CD27 Signaling Increases the Frequency of Regulatory T Cells and Promotes Tumor Growth

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Abstract

Signaling of the TNF receptor superfamily member CD27 activates costimulatory pathways to elicit T- and B-cell responses. CD27 signaling is regulated by the expression of its ligand CD70 on subsets of dendritic cells and lymphocytes. Here, we analyzed the role of the CD27–CD70 interaction in the immunologic control of solid tumors in Cd27-deficient mice. In tumor-bearing wild-type mice, the CD27–CD70 interaction increased the frequency of regulatory T cells (Tregs), reduced tumor-specific T-cell responses, increased angiogenesis, and promoted tumor growth. CD27 signaling reduced apoptosis of Tregs in vivo and induced CD4⁺ effector T cells (Teffs) to produce interleukin-2, a key survival factor for Tregs. Consequently, the frequency of Tregs and growth of solid tumors were reduced in Cd27-deficient mice or in wild-type mice treated with monoclonal antibody to block CD27 signaling. Our findings, therefore, provide a novel mechanism by which the adaptive immune system enhances tumor growth and may offer an attractive strategy to treat solid tumors. Cancer Res. 1–13. ©2012 AACR.

Introduction

Clinical observations and experimental data support the hypothesis that the immune system contributes to cancer surveillance (1). However, different escape mechanisms of cancer cells explain the failure of an efficient immune control in progressing cancer. These include immunologic ignorance of tumors developing outside secondary lymphoid organs (2), the expression of inhibitory molecules on cancer cells such as Fas ligand (3), the generation of MHC- and/or antigen-loss variants (4), and the induction of Tregs (5). CD4⁺CD25⁺FoxP3⁺ Tregs have been shown to hinder tumor immunity in different murine models, and depletion of Tregs promotes tumor-specific immune responses (6). Furthermore, the frequency of Tregs is increased in peripheral blood and tumor-infiltrating lymphocytes (TIL) of cancer patients, and accumulation of Tregs in the tumor predicts poor prognosis and survival (7).

In healthy individuals, Tregs constitute 5% to 10% of peripheral CD4⁺ T cells. These natural (n)Tregs arise in the thymus and depend on a strong T-cell receptor (TCR) activation (8). In addition, Tregs can be induced outside the thymus from CD4⁺ CD25⁺ FoxP3⁻ naive T cells. This conversion of naive T cells to induced (iT)regs depends on TCR stimulation, interleukin (IL)-2, and TGF-β (9). Whether the increased frequency of Tregs in tumor tissue and draining lymphatic tissue is a result of an expansion and/or accumulation of nTregs, or if they are locally induced, is controversial (10).

CD27, a TNF receptor superfamily member, acts in a costimulatory pathway to elicit T- and B-cell responses. CD27 signaling activates NF-κB, promotes cell survival, enhances antigen receptor–mediated proliferative signals, and increases effector function (11). In addition, CD27 signaling increases the production of the T-cell growth/survival factor IL-2 (12, 13). CD27 signaling either leads to improved T-cell function or to T-cell dysfunction, probably depending on the amount, duration, and timing of the expression of the CD27 ligand (CD70; refs. 14–16). As a result, CD70 expression is tightly regulated, and it is only transiently expressed on activated T and B cells, as well as on subsets of professional antigen-presenting dendritic cells (DC) and natural killer (NK) cells (11). In contrast to the very limited expression of CD70 in a normal healthy individual, constitutive expression of CD70 has been documented in cancer (17–19) and chronic viral diseases (14).

Current evidence supports the view that the CD27–CD70 interaction improves antitumor immunity (20–22). Injection of CD27-activating antibody improved tumor rejection (23, 24) and Cd70 transgenic mice were protected against poorly immunogenic tumor cells (25, 26). Certain human tumors such as brain tumors (19), renal cell carcinomas (27) and some lymphomas (17, 18) have been shown to express CD70. Somewhat controversial is the proposed improved T-cell response after CD27 signaling, expression of CD70 on tumors often correlates with increased aggressiveness because of increased metastasis (28). Treg formation (17, 18), or death of effector cells (19). Similar contradictory observations on tumor formation also exist for other TNF receptor superfamily members, for
example, improved tumor control by systemic administration of stimulating anti-CD137 (4-1BB) antibody (29, 30) versus improved tumor control in Cd137-deficient mice (31).

