Tumor Burden Limits Bispecific Antibody Efficacy through T-cell Exhaustion Averted by Concurrent Cytotoxic Therapy

Erin W. Meermeier1, Seth J. Welsh1, Meaghen E. Sharik1, Megan T. Du1, Victoria M. Garbitt1, Daniel L. Riggs1, Chang-Xin Shi1, Caleb K. Stein1, Marco Bergsagel1, Bryant Chau2, Matthew L. Wheeler3, Natalie Bezman2, Feng Wang2, Pavel Strop2, P. Leif Bergsagel1, and Marta Chesi1
ABSTRACT

BCMA/CD3-targeting bispecific antibodies (BsAb) are a recently developed immunotherapy class that shows potent tumor killing activity in multiple myeloma. Here, we investigated a murine BCMA/CD3-targeting BsAb in the immunocompetent Vk*MYC model and its immunomodulatory imide drug (IMiD)-sensitive derivative Vk*MYC<sub>[CRIEM]</sub> model of multiple myeloma. The BCMA/CD3 BsAb was safe and efficacious in a subset of mice but failed in those with high tumor burden, consistent with clinical reports of BsAb in leukemia. The combination of BCMA/CD3 BsAb with pomalidomide expanded lytic T cells and improved activity even in IMiD-resistant high-tumor burden cases. Yet, survival was only marginally extended due to acute toxicity and T-cell exhaustion, which impaired T-cell persistence. In contrast, the combination with cyclophosphamide was safe and allowed for a tempered proinflammatory response associated with long-lasting complete remission. Concurrent cytotoxic therapy with BsAb actually improved T-cell persistence and function, offering a promising approach to patients with a large tumor burden.

SIGNIFICANCE: BCMA-targeted therapy induces deep but transient clinical responses. We developed an immunocompetent, IMiD-sensitive genetically engineered mouse model and show that IMiDs potentiate T-cell activation, increasing short-term efficacy of anti-BCMA/CD3 BsAb, but exacerbate T-cell exhaustion. Surprisingly, by reducing tumor burden and depleting regulatory T cells, cyclophosphamide prevents BsAb-induced T-cell exhaustion and promotes long-term multiple myeloma control.

See related commentary by Louvet et al.

INTRODUCTION

Although chemotherapeutic agents and molecular medicine are pillars of successful treatment of cancer, the recent clinical development of immunotherapies shows compelling promise in the treatment of many tumor types. In hematologic malignancies, immunotherapies centered upon cytolytic T lymphocytes as drugs, such as chimeric antigen receptor (CAR)-T cells and bispecific T-cell engagers (BiTE) or antibodies (BsAb), are central among these advances. BiTEs and BsAbs are “off-the-shelf” drug therapies that circumvent the need for time-consuming and expensive ex vivo manipulation of patient cells. These agents often consist of monoclonal antibodies or single-chain variable fragments in the case of BiTEs, engineered with one binding site directed toward a tumor-specific antigen and another against the T-lymphocyte activating receptor CD3-epsilon. BsAbs redirect T cells to kill tumors by bringing them into physical contact and activating secretion of cytotoxic molecules (1). Due to their novel mode of action, BsAb therapeutics may provide an effective option for all patients, including those with cytogenetically high-risk or heavily pretreated disease that renders them more resistant to standard-of-care therapy.

Multiple myeloma is a largely incurable malignancy caused by monoclonal expansion of plasma cells (PC) in the bone marrow (BM). Although most patients with multiple myeloma respond well to initial chemotherapy combinations, the disease almost always relapses and eventually becomes resistant to therapy. BsAbs have shown particular efficacy in B cell malignancies, with some of the most promising clinical trials in development for multiple myeloma with agents targeting the antigen BCMA, encoded by the TNFRSF17 gene (2). There are multiple BCMA/CD3 BsAbs or BiTEs in phase I clinical trials in heavily pretreated patients with multiple myeloma. Preliminary results from these trials show promising efficacy with the majority of patients responding at optimized doses (3–8). Although still under investigation, durability of this therapy in multiple myeloma is still unclear. Additionally, the mechanisms underpinning the spectrum of responses remain unknown, as do methods to deepen response and prolong remission. Moreover, frequent immunorelated adverse events, similar to those observed with CAR-T therapy, are noted, with cytokine release syndrome putting patients with greater disease burden at higher risk.

Multiple myeloma creates an immunosuppressive BM tumor microenvironment (TME) through a variety of mechanisms (9–12), and its complexity may modulate the efficacy of BsAb multiple myeloma therapy as it does for AMG-420 (13) and blinatumomab in leukemia therapy (14, 15). Many multiple myeloma standard-of-care drugs act directly by killing the tumor and remodeling the TME to break cycles of tumor survival. For example, the DNA-alkylating agent cyclophosphamide (Cy), in addition to inducing DNA damage, preferentially kills regulatory T cells (Treg), induces an acute secretory activating phenotype in tumor cells stimulating phagocytic activity, and promotes immunogenic tumor cell death (ICD), all of which can boost immunotherapy (16). Furthermore, thalidomide and derivatives (immunomodulatory

1Department of Medicine, Division of Hematology/Oncology, Mayo Clinic Arizona, Scottsdale, Arizona. 2Discovery Biotherapeutics, Bristol Myers Squibb, Redwood City, California. 3Tumor Microenvironment Thematic Research Center, Bristol Myers Squibb, Redwood City, California.

Note: Supplementary data for this article are available at Blood Cancer Discovery Online (https://bloodcancerdiscov.aacrjournals.org/).

Corresponding Author: Marta Chesi, Mayo Clinic, 13400 East Shea Boulevard, Cr3-040, Scottsdale, AZ 85259. Phone: 480-301-4703. E-mail: chesi.marta@mayo.edu

Blood Cancer Discov 2021;2:1–16
doi:10.1186/2643-3230.BCD-21-0038
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inside drugs, IMiD), also known as Cereblon (CRBN) modulators, have pleiotropic effects on the immune system that include upregulating cytokine production and potentiating growth and survival of effector T lymphocytes while reducing Treg expansion and function (17, 18). The potential ability of IMiDs to augment immunotherapy has recently been highlighted through effective preclinical combinations with anti–multiple myeloma CAR-T cells in xenograft models (19, 20), but caution is warranted given the unpredictable toxicity noted during clinical combination with the anti–PD-1 checkpoint inhibitor pembrolizumab (21). Combining BsAb with currently approved drugs for multiple myeloma is a rational direction forward if the two approaches provide synergistic effects with nonoverlapping toxicity.

