Anti-CD20 Antibody Promotes Cancer Escape via Enrichment of Tumor-Evoked Regulatory B Cells Expressing Low Levels of CD20 and CD137L

Monica Bodogai1, Catalina Lee Chang1, Katarzyna Wejksza1, Jinping Lai4, Maria Merino4, Robert P. Wersto3, Ronald E. Gress5, Andrew C. Chan6, Charles Hesdorffer2, and Arya Biragyn1

Abstract

The possible therapeutic benefits of B-cell depletion in combating tumoral immune escape have been debated. In support of this concept, metastasis of highly aggressive 4T1 breast cancer cells in mice can be abrogated by inactivation of tumor-evoked regulatory B cells (tBreg). Here, we report the unexpected finding that B-cell depletion by CD20 antibody will greatly enhance cancer progression and metastasis. Both murine and human tBregs express low levels of CD20 and, as such, anti-CD20 mostly enriches for these cells. In the 4T1 model of murine breast cancer, this effect of enriching for tBregs suggests that B-cell depletion by anti-CD20 may not be beneficial at all in some cancers. In contrast, we show that in vivo–targeted stimulation of B cells with CXCL13-coupled CpG oligonucleotides (CpG-ODN) can block cancer metastasis by inhibiting CD20low tBregs. Mechanistic investigations suggested that CpG-ODN upregulates low surface levels of 4-IBBL on tBregs to elicit granzyme B–expressing cytolytic CD8+ T cells, offering some explanatory power for the effect. These findings underscore the immunotherapeutic importance of tBreg inactivation as a strategy to enhance cancer therapy by targeting both the regulatory and activating arms of the immune system in vivo. Cancer Res; 73(7); 1–12. ©2013 AACR.

Introduction

Cancer metastasis involves an active hijacking of regulatory immune cells to suppress antitumor effector immune responses. As a result, the increase in myeloid and myeloid-derived suppressor cells (MSC and MDSC) and regulatory T cells (Treg) is often a sign of poor disease outcome in both mice and humans with cancer (1–3). However, the role of B cells, in particular regulatory B cells (Breg), in this process remains poorly understood and is still debatable, although the existence of suppressive B cells has been known for more than 30 years. Protection against autoimmune diseases in mice and humans is shown to be mediated by unique subsets of Bregs [the definition first used by Mizoguchi and colleagues (4)], such as murine interleukin (IL)-10–producing B10 and B1b Bregs (4, 5); human IL-10–producing memory CD24HighCD27− B cells (6), CD25HighCD27−HighCD86HighCD11cHighCD1dHigh B cells (7), and CD19+CD24HighCD238High B cells (8). As such, the inactivation of B cells or Bregs exacerbates ulcerative colitis in patients with non-Hodgkin’s lymphoma, colitis, and Graves disease and increases the incidence of psoriasis in patients with psoriatic arthropathy (9–11). B cells also facilitate carcinogenesis of methylcholanthrene-induced (12, 13) and transplanted tumors (14). In humans with metastatic ovarian carcinoma, infiltration of CD19+ B cells was associated with worse disease outcome (15). Unless replenished with B220+ B cells, orthotopic tumors progress poorly in syngeneic mice deficient in B cells (16, 17). B cells promote a tumor-suppressive milieu through the production of immunoglobulin or and immunomodulatory factors and cytokines or inducing the generation of Tregs (18). For example, B-cell–expressed lymphotixin-α/β was linked with the androgen-independent growth of prostate cancer cells (19); and B-cell–expressed immunoglobulin was linked with inflammation in premalignant tissues and growth of HPV16–induced tumors (20). B cells can also mediate T helper 2 cell (TH2) polarization and inhibition of antitumor cytotoxic activity of CD8+ T and natural killer (NK) cells by producing IL-10 (21) and TNF-α (22).

