Combination of 4-1BB Agonist and PD-1 Antagonist Promotes Antitumor Effector/Memory CD8 T Cells in a Poorly Immunogenic Tumor Model

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Abstract

Immunotherapies targeting the programmed death 1 (PD-1) coinhibitory receptor have shown great promise for a subset of patients with cancer. However, robust and safe combination therapies are still needed to bring the benefit of cancer immunotherapy to broader patient populations. To search for an optimal strategy of combinatorial immunotherapy, we have compared the antitumor activity of the anti–4-1BB/anti–PD-1 combination with that of the anti–PD-1/anti–LAG-3 combination in the poorly immunogenic B16F10 melanoma model. Pronounced tumor inhibition occurred only in animals receiving anti–PD-1 and anti–4-1BB concomitantly, while combining anti–PD-1 with anti–LAG-3 led to a modest degree of tumor suppression. The activity of the anti–4-1BB/anti–PD-1 combination was dependent on IFNγ and CD8+ T cells. Both 4-1BB and PD-1 proteins were elevated on the surface of CD8+ T cells by anti–4-1BB/anti–PD-1 cotreatment. In the tumor microenvironment, an effective antitumor immune response was induced as indicated by the increased CD8+/Treg ratio and the enrichment of genes such as Cx3c, Ccl4, Ifng, and Eomes. In the spleen, the combination treatment shaped the immune system to an effector/memory phenotype and increased the overall activity of tumor-specific CD8+ CTLs, reflecting a long-lasting systemic antitumor response. Furthermore, combination treatment in C57BL/6 mice showed no additional safety signals, and only minimally increased severity of the known toxicity relative to 4-1BB agonist alone. Therefore, in the absence of any cancer vaccine, anti–4-1BB/anti–PD-1 combination therapy is sufficient to elicit a robust antitumor effector/memory T-cell response in an aggressive tumor model and is therefore a candidate for combination trials in patients.

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Introduction

Immunotherapy has emerged as a promising treatment for cancer in recent years, showing durable responses in subsets of patients, and thus was selected as the Breakthrough of Year 2013 by the journal Science (1). For example, ipilimumab, an anti-CTLA-4 agonist, reversed tumor growth in patients with metastatic melanoma. However, treatment-related grade 3 toxicity was seen in 10% to 15% of the patients (2). Targeting the programmed death 1 (PD-1) axis resulted in a higher response rate of up to 37%, whereas treatment-related grade ≥ 3 toxicity rates were 9% to 33% in the melanoma cohorts of multiple phase I trials (3). The combination of two checkpoint inhibitors, anti–CTLA-4 and anti–PD-1, increased the response rate up to 53% in a phase I trial with advanced melanoma; however, severe treatment-related adverse events (grade ≥ 3) were also reported in 53% of cases and treatment was discontinued in 21% of the patients (3, 4). Although these results are promising, it is clear that increasing the frequency of response while limiting toxicities will be crucial for the success of combinatorial cancer immunotherapy in a wider population of patients with cancer.

4-1BB (CD137 and TNFRSF9) belongs to the TNF receptor superfamily (TNFRSF), and its expression is generally activation dependent on a subset of immune cells, including T cells and natural killer (NK) cells (5). The ligand that stimulates 4-1BB (4-1BBL) is expressed on antigen-presenting cells, including dendritic cells (DC), B cells, and macrophages (6). Ligation of 4-1BB receptors elicits a variety of immune cell–specific biologic responses. For instance, 4-1BB activation promotes cell proliferation, survival, and cytokine production in T cells. In several tumor models, 4-1BB agonists have demonstrated antitumor efficacy (6, 7). Interestingly, in some autoimmune models, 4-1BB agonist also inhibited autoimmune reactions partly by antagonizing Th17 cell polarization (8, 9). This dual immunoregulatory activity of 4-1BB offers the possibility to enhance antitumor activity while simultaneously dampening autoimmune side effects associated with immunotherapy approaches.

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that break immune tolerance. Agonistic antibodies to 4-1BB (urelumab, BMS, and PF-05082566; Pfizer) are currently being tested in humans with advanced cancer, and PF-05082566 was found well tolerated with evidence of disease stabilization in multiple patients (10, 11).

PD-1 is an inhibitory receptor expressed on activated T cells as well as other immune cells, and its expression can be associated with T-cell exhaustion (12). PD-1 binds to two ligands, PD-L1 (B7-H1) and PD-L2 (B7-DC) that are often overexpressed on tumor cells. Such interactions deliver a negative signal to T cells to dampen the immune response. Antibody blockade of PD-1 was shown to enhance effector T-cell responses and induce T-cell-mediated tumor rejection in some mouse models (12). Additive or synergistic antitumor effects were also reported when PD-1 blockade was combined with other immune checkpoint blockade such as T-cell immunoglobulin mucin 3 (TIM-3) or lymphocyte activation gene 3 (LAG-3) in different tumor models (13, 14).