Evaluating in vitro mechanisms of multiple myeloma immunotherapeutic antibodies alone or in combination has been hampered by a lack of appropriate immunocompetent mouse models and murine reagents. Specifically, murine CRBN binds to IMiDs but fails to undergo the conformational modification required to induce CK1α, IKZF1, or IKZF3 ubiquitination and degradation (22–24). Furthermore, murine T cells do not release IL2 following IMiD treatment (22), and we have shown that IMiDs are the only class of drugs active in patients with multiple myeloma but inactive in Vk*MYC mice (26, 27). Here, to explore ways to improve the quality and longevity of BsAb therapy in the presence of the native TME, we generated a BCMA/CD3 BsAb that binds both human and mouse BCMA with one arm and murine CD3 with the other arm to induce T cell–mediated cytotoxicity. To evaluate BsAb combination therapy with IMiDs, we generated two bacterial artificial chromosome (BAC) transgenic mouse lines expressing human CRBN (hCRBN) and crossed them to the Vk*MYC mouse to generate an immunocompetent mouse model of multiple myeloma, Vk*MYC(hCRBN), sensitive to IMiDs. We identify tumor burden and T-lymphocyte function kinetics as determinants of BsAb efficacy. We define mechanisms by which two different standard-of-care treatments for multiple myeloma, the IMiD pomalidomide (Pom) and Cy, potentiate BsAb therapy through their dual actions on the tumor and microenvironment. These results highlight the need for additional investigation of the effects of anti–multiple myeloma standard-of-care drugs on the patients’ immune system in the context of modern anti–multiple myeloma immunotherapy combinations.

RESULTS

**BCMA Is a Specific Target for Immunotherapy in the Vk*MYC Model of Multiple Myeloma**

We have previously described the utility of the de novo (aged mice that have spontaneously developed multiple myeloma) Vk*MYC model of multiple myeloma and its derivative syngeneic transplantable lines in elucidating the mechanism of therapies that depend upon the microenvironment, including IAP antagonists and checkpoint inhibitors (10, 27–32). Here, we establish Vk*MYC as an appropriate model for optimizing T cell–based BCMA-targeted immunotherapy. Using a previously generated data set, GSE111921 (33), we determined the expression of Tnfrsf17/BCMA transcript in murine normal PCs and Vk*MYC-derived Burkitt’s lymphoma, Balb/c plasmacytoma, de novo Vk*MYC multiple myeloma, and transplantable Vk*MYC multiple myeloma cell lines (Fig. 1A). We found that murine Tnfrsf17 is universally expressed in all normal and malignant PCs at significantly higher levels than in lymphoma cells. De novo and transplantable Vk*MYC multiple myeloma cells shared a similar range in Tnfrsf17 expression. Despite abundant RNA expression, BCMA was barely detectable on the surface of murine multiple myeloma and plasmacytoma cell lines grown in vitro and in vivo (Fig. 1B, top). In contrast, the same human/murine BCMA cross-reactive antibody readily stained the human multiple myeloma cell line H929. It has been reported that BCMA is commonly shed from normal and malignant PC surface due to direct cleavage of its transmembrane domain by endogenous gamma-secretases (Gs; refs. 34, 35). Consistently, we detected high levels of soluble BCMA (sBCMA) in the serum of Vk*MYC tumor–bearing mice, but not in age-matched controls (Fig. 1C). As reported for human multiple myeloma, the levels of sBCMA correlated with tumor burden, with transplanted mice bearing extramedullary multiple myeloma displaying higher sBCMA. Treatment with GS inhibitors (Gs) stabilized BCMA on the surface of multiple myeloma cells both in vitro and in vivo (Fig. 1B, bottom, and 1D).

**Murine PC Killing In Vitro by Anti-BCMA/CD3 BsAb Is Dependent upon BCMA Expression Levels and BsAb Concentration**

A mouse BCMA/CD3 IgG1 BsAb antibody, together with the negative control anti-KLH/CD3 BsAb, was generated using the “Electrostatic steering coupled with inter-chain disulfide bond” technology developed at Bristol Myers Squibb (36). For the anti-mCD3 arm, we chose the variable region of the anti-mouse CD3ε antibody 145-2C11; for the anti-mBCMA arm, we used the variable region of an anti-hBCMA antibody that was identified to be cross-reactive to mouse BCMA. The D265A mutation was introduced into the mlgG1-Fc to silence the FcyR effector function (36). Surface plasmon resonance analysis confirmed that mouse BCMA/CD3 bispecific binds to mouse BCMA extracellular domain with KD = 5 nmol/L and mouse CD3ε complex with KD = 169 nmol/L, respectively (Supplementary Fig. S1).

Given the variable expression of BCMA by murine PCs, we first sought to evaluate the efficacy of BCMA-targeted therapy in vitro. Tumor cell lines, including the Balb/c plasmacytoma J558, J558 engineered to overexpress BCMA, and two Vk*MYC-derived multiple myeloma cell lines that grow in vitro (Vk14750VITRO and Vk32245VITRO; Table 1) were cultured with whole splenocytes and a titration of BsAb. Here, tumor cell killing was dependent upon both the dose of antibody and the level of tumor BCMA expression (Fig. 1E). The parental J558 cell line and Vk14750VITRO cells, with very low BCMA expression, were sensitive to treatment only when 10 μg/mL of BsAb was used. In contrast, J558 overexpressing BCMA and the high BCMA expresser Vk32245VITRO were efficiently killed even at a 100-fold lower antibody concentration.
Moreover, consistent with the mechanism of action of BsAbs, anti-BCMA/CD3 treatment of Vk32245SvTRO induced a dose-dependent CD8\(^+\) and CD4\(^+\) T-cell proliferation and activation (Fig. 1F). We noted that in vitro, and subsequently, in vivo, anti-BCMA/CD3 treatment induced higher proliferation of CD8\(^+\) T cells than CD4\(^+\) T cells, which may reflect intrinsic proliferative kinetic differences between cell types (37).

**Anti-BCMA/CD3 BsAb Is Active In Vivo against Vk*MYC Multiple Myeloma**

Next, we sought to investigate the ability of anti-BCMA/CD3 to induce tumor regression in vivo in the aged, de novo Vk*MYC mice that we believe best model newly diagnosed patients with multiple myeloma and display features of T-cell...
senescence reported in patients with multiple myeloma (ref. 38; Supplementary Fig. S2). We chose six mice with a serum gamma/albumin (G/A) ratio on day 0 of 0.5 (corresponding to an M-spike = 7 g/L), and treated them with anti-BCMA/CD3 at 0.1, 1, or 10 mg/kg on days 1 and 8. M-spike levels, measured weekly over time and compared with initial levels, demonstrated a significant response (defined as >50% reduction in M-spike) in all treated mice, already evident after only one dose of BsAb, which was similarly sustained with 1 and 10 mg/kg doses (Fig. 1G). We therefore selected a dose of 1 mg/kg once per week for 2 weeks of anti-BCMA/CD3 for all subsequent experiments and treated six Vk*MYC mice with variable levels of tumor burden (G/A on day 0 ranging from 0.2–0.6, corresponding to M-spike levels between 5 and 16 g/L). Although all mice achieved a complete response (CR; complete disappearance of the M-spike), mice with an initial high tumor burden (G/A >0.5, corresponding to an M-spike >14 g/L at day 0) rapidly relapsed after treatment discontinuation, whereas mice with a day 0 G/A <0.4 showed a slower but progressive deepening of the response even after treatment discontinuation, with two of them remaining tumor free for more than a year after treatment (Fig. 1H). This initial study indicates a tolerable, rapid, and strong effect of anti-BCMA/CD3 across aged mice, and more likely to produce IFNγ+ T cells, although the antibody was less efficacious at high–tumor burden situations. We observed that adding a GSi concurrently, although mildly toxic, only transiently improved BsAb activity (Supplementary Fig. S3A) and did not extend survival (Supplementary Fig. S3B and S3C). Three days after treatment, we determined cellular changes in the SPL by flow cytometry (FCM; Fig. 2G–L). Anti-BCMA/CD3 reduced tumor cells and dramatically increased the number of CD3+ T cells already after 72 hours of treatment (Fig. 2C).