To the best of our knowledge, only 2 clearly defined examples of cancer escape-promoting Bregs are reported. First, B10 cells reduce the therapeutic efficacy of anti-CD20 antibody against lymphoma by inhibiting monocyte activity and surface expression of FcγR in an IL-10–dependent fashion (23). Second, we recently found that 4T1 carcinoma cells actively convert normal B cells into TGF-β–producing Bregs, designated tumor-evoked Bregs (tBregs) to successfully metastasize (17). tBregs differ from the immune tolerance-inducing IL-10–producing Bregs and B cells (24–26). Phenotypically, they are poorly proliferative B2-like cells (IgDHigh) that express constitutively active Stat3 and surface markers CD25HighB7-.
tBregs facilitate lung metastasis by converting non-Treg CD4+ T cells into metastasis-promoting FoxP3+ Tregs using TGF-β (17), which in turn inactivate antitumor NK cells and protect metastasizing cancer cells (27). Because tBreg-like cells can be readily generated by treating normal human donor B cells ex vivo with conditioned media of various human cancer lines (17), human cancer metastasis may also use a similar mechanism. The clinical implication of tBregs is that, as long as cancer persists, it will induce tBregs, and thereby initiate the chain of suppressive events. Thus, strategies that abrogate any step of this process are expected to inhibit cancer escape and metastasis. Indeed, the depletion of Tregs and tBregs with PC61 anti-CD25 antibody successfully abrogates 4T1 breast cancer lung metastasis (17, 27). Despite these data, anti-CD20 antibody-mediated B-cell depletion instead increased the tumor burden in the lungs of mice intravenously injected with B16-F10 melanoma (28). Similarly, depletion of B cells with rituximab (anti-CD20 antibody for treatment of human B-CLL) treated with rituximab (anti-CD20 antibody for treatment of humans with B-cell malignancies) did not provide clinical benefit in patients with renal cell carcinoma and melanoma (29), calling into question the importance of B cells or Bregs in cancer escape.

To reconcile this discrepancy, we hypothesized that the results could be explained if the anti-CD20 antibody treatment only depleted "normal functioning" or "immune stimulatory" CD20+ B cells that participate in induction of adaptive anti-tumor immune responses (30), promoting favorable disease outcome in some patients with cancer (31). Indeed, our modeling study in mice with 4T1.2 breast cancer and analyses of B cells from patients with B-cell chronic lymphocytic leukemia (B-CLL) treated with rituximab indicate that anti-CD20 antibody enriches for 4-1BBL+CD20-CD19- tBregs by depleting stimulatory B cells. As a result, this exacerbates both progression of primary tumor in the mammary gland and lung metastasis, suggesting that anti-CD20 antibody-mediated depletion of B cells may not provide therapeutic benefits for some cancers. To circumvent this problem, we devised a simple CXCL13-based strategy that blocks the generation of tBregs in vivo and activates B cells by delivering stimulatory CpG oligonucleotides (CpG-ODN) via their CXCR5 receptor. We found that CpG-ODN not only inhibits the activity of tBregs, but also enhances surface expression of 4-1BBL needed for the stimulation of T-cell responses.

Materials and Methods

Female BALB/c, C57BL/6 mice, and μMT mice with mature B-cell deficiency (B6.129P2-Igh-Ifm1Cgn/J) were from the Jackson Laboratory. Jh B-cell knockout mice were from Taconic Farms Inc., The T-cell receptor (TCR) transgenic pmel-1 (Vα1Vβ13 T-cell receptor for H-2Db-restricted mouse and human gp100 epitope) mice have been described previously (32). B16-F10 (CRL-6475), MDA-MB-231 (HTB-26), SW480 (CLL-228), and MCF7 (HTB-22) cells were purchased from the American Type Culture Collection. 4T1.2 cells, a subset of 4T1 cells, were a gift from Dr. Robin L. Anderson (Peter McCallum Cancer Center, East Melbourne, Australia). 938-mel was a gift from Dr. Ashani Weeraratna (Wistar Institute, Philadelphia, PA). Animal care was provided in accordance with the procedures outlined in the Guide for the Care and Use of Laboratory Animals (NIH Publication No. 86–23, 1985). The experiments were carried out using 4- to 8-week-old female mice in a pathogen-free environment at the National Institute on Aging Animal Facility (Baltimore, MD). 4T1.2 cells (5 × 10^5 to 1 × 10^6). Mice were subcutaneously challenged into the fourth mammary gland of mice and tumor progression and lung metastasis was assessed as previously described (27). B cells were depleted by 2 to 4 intraperitoneal injections of anti-CD20 antibody (250 μg/mouse, clone 5D2, Genentech, Inc.), as indicated in the figure legends. Control immunoglobulin G (IgG) was from Sigma and in-house purified IgG2a from murine A20 lymphoma.

