Antibody Blockade of Semaphorin 4D Promotes Immune Infiltration into Tumor and Enhances Response to Other Immunomodulatory Therapies


Abstract

Semaphorin 4D (SEMA4D, CD100) and its receptor plexin-B1 (PLXNB1) are broadly expressed in murine and human tumors, and their expression has been shown to correlate with invasive disease in several human tumors. SEMA4D normally functions to regulate the motility and differentiation of multiple cell types, including those of the immune, vascular, and nervous systems. In the setting of cancer, SEMA4D–PLXNB1 interactions have been reported to affect vascular stabilization and transactivation of ERBB2, but effects on immune-cell trafficking in the tumor microenvironment (TME) have not been investigated. We describe a novel immunomodulatory function of SEMA4D, whereby strong expression of SEMA4D at the invasive margins of actively growing tumors influences the infiltration and distribution of leukocytes in the TME. Antibody neutralization of SEMA4D disrupts this gradient of expression, enhances recruitment of activated monocytes and lymphocytes into the tumor, and shifts the balance of cells and cytokines toward a proinflammatory and antitumor milieu within the TME. This orchestrated change in the tumor architecture was associated with durable tumor regression in murine Colon26 and ERBB2+ mammary carcinoma models. The immunomodulatory activity of anti-SEMA4D antibody can be enhanced by combination with other immunotherapies, including immune checkpoint inhibition and chemotherapy. Strikingly, the combination of anti-SEMA4D antibody with antibody to CTLA-4 acts synergistically to promote complete tumor regression and survival. Inhibition of SEMA4D represents a novel mechanism and therapeutic strategy to promote functional immune infiltration into the TME and inhibit tumor progression. Cancer Immunol Res; 3(6): 689–701. ©2015 AACR.

Introduction

Tumor growth depends on dynamic interactions within a complex ecosystem, including the proliferating neoplastic cells, immune cells, and stroma that constitute the tumor microenvironment (TME; refs. 1, 2). There is increasing evidence that effective immunotherapies can harness the immune system to promote durable tumor regression and prolong survival. To lyse effectively immunotherapies can harness the immune system to promote durable tumor regression and prolong survival. To lyse...
SEMA4D antibody in combination with other immunomodulation by comparing and contrasting the effect of anti-mammary tumor model. We further investigate the mechanism of action of SEMA4D (16), and the balance of M1/M2 macrophage has been shown to induce activation and migration of endothelial cells and regulate migration of tumor cells (26, 28). PLXN8 binds to and can transactivate oncogenic membrane tyrosine kinases, such as cMET and ERBB2 (21, 22, 26, 28), when cross-linked by SEMA4D. PLXN8, whose best characterized ligand is SEMA4C, also binds SEMA4D with intermediate affinity. A recent report indicates that PLXN8 is expressed on keratinocytes and can activate SEMA4D-positive γδ T cells to contribute to epithelial wound repair (29). CD72 is a relatively low-affinity (KD = 300 nmol/L) SEMA4D receptor (2) that is expressed primarily on B cells, APCs, and platelets (30).

Our understanding of the complex role of SEMA4D and its receptors in the process of tumor growth and metastasis is evolving. In this report, we describe the effects of antibody blockade of SEMA4D on modulation of the stroma, focusing on tumor-directed immune responses in two syngeneic tumor models. Because TAMs have been reported as a stromal source of SEMA4D (16), and the balance of M1/M2 macrophage has been identified as a prognostic factor in colon cancer (31), we selected a murine colon cancer model. In addition, given the reported role of PLXN8 and ERBB2 interactions in oncogenic signaling (21), we also investigated the effect of anti-SEMA4D in an ERBB2-dependent mammary tumor model. We further investigate the mechanism of action by comparing and contrasting the effect of anti-SEMA4D antibody in combination with other immunomodulatory therapies.

### Materials and Methods

#### Cell lines

Colon26 cells were purchased from the NCI (DTP, DCTD Tumor Repository, Frederick, MD) and were cultured in RPMI-1640 with 20% FBS and 0.05 mmol/L 2-mercaptoethanol. Tubo cells, a generous gift from Guido Forni (University of Turino, Italy), were cultured in DMEM with 20% FBS. Clone Tubo.A5 was cultured to have ≥95% purity and ≤5% high-molecular-weight species. Other antibody clones, including anti-CD11c/MAB102, anti-CD8/MAB116, antiCD8/MAB2.43, and anti-CD4/MAB8.5, were purchased from BioXCell and were verified to have ≥95% purity and ≤5% high-molecular-weight species before in vivo use.

