3 ± 7</td>
<td>65.9 ± 71</td>
<td>0.16</td>
<td>0.10</td>
</tr>
<tr>
<td>IL-12p40</td>
<td>ND</td>
<td>NA</td>
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<tr>
<td>IL-12p70</td>
<td>88 ± 87.8</td>
<td>91.6 ± 77.6</td>
<td>1.13</td>
<td>0.41</td>
<td>23.4 ± 19.4</td>
<td>143.6 ± 162.1</td>
<td>0.16</td>
<td>0.10</td>
</tr>
<tr>
<td>IL-13</td>
<td>ND</td>
<td>NA</td>
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<td>NA</td>
<td>ND</td>
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<tr>
<td>IL-15</td>
<td>40.8 ± 34.7</td>
<td>56.1 ± 62.3</td>
<td>0.73</td>
<td>0.50</td>
<td>41.8 ± 35.1</td>
<td>103 ± 123.3</td>
<td>0.41</td>
<td>0.35</td>
</tr>
<tr>
<td>IL-17</td>
<td>103.8 ± 97</td>
<td>130.1 ± 147.4</td>
<td>0.8</td>
<td>0.50</td>
<td>114.4 ± 125.8</td>
<td>125.6 ± 109.8</td>
<td>0.91</td>
<td>0.50</td>
</tr>
<tr>
<td>IL-18</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>IP-10/CXCL10</td>
<td>3,810 ± 1,122</td>
<td>268.7 ± 268.8</td>
<td>14.18</td>
<td>0.05</td>
<td>267.3 ± 215.3</td>
<td>115.8 ± 100.2</td>
<td>5.76</td>
<td>0.05</td>
</tr>
<tr>
<td>LIF</td>
<td>13,478 ± 11,843</td>
<td>6,288 ± 5,508</td>
<td>2.14</td>
<td>0.25</td>
<td>188.1 ± 16.4</td>
<td>2,258 ± 383.4</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>MCP-1/CCL2</td>
<td>522.8 ± 46.8</td>
<td>5.3 ± 1.6</td>
<td>98.29</td>
<td>0.04</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MCP-3/CCL7</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>M-CSF</td>
<td>86.7 ± 75.7</td>
<td>30.7 ± 35.7</td>
<td>2.92</td>
<td>0.17</td>
<td>121.4 ± 103.6</td>
<td>27.7 ± 30.5</td>
<td>4.38</td>
<td>0.17</td>
</tr>
<tr>
<td>MIF</td>
<td>9,475 ± 522.8</td>
<td>246.7 ± 54.9</td>
<td>26.25</td>
<td>0.05</td>
<td>13,356 ± 3,597</td>
<td>874.3 ± 236.8</td>
<td>15.28</td>
<td>0.05</td>
</tr>
<tr>
<td>MIG/CXCL9</td>
<td>47 ± 1.4</td>
<td>5.1 ± 0.6</td>
<td>9.17</td>
<td>0.05</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MIP-1/CCL3</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MIP-1/CCL4</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>PDGF-bb</td>
<td>65.7 ± 44.1</td>
<td>57 ± 67</td>
<td>1.15</td>
<td>0.35</td>
<td>22.9 ± 14.4</td>
<td>93.3 ± 82.6</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>RANTES/CCL5</td>
<td>330.4 ± 12.1</td>
<td>28.7 ± 11.6</td>
<td>11.5</td>
<td>0.05</td>
<td>29 ± 10.4</td>
<td>27.3 ± 22.7</td>
<td>1.06</td>
<td>0.35</td>
</tr>
<tr>
<td>SCF</td>
<td>40.6 ± 35.6</td>
<td>44.4 ± 40.1</td>
<td>0.91</td>
<td>0.50</td>
<td>77.2 ± 66.9</td>
<td>20 ± 28.2</td>
<td>3.87</td>
<td>0.27</td>
</tr>
<tr>
<td>SCGF-β</td>
<td>1,025 ± 405.7</td>
<td>1,290 ± 431.5</td>
<td>0.79</td>
<td>0.20</td>
<td>832.9 ± 226.9</td>
<td>2,916 ± 2,790</td>
<td>0.29</td>
<td>0.05</td>
</tr>
<tr>
<td>SDF-1α</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>TNF-α</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>TNF-β</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
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<td>ND</td>
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<td>NA</td>
</tr>
<tr>
<td>VEGF</td>
<td>36,847 ± 6,117</td>
<td>44,477 ± 33,965</td>
<td>0.83</td>
<td>0.35</td>
<td>16,688 ± 5,206</td>
<td>55,394 ± 46,310</td>
<td>0.3</td>
<td>0.35</td>
</tr>
</tbody>
</table>