Antibodies used for fluorescence-activated cell sorting (FACS) staining, such as anti-mouse and human FoxP3, anti-mouse CD20 were from eBioscience, whereas anti-mouse and human CD19, CD81, CD25, 4-1BBL, CD8, CD3, Ki67, IFN-γ, and Fc block were from Biolegend. Anti-immunoglobulin M (IgM) was from Jackson ImmunoResearch Laboratories, Inc., Toll-like receptor (TLR) ligands from Invivogen, and phosphorothioated CpG-ODN, such as ODN1826 and control ODN1826, were from Sigma Genosys. BLC-arp (Biragyn and colleagues, US patent pending), murine CXCL13 containing a ssDNA/RNA–binding domain (RBD) portion of the capsid antigen of hepatitis B virus–encoding sequence, were constructed by replacing the PE38 fragment from chemotoxin constructs described elsewhere (33). BLC-arp was purified (>95% purity, verified by Coomassie Blue staining and Western blotting) from yeast supernatant using SP-Sepharose Fast Flow and Heparin-HP trap columns (Invitrogen) on Fast performance liquid chromatography (Bio-Rad BioLogic Duolow).

Human peripheral blood cell isolation

Human peripheral blood was collected by the Health Aphe¬sis Unit and the Clinical Core Laboratory, the National Institute on Aging, under Human Subject Protocol # 2003054 and Tissue Procurement Protocol # 2003-071. Peripheral blood mononuclear cells were isolated using Ficoll-Paque (GE Healthcare) density gradient separation according to the manufacturer's instruction. B cells were isolated using B-cell–negative isolation (Miltenyi Biotec). CD3+ cells were isolated using the T-cell enrichment columns from R&D Systems.

In vitro tBreg and T-cell suppression assays

In vitro tBreg and T-cell suppression assays were conducted as previously described (17). In brief, tBregs were generated from murine splenic B cells (>95% purity, isolated by negative selection using the RoboSep system, StemCell Technologies) or human peripheral blood B cells by incubating for 2 days in 50% conditioned medium of 4T1-PE cells (CM-PE), or MDA-MB-231, SW480, MCF7, or 938-mel cells in cRPMI ( RPMI-1640 with 10% heat-inactivated FBS, 10 mmol/L HEPES, 1 mmol/L sodium pyruvate, 0.01% 2-mercaptoethanol, 2 mmol/L L-glutamine, 100 U/mL penicillin, and 100 μg/mL streptomycin) at a 37°C in humidified atmosphere with 5% CO2. Control B cells were treated with 100 ng/mL of recombinant mouse BAFF (B-cell activating factor, BlyS; R&D) in cRPMI. To assess
In vivo–generated tBregs in tumor-bearing mice, B cells were magnetically isolated from lymph nodes or spleens of tumor-bearing or naïve mice using anti-CD19-FITC antibody (Biolegend) and anti-fluorescein isothiocyanate (FITC) MicroBeads (Miltenyi Biotec). To test the suppressive activity of B cells, carboxylfluorescein succinimidyl ester (CFSE) or eFluor670 (eBioscience)–labeled splenic CD3+ T cells were with B cells for 5 days in the presence of 1.5 to 3 μg/mL of soluble anti-mouse CD3 antibody (BD Biosciences) or anti-CD3/28–coated beads (Invitrogen). Decrease in dye expression within T cells for 5 days in the presence of 1.5 to 3 μg/mL of soluble anti-mouse CD3 antibody (BD Biosciences) or anti-CD3/28–coated beads (Invitrogen). Decrease in dye expression within T cells correlates with their proliferation. The suppressive activity was also tested by determining the Ki67 expression in target CD3+ T cells. For granzyme B induction in CD8+ T cells by Cpg-treated Bregs, we followed the same protocol as for the suppression assay.

To assess antigen-specific expansion of effector CD8+ cells in mice with B16-F10 melanoma, draining lymph node cells and splenocytes were stimulated ex vivo for 5 to 7 days with 5 μg melanoma gp10025–32 peptide and 20 U/mL IL-2 and stained for CD8, Ki67, and GrzB.

In vivo manipulations

Animal care was provided in accordance with the procedures outlined in the Guide for the Care and Use of Laboratory Animals (NIH Publication No. 85–23, 1985). The experiments were carried out using 4- to 8-week-old female mice in a pathogen-free environment at the National Institute on Aging Animal Facility. 4T1.2 cells (5 x 105) were subcutaneously challenged into the fourth mammary gland of BALB/c and Jh knockout mice, and tumor progression and lung metastasis was assessed as previously described (27). B cells were depleted by intraperitoneal injections of anti-CD20 antibody (250 μg/mouse, 2–4 times). B16-F10 cells (1 x 105) were subcutaneously injected into C57BL/6, μMT, or TCR transgenic pmel-1 mice and tumor progression was measured every other day as previously described (34). Ex vivo–generated tBregs or B cells (5 x 105) were injected intravenously into congenic mice 1 day before and 5 days after tumor challenge.