Anti–4-1BB agonist has been investigated extensively in preclinical studies to treat cancer when combined with other immunomodulatory antibodies. Synergistic antitumor effects have been observed for combinations of anti–4-1BB with anti–TIM-3 (15) or with anti–PD-1 (16, 17) in the ID8 murine ovarian cancer model. Studies on ID8 ovarian carcinoma also indicated that the anti–4-1BB/anti–PD-1 combination had moderate impact on survival, which could be further improved with additional vaccination (18). The anti–4-1BB/anti–CTLA-4 combination significantly delayed MC38 colon carcinoma growth over anti–4-1BB or anti–CTLA-4 alone; however, the same regimen failed to control B16F10 melanoma growth (19). The anti–4-1BB/anti–CTLA-4 combination also failed to prolong the survival of B16F10 tumor-bearing mice (20). Further studies showed that active vaccination was required for the anti–4-1BB/anti–CTLA-4 combination to effectively control the growth of B16-BL6 melanoma (21). These studies suggested that not all combinations are therapeutically equivalent and different models might respond to treatment differently. Here, we report that the anti–4-1BB/anti–PD-1 combination is more efficacious than that of anti–PD-1/anti–LAG-3 in suppressing B16F10 melanoma growth without adjuvant or vaccination. We investigated the cellular mechanism underlying this synergy. Finally, we showed that the combination was well tolerated in naïve or tumor-bearing mice, indicative of a potential therapeutic index for the combination.

Materials and Methods

Mice

Six- to 8-week-old female C57BL/6 mice and IFNγ-deficient mice were purchased from The Jackson Laboratory. Mice were maintained and all animal experiments were conducted according to the protocols approved by the Institutional Animal Care and Use Committee of Rinat (South San Francisco) and World-Wide Research and Development (La Jolla), Pfizer Inc.

Cell lines

The B16F10 melanoma cell line was purchased from the ATCC in 2010. The MC38 colon carcinoma cell line was kindly provided by Dr. Antoni Ribas at UCLA (Los Angeles, CA) in 2011. Cells were cultured in DMEM medium supplemented with 10% FBS and 2 mmol/L glutamine, and IMPACT tested for pathogens at the Research Animal Diagnostic Laboratory. No other authentication assay was performed. Pathogen-free cells growing in an exponential growth phase were harvested and used for tumor inoculation.

Antibodies for immunotherapy and flow cytometry

Therapeutic rat anti-mouse 4-1BB mAb (clone MAB9371) was purchased from R&D systems. Rat anti-mouse PD-1 mAb (clone RMP1-14) and IgG2a isotype control were purchased from BioXcell. Rat anti-mouse LAG-3 mAb (clone eBioC9B7W) was purchased from eBioscience. mAbs used for cell-surface or intracellular stains were purchased from BD Biosciences or BioXcell. Rat anti-mouse PD-1 mAb (clone J43), rat anti-mouse CD4 (clone RM4-5), rat anti-mouse CD8α (clone 53-6.7), rat anti-mouse CD25 (clone PC61), hamster anti-mouse CD137 (4-1BB, clone 17B7), hamster anti-mouse CD279 (PD-1, clone J43), rat anti-mouse FoxP3 (clone FJK-16s), rat anti-mouse Eomes (clone, Dan11mag), hamster anti-mouse KLRC1 (clone 2F1), and rat anti-mouse NK-1.1 (clone PK136). Live cells were separated from dead cells using the LIVE/DEAD Fixable Blue Dead Cell Stain Kit (Invitrogen).

Immune-cell phenotyping using flow cytometry

Spleens from tumor-bearing mice were harvested and dissociated mechanically into single-cell suspension in ice-cold PBS. Splenocytes were treated with Red Blood Cell Lysing Buffer Hybrid Max (Sigma-Aldrich), washed twice with PBS, and resuspended in PBS supplemented with 2% FBS and 0.9% NaCl. An aliquot of approximately 1 × 10⁸ splenocytes was preincubated with 10 μg/mL of mouse BD Fc Block (BD Biosciences) for 10 minutes before phenotyping mAb cocktail was added to specifically stain immune cells.

Tumor-infiltrating lymphocytes (TIL) were prepared using the Mouse Tumor Dissociation Kit and the GentleMACS Dissociator according to the manufacturer’s instructions (Miltenyi Biotec). Cell-surface antigens were labeled by incubating cells at 4°C for 30 minutes. Intracellular staining was carried out using a FoxP3/Transcription Factor Staining Buffer set according to the manufacturer’s protocol (eBioscience). Flow-cytometry data were acquired using LSR Fortessa (BD Biosciences) and analyzed using FlowJo (TreeStar Inc.).