Although stimulating CD27 by overexpressing CD70 or by monoclonal antibody (mAb) clearly improves tumor control (23–25), the physiologic role of the CD27–CD70 interaction in tumor formation has not been analyzed so far. Using Cd27-deficient mice, we found that CD27 signaling increased tumor-specific T-cell responses after immunization with tumor cells as single-cell suspension. In contrast, tumor formation of transplanted tumors and chemically induced tumors was reduced in Cd27−/− mice. CD27 signaling increased the frequency of Tregs in vivo by reducing apoptosis and thereby increased tumor growth.

Materials and Methods

Mice

C57BL/6 (BL/6), H8 (32), Ubc-Gfp mice (33), and Rag-1−/− mice were from the Institute of Laboratory Animal Science (Zurich, Switzerland). Cd27−/− mice (34) were from the Netherlands Cancer Institute (Amsterdam, Netherlands). All experiments were approved by the local Experimental Animal Committee.

Cell lines

The murine tumor cell lines fibrosarcoma MC57 and MC57-GP, melanoma B16F10 and B16F10-GP, colon adenocarcinoma MC38 and MC38-GP, and lymphoma RMA-S have been described before (35, 36). MC57-CD70 cells were transfected with the mCD70/pcDNA3.1(+) plasmid (provided by H. Yagita, Department of Immunology, Juntendo University School of Medicine, Tokyo, Japan) and cultured in the presence of 1 mg/mL G418 (Invitrogen). MC38 and MC38-GP, and lymphoma RMA-S have been described before (35, 36). MC57-CD70 cells were transfected with the mCD70/pcDNA3.1(+) plasmid (provided by H. Yagita, Department of Immunology, Juntendo University School of Medicine, Tokyo, Japan) and cultured in the presence of 1 mg/mL G418 (Invitrogen).

Tumor induction

Tumors were induced as described in Matter and colleagues (2). To investigate the role of CD27 signaling in tumor growth, we transplanted solid fragments (2). In all experiments, tumor progression was faster in Cd27−/− mice. In all experiments, tumor progression was faster in Cd27−/− mice.

Tumor induction in vitro

A total of 6 to 105 MACS-purified splenic CD4+ T cells or 3 × 105 FACS-purified splenic CD4+CD25hi T cells were cultured in RPMI (10% fetal calf serum, 5 ng/mL rh-TGF-β1; R&D Systems) in the presence or absence of 5 U/mL rm-IL-2 in anti-CD3e-coated (10 μg/mL) 48-well or 96-well tissue culture plates. For CD27 stimulation, 5 × 105 irradiated (120 Gy) MC57 or MC57-CD70 tumor cells were added to the culture. CD4+ T cells were labeled with CFSE (Invitrogen). IL-2 protein levels in the supernatant were measured using a multiplexed particle-based flow cytometry cytokine assay (R&D Systems).

Statistics

Data were analyzed using GraphPad Prism 5.0 and unpaired, 2-tailed Student t test, Mann–Whitney U test, one-way ANOVA (Tukey’s multiple comparison test) or 2-way ANOVA (Bonferroni posttest). Data are displayed as mean ± SEM. P < 0.05 was considered significant (*, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001).

Results

Improved control of solid tumors in Cd27-deficient mice

The transplantation of solid tumor fragments allows studying tumor development in the context of an already established tumor stroma. When transplanted as solid fragments, even very immunogenic tumors grow in immunocompetent hosts (2). To investigate the role of CD27 signaling in tumor growth, we transplanted solid fragments (~1 mm3) of MC57 fibrosarcoma, MC38 colon adenocarcinoma, or B16F10 melanoma subcutaneously into the flanks of BL/6 and Cd27-deficient mice. In all experiments, tumor progression was faster in BL/6 (or Cd27−/− littersmates, data not shown) than in Cd27-deficient mice.
Cd27−/− mice (Fig. 1A–C). Similarly, MC38 and B16F10 tumors expressing the LCMV-GP as a tumor-model antigen developed faster in BL/6 mice (Fig. 1E and F). As shown before (41), GP-expressing MC57 tumors were rejected in BL/6 mice because of a very efficient induction of antitumoral CD8+ T cells. Similarly, MC57-GP did not lead to tumor formation in Cd27−/− mice (Fig. 1D). In addition, MC57 single-cell suspensions failed to grow in both groups of mice (Fig. 1G) because of an efficient immune response (2, 42).