Statistical analysis

The results are presented as the mean of triplicates ± SEM of at least 3 experiments. Differences were tested using Student t test and a two-sided P value less than 0.05 was considered statistically significant.

Results

Cancer metastasis is enhanced by treatment with anti-CD20 antibody

Because tBregs actively facilitate lung metastasis by suppressing antitumor immune responses (17), the absence of tBregs is expected to hamper this process and inhibit cancer progression. Indeed, unlike wild-type (WT) BALB/c mice, which had readily progressing 4T1.2 breast cancer cells in the mammary gland (primary site of challenge) and metastasis in the lungs (Fig. 1A and B), congenic Jh knockout mice deficient in B cells (due to a deletion in the J segment of the immunoglobulin heavy chain locus) poorly supported primary tumor growth (Fig. 1A) and lung metastasis (Fig. 1B). These responses in Jh knockout mice were completely reversed by adoptive transfer of tBregs from WT mice (Fig. 1A and B), confirming the importance of tBregs in cancer escape (17). Thus, cancer progression and escape may also be therapeutically controlled by inactivation of B cells. To test this idea, we depleted B cells with anti-CD20 antibody in WT BALB/c mice before the challenge with 4T1.2 cancer cells. As shown in Fig. 1C, B-cell–depleted mice also abrogated lung metastasis of 4T1.2 cells, suggesting that this therapy successfully used in humans to combat B-cell malignancies may also be used to treat metastasis in solid tumors. However, when we tested the therapeutic efficacy of anti-CD20 antibody in mice with established 4T1.2 cancer, all mice surprisingly succumbed to massive cancer growth and metastasis (Fig. 1D and E). In fact, compared with control Ig-treated tumor-bearing mice (Fig. 1D and E), the anti-CD20 antibody treatment of mice with already established cancer further and significantly enhanced tumor growth (Fig. 1D) and metastasis in the lungs (Fig. 1C).

This surprising result was not due to inability or poor efficiency of B-cell depletion, as every mouse treated with anti-CD20 antibody had drastically reduced numbers of CD19+ B cells in peripheral blood, secondary lymphoid organs, and lungs of tumor-bearing mice (>80%; Fig. 2A). However, and importantly, the remaining B cells expressed enhanced levels of surface markers characteristic of tBregs (CD25+ CD84hi with CD19+ cells; Fig. 2B; Supplementary Fig. S1A), suggesting that they could be enriched for tBregs. To confirm this possibility, we isolated CD19+ B cells from tumor-bearing mice treated with anti-CD20 antibody or control IgG2a to test their ability to suppress the activity of T cells ex vivo. As we reported that 4T1.2 cancer induces the generation of tBregs in vivo (17, 27), B cells from IgG2a–treated tumor-bearing mice significantly suppressed the activity of CD4+ and CD8+ T cells as compared with B cells from naïve mice (Fig. 2C). However, their suppressive activity was drastically enhanced if B cells were isolated from tumor-bearing mice treated with anti-CD20 antibody (Fig. 2C). Moreover, these enriched B cells (Fig. 2D) as well as ex vivo–generated tBregs [by treating normal B cells with cancer conditioned media (17); Supplementary Fig. S1B] expressed only low levels of CD20. Taken together, these results suggest that, although cancer progression and metastasis require B cells, the anti-CD20 antibody–mediated depletion of CD20hi B cells instead worsens the disease by enriching for CD20low tBregs.

Rituximab enriches for human tBregs expressing low levels of CD20

We reported that human cancers also induce the generation of tBreg-like cells (17), which may function similarly by regulating immune responses at the sites of tumor progression and metastasis. In concordance, we detected clusters of B cells residing in the lungs as well as in primary tumors and surrounding stromal tissues of humans with metastatic breast cancer (5 of 5 cases; Supplementary Fig. S1C). Thus, human tBregs may also be CD20low and, as such, may escape anti-CD20 antibody–mediated depletion. Because the lack of access...
to fresh samples from patients with breast cancer hampers their characterization, we first tested this possibility by evaluating expression of CD20 on the surface of ex vivo–generated tBregs by treating human peripheral blood B cells with conditioned media of MDA-MB-231 breast cancer cells or SW480 colon cancer cells (17). Unlike control B cells (mock-treated or cultured with conditioned media of breast cancer MCF7 cells or 938 melanoma cells; Fig. 3A; Supplementary Fig. S1D), tBregs not only efficiently suppressed the activity of human T cells (B-MDA; Fig. 3A; and B-MDA and BSW480; Supplementary Fig. S1D) but also expressed significantly reduced surface CD20 (Fig. 3B and Supplementary Fig. S1E). The regulatory activity of human tBregs was mostly retained in CD20Low B cells when they were segregated using a FACS-sorter (purity >95%; Fig. 3C; Supplementary Fig. S2A). Similarly, CD20Low B cells remaining after in vitro anti-CD20 antibody-mediated depletion of CD20High B cells also efficiently suppressed T-cell activity (Supplementary Fig. S2B and S2C).