#### Immunohistochemistry

Paraformaldehyde-fixed, paraffin-embedded sections (5 μm) were stained with the following antibodies: polyclonal anti-CD8 (AbBiotec), anti-CD86 (BioSS), anti-CD20 (Epitomics), anti-FoxP3 (FJK-16s biotin-conjugated; ebioscience), anti-F4/80 (AbBiotec), anti-CD86 (BioSS), anti-CD20 (Epitomics), anti-CD11c (AP-MAB0806; Novus). Slides were imaged at 20 magnification using a Retiga QICAM-12-bit camera (bright-field) or QICAM Aqua-16 bit (Fluorescent) coupled to an Olympus ks50 microscope. Additional details are included in Supplementary Methods.

#### Functional analysis of immune cells

Cohorts of tumor-bearing mice were sacrificed at a predetermined endpoint, based on mean tumor volume (MTV) of the control group. Tumor-infiltrating leukocytes (TILs) were isolated by dissociating tissue into small pieces and digestion with 2 mg/mL collagenase D and 0.1 mg/mL DNase I for 20 minutes at 37°C. Digested tumors were then clarified by passing through a 0.07-mm cell strainer, followed by RBC lysis (Biocoll) for 5 minutes at room temperature. TILs were further enriched from tumor suspensions using Lymphocyte-M (maximum of 25 x 10^6 cells with 5 mL Lympholyte-M), or alternatively were mixed with αCD45 microbeads (Miltenyi Biotec) and enriched into CD45^+.
leukocytes by positive selection on an AUTOMACS column. Spleens were dissociated into small pieces and the tissue homogenate was pressed through a 0.07-mm cell strainer, followed by RBC lysis (Bioscience) for 5 minutes at room temperature.

Splenocytes and TILs were assayed by Cytometric Bead Array (CBA) cytokine analysis. Cells (200,000) were cultured in triplicate. On day 2, culture supernatants were collected. Fifty micro liters of supernatant was pressed through a 0.07-mm cell strainer, followed by leukocytes by positive selection on an AUTOMACS column.

Neutralization of SEMA4D modulates immune-cell interaction CBA kit on a FACSCanto II flow cytometer. CBA data analysis was completed using FCAP Array software.

Colon26 splenocytes and TILs were assayed for tumor-specific CD8⁺ responders using Mouse IFNγ ELISPOT Ready-SET-GO (Affymetrix), according to the manufacturer’s instruction. Cells (5,000–10,000 TILs/well or 250,000 splenocytes/well) were plated in triplicate on MAIPS-4510 Immobilon—P membrane (Millipore) ELISPOT plates, and incubated for 18 hours at 37°C, in the presence or absence of MHC-I/H-2Ld-restricted immunodominant AH1 peptide of gp70 (0.01 mmol/L; ref. 33). The plates were developed using AEC (Sigma) substrate solution and analyzed by Cellular Technology Ltd.

FACS analysis
Fluorescent-conjugated rat or hamster MAbs to CD3 (clone: 17A-2), CD8a (clone: 53-6.7), CD11b (clone: M1/70), Gr-1 (clone: RB6-8C5), CD69 (clone: H1.2F3), CD25 (clone: PC61) with appropriate isotype controls were purchased from BioLegend. Samples were run on a FACScanto II flow cytometer and analyzed using the FlowJo software.

Statistical analysis
GraphPad was used for statistical and graphical analysis. Prism reports results as statistically nonsignificant (ns) at P > 0.05, statistically significant at 0.01 < P ≤ 0.05 (symbolized as *), very significant (**) at 0.001 < P ≤ 0.01, and extremely significant (***) at P ≤ 0.001. All error bars on graphs depict SEM. Additional information is included in Supplementary Data.