We next evaluated the efficacy of anti-BCMA/CD3 treatment using the more aggressive transplantable Vk12598 multiple myeloma line, where tumor establishes in the BM and expands to extramedullary sites, predominantly in the spleen (SPL; Table 1). Again, anti-BCMA/CD3 significantly reduced M-spike levels by the end of the 2-week treatment and improved overall survival (OS; Fig. 2D–F). As noted for the de novo mice (Fig. 1H), efficacy related to initial tumor burden: Only mice with a G/A less than 0.5 on day 0 displayed reduction in M-spike levels. Additionally, most responses were transient with relapses occurring within 3 weeks of treatment. We next tested whether the addition of GSi to increase BCMA surface levels would increase the efficacy of anti-BCMA/CD3 in high–tumor burden situations. We observed that adding a GSi concurrently, although mildly toxic, only transiently improved BsAb activity (Supplementary Fig. S3A) and did not extend survival (Supplementary Fig. S3B and S3C). Three days after treatment, we determined cellular changes in the SPL by flow cytometry (FCM; Fig. 2G–L). Anti-BCMA/CD3 reduced tumor cells and dramatically increased the number of CD3+ T cells per SPL, resulting in a considerably higher CD8+ T cell–to–tumor ratio. CD8+ T cells were more proliferative and more likely to produce IFNγ and granzyme B. Similar increases were observed in IFNγ+ CD4+ T cells, although the total numbers of these cells per SPL did not change (Fig. 2I–K). Importantly, whereas the antibody was less efficacious at high tumor burden, this was not due to lack of activated cytotoxic CD8+ T cells, which were present 3 days after treatment than other multiple myeloma transplantable lines (Table 1). Anti-BCMA/CD3 significantly reduced M-spike levels in all treated mice, and seven of eight mice achieved and maintained a CR for the duration of the study (16 weeks; Fig. 2A and B). Survival differences were not measured in this experiment due to the indolent nature of this tumor. IHC on sections of the BM demonstrated a reduction in IFNγ+ multiple myeloma cells and accumulation of CD3+ T cells already after 72 hours of treatment (Fig. 2C).

To evaluate the efficacy of anti-BCMA/CD3 treatment against aggressive and drug-resistant transplantable multiple myeloma, we challenged C57BL/6 wild-type (WT) mice with the Vk29790 cell line and initiated treatment when M-spike levels reached a G/A >0.1. Vk29790 is an indolent BM-homing tumor cell line with relatively slower time to engraftment than other multiple myeloma transplantable lines (Table 1). Anti-BCMA/CD3 significantly reduced M-spike levels in all treated mice, and seven of eight mice achieved and maintained a CR for the duration of the study (16 weeks; Fig. 2A and B). Survival differences were not measured in this experiment due to the indolent nature of this tumor. IHC on sections of the BM demonstrated a reduction in IFNγ+ multiple myeloma cells and accumulation of CD3+ T cells already after 72 hours of treatment (Fig. 2C).

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Anti-BCMA/CD3 BsAb Treatment Leads to Broad T-cell Activation, but Its Efficacy Is Variable and Affected by Both Tumor Burden and Tumor Growth Kinetics

Table 1. Cell line characteristics

<table>
<thead>
<tr>
<th>Line</th>
<th>Species</th>
<th>Strain/ genotype</th>
<th>Growth</th>
<th>Drug sensitivity</th>
<th>Time to G/A 0.25</th>
<th>Median OS from G/A 0.25</th>
<th>Tnfrsf17</th>
<th>Modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vk12598</td>
<td>C57BL/6</td>
<td>Vk*MYC</td>
<td>E-MM</td>
<td>Cy</td>
<td>5 weeks</td>
<td>10 days</td>
<td>50</td>
<td>n.a.</td>
</tr>
<tr>
<td>Vk27181</td>
<td>C57BL/6</td>
<td>Vk*MYC/Lox</td>
<td>E-MM</td>
<td>Cy, Bor</td>
<td>7 weeks</td>
<td>20 days</td>
<td>29</td>
<td>n.a.</td>
</tr>
<tr>
<td>Vk29790</td>
<td>C57BL/6</td>
<td>Vk*MYC/Lox × C123 × mCRBN</td>
<td>MM</td>
<td>Cy, Pom</td>
<td>14 weeks</td>
<td>99 days</td>
<td>54</td>
<td>n.a.</td>
</tr>
<tr>
<td>Vk32908</td>
<td>C57BL/6</td>
<td>Vk*MYC/Lox × C123 × mCRBN</td>
<td>E-MM</td>
<td>Cy, Pom</td>
<td>4 weeks</td>
<td>19 days</td>
<td>208</td>
<td>n.a.</td>
</tr>
<tr>
<td>Vk14750</td>
<td>C57BL/6</td>
<td>Vk*MYC</td>
<td>VITRO</td>
<td>Pom</td>
<td>n.a.</td>
<td>n.a.</td>
<td>29</td>
<td>pWPI-hCRBN</td>
</tr>
<tr>
<td>Vk32245</td>
<td>C57BL/6</td>
<td>Vk*MYC</td>
<td>VITRO</td>
<td>Pom</td>
<td>n.a.</td>
<td>n.a.</td>
<td>150</td>
<td>pWPI-hCRBN</td>
</tr>
<tr>
<td>J558</td>
<td>Balb/c</td>
<td>WT</td>
<td>VITRO</td>
<td>n.d.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>pWPI-mBCMA</td>
</tr>
<tr>
<td>H929</td>
<td>Human</td>
<td>WT</td>
<td>VITRO</td>
<td>n.d.</td>
<td>n.a.</td>
<td>1,477</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

NOTE: The genotype and sensitivity to drugs of the cell lines used in this study are reported. MM, E-MM, and VITRO indicate growth restricted to the BM, extramedullary dissemination, or growth in vitro, respectively. For transplantable lines, the time to engraftment, measured as the number of weeks required after transplantation for the M-spike to reach a G/A ratio = 0.25, is reported, as well as the median survival, in days, following the detection of a G/A = 0.25. RMA-summarized Tnfrsf17 transcript expression is indicated. For cell lines grown in vitro, the transduced genes are listed.