Next, to confirm the enrichment of CD20Low tBregs after anti-CD20 antibody treatment in humans, we tested B cells from 13 patients with B-CLL and found 9 of them clearly containing CD20Low B cells in the peripheral blood (Table 1 and Fig. 3D), compared with untreated patients (patient 2; Fig. 3D; Table 1) or healthy subjects (Fig. 3B and D). Importantly, these CD20Low B cells functioned like tBregs, that is, efficiently suppressed activity of T cells (Fig. 3E) and induced FoxP3+ Treg conversion from CD25+CD4+ non-Tregs (Fig. 3F). Because all 6 of 9 samples with CD20Low B cells were from people treated with rituximab (Table 1), it is tempting to speculate that they were enriched by anti-CD20 antibody-induced B-cell depletion as in mice with 4T1.2 cancer. For example, while B cells from the patient 1 before the treatment did not reveal the presence of suppressive CD20Low B cells (Fig. 3D–F), the majority of its B cells after rituximab treatment became CD20Low (Fig. 3D) and readily suppressed T-cell activity (Fig. 3E) and converted Tregs (Fig. 3F).

Figure 1. Depletion of CD20+ B cells promotes metastasis. 4T1.2 cells (5 × 10⁴) were subcutaneously injected in the fourth mammary gland of Jh knockout (KO; A and B) and BALB/c (A–E) mice to assess tumor progression (A and D) and number of metastatic foci (at day 32 postchallenge in B, C, and E). To evaluate the role of tBregs (A and B) or anti-CD20 antibody-mediated B-cell depletion (C–E), 4T1.2 tumor-bearing Jh knockout mice were adoptively transferred with tBregs (A and B) or BALB/c mice were intraperitoneally injected with 250 μg/mouse anti-CD20 antibody, or control isotype-matched antibody (IgG), or PBS (mock) at 5, 10, and 15 days post tumor challenge (D and E) or at −10, −6, and −2 before tumor challenge (C). Y-axis shows tumor size (A and D) or number of metastatic foci (B, C, and E) ± SEM of 4 to 8 mice per group experiments reproduced at least 3 times. *, P < 0.05 of indicated differences between groups is considered significant.
Activation of TLR9 blocks the generation and function of tBregs

Considering the failure of anti-CD20 therapy to deplete tBregs, we decided to seek a different strategy to neutralize tBregs. When we screened various TLR ligands for their ability to inactivate tBregs, the majority of them failed to do so (Fig. 4A and B and Supplementary Fig. S3A). For example, lipopolysaccharide (LPS) did not inhibit tBregs (Fig. 4A and B and Supplementary Fig. S3A) nor convert B cells into tBregs (17), despite expression of TLR4 (data not shown). In contrast, only TLR7-9 ligands (single-stranded RNA and unmethylated CpG-ODN) reversed the phenotype (upregulated CD20 and downregulated CD25^HI^CD81^High^; Fig. 4A; Supplementary Fig. S3A and S3B) and blocked the regulatory activity of murine and human tBregs (Fig. 4B and Supplementary Fig. S3A–S3C). Hence, CpG-ODN can efficiently inhibit tBregs and, as such, it may also provide therapeutic benefit in tumor-bearing mice blocking tBreg-mediated metastasis.

Targeted delivery of CpG-ODN to CXCR5-expressing cells abrogates lung metastasis by inhibiting tBregs and activating B cells to promote antigen-specific CD8^T^ cells

Because systemic injections of free CpG-ODN can promote lymphoid follicle destruction and immunosuppression (35), to circumvent this potential problem, we devised a CXCL13-based strategy (BLC-arp; Supplementary Fig. S3D) to deliver CpG-ODN to CXCR5-expressing B cells in vivo. As we previously showed that an RBD-containing chemokines bind and transduce cells with oligonucleotides via chemokine receptors (36), CpG-ODN efficiently transduced (Fig. 4C) and inactivated tBregs (Fig. 4D) inducing B-cell activity even at suboptimal