Results
Neutralization of SEMA4D modulates immune-cell distribution and cytokine profile within the TME
Complex interactions between the tumor and stroma, including lymphocytes and abundantly present macrophages, influence tumor growth and invasion. SEMA4D and its receptors are expressed on both tumors (Supplementary Fig. S1) and stromal cells. To evaluate the effects of SEMA4D in this complex environment, we first assessed SEMA4D expression in the TME in situ. Although expression of SEMA4D on Colon26 cells cultured in vitro was determined to be low by FACS analysis (data not shown), SEMA4D expression is strongly induced in vivo, forming a gradient with particularly high expression at the invasive margin of the tumor (Fig. 1A and Supplementary Fig. S2A). This area of high SEMA4D expression demarcated a striking pattern of mononuclear phagocytic cell distribution, with F4/80⁺ cells restricted to the inner core and CD11c⁺ cells and CD206⁺ M2 macrophage restricted to the outer stromal edge. Anti-SEMA4D antibody blockade with murine MAb67 disrupted this gradient and was associated with increased penetration of double-positive F4/80⁺/CD11c⁺ inflammatory APCs and an apparent decrease in the density of protumorigenic CD206⁺ M2 TAMs at the leading edge (Fig. 1A–D).

Concomitantly with the altered distribution of APCs, we observed increased infiltration of CD8⁺ staining T cells into the tumor leading edge (Fig. 2A). CD45⁺ TILs were isolated from dissociated tumors, and an increase in CD8⁺ TILs was confirmed by FACS analysis (Fig. 2B). Functional activity of CD8⁺ TILs was evaluated using ELISPOT to determine tumor-specific CTL activity in response to a previously identified Colon26 MHC-I-restricted immunodominant peptide, AH1 (34). Tumor peptide–specific CD8⁺ T cells secreting IFNγ were significantly increased in tumor following in vivo treatment with MAb67 (Fig. 2C).

To evaluate cytokine activity associated with an increase in activated APCs following anti-SEMA4D MAb67 antibody treatment, total TILs and splenocytes were isolated from Colon26 tumor–bearing mice. TILs from mice treated with MAb67 produced higher levels of proinflammatory Th1 cytokines, IFNγ and TNFα, with a decrease in the immune-suppressive cytokine MCP-1 (Fig. 2D; ref. 35). In contrast, no statistically significant changes in cytokine levels were observed in the spleens of mice treated with MAb67 (Fig. 2E). Collectively, these data demonstrated that MAb67 enhanced APC and T-cell infiltration and promoted a Th1 cytokine milieu in the TME. The effects appear to be localized to the TME, as there was no evidence of similar activity in peripheral lymphoid tissue.

Tumor growth delay by anti-SEMA4D antibody is CD8⁺ T cell–dependent in Colon26 tumor model
In Balb/c mice, MAb67 delayed Colon26 tumor growth and increased survival by as much as 29% (P < 0.0001; Fig. 3A and B). Significant tumor-growth delay (TGD), ranging from 8% to 29%, and complete tumor regression (CR) of approximately 8% were reproducible effects observed in many independent experiments performed in the Colon26 Balb/c tumor model (Table 1), both in our laboratory and as determined independently at Charles River Discovery Services. Mice that underwent complete tumor regression remained tumor free for at least 20 weeks and subsequently rejected rechallenge with homologous Colon26 tumor (Table 1). It was, therefore, striking that depletion of CD8⁺ T cells completely abrogated antitumor effects of MAb67 treatment (Fig. 3C), indicating that CTLs are the main effectors of tumor inhibition in this model.

Despite the evidence for a changed bias in the distribution of immune subsets in TME, the effect of anti-SEMA4D/MAb67 on Colon26 tumor growth was relatively modest. We considered the possibility that the modest effect of anti-SEMA4D on tumor growth might be due to relatively low immunogenicity and a corresponding paucity of immune cells that might benefit from enhanced tumor infiltration mediated by anti-SEMA4D antibody. In view of recent findings of durable antitumor effects of blocking immune checkpoint signals, as well as data that immunomodulatory therapies can be greatly improved when combinations are used (36, 37), we hypothesized that enhanced immune infiltration into tumor induced by anti-SEMA4D antibody may be particularly effective in combination with inhibitors of immune checkpoint blockade.