Abbreviations: Bor, bortezomib; MM, multiple myeloma; n.a., not available; n.d., not detected; OS, overall survival; RMA, robust multi-array average.
Figure 2. The activity of anti-BCMA/CD3 is transient and related to initial tumor burden. **A**, M-spike levels (G/A ratio) measured over time in Vk29790 tumor-bearing mice treated with control anti-KLH/CD3 BsAb or anti-BCMA/CD3 at 1 mg/kg on days 1 and 8. **B**, M-spike levels (% of day 0) in Vk29790 tumor-bearing mice measured 14 days after treatment. Each dot represents an M-spike from an individual mouse. Bars show mean M-spike levels with SD. **C**, IHC staining (surface CD3 in red and nuclear IRF4 in blue) of BM sections from mice treated in **A**. Scale bar is shown in the bottom right corner. Images are representative of two mice necropsied from each treatment arm. H&E, hematoxylin and eosin. **D**, M-spike levels (G/A) quantified over time in response to control anti-KLH/CD3 or anti-BCMA/CD3 BsAb given at 1 mg/kg on days 1 and 8 in Vk12598 tumor-bearing mice. **E**, M-spike levels (% of day 0) in Vk12598 tumor-bearing mice measured 14 days after treatment. **F**, Kaplan-Meier survival plot in days from the initiation of treatment of Vk12598 tumor-bearing mice receiving the BsAb or control treatment. P values derived from Mantel-Cox log-ranked X² test. **G-L**, FCM analysis of splenocytes from Vk12598 tumor-bearing mice harvested 3 days after treatment initiation as in **D**. **H**, NK, natural killer. **M**, Representative CD3 and IRF4 staining by IHC of SPL sections harvested 3 days after treatment initiation as in **D**. Unpaired t test P values in **B** and **E** are represented by asterisks. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001.

even in the example case with the highest G/A ratio at day 0 (1.05, corresponding to M-spike of 28 g/L), indicating that the therapy is able to activate T cells regardless of tumor burden (Fig. 2L). IHC analysis of SPL sections demonstrated expansion of CD3+ T cells infiltrating the interfollicular space and replacing the IRF4+ tumor cells (Fig. 2M).

An Immunocompetent hCRBN- Transgenic Mouse Model of Multiple Myeloma Sensitive to IMiDs

To overcome lack of activity of BsAb therapy in a high-tumor burden setting, we explored combination therapies that could boost T-cell function. We hypothesized that the
immunomodulatory effects of IMiDs on the host and tumor would enhance bispecific activity twofold, in direct clearance of tumor and costimulation of the redirected T cells. IMiDs binding to CRBN leads to degradation of IKZF1 and IKZF3 transcription factors, which control the expression of IRF4, essential for PC survival, and inhibit transcription of the IL2 promoter, explaining the costimulatory activity of IMiDs in T cells. A few amino acid differences in the mouse CRBN sequence renders the mice resistant to IMiDs. We generated transgenic mice expressing hCRBN by microinjecting into pure C57BL/6 pronuclei two BACs spanning the entire hCRBN gene and differing in the regulatory regions included (Fig. 3A). We obtained a founder line from each BAC, hC123, and hC343, expressing a founder line from each BAC, hC123, and hC343, expressing different hCRBN levels (Fig. 3B). In order to avoid potentiating the two hCRBN founder lines with the more potent IMiD Pom, Dex HCl, or hC343 (representing hC343, yellow, hC123). B, Western blot of splenocyte protein extracts generated from necropsied mice treated for 6 or 24 hours with 10 mg/kg iberdomide/CC220 and probed with antibodies against the listed proteins. Mouse strains are listed on the top as WT (C57BL/6), hC123, or mCrbn−/−. mide/CC220 and probed with antibodies against the listed proteins. Mouse strains are listed on the top as WT (C57BL/6), hC123, or hc343 (representing hC343). B, Depiction of the location on human chromosome 3 of the two BACs (RP11-1042H15 and CTD-2335G19) chosen to generate hCRBN. Genes on this map are only those generally associated with CRBN. The two BACs were chosen to cover the entire hCRBN gene.

Figure 3. Pom enhances hCRBN transgenic CD8 T-cell proliferation, cytokine production, and tumor killing induced by anti-BCMA/CD3 in IMiD-resistant tumor cells. A, Depiction of the location on human chromosome 3 of the two BACs (RP11-1042H15 and CTD-2335G19) chosen to generate hCRBN transgenic mice. Genes included in BAC are shown, and then the enhancer regions (identified by H3K27Ac peaks), followed by the span of each BAC (blue hC343, yellow, hC123). B, Western blot of splenocyte protein extracts generated from necropsied mice treated for 6 or 24 hours with 10 mg/kg iberdomide/CC220 and probed with antibodies against the listed proteins. Mouse strains are listed on the top as WT (C57BL/6), hC123, or hC343 (representing two different transgenic founder lines expressing hCRBN) and mCrbn−/−. C, Ikaros expression measured by FCM in CD19+ or CD3− cell-surface–stained splenocytes harvested from hC343 transgenic mice treated in vivo for 6.5 hours with the indicated dose of Pom. Mean fluorescence intensity (MFI) is reported on the left of each histogram. FMO, fluorescence minus one. D, M-spike levels (% of day 0) in WT mice bearing the indicated Vk by microinjecting into pure C57BL/6 pronuclei two BACs spanning the entire hCRBN gene and differing in the regulatory regions included (Fig. 3A). We obtained a founder line from each BAC, hC123, and hC343, expressing different hCRBN levels (Fig. 3B). In order to avoid potential competition for IMiDs binding between the endogenous murine and human CRBN, both hCRBN lines were bred into a murine CRBN−/− background (39). To test for proper IKZF1/3 degradation in response to IMiDs, we treated WT, mCRBN−/−, and the two hCRBN−/− founder lines with the more potent IMiD iberdomide (CC-220; at 10 mg/kg; ref. 40), harvested splenocytes...
after 6 or 24 hours, and monitored IKZF1/3 and CRBN protein levels over time (Fig. 3B). We noted that the higher hCRBN expression in hC343 splenocytes correlated to deeper IKZF1/3 downregulation following CC-220 treatment. However, these effects were transient, and both proteins returned to baseline levels within 24 hours of treatment. Similarly, we treated hC343 mice with escalating doses of Pom for 6.5 hours and detected a dose-dependent increase in intracellular IKZF1 levels in B and T cells by FCM (Fig. 3C). Based on these results, we chose to dose Pom at 50 mg/kg twice per day for subsequent experiments. Moreover, as the hC343 line displayed the higher CRBN levels and strongest IKZF1/3 degradation with IMiD, we selected it for use as the host for subsequent transplantation experiments. We also bred both hC123 and hC343 lines with Vk*MYC mice to generate a new genetically engineered immunocompetent mouse model of multiple myeloma responsive to IMiDs (referred to as Vk*MYC<hCRBN>). We obtained two transplantable lines from two independent aged Vk*MYC<hCRBN> multiple myeloma tumors, displaying different growth characteristics and tropism (Table 1). For both lines, upon engraftment into WT mice, Pom delayed tumor progression, whereas responses were observed in combination with dexamethasone, as seen in human multiple myeloma (Fig. 3D). Overall, these data demonstrate that hCRBN expression in vivo is sufficient to induce IMiD responsiveness to murine cells and IMiD sensitivity to murine multiple myeloma (41). They also confirm that the extent of IKZF1/3 degradation correlates with CRBN levels (41, 42).