Figure 2. Depletion of CD20^B^ cells after tumor challenge enriches for tBregs. Anti-CD20 antibody efficiently depletes CD19^B^ cells in various organs (A) of 4T1.2 tumor-bearing BALB/c mice used in Fig. 1D and E but enriches for tBregs (CD81^HI^CD25^HI^ within CD19^B^ gated cells; B). CD19^B^ cells isolated from lymph nodes (LN) of tumor-bearing mice suppressed proliferation of syngeneic CD4^T^ and CD8^T^ T cells (C). In particular, B cells from anti-CD20 antibody-treated mice were much more suppressive for both CD4^T^ and CD8^T^ T cells (C). Proliferation was assessed using CFSE dilution assay of T cells stimulated with anti-CD3 antibody and incubated with equal numbers of B cells for 5 days. CD19^B^ cells from the spleen of tumor-bearing mice treated with anti-CD20 antibody expressed low levels of surface CD20 as compared with naive mice (naïve; D) and nontreated tumor-bearing mice (tumor-bearing; D). Representative FACS staining dot plots of CD20^B^ cells within CD19^B^ gated cells (D). Y-axis shows percentage of CD19^B^ cells (A), tBregs (B), or proliferated CD4^T^ and CD8^T^ T cells (C) ± SE of 4 to 8 mice per group experiments reproduced at least 3 times. *, P < 0.05.
To test the clinical relevance of tBreg inactivation, 4T1.2 tumor-bearing mice were treated 5 times intravenously with BLC-arp (BLC-arp/CpG). While all control mice succumbed to massive lung metastasis, B cells from BLC-arp/CpG-treated mice (BLC-arp/CpG) efficiently reversed metastasis of 4T1.2 cancer cells (Fig. 5D). Hence, an inefficient induction of cytolytic CD8$^+$ T-cell responses in these cancer model (compare naïve vs. tumor; Fig. 5D) can be efficiently reversed using BLC-arp/CpG by inactivating tBregs and rendering B cells stimulatory.

Next, to confirm that the observed results were due to B-cell activation, we first depleted B cells in tumor-bearing mice by injecting anti-CD20 antibody at days 3 and 5 post tumor challenge and, then at days 10 and 15, the mice were adoptively transferred with mock or CpG-ODN–pretreated B cells from syngeneic naïve mice. The enhanced metastasis of 4T1.2 cancer-bearing mice after anti-CD20 antibody treatment (Fig. 5E and also see Fig. 1E) was not only reversed, but metastasis was almost completely lost if the mice were adoptively treated with BLC-arp/CpG.
transferred with CpG-treated B cells (Fig. 5E) or CpG-treated tBregs (data not shown). These results were in striking contrast with the transfer of mock-treated B cells, which only slightly reduced the enhanced lung metastasis to the levels of control untreated mice (presumably indicating the restoration of B-cell responses; Fig. 5E), suggesting a dominant effect of adoptively transferred CpG-treated B cells/tBregs over in situ tBregs. This is not an artifact of the cancer model or mouse strain we used, as a different tumor, B16 melanoma in congenic B-cell-deficient μMT mice also progressed poorly unless replenished with tBregs from WT C57BL/6 mice (Supplementary Fig. S5A; ref. 17). The transfer of tBregs inhibited melanoma peptide gp10025–32–specific IFN-γ–expressing CD8+ T cells in μMT mice (Supplementary Fig. S5B and S5C) and in B-cell–competent pmel mice (transgenic for CD8+ T cells specific for gp10025–32 (32), Supplementary Fig. S5D and S5E), which was almost completely lost if tBregs were treated with CpG (Supplementary Fig. S5A–S5E).

CpG–mediated T-cell activation requires upregulation of 4-1BBL on tBregs

T cells as well as LPS-stimulated B cells (B-LPS) upregulated CD40, B7.1, and B7.2 (17), excluding their direct involvement in suppression of T cells. However, we found that, compared with B-LPS or even with normal B cells, expression of 4-1BBL, an

Table 1. CD20<sup>lo</sup>CD19<sup>+</sup> B cells from patients with B-CLL suppress T cells

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NOTE: CD19<sup>+</sup> B cells from patients with B-CLL were phenotyped for CD20 and 4-1BBL expression and tested for T-cell suppression. Abbreviation: ND, not determined.