In vivo tumor efficacy studies

C57BL/6 mice were inoculated subcutaneously at the right flank with 1 × 10⁶ B16F10 or MC38 cells in 0.1 mL of serum-free DMEM medium or PBS. Treatment was started when tumors reached 50 to 154 mm³ in size. Antibodies to 4-1BB (1 mg/kg), PD-1 (10 mg/kg), and LAG-3 (10 mg/kg), alone or in combination, were administered twice i.p. 5 days apart. In the study of treating larger tumors (range of 126–350 mm³), antibodies were given four times i.p. 3 days apart. To treat IFNγ-deficient mice, antibodies were given three times 3 days apart. To deplete CD8+ T cells, anti-CD8 (53.5.8, BioXcell) was given as described previously (22). Briefly, depleting antibody (100 μg) was administrated 1 day before anti–4-1BB/anti–PD-1 administration and every 5 days thereafter for a total of three doses. Tumor size was measured in two dimensions using calipers, and the volume was expressed in mm³ using the following formula: \(V = 0.5 \times L \times W^2\), where \(L\) and \(W\) are the long and short diameters of the tumor, respectively.

Antigen-specific immune response assay

Frozen splenocytes from MC38 tumor-bearing mice after antibody treatment were thawed and rested for 12 hours. Viable
cells were plated at $1 \times 10^6$ per well in duplicate in the presence of 0.5 μg/ml of CD8-restricted MC38 immunodominant peptide KSPWFTIL (Proimmune) or the positive activation control ConA at 5 μg/ml (Sigma-Aldrich) for 48 hours. The assay was developed according to the manufacturer’s instructions and read on a CTA ELISpot reader followed by spot enumeration using Immunospot 5.0.3. The upper sensitivity limit of the assay was 500 spots. Samples with no detectable ConA response were removed from the analysis.

**Quantitative RT-PCR**

B16F10 or MC38 tumor samples (~2 mm3) were collected into RNAlater stabilization reagent at the end of efficacy studies. Tumor pieces were homogenized into RLT buffer containing 1% 2-mercaptoethanol using a Qiagen TissueLyser and 5-mm steel beads. RNA was isolated from the homogenate using RNAeasy mini spin columns, and quantified via UV absorbance using a Nanodrop 8000 spectrophotometer. Total RNA per sample (1 μg) was used as template to prepare cDNA used as template for TaqMan primer probe sets targeting mouse Cd8e, Cd8a, Ifng, Eomes, Pdk1, Cd274, Tnfrsf9, Cd4, Foxp3, Gapdh, and Actb. Samples were amplified in duplicate in 384-well plates using an Applied Biosystems Viia7 Real Time PCR system. Relative quantity (RQ) was calculated via the ΔΔCt method relative to the average of the PBS control group.

**Mouse toxicity study**

 naïve C57BL/6 (n = 5/group) were given a single subcutaneous administration of test articles or control (PBS) and clinical and anatomic pathology was analyzed 10 days later. At necropsy, the following tissues were collected for histology: cecum, colon, duodenum, epididymides, heart, ileum, jejunum, kidneys, liver, lung, spleen, pancreas, stomach, and testes. The testes and epididymides were preserved in modified Davidson’s solution, and all other tissues were fixed in 10% neutral-buffered formalin. All tissues were routinely processed, embedded in paraffin and sectioned, stained with hematoxylin and eosin (H&E), and analyzed by a board certified veterinary pathologist. In addition, blood and serum were collected for hematology using the Advia 2120 (Bayer) and clinical chemistry analysis using the Advia 1200 (Siemens).

Potential toxicity was also assessed in B16F10 tumor-bearing mice. Mice with average tumors of approximately 100 mm3 (n = 5/group) received a single s.c. dose of antibodies and clinical and anatomic pathology was analyzed 10 days later. Spleen and liver were processed and evaluated as described above for the tumor-free mice. Whole blood was analyzed for complete blood count and liver enzymes by the Diagnostic laboratory, Department of Comparative Medicine, Stanford University (Stanford, CA).

**Statistical analysis**

Results were expressed as mean ± SEM. Statistical analyses were performed using GraphPad Prism 6.0 one-way or two-way ANOVA to compare the differences among multiple groups. A P value of <0.05 was considered as significant difference.

**Results**

4-1BB activation and PD-1 blockade but not LAG-3 and PD-1 dual blockade resulted in synergistic antitumor effects in murine B16F10 melanoma

To evaluate the antitumor efficacy of combination immunotherapy against established B16F10 tumors, an anti–4-1BB dosing regimen was selected on the basis of prior studies that showed efficacy in the CT26 model (23) and anti–PD-1 and anti–LAG-3 dosing regimens as previously reported (14, 21). Consistent with published results, anti–4-1BB, anti–PD-1, or anti–LAG-3 alone did not consistently inhibit B16F10 tumor growth when treatments were started on tumors of 50 to 154 mm3 in size (Fig. 1A and B). Combining anti–PD-1 with anti–LAG-3 resulted in 54% of tumor growth inhibition (TGI) relative to the isotype control (P < 0.001), but no mice were tumor free. In contrast, when animals were concurrently administered anti–4-1BB and anti–PD-1 antibodies, a dramatic efficacy of 85% TGI relative to the isotype control (P < 0.0001) was observed and 7 of 10 treated animals were tumor free (Fig. 1A and B). Combinatory efficacy was reproducible in an independent study by different experimenters (Supplementary Fig. S1). Furthermore, significant TGI (51% relative to the control group; P < 0.0001) was observed for the anti–4-1BB/anti–PD-1 combination when treatment was applied to very large tumors (size between 126 and 350 mm3), whereas the anti–PD-1/anti–LAG-3 combination was ineffective (Fig. 1C).