**IMiDs Modulate T cell–Based BsAb Immunotherapy in Multiple Myeloma**

IMiDs have cosupulatory effects on human T cells resulting in increased proliferation and cytokine production (18). Here, we cultured T cells from WT, mCRBN<sup>-/-</sup>, hC123, and hC343 hCRBN<sup>+</sup> mice in the presence of Vk32245<sup>VITRO</sup> target multiple myeloma cells and BsAbs, with or without Pom, and noticed marked T-cell expansion in the presence of Pom and hCRBN (Fig. 3E), which resulted in significantly more efficient killing of tumor cells (Fig. 3F). We also observed the same effects in a parallel assay with purified T cells instead of splenocytes, suggesting this increased tumor killing is due to a direct effect of Pom upon cytolytic T cells (Supplementary Fig. S4).

These results prompted us to test if the immunomodulatory properties of Pom could enhance multiple myeloma cell killing by BsAb treatment in IMiD-resistant tumors in vivo, especially in high–tumor burden settings, where anti-BCMA/CD3 was not sufficient as a single agent to control tumor growth. We evaluated the combination of anti-BCMA/CD3 treatment with Pom in hC343 hosts transplanted with the hCRBN<sup>-/-</sup> IMiD-resistant Vk12598 multiple myeloma cell line (Fig. 3G). We initiated 2 weeks of treatment with anti-BCMA/CD3 with or without Pom, starting when M-spike reached a G/A up to 1.2 (M-spike > 30 g/L), indicative of high tumor burden. After 1 week of treatment, M-spike was significantly lower upon anti-BCMA/CD3 treatment compared with anti-KLH/CD3 but still higher than day 0 levels, indicating that the treatment only delayed tumor growth (Fig. 3H and I). In contrast, the addition of Pom significantly reduced M-spike below their respective day 0 levels in all treated mice regardless of initial tumor burden. However, these effects remained transient and did not statistically improve OS of treated mice (Fig. 3J).

We performed FCM on SPL cells after 3 days of treatment to monitor the immunomodulatory, tumor-extrinsic effects of IMiDs on T cells during treatment. CD8<sup>+</sup> T-cell number increased 6- to 7-fold following treatment with anti-BCMA/CD3, with or without Pom (Fig. 3K). CD8<sup>+</sup> T cells were equally highly proliferative, with a similar proportion expressing granzyme B (Fig. 3L and M) but a higher proportion expressing IFNγ with Pom (Fig. 3N). The effector–target ratio in the SPL and CD8<sup>+</sup> T-cell number in the peripheral blood were higher in mice receiving anti-BCMA/CD3 with Pom compared with the single agents (Fig. 3O and P). IHC confirmed more effective tumor depletion after 3 days of anti-BCMA with Pom treatment (Supplementary Fig. S5). Overall, in the context of BsAb-directed activation, these data strongly support the use of Pom even in IMiD-resistant tumors to increase the pool of activated IFNγ-producing T cells in the TME and their migration through the blood.

**Tumor-Intrinsic and Extrinsic IMiD Activity in Combination with Anti-BCMA/CD3**

Pom boosted BsAb-driven T-cell activation even in the absence of a tumor cell–autonomous direct effect. Next, we sought to determine the additional contribution of Pom’s direct anti–multiple myeloma activity on T-cell function following anti-BCMA/CD3 treatment using in vitro and in vivo methods. Initially, we quantified relative in vitro tumor killing in separate tests, where combinations of WT or hCRBN-expressing tumor cells or splenocytes were cocultured together with or without suboptimal doses of anti-BCMA/CD3 and Pom. When the tumor was sensitive to Pom (Fig. 4A), tumor cell viability, as expected, was reduced to approximately 50% by Pom treatment alone. When tumor cells were cocultured with WT splenocytes, anti-BCMA/CD3, and Pom, tumor cell survival was further reduced to 32% of untreated. Moreover, the use of hC343 splenocytes with this combination additionally reduced tumor cell viability to 8% of untreated tumor. As expected, Pom boosted T-cell proliferation and hCRBN<sup>+</sup> tumor cell killing only in the presence of hC343, but not WT splenocytes and anti-BCMA/CD3 (Fig. 4B).

Having demonstrated a significant synergy in vitro between anti-BCMA/CD3 and Pom when both multiple myeloma and T cells were IMiD sensitive, we sought to determine if the addition of Pom is able to overcome resistance in vivo, in settings where anti-BCMA/CD3 was not sufficient as a single agent to control tumor growth. We challenged hC343 IMiD-sensitive mice with the IMiD-sensitive hCRBN<sup>+</sup> Vk32908 multiple myeloma cell line, and upon tumor engraftment we initiated 2 weeks of treatment with anti-BCMA/CD3 and Pom (Fig. 4C). VK32908 is the most aggressive SPL and BM-homing multiple myeloma cell line with faster engraftment time than other transplantable lines and relatively high BCMA expression (Table 1). Anti-BCMA/CD3 alone slowed tumor growth relative to controls but had no effects on OS. In contrast, the combination of anti-BCMA/CD3 with Pom induced a CR in all treated mice but one and extended OS (Fig. 4D–F). Although none of the five mice with a G/A at day 0 >0.3 (M-spike >8 g/L) responded to the single agents anti-BCMA/CD3, all but one
of the five mice with high tumor burden receiving the combination therapy achieved a CR. However, as we noted with our other transplanted models, tumor depletion was transient, and all mice relapsed within 3 to 4 weeks. Unique to this treatment, 3 of the 25 mice receiving anti-BCMA/CD3 and Pom, regardless of their day 0 M-spike values, rapidly lost >20% body weight at the third day of treatment, resulting in early mortality, thereby suggesting a therapeutic toxicity of the combination (Supplementary Fig. S6A).

By FCM, anti-BCMA/CD3 BsAb transiently decreased multiple myeloma cell number in the SPL and BM in the presence of low but not high tumor burden. In contrast, the addition of Pom led to a deeper and more prolonged tumor reduction in all treated mice (Fig. 4G). T cells rapidly accumulated during the first week of treatment in the SPL and BM of mice treated with anti-BCMA/CD3 BsAb with or without Pom (Fig. 4H), and a similar frequency expressed Ki67 (Fig. 4I). Pom increased the frequency of IFNγ and granzyme B+ CD8+ T cells in the first week of treatment with BsAb (Fig. 4J and K). However, T-cell number contracted during the second week, even when Pom was added, to levels at or below control-treated mice (Fig. 4H). Nevertheless, the efficient tumor killing and T-cell expansion were reflected by a significantly higher CD8+ T-cell–to–tumor ratio in the SPL of mice treated with anti-BCMA/CD3 and Pom over the single agent during the 2 weeks (Fig. 4L).