To verify our findings in a different experimental model, we injected 3-methylcholanthrene. All BL/6 mice developed clinically detectable subcutaneous tumors within 2 to 3 months (101 ± 10 days). In contrast, tumor formation in Cd27−/− mice was delayed up to 10 months (219 ± 23 days; Fig. 1H).

Reduced tumor cell proliferation, reduced tumor angiogenesis, and increased T-cell infiltration of tumors in Cd27−/− mice

The complete rejection of MC57 tumors by the majority of Cd27−/− mice prevented further analysis of the underlying mechanisms in the tumor. Therefore, larger fragments (8 mm³) were transplanted in all subsequent experiments, resulting in sufficient initial tumor growth to carry out histologic sections and to analyze the function of TILs in both BL/6 and Cd27−/− mice (Supplementary Fig. S1A). Tumor cell proliferation was increased in the presence of an intact CD27–CD70 interaction (Fig. 2A and B). In contrast, no differences in tumor cell apoptosis were observed (Fig. 2A and C). Furthermore, tumors were significantly more vascularized in BL/6 mice than in Cd27−/− mice (Fig. 2A and D). Finally, CD3+ T cells infiltrated significantly less into tumors of BL/6 than Cd27−/− mice (Fig. 2A and E). These data suggested that the enhanced tumor progression in BL/6 mice correlates with increased tumor cell proliferation, improved tumor vascularization, and poor T-cell infiltration.

CD8+ T cells are the main effector mechanisms that control tumor growth in the tumor models used so far (35). Depletion of NK cells in Rag−/− mice carrying the primary tumor using anti-asialo-GM1 antibody before transplantation did not influence tumor growth, formally excluding that NK cells transplanted within the tumor fragments were responsible for the observed different tumor growth in BL/6 versus Cd27−/− mice (Fig. 2F). In addition, the NK cell–controlled RMA-S tumor fragments (36) grew equally in BL/6 and Cd27−/− mice (Fig. 2G).
Antitumoral immune responses are increased in Cd27−/− mice

We compared antitumoral CTL responses after subcutaneous injection of irradiated MC57-GP single-cell suspensions. In BL/6 mice, frequencies of IFN-γ- and TNF-α–producing gp33-specific CD8+ T cells were significantly higher than in Cd27−/− mice (Fig. 3A and Supplementary Fig. S1B). Similar results were obtained with nonirradiated tumor cells or intraperitoneal injections (data not shown). These results confirmed that after injection of tumor cells as single-cell suspensions, CD27 costimulation improves specific antitumoral T-cell responses.

In a next step, antitumoral immune responses were analyzed 20 to 30 days after tumor transplantation. Frequencies of IFN-γ- and TNF-α–producing CD4+ and CD8+ T cells in spleens did not significantly differ. However, in tumor-draining inguinal lymph nodes and TILs of Cd27−/− mice, frequencies IFN-γ- and TNF-α–producing CD4+ and CD8+ T cells were significantly increased (Fig. 3B and Supplementary Fig. S1C).

In addition, an immune gene profile in total tumor RNA 14 days after transplantation revealed that 11 effector/activation markers were significantly increased in tumors isolated from Cd27-deficient mice (Supplementary Fig. S1D).

To analyze whether the induction of a CTL response is suppressed in the presence of growing solid tumors, gp33-expressing DCs were injected into tumor-bearing or naive mice. gp33-specific IFN-γ and TNF-α CTL responses were suppressed approximately 20% to 40% in spleens and lymph nodes of tumor-bearing versus naive BL/6 mice (Fig. 3C and data not shown). In contrast, gp33-specific CTL responses were comparable in tumor-bearing and naive Cd27−/− controls.

Our results indicated that the CD27−CD70 interaction increases the tumor-specific CD8+ T-cell response against tumor cells injected as single-cell suspension, but suppresses CD8+ T-cell responses in the presence of growing solid tumors.
The CD27–CD70 interaction induces Treg accumulation

Tregs reduce antitumoral immune responses and enhance tumor progression (6, 7, 43). As reported before (15), the frequency of Tregs in naive Cd27−/−/− and BL/6 mice was comparable. This held also true for CD4+CD25+FoxP3+ Tregs. In contrast, after tumor transplantation, BL/6 mice had significantly higher frequencies of CD25+ and CD25− Tregs than Cd27−/− mice in the spleens and in tumor-draining inguinal lymph nodes. Importantly, the frequency of intratumoral CD25+ Tregs was increased in BL/6 compared with...
**Cd27−/−** mice, whereas there was no difference for **CD25−** Tregs (Fig. 4A).