Anti-SEMA4D antibody enhances efficacy of immunomodulatory therapies anti–CTLA-4, anti–PD-1, and cyclophosphamide
The combination of anti-SEMA4D and anti–CTLA-4 antibodies was evaluated in Colon26 tumor–bearing mice. To determine additive effects in this model, a suboptimal anti–CTLA-4 regimen

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was empirically determined (data not shown). As shown in Fig. 4A, under these conditions, anti–CTLA-4 as single agent resulted in 3% TGD ($P = 0.0706$). Anti-SEMA4D significantly delayed tumor growth by 9% ($P = 0.0064$) and tumors regressed in 10% of mice. Strikingly, the combination of anti–CTLA-4 with anti–SEMA4D resulted in maximum possible TGD of 114% and 85% CR ($P < 0.0001$ compared with control Ig or monotherapy treatments). It has been reported that combination with anti–PD-1 can also significantly improve the response to anti–CTLA-4 in this model (38). As a benchmark, we compared the combination of anti–CTLA-4 with anti–PD-1, resulting in 60% CR ($P < 0.0001$). The combination of anti–SEMA4D with anti–PD-1 significantly improved the response to 67% TGD ($P < 0.0001$ compared with control and $P = 0.0014$ compared with anti–PD-1 monotherapy) and 35% CR ($P = 0.003$ compared with control and $P = 0.04$ compared with anti–PD-1 monotherapy). The additive benefit of this combination, however, contrasts with the more dramatic effect of anti–SEMA4D in combination with anti–CTLA-4. As discussed below, this is consistent with the different locus of activity of each of these agents.

Figure 1.
Neutralization of SEMA4D gradient at the invasive tumor front allows infiltration and activation of tumor-reactive macrophage. Colon26 tumors were collected on day29 from Balb/c mice treated with control IgG1 or MAb67. Serial sections were stained for expression of A. SEMA4D (left), CD11c (red) and F4/80 (green; middle), and merge (right). B. SEMA4D (left), F4/80 (green), CD206+ M2-polarized macrophages (red), with DAPI (blue) counterstain (right). A region of strongly SEMA4D-positive tumor and stroma was observed in control tumors indicated by brackets. Both SEMA4D gradient and distribution of monocytes and T cells were altered by SEMA4D blockade. Visual assessment suggests increased infiltration of F4/80CD11c+ DCs and a dispersal of M2-polarized CD206+ TAMs away from the tumor leading edge following MAb67 treatment. Infiltration of CD8+ cells (arrows) appeared to increase following MAb67 treatment, particularly at the invasive margin. For purposes of quantitation, entire tumor sections were scanned and density of stained pixel area was determined as a percentage of total tumor area (C) or the tumor margin area (D), which was defined as a 300-pixel-wide area that corresponded to the region of most intense SEMA4D staining without treatment. Group averages were calculated ($n = 10$ for each group).
Cyclophosphamide has been shown to mitigate Treg-mediated immunosuppression in rodents and in patients with cancer (34), as well as to promote immunogenic cell death and T cell-mediated immunity (40). To determine combination effects with anti-SEMA4D, a suboptimal dose of cyclophosphamide was administered 1 day before immunotherapy. Both MAb67 and cyclophosphamide significantly improved survival, with 10% and 15% CR, respectively, while the combination improved the TGD to 256% and significantly increased regression frequency to 40% CR ($P < 0.001$ for treatment effect and survival; $P = 0.0033$ for CR; Fig. 4C). Although the survival difference between cyclophosphamide monotherapy and the combination of cyclophosphamide plus MAb67 was not statistically significant ($P = 0.1$), these results suggest a trend to improved response and warrant additional studies with this and other chemotherapeutic combinations.