**Anti-BCMA/CD3 Treatment Leads to T-cell Exhaustion**

Fewer T cells in the SPL and BM expressed Ki67, IFNγ, and granzyme B in the second week of BsAb treatment. This occurred regardless of whether tumor antigen remained to provide T-cell stimulation, which led us to hypothesize that in the setting of aggressive tumor, the T cells activated by the BsAb are less functional over time. This prompted us to evaluate additional parameters of T-cell functions and exhaustion in response to treatment. PD-1 is upregulated on T cells after activation, and its continued expression interrupts T-cell signaling. Anti-BCMA, alone and in combination with Pom, induced expression of PD-1 on CD4+ and CD8+ T cells that increased over the 2 weeks of treatment (Fig. 4M; Supplementary Fig. S6B). A similar trend was noted for KLRG1, normally expressed on terminally differentiated short-lived effector CD8+ T cells (Supplementary Fig. S6C) and LAG3, a surface marker associated with activated T cells, among other cell types, with a documented role in CD8+ T-cell exhaustion (ref. 43; Fig. 4N; Supplementary Fig. S6D). The combinatorial upregulation of these markers extending through the weeks of treatment suggests that T cells become functionally exhausted and less responsive to anti-BCMA/CD3 over time, and this is potentiated by Pom. Furthermore, the ligand for PD-1, PD-L1, homeostatically expressed in proinflammatory milieu and upregulated by IFNγ, was expressed on nearly all tumor cells during the second week of anti-BCMA/CD3 treatment (example shown in Fig. 4O). Finally, we observed an increase in regulatory CD4+ T cells in mice treated with Pom during the second week of treatment (Supplementary Fig. S6E and S6F), which could contribute to suppressing the BsAb response.

IHC identified prominent infiltration of CD3+ T cells in the BM and SPL of anti-BCMA/CD3–treated mice with low but not high tumor burden at day 0 (Fig. 4P; Supplementary Fig. S7). However, the majority of T cells expressed IRF4, which we had not found in other models. IRF4 is a nutrient-sensitive regulator of gene expression and cell fate in B and T cells. In parallel to B cells, IRF4 induction is linked to the strength of T-cell receptor signaling, and IRF4 represents an important transcription factor in expansion and differentiation of effector T cells (44). Furthermore, the intensity of IRF4 expression during T-cell proliferation correlates with terminal effector differentiation as opposed to self-renewal programs (45). Together with the high expression of exhaustion markers, this suggests that BsAb-activated T cells, in the context of Vk32908 hCRBN+ multiple myeloma, are hyperactivated, which favors generation of short-lived effectors with potent tumor killing activity but also exhausted cells, and this is potentiated by combination with Pom.

**Sustained Anti–Multiple Myeloma Response with Anti-BCMA/CD3 and Cy Combination Therapy**

Our data establish that a lower tumor burden is associated with greater efficacy of the BCMA BsAb. Cy is a drug with strong tumorcidal action as a DNA-alkylating agent in tumor cells. We hypothesized that the tumor debulking activity of Cy would potentiate BsAb therapy when used in combination by decreasing the hyperactivation, proliferation, and terminal effector T-cell differentiation we noted in mice treated with the BsAb alone or with Pom combination.
We also recognized that Cy can slow immune cell replication and act as a lymphodepletating agent, activities that could potentially antagonize BsAb therapy. However, we reasoned that this effect may also target Tregs and therefore may benefit BsAb therapy of aggressive multiple myeloma. For these reasons, we next tested the combination of concurrent Cy with the anti-BCMA/CD3 antibody in hC343 mice bearing aggressive Vk32908 tumor cells to allow a direct comparison with Pom combination therapy (Fig. 5). We initiated 2 weeks of treatment with concurrent anti-BCMA/CD3 and Cy when M-spikes reached a G/A >0.25 (>7 g/L). After 2 weeks of treatment, M-spikes, relative to day 0, were significantly lower upon treatment with Cy compared with control and anti-BCMA/CD3 alone, with the combination inducing a uniform CR in all but one treated mouse (Fig. 5A and B). Moreover, although the mice treated with Cy alone relapsed quickly after treatment, the combination with anti-BCMA/CD3 induced longer remission and increased OS (Fig. 5B and C). Importantly, no toxicity was observed in the combination treatment arm.

Upon necropsy, we confirmed superior antitumor activity in mice receiving combination treatment (Fig. 5D and E). As previously noted, we observed an increase in the absolute number of T cells in the SPL and BM with anti-BCMA/CD3, whereas with Cy, their number decreased (Fig. 5F and G). These dynamic cellular changes during treatment resulted in a higher CD8+ T cell–to–tumor ratio in the combination arm by the end of treatment (Fig. 5H). As expected, Cy also decreased the number of Tregs in the TME (Supplementary Fig. S6E and S6F). Both CD8+ and CD4+ T cells remaining at the end of 2 weeks of treatment were of naive and central memory compartments (Fig. 5I). A similar frequency of the CD8+ T cells was able to produce IFNγ and granzyme B as compared with control treatment, indicating a lack of expansion of activated T cells (Fig. 5J and K). However, upon closer evaluation of early activation markers, existing CD8+ T cells were still activated by the BsAb in the presence of Cy, as represented by upregulation of LAG3 and (to a lesser degree) PD-1 (Fig. 5L and M). In support of the observation of tempered T-cell activation, PD-L1 was not upregulated on tumor cells with Cy and anti-BCMA/CD3 treatment, as it was during anti-BCMA/CD3 single-agent treatment (Fig. 5N). Furthermore, we assessed T-cell expression of TCF1 over the course of these treatments. TCF1 is an essential transcription factor in T-cell development, and in antigen-activated CD8+ T cells, it limits effector cell differentiation and promotes self-renewal of memory cells (46–48). The loss of TCF1 promotes terminally differentiated KLRG1-expressing T cells. At the end of 2 weeks of treatment, more T cells in the SPL and BM of anti-BCMA/CD3 and Cy-treated mice expressed TCF1, whereas fewer expressed this self-renewal transcription factor from anti-BCMA/CD3 alone (Fig. 5O).

Overall, our data suggest that the tumor debulking activity of Cy limits T-cell activation by rapidly depleting tumor antigen, thus preventing hyperactivation of T cells and release of IFNγ, limiting upregulation of PD-L1 on tumor cells and preserving antitumor functionality. Most of the remaining T cells have a naive or central memory phenotype, express TCF1, and can be readily activated by anti-BCMA/CD3 BsAb to control relapse in a TME that is depleted of immunosuppressive Tregs.

Combination of Anti-BCMA/CD3 and Cy Induces Long-lasting Remission and Protection

We repeated the immunotherapy combination of anti-BCMA/CD3 and Cy in our widely used Vk12598 transplantable model (Fig. 6A). After 1 week of treatment, M-spikes mimicked the trends noted in the Vk32908 model (Fig. 6B and C). Tumors in mice treated with Cy alone grew rapidly after 2 weeks of treatment, whereas the combination with anti-BCMA/CD3 induced a CR resulting in long-lasting control and curative remission (Fig. 6C and D). To validate the cellular changes underpinning this curative combination, we performed necropsy after 3 days of treatment and confirmed a more profound decrease in tumor cells in mice receiving Cy (Fig. 6E). The number of T cells expanded in the SPL during anti-BCMA/CD3 as observed previously, and Cy largely prevented this. Again, Cy decreased the number of Tregs in the TME (Fig. 6E). Due to these dynamic alterations, the CD8+ T cell–to–tumor cell ratio was highest in the group receiving Cy and anti-BCMA/CD3 (Fig. 6F). As noted in Vk32908 in vivo studies, anti-BCMA/CD3 with Cy modulated the frequency of T-cell proliferation, IFNγ, and granzyme B production among CD8+ T cells (Supplementary Fig. S8A). In comparison, the addition of bortezomib, another cytotoxic agent, induced only a transient deepening of response to the BsAb alone, without affecting anti-BCMA/CD3–induced T-cell expansion and without downregulating Tregs (Supplementary Fig. S8B–S8D). These data confirm the essential tumor debulking activity of Cy and highlight the unexpected improvement in T-cell function and composition for successfully controlling multiple myeloma.