To test whether **CD4+CD25+** Tregs are responsible for the **Cd27−CD70−**-mediated tumor progression, MC57 tumor growth was analyzed in **CD4−** or **CD25−** T-cell–depleted mice (Fig. 4B and C). **CD4−** T-cell depletion induced complete tumor rejection in **Cd27−/−** and BL/6 mice (Fig. 4B). Anti-CD25 antibody was administered 4 days before tumor transplantation, allowing efficient depletion of **CD25+** Tregs up to 20 days after transplantation without impairing the generation of **CD25−** antitumor effector cells (44). Initially, **CD25−** T-cell–depleted BL/6 and **Cd27−/−** mice similarly controlled tumor growth (Fig. 4C). However, 4 weeks after CD25 depletion, the frequency of Tregs increased and reached significantly higher levels in **Cd27−/−** mice than in untreated mice (Fig. 4D).

**Figure 4.** The frequency of Tregs is increased in tumor-bearing BL/6 mice. A, frequencies of **CD25+** and **CD25−** Tregs within total **CD4+** T cells in spleens, tumor-draining inguinal lymph nodes and TILs in naive mice and 30 days after transplantation of MC57 tumor fragments. B, MC57 tumor growth in untreated or **CD4−** T-cell–depleted mice. C, MC57 tumor growth in mice treated with depleting anti-CD25 antibody 4 days before tumor transplantation. D, frequencies of Tregs in **CD25−**-depleted mice at different time points after tumor transplantation. E and F, on the day of tumor transplantation, BL/6 or **Cd27−/−** CD4+ cells were injected intravenously into recipient mice. E, analysis of tumor growth. F, frequencies of adoptively transferred congenic BL/6 and endogenous **Cd27−/−** CD4+ T cells in TILs of tumor-bearing **Cd27−/−** mice 26 days after transplantation. G–J, tumor-bearing BL/6 mice were treated with FR70 antibody or rat-IgG (arrows), starting 1 day before (G) or 18 days after (I) transplantation. H, **CD25+** Treg frequency in blood before and 10 days after transplantation. J, **CD25+** Treg frequency in tumors 38 days after transplantation. LN, lymph nodes.
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levels in BL/6 mice (Fig. 4D). As a consequence, 5 of 10 tumors in BL/6 mice grew, whereas only one tumor grew in Cd27+/− mice (Fig. 4C).

To more directly define the contribution of CD27 signaling on Tregs, we adoptively transferred FACs-sorted CD4+ or CD4+CD25hi T cells from Cd27+/+ or BL/6 mice into tumor-bearing Cd27+/− mice. The transfer of BL/6 CD4+ or CD4+CD25hi T cells to Cd27+/− recipient mice completely reconstituted tumor growth (Fig. 4E). As a control, the transfer of Cd27+/−/CD4+ or Cd4+CD25hi T cells did not affect tumor growth and all tumors were rejected. The adaptively transferred CD4+ or CD4+CD25hi T cells from BL/6 mice reached higher frequencies in TILs than the endogenous Cd27+/− CD4+ T cells (Fig. 4F). These data indicated that direct CD27 signaling on Cd25+ Tregs contributes to the observed differences in tumor growth between Cd27+/− and BL/6 mice.

Anti-CD70 treatment reduces tumor progression in BL/6 mice

To analyze whether blocking the CD27–CD70 interaction by mAb (FR70) is a possibility to treat solid tumors, 2 treatment protocols were carried out. First, early FR70 treatment starting one day before MC57 tumor transplantation significantly reduced tumor growth (Fig. 4G). In addition, the frequency of CD25+ Tregs of rat-IgG–treated BL/6 mice significantly increased 10 days after transplantation compared with FR70-treated mice (Fig. 4H). Second, late FR70 treatment starting 18 days after tumor transplantation (when tumors were clinically detectable) significantly delayed tumor growth (Fig. 4I) and prevented intratumoral accumulation of CD25+ Tregs (Fig. 4J) without affecting other T-cell subsets (Supplementary Fig. S2A). However, early treatment was more effective. These data indicated that treatment with blocking anti-CD70 antibody significantly inhibits Treg accumulation and reduces tumor progression.