**Anti-SEMA4D enhances antitumor immune activity of anti-CTLA-4**

To further investigate the mechanism of action for the highly effective combination of anti-SEMA4D plus anti-CTLA-4, a series of experiments were conducted to assess effects on immune-cell...
composition and activity in tumor. Colon26 tumor-bearing mice were treated with antibodies (50 mg/kg i.p., weekly at 2 dpi): control IgG1 (n = 18) or MAb67 (n = 15). MTV was evaluated using ELISPOT (Fig. 5B). Similar to previous results, anti-SEMA4D significantly increased the frequency of tumor peptide–specific CD8\(^+\) T cells secreting IFN\(\gamma\) within the tumor, either as a single agent or in combination with anti–CTLA-4. Although, as expected, anti–CTLA-4 antibody increased the frequency of tumor-reactive CTLs in both tumors and spleens, there was not a further increase in activated CD8\(^+\) cells in the spleens of mice treated with the antibody combination, suggesting that the activity mediated by anti-SEMA4D treatment is localized to the tumor, even when combined with anti–CTLA-4 treatment. The important role of CD8\(^+\) T cells in protective immunity induced by treatment with the combination of anti-SEMA4D and anti–CTLA-4 is further supported by the demonstration that in mice that have rejected tumor following such combination treatment, depletion of CD8\(^+\) cells abrogates the specific immunologic memory response to a subsequent challenge with homologous tumor (Supplementary Fig. S4).

Anti–CTLA-4 therapy has been reported to increase the ratio of effector cytotoxic T cells (Teff) to suppressor regulatory T cells (Treg). Anti-SEMA4D and anti–CTLA-4 demonstrated independent and combinatorial effects on Teff to Treg ratios as determined by FACS analysis (Teff = CD8\(^+\)/CD69\(^+\); Treg = CD4\(^+\)/CD25\(^+\); Fig. 5C and Supplementary Fig. S5A). In support of this observation, IHC analysis using an alternate set of markers (CD8 and FoxP3) also demonstrated that the combination of anti–CTLA-4 with anti-SEMA4D significantly increased the Teff/Treg ratio compared with either monotherapy.

We also evaluated the balance of other immune cells and cytokines in this model. Anti-SEMA4D treatment increased the percentage of activated monocytes (CD86\(^+\)–\(\text{IHC} \)) localized to the tumor, even when combined with anti–CTLA-4. Anti-SEMA4D blockade promotes tumor rejection and immunologic memory in an Erbb2\(^\ast\) breast cancer model

Collectively, these data demonstrate a novel immunomodulatory mechanism of action for SEMA4D that enhanced the activity of other immunomodulatory agents and resulted in durable tumor rejection and resistance to subsequent tumor challenge (Table 1).

**Figure 3.**
Functional CD8\(^+\) T cells are required for MAb67-mediated TGD. Colon26 cells were implanted s.c. into syngeneic Balb/c mice (50,000 cells). A and B, tumor-bearing mice were treated with antibodies (50 mg/kg i.p., weekly at 2 dpi): control IgG1 (n = 18) or MAb67 (n = 15). MTV (A) and Kaplan-Meier survival curve (B), calculated using the endpoint time to tumor rejection, at a time when tumor volumes of treated mice were comparable (Supplementary Fig. S3). Combination therapy significantly enhanced the percentage of CD8\(^+\) cells in TILs (Fig. 5A). Functional activity of these T cells was evaluated using ELISPOT (Fig. 5B).
MAb67 was sacrificed because of tumor burden, another tumor had shrunken from a maximum of 718 to 214 mm³, one mouse had never developed measurable tumor, and 12 additional mice were tumor-free regressors. Similar effects were observed at doses as low as 3 mg/kg of MAb67 anti-SEMA4D antibody (Supplementary Fig. S5B), which corresponds to serum drug levels of 0.003 to 0.005 mg/mL and is also the minimal drug concentration required to fully saturate SEMA4D on circulating T cells (Supplementary Fig. S6C). This suggests that antibody saturation of SEMA4D on circulating T cells may serve as a useful PD marker in further clinical development.

To investigate immunologic memory, 12 tumor-free regressor mice were rechallenged with viable Tubo.A5 tumor in the contralateral breast tissue on day 90 (Fig. 6B). All of the MAb67-treated regressor mice rejected subsequent challenge with Tubo.A5. In other experiments, Tubo.A5 regressor mice challenged with Colon26 were unable to reject that challenge (data not shown), demonstrating that MAb67 monotherapy promoted a tumor-specific memory response (see also Table 1).