<sup>a</sup>+++ and − correspond to >40% decrease or no change compared with healthy donor B cells, respectively.
immunostimulatory receptor that activates CD8⁺ T cells and NK cells via 4-1BB (37, 38), was significantly reduced on murine and human tBregs (Fig. 6 and Supplementary Fig. S6A and S6B). Compared with naive mouse B cells, the expression of 4-1BBL was reduced in CD25⁺ B cells homing to the primary tumor, the secondary lymphoid organs and lungs of 4T1.2 cancer-bearing mice (Fig. 6B), which was further decreased in tBregs from mice treated with anti-CD20 antibody (Supplementary Fig. S6B). However, BLC-arp/CpG treatment reversed the reduced expression of 4-1BBL on murine and human tBregs (Fig. 6C) as well as in vivo in tumor-bearing mice (Fig. 6D). Importantly, B cells from tumor-bearing mice, which were protected from lung metastasis as a result of BLC-arp/CpG–induced inactivation of tBregs and induction of cytolytic CD8⁺ T cells (Fig. 5A–E), also expressed significantly upregulated 4-1BBL (Fig. 6D). Thus, CpG could render tBregs stimulatory by reversing the insufficient signaling of the 4-1BBL/4-1BB axis. Indeed, tBregs could not suppress and instead activated T cells, if the missing signaling was substituted with the agonistic anti-4-1BB antibody (anti-CD137 antibody; Fig. 6E).

Discussion

Here, we provide a new mechanistic insight to reconcile the debate of the last 30 years (12–14) on the role of B-cell inactivation in cancer therapy. The hypothesis was that if B cells promote carcinogenesis in mice (12–14, 19, 20) and their genetic dysfunction usually retards tumor progression (16, 17),
anti-CD20 treatments should provide therapeutic benefit in mice bearing highly metastatic 4T1.2 breast cancer. However, although 4T1.2 cancer loses its ability to metastasize in B-cell deficient mice, the outcome of anti-CD20 antibody treatment in immune-competent mice differed depending on the time of use. While 4T1.2 cancer metastasis was abrogated in mice treated with anti-CD20 antibody before tumor challenge, surprisingly its metastasis was instead significantly enhanced if B cells were depleted with anti-CD20 antibody in mice with already established tumor. Our data indicate that this is due to anti-CD20 antibody-induced enrichment of CD20Low tBregs after the depletion of “immunostimulatory” CD20High B cells, which are presumably de novo generated from normal B cells in response to 4T1.2 cancer (17). We also confirmed similar enrichment of suppressive CD20Low tBregs in modeling studies with B cells treated with cancer cell conditioned media in vitro and, importantly, in 6 of 13 human patients with B-CLL after treatment with rituximab. In 1 patient, while B cells before the treatment did not reveal signs of tBregs, the majority of the remaining B cells after rituximab depletion were CD20Low tBregs. Because these CD20Low tBregs readily suppressed T-cell activity and induced FoxP3⁺ Tregs from non-Treg CD4⁺ T cells, a function we previously associated with murine breast cancer-induced tBregs (17), it is tempting to speculate that rituximab (which mostly depletes mature and memory CD20⁺ B cells, but not long-lived plasma cells; ref. 39) may also promote immunosuppression in some patients with cancer. For example, it remains to be seen whether recent failure of rituximab to benefit patients with renal cell carcinoma and melanoma (29) may also be governed by a similar mechanism. However, CD20⁺ B cells are required for optimal anticancer immunity, and their presence in metastatic lymph nodes is a sign of favorable disease outcome in patients with head and neck cancer (31). In support, anti-CD20 antibody-induced stimulation...
progression of B16 melanoma in C57BL/6 mice is thought to be a result of the depletion of CD20<sup>+</sup> B cells (28) that induce antitumor effector immune responses (40). Thus, in cancers where tBregs facilitate escape and metastasis, the therapeutic emphasis should be to avoid further worsening the disease outcome by depleting also the beneficial antitumor CD20<sup>+</sup> B cells. For this purpose, we created an alternative strategy that inactivates tBregs and at the same time activates antitumor B cells. Although administration of free CpG-ODN can induce lymphoid follicle destruction and immunosuppression (35), here we show that relatively low doses of CpG-ODN (<10 µg) can neutralize the metastasis-promoting activity of tBregs if delivered in vivo into CXCR5-expressing B cells using modified CXCL13 chemokine (BLC-arp). BLC-arp/CpG efficiently abrogated lung metastasis in mice bearing an aggressive 4T1.2 breast cancer by activating B cells to elicit cytolytic antitumor CD8<sup>+</sup> T cells.