Preferential expression of CD70 on CD4+ TILs

Analysis of CD70 expression on tumor-infiltrating immune cells in BL/6 and Cd27+/− mice revealed highest levels of CD70 expression on CD4+ TILs in Cd27+/− mice (Fig. 5A and B). This is in line with previous findings indicating that CD70 is shed from the cellular surface after ligation CD27 in BL/6 mice (15, 45). Analysis of CD4+ subsets in TILs of Cd27+/− mice revealed that CD70 was expressed on Tregs and Teffs as well as on CD4+CD25+FoxP3+ cells (Fig. 5C and D). In contrast, CD70 expression in both Cd27+/− and BL/6 mice was low on nontumor–infiltrating immune cells (Fig. 5B and data not shown).

CD27 is preferentially expressed and ligated on intratumoral CD25+ Tregs

In tumor-bearing BL/6 mice, the expression of the CD27 receptor was strongly downregulated on CD4+ and CD8+ TILs as compared with CD4+ and CD8+ T cells from tumor-draining inguinal lymph nodes and spleens (Fig. 5E). This downregulation of CD27 may be due to shedding after ligation with CD70 (46). In accordance with this hypothesis, blocking CD70 in tumor-bearing BL/6 mice by FR70 resulted in an upregulation of CD27 expression on intratumoral CD25+ Tregs, whereas the expression of CD27 on Tregs in the spleen remained unchanged (Fig. 5F and G and data not shown). Analysis of CD27 mean fluorescence intensity (MFI) in TILs and spleens of FR70- versus rat-IgG–treated tumor-bearing BL/6 mice revealed that CD27 is preferentially ligated on CD25+ Tregs in the tumor (Figs. 5F and G) but also on Teffs in the spleen. However, the frequency of CD4+CD25+FoxP3+ Teffs in spleen was very low (Fig. 5F). These experiments indicated that CD70 is locally expressed on TILs and leads to CD27 ligation on intratumoral Tregs.

CD27 signaling favors Treg accumulation in vivo by reducing Treg apoptosis

To analyze the mechanism of the CD27-mediated increased in Treg numbers, purified CD4+ T cells from GFP-expressing BL/6 or Cd27+/− mice were transferred to recipient mice one day before transplantation. Twenty days after tumor transplantation, the frequencies and absolute numbers of GFP+ and GFP−CD25+ Tregs were determined in the spleen (Fig. 6A). Transferring Cd70–competent CD4+ T cells resulted in significantly higher frequencies and numbers of GFP−CD25+ Tregs than transferring Cd70–deficient CD4+ T cells. This held true for BL/6 and Cd27+/− recipient mice (Fig. 6B). In addition, blocking the CD27–CD70 interaction of CD4+ T cells from BL/6 mice transferred to Cd27+/− recipient mice by FR70 treatment reduced the frequency and numbers of GFP+CD25+ Tregs (Fig. 6B). Due to shedding of CD70 after ligation with CD27, CD70 expression is higher in Cd27+/− mice than in BL/6 mice (Fig. 5A and data not shown). This might explain the higher frequencies of BL/6 CD25+ Tregs after transfer into Cd27+/− recipient mice when compared with BL/6 recipient mice.

In contrast, the transfer of Cd70–competent CD4+ T cells to Cd27+/− recipient mice did not affect the frequency of the endogenous Cd27+/− CD25+ Tregs (GFP; Supplementary Fig. S2B). This further confirmed a direct effect of CD27 signaling on CD25+ Tregs.

Tumor-infiltrating Tregs consist of nTregs and iTregs (9, 10). To discriminate whether CD27 signaling leads to a preferential accumulation of nTregs or an increased generation of iTregs, we used the recently identified transcription factor Helios (47). About 60% of CD25+ Tregs in the spleens and inguinal lymph nodes of naive and tumor-bearing BL/6 and Cd27+/− mice were Helios− nTregs. In contrast, only about 40% of tumor-infiltrating CD25+ Tregs were Helios+ (Fig. 6C). Importantly, no differences in the frequencies of CD25+ nTregs in BL/6 versus Cd27+/− mice were found. These data suggested that the increased frequency of CD25+ Tregs in BL/6 mice is the consequence of an accumulation of both, nTregs and iTregs. A higher frequency of Tregs in Cd70–competent mice may be due to prolonged cell survival and/or due to increased cell cycling. BrdUrd incorporation and 4′,6-diamidino-2-phenylindole (DAPI) experiments revealed no significant differences in proliferation of Tregs between tumor-bearing BL/6 and Cd27+/− mice (Fig. 6D and E). In contrast, CD25+ Tregs isolated from tumor-draining lymph nodes and tumors of BL/6 mice contained a significantly lower percentage of Annexin V+ cells (Fig. 6F). Similarly, the frequency of Annexin