After nearly 3 months posttreatment, all of the anti-BCMA/CD3–Cy-treated mice remained in CR (Fig. 6D). We wanted to test if the combination treatment had provided long-term protection through immunosurveillance or if it simply had been effective in clearing all of the tumor. We sampled peripheral blood from all of the anti-BCMA/CD3–Cy mice and six littermate naive age-matched control mice (Fig. 6G–I). The tumor did not grow back in the same Vk12598 tumor cell line and monitored weekly for an M-spike (Fig. 6A, D, and J). The tumor did not grow back in the combination arm by

DISCUSSION

Bispecific T cell–engaging antibodies are novel immuno-therapies for multiple myeloma and show promising clinical
Preclinical Optimization of Anti-BCMA/CD3 Therapy in Myeloma

**Figure 5.** Effective combination of Cy and anti-BCMA/CD3. hC343 mice bearing Vk32908 multiple myeloma cells were treated with anti-KLH/CD3 BsAb or anti-BCMA/CD3 BsAb (1 mg/kg on days 1 and 8) with or without Cy concurrently (100 mg/kg on days 1 and 8). A, M-spike levels (% of day 0) measured 14 days after treatment. Each dot represents an M-spike from an individual mouse. Bars show mean M-spike levels with SD. Unpaired t test: *P < 0.05; **P < 0.01; ***P < 0.001; ****P < 0.0001. ns, not significant. B, M-spike levels (G/A) measured weekly for the treatment groups in A. Each dot represents an individual mouse. C, Kaplan-Meier survival plot in groups A and B. M-spike levels (G/A) measured 14 days after treatment. Each dot represents an M-spike from an individual mouse. D, T-cell expression of immediate activation markers LAG3 and PD-1 3 days after treatments indicated on top of each graph. E, Percentage of splenic CD8+ T cells expressing PD-1, LAG3, and KLRG1. F, Percentage of Vk32908 tumor cells expressing PD-L1 10 days after treatment initiation. G, Example dot plots of CD8+ T-cell expression of immediate activation markers LAG3 and PD-1 3 days after treatments indicated on top of each graph. H, Tumor cells

**Table 1.**

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<tr>
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<td>Anti-BCMA/CD3 + Cy + Cy</td>
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**Figure 6.** Association for Cancer Research.
results. Their cellular activity induces interrelated changes in the tumor and its microenvironment, containing cytolytic T cells, that determine their efficacy. Here, we model anti-BCMA/CD3–treated mice to rechallenge with Vk12598.

Figure 6. The combination of Cy and anti-BCMA/CD3 is curative and induces long-lasting protection from tumor rechallenge. A, WT mice bearing Vk12598 tumors were treated as indicated with control or anti-BCMA/CD3 with or without Cy for 2 weeks. B, Relative M-spike levels (% of day 0) measured 7 days after the indicated treatment. Each dot represents an M-spike from an individual mouse. Bars show mean M-spike levels with SD. C, M-spike levels (G/A) measured weekly. Each line indicates one mouse. D, Kaplan–Meier survival plot in days from the initiation of treatment of Vk12598 tumor–bearing mice receiving treatments in A. E, No. of CD3+ T cells per spleen measured by FCM of samples from necropsied mice 3 days after treatment initiation of groups in A. F, Ratio of CD8+ T cells to CD138+ tumor cells per mouse. G, Representative example of FCM measurement of circulating memory T cells collected from mice in F on day 90, prior to rechallenge with Vk12598. H, Quantification of effector memory CD4+ and CD8+ T cells per µL of blood on day 90, prior to challenge. I, Frequency of IFNγ-producing effector memory CD4+ and CD8+ T cells in the blood of mice prior to challenge with Vk12598 in J. J, M-spike (G/A) after rechallenge of cured or matched WT control mice with Vk12598 cells. P values derived from unpaired t tests. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001. ns, not significant.

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long-lasting remission in two models of multiple myeloma, whereas the single agents achieved only transient control of the tumor. The superior efficacy of the combination treatment was associated with tempered activation of T cells with self-renewal capacity and a lack of classic immunosuppressive features in the TME, including Tregs. As we have shown that immune activation with IMiDs and suppression with Cy have both positive and negative effects on T-cell function when used in combination with BsAb, we speculate that in the clinical development of drug combinations with BsAb, it will be important to carefully balance T-cell expansion and activation while minimizing exhaustion to maximize therapeutic responses.

We attribute a majority of Cy’s success in combination with the BsAb to our model tumors’ sensitivity to this drug, which is commonly used in combination with other anti-multiple myeloma drugs in patients with relapsed multiple myeloma. For those patients with multiple myeloma whose tumors are not sensitive to Cy, we speculate that the addition of other therapies that can induce cytoablation (e.g. glucocorticoids and proteasome inhibitors), which would need to be precisely tailored to the patient tumor, may similarly potentiate immunotherapy.

We were surprised that the BsAb combined with Cy induced long-term protection from relapse even after tumor rechallenge. This finding presents a contradiction to an accepted mechanism for Cy as a lymphodepleting and generally immunosuppressive agent. We suspect that at an optimized dose, Cy induces ICD of the tumor while increasing the frequency of T cells with self-renewing capacity, with opportunities to engage tumor antigen. On the other hand, the lack of long-term protection noted after combination treatment with BsAb and bortezomib, a cytotoxic agent also reported to induce ICD, suggests that unique mechanisms of action of Cy, for example Treg depletion, are required to maximize BsAb efficacy. These mechanisms, combined with the depletion of Tregs in the tumor environment, maximize BsAb efficacy and could provide an opportunity to prime a protective response. Future studies are warranted to elucidate how bystander effects may play a role in the superior efficacy of BsAb therapy combinations, including the mechanism of protection in BsAb with Cy, and whether tumor-specific memory T-cell immunity is generated in this combination. We conclude that the combination of cytoablated therapies with BCMA BsAb is an attractive proposal for future trials in multiple myeloma.

These results warrant future investigation of how to best use BsAb to treat patients whose T cells and microenvironment have undergone many rounds of previous therapies and may have senescent antitumor function. Our results show that combining BsAb with chemotherapy or immunomodulators can induce dramatic responses and prolong OS in a highly predictive mouse model of multiple myeloma, and in the right circumstance, can induce long-lasting protective antitumor immunity, which may be a prerequisite for cure in patients.