Likewise, a robust antitumor effect of the anti–4-1BB/anti–PD-1 combination was observed in the MC38 colon cancer model (Fig. 1D). At the end of the study (day 21 after tumor implant), the TGI for the combination treatment was 63% relative to the PBS control (P < 0.0001). The suppression was also significant when compared with the single agent alone (P < 0.05 vs. anti–4-1BB alone and P < 0.001 vs. anti–PD-1 alone).

The efficacy of anti–4-1BB/anti–PD-1 combination was dependent on IFNγ and CD8+ T cells

Given the antitumor efficacy of anti–4-1BB/anti–PD-1 combination, it is important to understand how the synergy was achieved. First, we compared tumor growth in response to anti–4-1BB/anti–PD-1 combination in wild-type and IFNγ-deficient mice. The combination suppressed tumor growth in wild-type animals, whereas such an antitumor effect was completely abolished in the IFNγ-deficient mice (Fig. 2A). To determine the immune-cell subset that is required for the antitumor effect, we depleted CD8+ T cells in B16F10 tumor-bearing mice and compared tumor growth after treatment. In the absence of CD8+ T cells, combination treatment–related tumor suppression was completely abrogated (Fig. 2B).

Anti–4-1BB/anti–PD-1 combination increased the availability of target molecules for therapeutic antibodies on CD8+ T cells

To further understand the mechanisms underlying the synergistic effects achieved by the anti–4-1BB/anti–PD combination, we examined the expression of 4-1BB and PD-1 on CD8+ T cells in response to antibody treatment. Splenocytes or TILs from B16F10 tumor–bearing mice after treatment were isolated, immunostained, and analyzed by flow cytometry. A representative flow cytometric gating strategy is shown in Supplementary Fig. S2. The anti–PD-1 (J43) used for detection does not compete with the therapeutic anti–PD-1 (RMP1-14) for the binding to PD-1, as determined by BIACore analysis (data not shown). In PBS- and isotype-treated animals, PD-1 expression was barely detected (<1%) on splenic CD8+ T cells (Fig. 2C). Anti–PD-1 treatment did not affect its own expression or that of 4-1BB. However, anti–4-1BB treatment induced the expression of PD-1 on 34% of splenic CD8+ T cells when administered alone (P < 0.0001 vs. isotype control) and on 29% of CD8+ T cells when coadministered with...
anti–PD-1 (P < 0.001 vs. isotype control). Combination therapy also induced PD-1 expression on 74% of TIL CD8⁺ T cells (P < 0.001 vs. isotype control; Fig. 2D).

Therapeutic 4-1BB agonist relies on 4-1BB expressed on primed T cells for efficacy (24, 25). Anti–4-1BB treatment induced its own expression, with the cell-surface expression detectable on 15% of splenic CD8⁺ T cells in the anti–4-1BB–treated group and 10% of the combination treatment group, compared with 0.2% in PBS- or isotype-treated groups (P < 0.0001 anti–4-1BB treatment vs. isotype control and P < 0.01 combination treatment vs. isotype control; Fig. 2E). There was a trend that the combination treatment upregulated 4-1BB expression on TIL CD8⁺ T cells, although the increase was not statistically significant (Fig. 2F). These results indicated that more abundant targets were available for
approximately 30% of the CD8 + T cells is shown in E and F, respectively. Each symbol represents an individual animal within the same treatment group. **, P < 0.01; ***; P < 0.001; and ****, P < 0.0001, when comparing groups as indicated by the horizontal lines.

Figure 2.

CD8 + T cells were immunomodulated and required for the efficacy of anti–4-1BB/anti-PD-1 combination treatment. Wild-type C57BL/6 or IFN-γ-deficient mice were inoculated s.c. (day 0) with 1 × 10⁶ B16F10. Mice were randomized into groups of 10 animals per group with an average tumor volume of approximately 80 mm³. A, mice were randomized on day 8, and anti–4-1BB (1 mg/kg)/anti-PD-1 (10 mg/kg) mAbs were dosed on days 8, 11, and 14 (indicated by arrows). B, mice were randomized on day 10. Isotype control IgG (100 μg) or anti-CD8 mAb was administered i.p. on days 11, 16, and 21 (indicated by blue arrows). Anti-4-1BB (1 mg/kg)/anti-PD-1 (10 mg/kg) mAbs were dosed on days 12, 17, and 22 (indicated by black arrows). Tumor size was measured two to three times a week. Mean ± SEM of each treatment group is shown. C to F, spleens and tumor fragments from B16F10 tumor-bearing mice after antibody treatment (Fig. 3A and Supplementary Fig. S3) were harvested and disaggregated into a single-cell suspension. After immunostaining, cells were analyzed by flow cytometry for the expression of CD5, CD4, CD8, PD-1, and 4-1BB. The expression of PD-1 on splenic and TIL CD8 + T cells is shown in C and D, respectively. The expression of 4-1BB on splenic and TIL CD8 + T cells is shown in E and F, respectively. Each symbol represents an individual animal within the same treatment group. **, P < 0.01; ***; P < 0.001; and ****, P < 0.0001, when comparing groups as indicated by the horizontal lines.