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V^+ CD4^+ Teffs in tumor-draining lymph nodes and tumors was lower in BL/6 mice (Supplementary Fig. S2C). Interestingly, a reduction of T-cell apoptosis was not detected in the spleen, correlating well to the low expression of CD70 in this organ (Fig. 5B and Supplementary Fig. S2C). Therefore, CD27 signaling reduces apoptosis of both, CD25^+ Tregs and Teffs. However, as outlined above and shown in Fig. 5F, the frequency of CD4^+ CD25^+ FoxP3^+ Tregs within total CD4^+ T cells is very low.

Importantly, the reduced apoptosis of CD25^+ Tregs decreases the intratumoral ratio of Teffs/Tregs in BL/6 mice (Supplementary Fig. S2A).

**CD27 signaling increases survival of Tregs in vitro by augmenting IL-2 production**

To analyze the mechanism of the CD27-induced increase in Tregs in more detail, we generated Tregs in vitro in the

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Figure 5. CD70 is expressed on tumor-infiltrating CD4^+ T cells. A, CD70 expression on immune cells in MC57 tumors. B, frequencies of CD70^+ immune cells in tumor-bearing Cd27^-/- mice (n = 3). C and D, CD70 expression on CD4^+ subsets in tumor-bearing Cd27^-/- mice (n = 4). E, CD27 expression on immune cells of tumor-bearing BL/6 mice. F and G, tumor-bearing BL/6 mice were treated once with FR70 antibody or rat-IgG on the day before analysis. F, representative histograms of CD25 expression on CD25^+ Tregs and MFIs (G) of CD27 expression on CD4^+ T cell subsets in spleens and TILs.
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Figure 6. CD27-CD70 interaction in the tumor environment favors the survival of Tregs. A and B, GFP⁺ BL/6 or Cd27⁻/⁻ CD4⁺ T cells were injected intravenously into irradiated recipients. Recovery of Tregs was identical in irradiated BL/6 and Cd27⁻/⁻ mice (data not shown). One day later, tumor fragments were transplanted. Twenty days later, the frequencies and total numbers of CD25⁺ Tregs in the GFP⁺ CD4⁺ T cell populations in the spleens were analyzed (n = 2–5). C, frequencies of Helios⁺ nTregs in tumor-bearing and naive mice. D, BrdUrd incorporation in FoxP3⁺ and FoxP3⁻ CD4⁺ T cells in tumor-bearing and naive mice. E, DAPI staining of CD4⁺ CD25hi TILs. F, Annexin V staining of CD4⁺ CD25hi T cells in tumor-bearing and naive mice. LN, lymph nodes.

presence of anti-CD3e and TGF-β. Splenic CD4⁺ T cells from naive BL/6 or Cd27⁻/⁻ mice were cocultured with irradiated MC57 or MC57-CD70 cells. CD27 ligation in cocultures with MC57-CD70 significantly increased the frequency of CD25⁺ Tregs from BL/6 mice when compared with CD25⁺ Tregs from Cd27⁻/⁻ mice at days 2 (Fig. 7A) and 4 (not shown). Similarly, the frequency of BL/6 CD25⁺ Tregs was higher in cocultures with MC57 cells when compared with Cd27⁻/⁻ CD25⁺ Tregs.
This may be due to the expression of CD70 by activated CD4\(^+\) T cells (data not shown). The CD25\(^+\) Treg population contained nTregs and iTregs, which both expanded similarly (Fig. 7B) and downregulated the CD27 receptor (Fig. 7C) upon CD70 stimulation. In contrast, we observed no differences in the frequency of CD25\(^+\)/CD27\(^-\) Tregs, regardless of CD27 ligation.

To distinguish between Treg cell division and apoptosis \textit{in vitro}, we carried out a CFSE dilution assay. CD27\(^-\)CD70\(^+\) and BL/6 CD25\(^+\) Tregs underwent a similar number of cell divisions at days 2 (Fig. 7D) and 4 (not shown). However, CD27 ligation led to significantly higher numbers of BL/6 Tregs before and after the first cell division.