Interestingly, besides being CD20<sup>low</sup>, tBregs also expressed low levels of 4-1BB, an important costimulatory molecule involved in activation and amplification of TH1-polarized T-cell responses, CD8<sup>+</sup> T cells, and NK cells by signaling through 4-1BB (CD137; refs. 37, 38). Although the biologic relevance of this pathway remains poorly understood and is a subject of a different study, we can speculate that the expression of 4-1BB is low to provide insufficient costimulatory signaling to T cells. Confirming this prediction, when we circumvented the missing signal to 4-1BB on T cells, such as by treating with agonistic anti-CD137 antibody or activating with CpG-ODN, the suppressive activity of tBregs was abrogated. Alternatively, by being 4-1BB<sup>low</sup>, tBregs may avoid a reverse signaling required for their inactivation, as 4-1BB signaling induces inflammatory responses from epithelial cells in renal ischemia–reperfusion injury (41).

Thus, our findings raise an interesting possibility that similar tBreg-like cells may also control autoimmune responses, if we consider that cancer escape is using an existing regulatory machinery. Moreover, the opposing results observed after depletion CD20<sup>+</sup> B cells with rituximab in humans with autoimmune diseases (such as impairment of T-cell responses (42) and amelioration of rheumatoid arthritis, multiple sclerosis, and TID (18) and exacerbation of ulcerative colitis and psoriatic arthropathy in patients with Graves disease and non-Hodgkin lymphoma (9–11) may also be due to the rituximab-induced misbalance of CD20<sup>+</sup> B cells and tBreg-like cells. Similarly, CD25<sup>+</sup> B cells that induce anergy of activated T cells by competing for IL-2 upon treatment with Staphylococcus aureus Cowan 1 antigen were recently reported (43), suggesting that tBregs may be induced by parasite infection. Unlike them, tBregs efficiently inhibit both resting and activated T cells, including CD4<sup>+</sup> and CD8<sup>+</sup> T cells without induction of cell death or use of IL-2. To date, we found that tBregs (17, 27) phenotypically and functionally differ from other Bregs involved in autoimmune responses (5, 44, 45) and LPS- or B-cell receptor (BCR)-activated suppressive B cells (46, 47).

Although earlier studies from others emphasized the role of tumor-induced Gr1<sup>+</sup> CD11b<sup>+</sup> MDSCs in metastasis of 4T1 cancer cells (48–50), the data presented here further confirm our previous reports underscoring the importance of tBregs and tBreg-induced Tregs in facilitation of lung metastasis (17, 27). The process can be inhibited and lung metastasis can be successfully abrogated by depleting tBregs with anti-B220 antibody (17) or by treatment with anti-CD25 antibody that depletes both tBregs and Tregs (17, 27). Further supporting this idea, we also observed that, although B-cell deficient mice did not support lung metastasis of 4T1.2 cells, the expansion of MDSCs [associated by others with lung metastasis (51)] was comparable with that in tumor-bearing WT mice (data not shown). Taken together, our data not only suggest that anti-CD20 antibody/rituximab may not provide benefits in solid tumors, as it enriches for CD20<sup>low</sup> 4-1BB<sup>low</sup> tBregs, and thereby further enhances lung metastasis by exacerbating tBreg-mediated immunosuppression. Instead, we propose an alternative and simple strategy to control cancer escape by targeting both the regulatory and effector arms of the immune system with a modified CXCL13 (BLC-arp). We show that BLC-arp-coupled CpG-ODN can efficiently abrogate lung metastasis by inactivating CD20<sup>low</sup> 4-1BB<sup>low</sup> tBregs and activating immunostimulatory B cells. Although 4T1 cancer poorly elicits CD8<sup>+</sup> T-cell responses, BLC-arp/CpG induced expansion of antigen-specific IFN-γ-expressing effector and cytolytic CD8<sup>+</sup> T cells due to the blockade of tBregs and activation of B cells.

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

**Authors’ Contributions**

- **Conception and design:** M. Bodogai, A. Biragyn
- **Development of methodology:** M. Bodogai, C.L. Chang, A. Biragyn
- **Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.):** K. Wejksza, M. Merino, R.P. Wersto, C. Hesdorffer
- **Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis):** M. Bodogai, A. Biragyn
- **Writing, review, and/or revision of the manuscript:** M. Bodogai, K. Wejksza, M. Merino, R.P. Wersto, E.E. Gress, A.C. Chan, C. Hesdorffer, A. Biragyn
- **Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases):** M. Bodogai, J. Lai, A.C. Chan, C. Hesdorffer
- **Study supervision:** A. Biragyn

**Other:** Immunohistochemistry, J. Lai

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The Importance of CD20Low CD137Low tBregs in Cancer Control

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Anti-CD20 Antibody Promotes Cancer Escape via Enrichment of Tumor-Evoked Regulatory B Cells Expressing Low Levels of CD20 and CD137L

Monica Bodogai, Catalina Lee Chang, Katarzyna Wejksza, et al.

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