NOTE: Human melanoma cell line M102 was cultured with temozolomide (100 μg/mL) or cisplatin (10 μg/mL) for 3 days. Supernatants were collected and the concentrations of various soluble factors were analyzed using xMAP multiplex technology. Data show the production of cytokines, chemokines, angiogenic, and growth factors in pg/mL ± SD from the supernatant of drug-treated cells compared with control cells. Results are representative of 3 independent samples analyzed. Secreted factors that are significantly upregulated after drug treatment are indicated in bold.

Abbreviations: ND, not detected; NA, not available. Mann–Whitney U test, 1-tailed.
Taken together, these data show that chemotherapy induces enhanced expression of CXCR3 ligands and CCL5 in chemotherapy-sensitive tumors. Furthermore, increased expression of these chemokines translates into enhanced T-cell infiltration, improved tumor control, and prolonged overall survival.

Discussion

In this study, we show that CXCR3 ligands and CCL5 are the main determinants of T-cell infiltration into cutaneous melanoma tumors. Moreover, we show that chemotherapy induces expression of these chemokines in human melanoma cell lines and that chemotherapy-induced chemokines correlate with T-cell infiltration in mice and human melanoma tumors. Finally, chemotherapy-induced chemokines is associated with tumor control and prolonged patient survival.

Although antitumor T cells are often detected in the blood of patients with melanoma, their presence only rarely translates into favorable clinical outcome (23). This applies to spontaneous T-cell responses as well as those induced by cancer vaccines; the vast majority of patients with cancer undergoing therapeutic vaccination have enhanced antitumor T-cell responses, but only a small percentage control their tumors. Several explanations have been proposed for this apparent paradox, including local immune suppression, tumor immune editing, and escape from immune attack (reviewed in ref. 24). In RETAAD mice, we found that the main reason why T cells do not control cutaneous tumors is because they fail to traffic to these tumors. We previously showed that cutaneous tumors are not immune-edited; resected cutaneous tumors are recognized ex vivo by antimalanoma T cells (17); moreover, CD8⁺ T cells retain their functionality in vivo and control visceral metastases (18). We now show that very few T cells infiltrate RETAAD skin tumors in comparison with the RETAAD visceral tumors or transplanted B16 skin tumors. The few T cells that infiltrate RETAAD skin tumors apparently retain their functionality because their density correlates inversely with tumor size. Moreover, transduction of CXCR3 ligands and CCL5 into the cutaneous tumors results in increased T-cell infiltration and reduced tumor growth. In patients with melanoma, tumor regressions have been observed with similar frequencies of tumor-infiltrating T cells (25, 26). Therefore in this model, differential T-cell trafficking is the main reason for tissue-specific control of metastases. Importantly, we extended this finding to cutaneous tumors from patients with melanoma treated by chemotherapy. In these patients, tumor control and prolonged survival are positively associated with increased T-cell infiltration and intratumoral expression of CXCR3 ligands and CCL5.

Several correlative studies have highlighted the importance of CCL5 and CXCR3 ligands in the progression of cutaneous melanoma. Harlin and colleagues identified several chemokines whose expression is associated with CD8⁺ T-cell infiltration; however, this study did not distinguish between chemokines that attract T cells and those that are produced by T cells (13). In patients with stage III disease, expression of CXCR3 by circulating memory T cells correlates with prolonged survival (27). IFN-α, a known inducer of CXCL9 and CXCL10, is approved for adjuvant treatment of high-risk (stages IIb and III) cutaneous melanoma (28, 29). On the basis of our data, it is tempting to speculate that induction of CXCR3 ligands participates in the antimelanoma activity of IFN-α. Expression of CXCL10 by peripheral blood mononuclear cell of patients with melanoma has been reported to correlate with tumor control (30). Interestingly, CXCR3 expression in cutaneous melanoma correlates negatively with lymphocyte infiltration (31). The mechanism underlying this correlation is unclear but this study suggests that cancer cells expressing CXCR3 might escape the immune response by competing for chemokines able to attract T cells. Expression of a nonfunctional allele of CCR5 results in decreased survival of patients with melanoma receiving immunotherapy (32). CXCR3 ligands and CCL5 have also been involved in other types of cancer, including colorectal and Ewing’s sarcoma (33, 34).