CD27 signaling has been shown to increase IL-2 secretion and IL-2 is a crucial growth and survival factor for Tregs (48). We therefore analyzed the IL-2 concentrations and found significantly higher amounts of IL-2 when the CD27\(^-\)CD70 interaction was present (Fig. 7E). Intracellular IL-2 stainings revealed that CD27 signaling significantly increased IL-2 production in FoxP3\(^-\) CD4\(^+\) T cells but not Tregs (Fig. 7F). This observation is in line with previous findings indicating that Tregs do not produce IL-2 (49).

As a consequence of the inability to produce IL-2, FACS-purified CD4\(^+\) CD25\(^+\) T cells from BL/6 or CD27\(^-\) mice could not be expanded in the absence of exogenous IL-2 (Fig. 7G). The addition of IL-2 resulted in a similar survival and proliferation of FACS-purified CD4\(^+\) T cells.
CD25\textsuperscript{hi} T cells from BL/6 and Cd27\textsuperscript{−/−} mice (Fig. 7I). Blocking IL-2 by neutralizing antibody completely blocked Treg formation (data not shown). In summary, these in vitro experiments confirmed a role of CD27 signaling on CD25\textsuperscript{+} Treg survival but not proliferation and underline the importance of IL-2 in Treg development and maintenance.

**Cd27\textsuperscript{−/−} and BL/6 Tregs are similarly capable to inhibit CD8\textsuperscript{+} T-cell expansion**

CD27 expression has been reported to correlate with the inhibitory capacity of Tregs (50). Therefore, we tested the capacity of titrated numbers of Cd27\textsuperscript{−/−} or BL/6 Tregs to inhibit the proliferation of CD8\textsuperscript{+} T cells in a \textsuperscript{3}H-Thymidine incorporation assay FACS-sorted CD4\textsuperscript{+}CD25\textsuperscript{hi} T cells of Cd27\textsuperscript{−/−} and BL/6 mice similarly inhibited the expansion of CD8\textsuperscript{+} responder T cells (Supplementary Fig. S3A and B). These experiments suggested that CD27 signaling mainly increases Treg numbers but not their T-cell suppressive capacity.

**Discussion**

CD27 signaling increases T-cell expansion and function and is of importance in the maintenance of T-cell memory (12, 51). This improves the control of acute viral infections and of tumors in certain model situations (15, 20, 22). However, it is well documented that the tumor microenvironment favors a chronic, smoldering inflammation that differs substantially from inflammatory processes in secondary lymphoid organs during an acute infection. This chronic inflammatory condition may promote tumor progression by generating an immunosuppressive environment (52). Especially Tregs account for substantial inhibition of antitumoral immunity by reducing effector cell expansion and function as well as the function of professional APCs (5).

In our model, the CD27–CD70 interaction promoted tumor growth. It is of importance to state that in mice transplanted with solid tumor fragments, significant expression of CD27 was only detected on TILs. Therefore, the CD27–CD70 interaction occurred mainly in the immunosuppressive tumor microenvironment. This is in contrast to previous studies (23–25) that analyzed the potential to provide maximal CD27 stimulation by the administration of stimulating anti-CD27 mAbs or by injecting tumors into Cd70 transgenic mice to improve tumor control. In these situations, CD27 ligation is not only provided in the immunosuppressive tumor microenvironment but in the entire lymphoid tissue, especially in the proinflammatory microenvironment of lymph nodes and spleen.

Similarly divergent observations have been made with other TNF-receptor superfamily members, such as CD137 (4-1BB). Agonistic anti-CD137 antibodies improved CD8\textsuperscript{+} T-cell responses and tumor control (29, 30). In contrast, tumor growth was reduced in Cd137\textsuperscript{−/−} mice (31). Therefore, as reported before (15), costimulatory molecules of the TNF receptor superfamily have different effects on the immune response depending on the signaling conditions.

We could show that CD25\textsuperscript{+} Treg frequencies were increased in TILs and tumor-draining lymph nodes of BL/6 versus Cd27\textsuperscript{−/−} mice. In addition to classical CD4\textsuperscript{+}CD25\textsuperscript{+}FoxP3\textsuperscript{+} Tregs, CD4\textsuperscript{+}CD25\textsuperscript{−}FoxP3\textsuperscript{+} Tregs exist in the tumor environment and may contribute to immunosuppression. However, CD27 signaling only increased the frequency of CD25\textsuperscript{+} Tregs in tumors and tumor-draining lymph nodes of BL/6 mice, suggesting that in the tumor microenvironment, CD25\textsuperscript{+} Tregs are less dependent on CD27 signaling. Our depletion and adoptive transfer experiments clearly indicate that CD25\textsuperscript{+} Tregs are responsible for the increased tumor growth.