therapeutic antibodies both in the tumor and in the spleen after combination treatment.

Anti–4-1BB/anti-PD-1 treatment promoted antitumor immune response in the tumor microenvironment

To provide further evidence of a localized antitumor immune response, TILs were isolated from B16F10 tumors 3 days after the second dose of antibodies and an immune-cell subset analysis was performed by flow cytometry. The combination treatment enriched CD8 + T cells with an 8-fold increase in the CD8 +/CD4 + ratio over the isotype group (P < 0.0001; Fig. 3A). Regulatory T-cell (Treg) abundance was not altered (Fig. 3B). However, the ratio of CD8 +/Treg was increased by 7-fold in response to the combination treatment (P < 0.0001; Fig. 3C). In agreement with published results [9], we observed the induction of KLRG1 on approximately 30% of the CD8 + T cells in the anti–4-1BB alone and combination groups (P < 0.001 vs. isotype; Fig. 3D).

In addition, we evaluated the genes associated with antitumor immune responses in B16F10 tumor samples by quantitative PCR. The RQ of each target gene was related to the average of the PBS control samples and calculated by the ΔΔCt method using GAPDH and actin housekeeping genes. Compared with the PBS group, combination treatment led to an enrichment of signals for Cd8a (P < 0.001), Ifng (P < 0.001), Eomes (P < 0.001), Tnfsf9 (P < 0.05), Pdcd1 (P = 0.0001), Cd274 (P < 0.001), and Fosp3 (P < 0.05; Fig. 4). No significant changes were noted for CD4 expression. The profile of mRNA enrichment observed here and in MC38 tumors (Supplementary Fig. S3) is largely congruent with the flow cytometric findings in the B16F10 tumors, supporting a strong enhancement of CD8 effector/memory cell phenotype induction by the anti–4-1BB/anti-PD-1 combination.

Anti–4-1BB/anti-PD-1 combination induced T-cell effector/memory differentiation

To explore modulation of the immune system systemically following anti–4-1BB/anti-PD-1 treatment, splenocytes were isolated from tumor-bearing mice and detailed phenotypic analysis of the immune cells was performed by flow cytometry. One of the characteristics of 4-1BB activation is to induce the expression of eomesodermin (Eomes), a transcription factor associated with T-cell effector/memory cell phenotype induction by the anti–4-1BB/anti-PD-1 combination.

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(PBS or isotype) did not express Eomes (<1%), whereas expression was increased to 2.8% of CD4⁺ T cells in the anti-4-1BB-treated group, and further increased to 8.3% of CD4⁺ T cells in the anti-4-1BB/anti-PD-1 combination group (P < 0.0001 vs. isotype group; Fig. 5B).

Memory is the hallmark of the acquired immune system. Thus, we characterized the memory phenotype of T cells at the end of a MC38 model (Supplementary Fig. S4).

To determine whether anti-4-1BB/anti-PD-1 treatment induced an antigen-specific immune response, we isolated splenocytes from MC38 tumor-bearing mice after treatment and stimulated with the CD8-restricted MC38 immunodominant peptide KSPWFTTL ex vivo. IFNγ production assayed by ELISpot was evaluated as a measurement of response. Anti-4-1BB treatment increased the number of IFNγ-producing cells (250 ± 36) compared with that of the PBS group (117 ± 28; P < 0.05; Fig. 6).

Anti-PD-1 treatment also increased IFNγ production (242 ± 46; P < 0.05 vs. PBS group). The combination of anti-4-1BB and anti-PD-1 further increased the numbers of peptide/tumor-specific T cells to 377 ± 24 and the increase was statistically significant as compared with those treated with PBS (P < 0.0001), anti-4-1BB alone (P < 0.05), or anti-PD-1 alone (P < 0.05). The data indicated that the combination elicited a greater antigen-specific CTL response than either single-agent alone.

Anti-4-1BB/anti-PD-1 combination immunotherapy resulted in moderate liver enzyme elevation in mice compared with anti-4-1BB alone.