As in the Colon26 model, neutralization of a strong SEMA4D gradient at the invasive tumor front (Supplementary Fig. S2B) was associated with a shift in the balance of proinflammatory monocyte infiltration and activity, as well as increased T-cell penetration in Tubo.A5 tumors. A significant increase in F4/80⁺/CD11c⁺ APCs (Fig. 6C) and a concomitant significant decrease in CD11b⁺ Gr1⁺ immunosuppressive myeloid-derived suppressor cells (MDSC; \( P < 0.0001 \)) and MCP-1 cytokine secretion \( (P = 0.0079) \) were observed in Tubo.A5 TILs (Fig. 6D). In addition, a significant increase in the frequency of CD3⁺ T cells \( (P = 0.0012; \) Fig. 6E) and a trend toward an increase in the ratio of Teffs and Tregs following treatment were also observed (Supplementary Fig. S5B).

In striking contrast to treatment of Colon26, anti-SEMA4D as a single agent resulted in maximum possible TGD and average of 61% complete tumor regression in the Tubo.A5 model. The kinetics of regression suggest that several weeks were required for an effective immune response to be induced in this model, during which time the development of an aggressive phenotype may have been held in check by blockade of the ERBB2 pathway. Accordingly, immune checkpoint blockade was found to be relatively ineffective by itself in the Tubo model (Supplementary Fig. S7A and Table 1). Anti–PD-1 was minimally effective in Tubo.A5 at doses up to 0.25 mg when administered either prophylactically at 6 dpi (data not shown) or therapeutically when tumor volume reached approximately 100 mm³. Anti–CTLA-4 treatment was only marginally effective (23% CR, ns), and combination of the two immune checkpoint antibodies did not significantly improve response in the Tubo model. This suggests that, in the absence of blocking the ERBB2 signaling pathway, immune resistance was not sufficient to inhibit tumor growth. The presence of an immune-independent mechanism in Tubo.A5 is further supported by the observation that MAb67 treatment induced modest, but significant, TGD in Tubo.A5 grown in SCID mice. This contrasts with results in the ERBB2-negative Colon26 model, where effects of MAb67 were completely abrogated in immune-deficient SCID mice (Supplementary Fig. S7B and S7C). Most importantly, however, the failure of tumor rejection in SCID mice highlights the requirement for lymphocytes as effectors in both models.

**Discussion**

These data demonstrate that SEMA4D expression at the invasive tumor edge creates a barrier to immune infiltration and biases the balance of regulatory and effector immune cells and signals. In effect, antibody-mediated SEMA4D blockade "opens the gates" to the tumor and shifts the balance toward antitumorigenic immune activity within the tumor. In two tumor models, we have

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<th>Table 1. Tumor regression and rechallenge summary</th>
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**NOTE:** Data are compiled from several independent studies, as indicated, to demonstrate the overall frequency of tumor rejection following primary tumor graft or subsequent rechallenge. Studies include effective doses of 3-50 mg/kg MAb67; doses and schedules of other treatments are described in the text. Statistical significance of complete tumor regression (CR) was determined by the Fisher exact test. Mice with CR were challenged with viable Colon26 (500,000 cells) or Tubo. A5 (30,000 cells) in contralateral tissue at least 60 days following final treatment dose. Six naive mice were implanted at time of rechallenge as controls for successful implant. Tumor growth was monitored for at least 30 days after challenge.

Abbreviation: ns, not statistically significant.

*Statistical significance between control Ig and indicated treatment group.

*Statistical significance between single agent aCTLA-4 and indicated treatment group.

*Statistical significance between single agent anti-PD-1 and indicated treatment group.

*Statistical significance between single agent cyclophosphamide and indicated treatment group.
described MAb67-mediated tumor rejection, corresponding with increased immune activity in the TME. Anti-SEMA4D treatment elicits a resilient antitumor response with immunologic memory, as demonstrated by durable regressions, lack of primary regrowth, or metastasis up to 17 weeks after tumor rejection, and resistance to rechallenge with the same, but not different, tumor. SEMA4D blockade represents a novel immunomodulatory mechanism to promote durable tumor rejection.