The adoptive transfer of purified Cd27-competent CD25\textsuperscript{+} Tregs to Cd27\textsuperscript{−/−} recipients suggests a Treg intrinsic effect of CD27 signaling on cell survival but not proliferation. In addition, CD25\textsuperscript{+} Tregs constitutively express high levels of the IL-2Rα subunit (CD25), and the IL-2 receptor pathway is crucial for Treg survival (50). Our in vitro experiments show a CD27-dependent accumulation of CD25\textsuperscript{+} Tregs because of an increase in IL-2 produced by non-Treg CD4\textsuperscript{+} T cells. Therefore, the accumulation of CD25\textsuperscript{+} Tregs in tumors of Cd27\textsuperscript{−/−} mice is most likely a consequence of both, direct CD27 signaling on Tregs and also on CD4\textsuperscript{+} Teffs leading to an increase in IL-2 production. The effect was similar on Helios\textsuperscript{+} nTregs as well as of Helios\textsuperscript{−} iTregs.

CD27 signaling increases cell survival of both Teffs and Tregs. The effect on tumor growth depends on the relative contribution of Teffs versus Tregs. In our model, the ratio of Teffs/Tregs was decreased in solid tumors of BL/6 compared with Cd27\textsuperscript{−/−} mice. In addition, T-cell function after in vitro restimulation and antigen-specific CTL responses in vivo were suppressed in solid tumor-bearing BL/6 but not Cd27\textsuperscript{−/−} mice. Therefore, at least part of the increased tumor growth in BL/6 mice may be consequent to a Treg-mediated reduced CD8\textsuperscript{+} T-cell responses. Indeed, we showed before that CD8\textsuperscript{+} T cells are the main effector mechanism in control of the tumors used in our study (35). Besides suppression of the adaptive antitumoral immune response, Tregs also favor tumor progression via modulation of innate immunity. For example, Tregs are able to skew monocyte differentiation toward alternatively activated macrophages (M2 type; ref. 53) that are known to support tumor angiogenesis (54). A reduction of Tregs in the absence of CD27 may lead to a shift in monocyte differentiation from protumoral M2 to antitumoral M1 macrophages. Indeed, IL-1α and Nos2, both markers of antitumoral M1 macrophages (55), were expressed at higher levels in tumors of Cd27\textsuperscript{−/−} than BL/6 mice.

Recently, a role for the Cd27–CD70 interaction in the induction of Tregs has been suggested for non-Hodgkin B cell lymphoma and for chronic lymphocytic leukemia (17, 18). CD70\textsuperscript{+}, but not CD70\textsuperscript{−}, lymphoma cells contributed to the activation-induced FoxP3 expression in intratumoral CD4\textsuperscript{+} CD25\textsuperscript{+} T cells in vitro. In contrast, we did not observe an effect of CD27 signaling on the frequency of iTregs in TILs or tumor-draining lymph nodes. Of note, the lymphoma cells that were used in these studies express CD70 directly, whereas in our tumor models CD70 was mainly expressed on tumor-infiltrating T cells, and none of our tumor cell lines expressed CD70 (data not shown).

Previous studies have shown that CD27 expression on human CD4\textsuperscript{+}CD25\textsuperscript{+} Tregs positively correlates with their suppressive activity in vitro and with the expression of FoxP3...
The reduced CD27 expression on intratumoral Tregs in our experiments, though, was reversible upon blocking CD70. In addition, we did not observe impaired CD8+ T-cell suppression by CD27- Tregs in vitro; indicating that Treg function on CD8+ T-cell expansion is independent of CD27 signaling.

The role of Tregs in the suppression of antitumoral immune responses has been recognized 40 years ago and has been confirmed in many experimental tumor models and in cancer patients (5). Therefore, defining pathways involved in the formation, accumulation, and function of Tregs in solid tumors is of importance and might lead to novel therapeutic strategies. In combination with other therapeutic regimens, blocking CD27 signaling is a promising approach to reduce Treg formation in the tumor environment and to improve tumor control.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors’ Contributions
Conception and design: C. Claus, C. Riether, C. Schirch, A.F. Ochsenbein
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Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): C. Claus, C. Riether, C. Schirch, M.S. Matter, A.F. Ochsenbein
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Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): C. Claus
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