Our study also reveals a striking synergism between CXCR3 ligands and CCL5 in attracting T cells into melanoma tumors of both humans and mice. At this stage, the exact mechanism
accounting for this synergy is unclear because circulating T cells only express very low levels of CCL5 receptors. In fact, less than 2% of CD8⁰ T cells in the RETAAD mice express CCL5 receptors. CCL5 transfection did not enhance CXCL9 expression in the tumor and transfection of CCL5 alone has no effect on T-cell attraction. However, we did observe an increased percentage of CD4⁰ and CD8⁰ T cells expressing CCR5 among the TIL, suggesting either that CCR5-expressing T cells are preferentially attracted into the tumor or that upon infiltration, T cells upregulate CCR5. We propose that intratumoral expression of CCL5 might facilitate the retention of CCR5-expressing T cells, thereby augmenting the percentage of CCR5⁰ TIL. We could not directly test this hypothesis in patients with melanoma, but we did find that intratumoral expression of CXCR3 ligands and CCL5 in chemotherapy-treated tumors does lead to a synergistic increase in T-cell infiltration.

This study provides evidence for a novel mode of action of chemotherapeutic drugs. First, we show that dacarbazine, cisplatin, and temozolomide induce expression of T-cell-attracting chemokines in several melanoma cell lines. Transcription of CCL5, CXCL9, and/or CXCL10 was induced in all tested cell lines, even though each cell line displayed a unique profile of response to the chemotherapeutic drugs. Time-course experiments showed that under most experimental conditions tested, transcription of the chemokine genes preceded cell death. Secretion of the chemokines was confirmed for one of the cell lines. Chemokine induction was highly...
specific because of 48 soluble factors analyzed, only 5 chemokines and 1 chemokine-like factor were significantly induced by temozolomide; whereas only 2 chemokines and 1 chemokine-like factor were induced by cisplatin. Treatment of tumor-bearing mice with temozolomide also induced intratumoral chemokine expression and CXCR3-dependent T-cell infiltration. Chemotherapies are known to alter the cancer cell transcriptome (reviewed in ref. 35). By damaging the tumor and stimulating a wound healing response, chemotherapy may also induce epithelial–mesenchymal transition and favor the outgrowth of cells with higher motility and invasiveness (36); it may also select drug-resistant cells with stem cell and metastasis-initiating properties (37). Levina and colleagues previously reported that in vitro treatment of some human cancer cell lines with doxorubicin or cisplatin induces expression of several cytokines, chemokines, and growth factors, which protect the cancer cells from drug-induced apoptosis (22). These previous reports identified cancer cell alterations that limit chemotherapy-induced cell death. By showing that chemotherapy can alter cancer cell phenotype in a way that favorably impacts immune cell trafficking to the tumor, this study reveals a novel mechanism of action of common chemotherapeutic agents. Chemotherapy induces clinical responses in about 20% of patients with melanoma (16). In our limited cohort, tumor regression or stabilization was observed in 6 of 13 patients and 11 of 20 tumors resected after chemotherapy. Remarkably, enhanced expression of CCL5, CXCL9, and CXCL10 after chemotherapy correlated with tumor response. Importantly, prolonged patient survival was associated with enhanced chemokine expression after chemotherapy.

In conclusion, this study identifies CXCR3 ligands and CCL5 as the main determinants of T-cell infiltration into cutaneous metastases and shows that chemotherapy, by inducing expression of these chemokines within human tumors, may trigger T-cell infiltration and tumor control, resulting in prolonged patient survival. Therefore, screening for chemotherapeutic products able to induce the expression of T-cell–attracting chemokines in cancer cells may identify drugs that improve the efficacy of immunotherapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References


Chemotherapy Induces Intratumoral Expression of Chemokines in Cutaneous Melanoma, Favoring T-cell Infiltration and Tumor Control

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