The ability of SEMA4D blockade to enhance leukocyte infiltration is consistent with reports that SEMA4D and SEMA3A can inhibit spontaneous and chemokine-induced migration of monocytes and B cells (12). The precise molecular mechanism...
Anti-SEMA4D and anti-CTLA-4 treatment is synergistic and increases the frequency of tumor-specific TILs and secretion of proinflammatory cytokines, while reducing suppressive signals. Tumors and spleens were isolated from Colon26 tumor-bearing mice following treatment. CD45+ TILs were enriched from dissociated tumor using CD45 Automacs selection. Because of the small tumor volumes, it was necessary to pool samples from each treatment group for FACS and functional assays. For functional assays, TILs were pooled from 9 to 18 mice, to make up a total tumor volume of at least 1.5 g/group, and spleens were pooled from 4 to 5 mice/group; assay replicates are shown. For FACS analysis, three to four pools (3–6 tumors/pool) were assessed for each treatment group; biologic replicates are shown. Individual tumors (n = 6–10/group) were independently assessed by IHC and quantified using entire FFPE tumor sections, which were stained and quantitated. A, percent CD8+ cells were assessed by FACS. B, IFNγ-secreting functional CD8+ cells were measured by ELISPOT. C, Teff:Treg ratios were determined by FACS (left), and IHC (right); the ratio of Teff cells/Treg cells was determined for each pool or animal. D, tumor sections were also stained by IHC for monocyte-activation marker CD86. E, CD45+ TILs were cultured ex vivo for 48 hours and assayed for cytokine secretion using CBA analysis.
controlling TIL recruitment in different tumor models remains to be determined, but may be explained by several reported activities for SEMA4D, including (i) inhibition of lymphocyte migration (12), (ii) regulation of stromal components and fibrotic ‘wound repair’ mechanisms (29), (iii) the SEMA4D–PLXNB1–RhoA signaling axis on endothelial cells regulating extravasation and/or angiogenesis (41), and (iv) the association of PLXNB1 with receptor tyrosine kinases, including ERBB2 and MET (26, 42), affecting neoplastic survival and perhaps increasing immunogenicity of the tumor.

Following SEMA4D blockade, we observed significantly reduced levels of MCP-1, which can enhance recruitment of immature monocytes into the tumor, where they may differentiate into TAMs depending on the microenvironment (43). We also observed SEMA4D-mediated effects on IL10, which can promote polarization toward a CD206+ M2 phenotype and decrease expression of CD86 within the TME (35). Indeed, along with MAb67-induced reduction in IL10, we observed an increase in activated CD86+ APCs with a concomitant decrease in CD11b+ Gr1+ MDSCs and in the density of CD206+ M2 macrophages following SEMA4D blockade. Tumor-associated M2 macrophages can interact with lymphocytes to promote tumor growth; for example, TAMs can regulate the influx of CD4+ Tregs and can inhibit cytotoxic CD8+ T-cell responses through several mechanisms (44). MCP-1 and IL10 can also affect Teff:Treg ratios and reduce IFNγ production (45, 46). By reducing these suppressive signals, we revealed an important shift toward functional tumor-specific, IFNγ-secreting, CD8+ cytotoxic T cells and an increase in the ratio of Teffs to Tregs. Increased T-cell activity also correlated with increased frequency of CD11c+ F4/80+ APCs, which