To understand the safety profile of the anti-4-1BB/anti-PD-1 combination therapy, we tested these antibodies either within or above their respective therapeutic dose range in non-tumor-bearing mice. C57BL/6 mice were administered a single s.c. injection of PBS, anti-4-1BB alone (at 0.1, 1, or 5 mg/kg), anti-PD-1 alone (at 20 mg/kg), and three combination treatment groups consisting of 20 mg/kg anti-PD-1 with each of the three dose levels of anti-4-1BB listed above. Ten days after dosing, the study was terminated and tissue, blood, and serum collected for clinical and anatomic pathology assessment.

Of the clinical chemistry pathology measured, only those associated primarily with liver toxicity and certain peripheral blood subsets were significantly affected. The groups treated with 1 or 5 mg/kg anti-4-1BB alone demonstrated increases in alanine aminotransferase (ALT) of 6- (P < 0.01) and 5-fold (P < 0.05), respectively, compared with the PBS group (Fig. 7A). The
combination groups with anti–PD-1 had slightly greater increases in ALT of 10- (P < 0.0001) and 8-fold (P < 0.0001), respectively, compared with the PBS group. Glutamate dehydrogenase (GLDH) potentially offers differential diagnostic potential in the investigation of liver disease, particularly when interpreted in conjunction with other hepatic enzyme test results. It is more concentrated in the central areas of the liver lobules than in the periportal zones and is usually only released from necrotic cells due to its exclusive mitochondrial localization (27). The results of the GLDH measurements were similar to those of ALT, with increases in the 1 mg/kg and 5 mg/kg anti–4-1BB single-agent and combination groups of 4-fold (P < 0.001), 3-fold (P < 0.01), 6-fold (P < 0.0001), and 5-fold (P < 0.0001), respectively, relative to the PBS group (Fig. 7B). Although the difference between the combination and the corresponding anti–4-1BB–alone groups was statistically significant (Fig. 7A and B), the magnitude of difference was small (~50% increase in combination vs. single agent for either ALT or GLDH). No effects on ALT or GLDH were observed in the other groups.

Aspartate aminotransferase (AST) followed a similar pattern as the other liver enzyme markers (Fig. 7C).

**Figure 4.** Anti–4-1BB/PD-1 combination enriched genes associated with antitumor immune response. B16F10 tumor samples were collected after antibody treatment and total RNA was isolated. Gene expression from each treatment group was calculated using real-time PCR analysis with Gapdh and Actb as the endogenous controls. Column dot plots are shown for the genes of Cd3e, Cd8a, Ifng, Eomes, Pdcd1, Cd274, Tnfrsf9, Cd4, and Foxp3. Except for 4-1BB expression, the relative expression for all other genes is shown in log scale due to the great variance within the group. Each symbol represents an individual animal within the same treatment group. *, P < 0.05; **, P < 0.01; and ***, P < 0.001, when comparing groups as indicated by the horizontal lines.
Several hematology parameters were affected by the study treatments. There were decreases in platelet counts in the 1 and 5 mg/kg anti–4-1BB alone (\( P < 0.001 \) and \( P < 0.0001 \), respectively, vs. PBS) and combination with anti–PD-1 groups (\( P < 0.0001 \) vs. PBS; Fig. 7D). Although there was a statistically significant decrease in platelets in the combination groups relative to the corresponding anti–4-1BB single-agent groups (\( P < 0.05 \) for the 1 mg/kg anti–4-1BB/anti–PD-1 vs. 1 mg/kg anti–4-1BB alone, and \( P < 0.01 \) for 5 mg/kg anti–4-1BB/anti–PD-1 vs. 5 mg/kg anti–4-1BB alone), the magnitude of the additional increase was quite modest (roughly 15%). No effects on platelets were observed in the other treatment groups. The 5-mg/kg anti–4-1BB alone and anti–PD-1 combination at 1 and 5 mg/kg showed dramatic lymphocyte decreases (~75%, \( P < 0.001 \) vs. PBS), whereas the decrease in other groups ranged from 18% to 35% relative to the PBS group (Fig. 7E). Not only is the difference between the combination at 1 mg/kg anti–4-1BB and the 1 mg/kg anti–4-1BB alone statistically significant (\( P < 0.0001 \)), but further decrease of lymphocyte count by 55% (combination vs. 4-1BB alone) may be biologically significant. Only the 5-mg/kg anti–4-1BB–alone group showed a statistically significant decrease in neutrophils (\( P < 0.001 \) vs. PBS), and addition of anti–PD-1 appeared to block the effects of anti–4-1BB on neutrophil decrease (Fig. 7F). Total white blood cells were also affected by the treatments, but this change was dominated by the lymphocyte effects (data not shown).