**METHODS**

**Cell Lines and Reagents**

Human multiple myeloma and Balb/c plasmacytoma cell lines have been previously described and were maintained in RPMI-1640 supplemented with 5% FBS and glutamine, without antibiotics (28). The VkMYC<sup>LOX</sup> cell lines were generated by culturing permissive transplantable VkMYC cell line in vitro in RPMI-1640 + 5% FBS supplemented with glutamine, penicillin, and streptomycin (“mouse medium”). All cell lines were tested for *Mycoplasma* contamination twice/year using the MycoAlert kit (Promega) and were periodically validated by copy-number polymorphism by PCR. VKMYC<sup>LOX</sup> lines expressing hCRBN were generated by lentiviral transduction using hCRBN cDNA subcloned into pWPI lentiviral vector (Addgene plasmid # 12254). Pure populations of EGFP-transduced cell lines were sorted on a five-laser Fortessa (Beckton Dickinson), and purity was checked prior to each experiment on a five-laser CytoFLEX (Beckman Coulter). The GSI DAPT and LY411575-I were obtained from Cayman Chemical; DAPT was solubilized in DMSO and used at 1 μmol/L, and LY411575-I was freshly suspended in 40% PEG300 + 5% Tween-80 + 45% saline before each *in vivo* administration. Pom and iberdoromide (CC-220), both at >98% purity, were purchased from Pharmablock USA and solubilized in DMSO for *in vitro* use, or in 0.5% carboxy-methylcellulose + 0.25% Tween-80 in water for oral gavage at 50 mg/kg twice per day on days 1 to 5 and 8 to 12 (Pom), or 10 mg/kg (CC-220); Cy, dexamethasone, and bortezomb were obtained from the clinical pharmacy and solubilized in saline for i.p. injection at 100 mg/kg on days 1 and 8, at 10 mg/kg on days 1 to 5 and 8 to 12, or at 0.5 mg/kg on days 1, 4, 8, 11, respectively.

**Expression and Purification of Murine BCMA/CD3 and KLH/CD3 BsAb**

BsAb was generated by transient cotransfection of four expression plasmids encoding anti-mBCMA heavy/light chain and anti-mCD3 heavy/light chain into Expi293 cell lines (Thermo Fisher Scientific). Heavy chains (HC) and light chains (LC) were transfected with a DNA ratio (by weight) of 1:1:1:1 for HC_BCMA:HC_CD3:LC_BCMA:LC_CD3. Six days after transfection, supernatant was harvested and purified on an AKTA Avant (GE Healthcare). The supernatant was loaded on MabSelect SUre (GE Healthcare) column, washed with phosphate-buffered saline (PBS), eluted in 100 mmol/L pH 3.6 sodium citrate buffer, neutralized, and dialyzed into PBS. The bispecific quality was examined by intact LC/MS after PNGase F (Prozyme or New Englabs Biolabs) deglycosylation. Control KLH/CD3 BsAb was generated following the same protocol as described above.

**Gene-Expression Analysis**

Gene-expression analysis was performed as previously described, using data set GSE111921 (33).

**Mice**

All experiments were performed under the approval of the Mayo Foundation Institutional Animal Care and Use Committee and conformed to all the regulatory environmental safety standards. The generation and initial characterization of the Vk*MYC<sup>LOX</sup> mice [Tg[kv5-3.5*-MYC]#Plb6c] and derived transplantable lines have been reported elsewhere (26–28). The original Vk*MYC mice (RRID: MMRRC_068099-MU) and their derivative lacking LoxP sites, Vk*MYCDLox (RRID: MMRRC_068099-MU), have been deposited to the MMRRC repository. Human CRBN transgenic mice were generated at the Mayo Clinic by microinjection into C57BL/6J founder nuclei of two independent BACs: CTD-2335G16 spanning the entire human CRBN gene and RP11-1042H15 extending to include additional regulatory regions. Two founder lines were obtained: hC123 from the former BAC and hC343 from the latter, both capable of germline transmission, detectable by PCR on tail DNA using primers TAAAGGTGCAAGCATGCGAAA and AGAGCCCCATCTGTTGATCA. Both founder lines were independently bred into murine CRBN<sup>null</sup> background (39) and to Vk*MYC or Vk*MYCDLox mice to generate Vk*MYC<sup>CRBN<sup>null</sup></sup> mice. De novo mice were aged and monitored.
for tumor burden by serum protein electrophoresis as previously described (33). M-spike was quantified by calculating the ratio of densitometric values of the M-spike and albumin bands (G/A), assuming albumin at a standard value of 27 g/L (49). Transplantation details are provided in Supplementary Methods. Transplanted mice were enrolled in drug studies when their M-spike was detected with a G/A >0.1, depending on the aggressiveness of the line. Mice were randomized to different treatment arms, stratified by the size of their M-spike. Unless specified, treatment duration was 12 days.

Detection of sBCMA

sBCMA was detected in the serum of VK*MYC collected from moribund mice at the time of necropsy and from age-matched WT mice using the Mouse BCMA DuoSet ELISA kit (R&D System), using the manufacturer’s instruction and diluting VK*MYC sera 1:500.

FCM

Single-cell suspensions of cell lines or ACK-lysed tissue preparations from necropsy of mice were stained using the antibodies listed in the Supplementary Methods. Samples were analyzed using a five-laser CytoFlex LX (Beckman Coulter).

FCM-Based Killing Assay to Monitor Redirected Killing of Myeloma Cells with CD3/BCMA Antibody

We isolated splenocytes from mice ages 8 to 12 weeks old and lysed red blood cells with ACK buffer. Then we stained splenocytes with CellTrace Violet or CFSE following the manufacturer’s instructions (Molecular Probes). We used J558, J558-BCMA, and VKMYC<sup>Cre<sup>Lox<sup> cells as targets, which we harvested from exponential growing <i>in vitro</i> cultures and stained with SNARF (Molecular Probes) following the manufacturer’s instructions or anti-CD138. We diluted and titrated antibodies and drugs in complete T-cell medium. The splenocytes, target cells, and antibodies were added together in a round-bottom 96-well plate and cultured in a humidified incubator at 37°C for 72 hours and then harvested for FCM analysis. In experiments with purified T cells, T cells were isolated from splenocytes using a bead-based T cell-negative selection kit (STEMCELL Technologies).

Authors’ Disclosures

M.L. Wheeler is currently employed by Bristol Myers Squibb and holds stock in Bristol Myers Squibb. N. Bezman reports other support from Bristol Myers Squibb outside the submitted work. P. Strop reports personal fees from Bristol Myers Squibb outside the submitted work. P.L. Bergsagel reports personal fees from Novartis and Pfizer outside the submitted work. F. Wang reports resources, supervision, methodology, writing-original draft. P.L. Bergsagel: Conceptualization, funding acquisition, writing-original draft, writing-review and editing. M. Chesi: Conceptualization, resources, formal analysis, supervision, funding acquisition, investigation, writing-original draft, writing-review and editing.

Acknowledgments

This work was supported by grants from the NIH (RO1CA234181, U54CA224018, and CA186781). The authors are grateful to Dr. Anjali Rajadhyaksha for sharing the Crbn knockout mice, which were shipped to us by Dr. Perlie Epling-Burnette. They thank Dr. Isaac Boss for helpful discussion, as well as Soochit Brown, Kennedy Todd, and Zachary Hammond for experimental assistance. Experimental schemes were created with BioRender.

Received February 23, 2021; revised April 6, 2021; accepted April 27, 2021; published first May 5, 2021.

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Preclinical Optimization of Anti-BCMA/CD3 Therapy in Myeloma


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Blood Cancer Discov Published OnlineFirst May 5, 2021.