Figure 6.
Anti-SEMA4D antibody regulates immune-cell infiltration and inhibits growth of Tubo.A5 orthotopic mammary carcinoma. Tubo.A5 cells were implanted s.c. into mammary fat pad of Balb/c mice. A, weekly treatment with anti-SEMA4D/MAb67 or isotype-matched control antibodies (50 mg/kg i.p., starting 6 dpi, n = 14) resulted in maximal TGD of 135%+ and 86% CR+ . B, tumor growth in individual mice is shown. At 90 days after implant (dotted line), 13 tumor-free mice, along with 6 naïve mice, were implanted with viable Tubo.A5 cells on the contralateral side. 0/12 mice developed tumors in MAb67-treated regressor mice, while 6 of 6 naïve mice developed tumors. Tumor-bearing animals were treated as above and tumors were harvested on day 39, before tumor rejection. At the time of harvest, the average tumor volumes were 528 and 323 mm3 for the control and MAb67 treatment groups, respectively, resulting in 38% tumor growth inhibition (P = 0.0015). C, frequency of F4/80+CD11c+ APCs was assessed by IHC on tumor sections. D and E, TILs were enriched using Lympholyte-M from dissociated Tubo.A5 tumors. Pooled samples were analyzed for T cells and MDSCs by FACS, and levels of MCP-1 by CBA analysis. Tubo.A5 tumors treated with MAb67 exhibit increased T-cell infiltration, with decreased levels of immunosuppressive MDSCs and MCP-1.
represent potent APCs that can cross-present tumor antigens and locally activate tumor-specific T cells (47). Coordinated infiltration of CD8+ and Th1 cytokine-secreting cells suggests that SEMA4D antibody blockade increases immunoscore. The observation that anti-SEMA4D promotes immune infiltration into the TME suggested that this therapeutic might act in synergy with other immunomodulatory therapies. Indeed, anti-SEMA4D enhanced activity of several therapies reported to promote antitumor immune responses through diverse modes of action. It was striking that combination of anti-SEMA4D with anti–CTLA-4 proved more effective than combination with another immune checkpoint blockade inhibitor, anti–PD-1. Both CTLA-4 and PD-1 are upregulated on activated T cells and promote T-cell hyporesponsiveness; however, each plays a nonredundant role in modulating immune responses. CTLA-4 plays a pivotal role in attenuating the early activation of naïve and memory T cells in draining lymph nodes where the corresponding ligands, CD80 (B7-1) and CD86 (B7-2), are highly expressed. In contrast, PD-1 is primarily involved in modulating T-cell activity in tissues via its interaction with locally induced PD-L1 and PD-L2. Because anti–CTLA-4 enables greater expansion of tumor-specific T cells in draining lymph nodes in the presence of cognate ligands, B7-1 and B7-2, anti-SEMA4D antibody can act synergistically to facilitate infiltration of these expanded T cells into the tumor. In contrast, to the extent that anti–PD-1 prevents PD-L1 expressed by tumor from inactivating tumor-specific T cells that have already penetrated into the tumor environment (48), the added benefit of anti-SEMA4D in facilitating tumor infiltration may be more limited. Other immunotherapeutic interventions that activate antitumor immune responses in the periphery, such as costimulatory factors and cancer vaccines, may also benefit from disruption of immune barriers by combination with anti-SEMA4D treatment and warrant further investigation.

In the Tubo.A5 model, potent single-agent efficacy of anti-SEMA4D treatment contrasts with the need for combination therapy in the Colon26 model. Tubo.A5, unlike Colon26, expresses both PLXNB1 and ERBB2. Cross-linking of PLXNB1 by SEMA4D has been reported to transactivate ERBB2, and it has been recently reported that the ERBB2 signaling pathway must be effective in some tumors that do not respond to immune checkpoint blockade, such as Tubo.A5, and, importantly, can combine synergistically with immunotherapies that either reduce negative feedback, such as checkpoint blockade, or enhance immune responses, such as costimulatory activity, vaccines, or chemotherapies that induce immunogenic cell death. Results of experiments reported here demonstrate the ability of anti-SEMA4D antibody to induce a significant and durable antitumor immune response and have motivated a phase I clinical trial of a humanized anti-SEMA4D antibody, VX15/2503, in patients with solid tumors. Results of this clinical study will be reported elsewhere.

Disclosure of Potential Conflicts of Interest
M. Zauderer has ownership interest (including patents) in Vaccinex, Inc. No potential conflicts of interest were disclosed by the other authors.

Authors’ Contributions
Conception and design: E.E. Evans, A.S. Jonason Jr, T.L. Fisher, E.S. Smith, M. Zauderer
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): E.E. Evans, A.S. Jonason Jr, H. Bussler, S. Torno, J. Veeraraghavan, C. Reilly, M.A. Doherty, J. Seils, L.A. Winter, S. Giralico, M. Scwirns, K. Klimatcheva, W.J. Bowers, M. Paris
Writing, review, and/or revision of the manuscript: E.E. Evans, A.S. Jonason Jr, C. Reilly, T.L. Fisher, W.J. Bowers, M. Paris, E.S. Smith, M. Zauderer
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): E.E. Evans, A.S. Jonason Jr, H. Bussler, J. Veeraraghavan, C. Reilly, J. Seils, R. Kirk, A. Howell, K. Klimatcheva
Study supervision: E.E. Evans, A.S. Jonason Jr, H. Bussler, W.J. Bowers, E.S. Smith

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Reference


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Elizabeth E. Evans, Alan S. Jonason, Jr, Holm Bussler, et al.


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