Among the tissues examined histopathologically, treatment-related findings were only observed in the liver and spleen. In the liver (Supplementary Table S1A), treatment with anti–4-1BB at 1 and 5 mg/kg led to an increased incidence and severity of mixed cell infiltration and caused single-cell necrosis that ranged from minimal to moderate in severity. Addition of anti–PD-1 did not cause additional effects. Mixed cell infiltration was present with minimal severity, and single-cell necrosis was absent in all other treatment groups. In the spleen (Supplementary Table S1B), the incidence of lymphoid hyperplasia was increased in all antibody-treated groups. The severity increased from minimal in the PBS group to minimal to mild in all other groups except the 5-mg/kg anti–4-1BB/anti–PD-1 combination group, in which it was mild to moderate. The incidence and severity of extramedullary hematopoiesis were

**Figure 5.** Anti–4-1BB/PD-1 combination induced T-cell effector/memory differentiation. At the end of efficacy studies, spleens from B16F10 tumor–bearing mice were harvested and disaggregated into a single-cell suspension. After surface staining, cells were fixed and permeabilized for intracellular marker staining, and finally analyzed by flow cytometry for the expression of CD3, CD4, CD8, CD44, CD62L, and Eomes. The expression of Eomes in CD8\(^+\) and CD4\(^+\) T cells is shown in A and B, respectively. The percentages of central memory (CD44~CD62L~) and effector memory (CD44~CD62L+) CD8\(^+\) T cells are shown in C and D, respectively. Each symbol represents an individual animal within the same treatment group. **, \( P < 0.01 \); ***, \( P < 0.001 \); and ****, \( P < 0.0001 \), versus PBS or rat IgG2a.
Anti-4-1BB/PD-1 combination enhanced antigen-specific T-cell response. At the end of the efficacy study as described in Fig 1D, splenocytes were isolated and fresh frozen. Viable cells after thaw were rested for 12 hours and challenged with CD8-restricted MC38 immunodominant peptide KSPWFTTL ex vivo. IFNγ production was assessed by ELISpot. The number of spots, an indication of the number of IFNγ-producing cells, was reported. Each symbol represents an individual animal within the same treatment group. *P < 0.05 and ****P < 0.0001, when comparing groups as indicated by the horizontal lines.

increased in the 1- and 5-mg/kg anti-4-1BB combination groups, but not significantly altered in all other groups.

To assess potential toxicity in tumor-bearing animals, mice with established B16F10 tumors were treated with isotype (20 mg/kg), anti-4-1BB (1 mg/kg), anti-PD-1 (20 mg/kg), or the anti–4-1BB (1 mg/kg)/anti–PD-1 (20 mg/kg) combination. Antibody treatment, tissue collection, and data analysis were performed in a similar manner to those for tumor-free mice. There were no statistically significant changes in the absolute number of peripheral platelets, lymphocytes, and neutrophils among all groups. ALT was elevated in the combination group (P < 0.05 vs. isotype; Supplementary Fig S5). However, the AST levels were highly variable and greatest in the control group, which prevented us from evaluating its changes in response to treatments (data not shown). The histopathology of the spleen and liver after treatments displayed similar patterns as described in the tumor-free mice (data not shown).

Discussion

T-cell activation is regulated through effective coordination of costimulatory signals provided by cell-surface coregulatory receptors in addition to the antigen-specific TCR signaling (28). Agonistic antibodies directed against activating receptors and blocking antibodies to inhibitory receptors may enhance T-cell stimulation and are under active investigation for cancer therapy (7, 29). Blockade of the suppressive signals via anti–CTLA-4, anti–PD-1, and anti–PD-L1 agents has shown clinical benefit (3). Dual blockade of immunosuppressive pathways via anti–CTLA-4 and anti–PD-1 or via anti–PD-1 and anti–LAG-3 has entered clinical trials (3, 4). Modulation of stimulatory signals by 4-1BB, OX40, or GITR pathway is still in the early stages of clinical evaluation (30). In preclinical studies, combinations of immunomodulators as well as in combination with chemotherapy, targeted agents, vaccination or irradiation, have been evaluated in various models (15–18, 31–33). Here, we show that the combination of anti–4-1BB with anti–PD-1 synergistically inhibited the growth of B16F10 melanoma and MC38 colon carcinoma in syngeneic C57BL/6 mice, and that the combination was reasonably well tolerated, supporting the clinical development of an anti–4-1BB/anti–PD-1 combination immunotherapy.

Anti–4-1BB therapy demonstrated promising but limited clinical benefits in early clinical trials (34). Potential mechanisms of 4-1BB agonistic antibody–mediated tumor regressions include breaking of immunologic ignorance and prevention of T-cell deletion and anergy (5, 35, 36). Given that 4-1BB is specifically expressed on antigen-experienced T cells (7, 37), the observed increase in 4-1BB+ T cells may implicate an enhanced immune response to tumor challenge in anti–4-1BB–treated animals. We and others have shown that 4-1BB activation upregulated PD-1 expression on effector T cells, and the PD-1/PD-L1 axis has been reported to confer tumor resistance to 4-1BB costimulatory therapy (38). In addition, PD-L1 was induced in anti–4-1BB/anti–PD-1–treated tumors in vivo (Fig. 4 and Supplementary Fig S3) as well as IFNγ-treated cells in vitro (data not shown and ref. 38). Therefore, cotreatment of anti–4-1BB with anti–PD-1 represents a mechanistically rational combination to maximize the antitumor potential. This hypothesis is further supported by directly comparing different combinations in the same model. Here, we show that anti–4-1BB/anti–PD-1 combination was more potent than anti–PD-1/anti–LAG-3 combination in suppression of both small and large B16F10 tumors (Fig. 1). The combination of anti–4-1BB with anti–PD-1 was also more efficacious than dual combinations of anti–CTLA-4/anti–PD-1 and anti–4-1BB/anti–CTLA-4 in the ID8 model (16, 17). Therefore, in at least two of the most aggressive and poorly immunogenic tumor models (ID8 and B16), anti–4-1BB/anti–PD-1 combination appears to exhibit the strongest antitumor effect among the dual-agent combinations of several widely studied pathways (CTLA-4, PD-1, LAG-3, and 4-1BB).

Previous work has implicated that the T-box transcription factors Eomes and T-bet act as master regulators in CD8+ T-cell effector and memory differentiation and function (26, 39–41). Recently, Eomes has been shown to be required for the antitumor immunity mediated by 4-1BB agonist immunotherapy (42). 4-1BB activation was able to induce Eomes expression in tumor-infiltrating T cells without affecting T-bet expression, and the high expression of Eomes promoted the development of novel KLRG1+Eomes+ T-cell subsets characterized by enhanced, multipotent cytotoxicity (9). We also show here that 4-1BB stimulation increased Eomes expression in splenic CD8+ T cells and to a lesser degree on CD4+ T cells, whereas anti–PD-1 alone had no effect. Consistent with the role of Eomes in T-cell polarization, we found the accumulation of CD8+ effector and central memory T cells in the spleen of tumor-bearing mice after anti–4-1BB/anti–PD-1 treatment. Furthermore, these CD8+ T cells were functionally active, and produced large amounts of IFNγ upon tumor antigen-specific restimulation ex vivo. The loss of antitumor protection when CD8+ T cells were depleted further...
supported their pivotal role in antitumor immunity. In agreement with the essential role of IFNγ for 4-1BB agonistic activity (43), the combination also required IFNγ as the antitumor activity was abolished in IFNγ-deficient mice (Fig. 2A). Durable efficacy is likely to occur given that the combination treatment induced tumor antigen-specific and memory phenotype T cells. In the tumors, we observed signals associated with antitumor activity, such as the increased CD8⁺/Treg ratio and induced KLRG1 on CD8⁺ T cells. By gene-expression analysis, we were able to demonstrate that an active antitumor immune response was induced with increases in the expression of mRNA encoding Cd8a, Ifng, and Eomes. Unlike published data (15, 17), our findings did not show changes in myeloid-derived suppressor cells in response to treatment (data not shown).

Finally, the combination of anti-4-1BB and anti–PD-1 antibodies was well tolerated in mice. There were no clinical signs of toxicity or mortalities from either of the single agents or the combination, and anti–PD-1 alone caused only minimal decreases in peripheral lymphocytes and splenic lymphoid hyperplasia. The effects in the combination arms, which included liver mixed cell infiltration and single-cell necrosis with associated increases in plasma liver enzymes, splenic lymphoid hyperplasia and extramedullary hematopoiesis, and decreases in peripheral white blood cell subsets and platelets, were driven predominantly by the anti–4-1BB antibody. These findings were observed with similar severity in the anti–4-1BB–alone treatment arms and have been described previously with another mouse-reactive anti–4-1BB (44). The human relevance of the mouse findings is apparent in a previous report listing neutropenia and transaminitis as two of the most common adverse events in a phase I trial of a 4-1BB agonist antibody in patients with cancer (45). The most notable combination effect in the mouse study was the synergistic decrease in peripheral lymphocytes observed at the 1-mg/kg dose of anti–4-1BB in combination with anti–PD-1. This observation likely represents the desired combined pharmacologic effect of lymphocyte activation and tissue sequestration.

Taken together, the pharmacologic effects of the anti–4-1BB/anti–PD-1 combination demonstrate a much greater synergy with respect to the antitumor efficacy than toxicity in syngeneic models with an intact immune system. This preclinical study provides a strong rationale for developing anti–4-1BB/anti–PD-1 combination immunotherapy in human patients. A study of 4-1BB agonist PF-05082566 plus the PD-1 inhibitor MK-3475 in patients with solid tumors (B1641003/KEYNOTE-0036) has been proposed.
Conception and design: McDermott DF, Atkins MB. PD-1 as a potential target in cancer therapy.

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Chen, L.-F. Lee, T.S. Fisher, M. Elliott, W. Evering, K. Logronio, G.H. Tu, K. Tsaparikos, H. Wang, C. Ying, M. Xiong

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Combination of 4-1BB Agonist and PD-1 Antagonist Promotes Antitumor Effector/Memory CD8 T Cells in a Poorly Immunogenic Tumor Model

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