

FcRL5 as a Target of Antibody–Drug Conjugates for the Treatment of Multiple Myeloma

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Abstract

Fc receptor-like 5 (FcRL5/FcRH5/IRTA2/CD307) is a surface protein expressed selectively on B cells and plasma cells. We found that FcRL5 was expressed at elevated levels on the surface of plasma cells from the bone marrow of patients diagnosed with multiple myeloma. This prevalence in multiple myeloma and narrow pattern of normal expression indicate that FcRL5 could be a target for antibody-based therapies for multiple myeloma, particularly antibody–drug conjugates (ADC), potent cytotoxic drugs linked to antibodies via specialized chemical linkers, where limited expression on normal tissues is a key component to their safety. We found that FcRL5 is internalized upon antibody binding, indicating that ADCs to FcRL5 could be effective. Indeed, we found that FcRL5 ADCs were efficacious *in vitro* and *in vivo* but the unconjugated antibody was not. The two most effective consisted of our anti-FcRL5 antibody conjugated through cysteines to monomethylauristatin E (MMAE) by a maleimidocaproyl-valine-citrulline-p-aminobenzyloxycarbonyl (MC-vcPAB) linker (anti-FcRL5-MC-vcPAB-MMAE) or conjugated via lysines to the maytansinoid DM4 through a disulfide linker (anti-FcRL5-SPDB-DM4). These two ADCs were highly effective *in vivo* in combination with bortezomib or lenalidomide, drugs in use for the treatment of multiple myeloma. These data show that the FcRL5 ADCs described herein show promise as an effective treatment for multiple myeloma. *Mol Cancer Ther*; 11(10); 2222–32. ©2012 AACR.

Introduction

Multiple myeloma is a malignancy of plasma cells characterized by skeletal lesions, renal failure, anemia, and hypercalcemia. It is essentially incurable by current therapies. Current drug treatments for multiple myeloma include combinations of the proteasome inhibitor bortezomib (Velcade), the immunomodulator lenalidomide (Revlimid), and the steroid dexamethasone. We have been searching for surface targets that could be used to develop antibody-based therapies for multiple myeloma. Unfortunately, unmodified antibodies to most surface targets have little, if any, efficacy. Therefore, in addition to the identification of potential targets, an appropriate technology to enhance the antibody antitumor efficacy needs to be

identified as well. One approach to making effective antibody therapies is to conjugate the antibodies to cytotoxic drugs via specialized chemical linkers creating antibody–drug conjugates (ADC). ADCs provide a means to target cytotoxic drugs to neoplastic cells, reducing the nonspecific systemic effects of the cytotoxic drug while retaining any efficacy of the antibody (1, 2), and this technology has been applied to multiple myeloma (reviewed in ref. 3).

One of the major obstacles to the development of ADCs for the treatment of multiple myeloma is the selection of a suitable surface antigen. Expression of the target antigen on normal tissues can result in dose-limiting toxicities; thus, tumor specificity of the ADC target is desirable. Such tumor-specific targets are rare in practice, limiting choices to those with highly selective expression in tumor tissues and/or normal tissue expression either at low levels on nonvital normal tissues, or, at a minimum, expression on tissues that are not susceptible to the drug. Clinical experiences with ADCs and naked antibody therapies to B-cell lineage restricted targets (e.g., CD20 and CD22) that deplete normal B-cells that have proven safe and effective (3). In principle, a target that is expressed on normal B cells and plasma cells as well as multiple myeloma cells could provide an appropriate target because the normal cell types can be regenerated and, in the case of targeted chemotherapies, the normal tissue would be less sensitive to the toxin. The well-characterized B–cell-specific antigens are lost when B cells mature into plasma

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cells. Surface markers associated with multiple myeloma such as CD38, CD138, and CD56 have relatively broad expression patterns including normal tissues that may cause target-dependent toxicity (3). However, several ADCs to some of these targets for the treatment of multiple myeloma are in clinical development (see discussion).

The Fc receptor-like 5 (FcRL5, also known as FcRH5 and IRTA2) belongs to a family of 6 recently identified genes of the immunoglobulin superfamily (IgSF). This family of genes is closely related to the Fc receptors with the conserved genomic structure, extracellular Ig domain composition and the ITIM- and ITAM-like signaling motifs (4). The ligand(s) for FcRL5 are unknown, but FcRL5 has been implicated in enhanced proliferation and downstream isotype expression during the development of antigen-primed B cells (5). The FcRL genes are clustered together in the midst of the classical FcR genes, FcγRI, FcγRII, FcγRIII, and FcεRI, in the 1q21–23 region of chromosome 1. This region contains 1 of the most frequent secondary chromosomal abnormalities associated with malignant phenotype in hematopoietic tumors, especially in multiple myeloma (6). FcRL5 is expressed only in the B-cell lineage, starting as early as pre-B cells, but does not attain full expression until the mature B-cell stage. Unlike all other B-cell-specific surface proteins (e.g., CD20, CD19, and CD22), FcRL5 continues to be expressed in plasma cells whereas other B-cell-specific markers are downregulated (7). In addition, FcRL5 mRNA is overexpressed in multiple myeloma cell lines with 1q21 abnormalities as detected by oligonucleotide arrays (8). The expression pattern indicates that FcRL5 could be a target for antibody-based therapies for the treatment of multiple myeloma. In this study, we showed that FcRL5 has a high prevalence on the surface of multiple myeloma, validated it as a target for the use of ADCs, characterized 2 ADCs that have the potential to be used in humans, and showed that these anti-FcRL5 ADCs increase the effectiveness of current multiple myeloma therapies in xenograft preclinical models.

Materials and Methods

Antibodies

Antibodies to FcRL5 were generated and characterized as previously described (7). Antibody cross-reactivity to *Cynomolgus* monkey (cyno) FcRL5 was tested by flow cytometry using a stably transfected cell line expressing cyno FcRL5 (the clone a kind gift from Sothy Yi). Both anti-FcRL5(13G9) and anti-FcRL5(10A8) cross-reacted to cyno FcRL5 and were humanized as previously described (9).

Cell lines

Because cultured multiple myeloma cell lines downregulate FcRL5, transgenic stable cell lines expressing human and cyno FcRL5 were established. The EJM and OPM2 multiple myeloma cell lines (no authentication was done by the authors) were transfected with human FcRL5 using the Amaxa Nucleofector system. After puromycin

selection, the EJM pool was sorted for human FcRL5 expression by flow cytometry (Epics Elite; Beckman Coulter) resulting in the EJM-CMV.PD.FcRL5.LSP.2 (EJM-FcRL5) cell line, and the OPM2 pool was sorted for human FcRL5 expression using the MACS Separation System (Miltenyi Biotec) resulting in the OPM2-CMV.PD.FcRL5.SP.2 (OPM2-FcRL5) cell line. The SVT2 cell line was transfected with cyno FcRL5 using Lipofectamine 2000 (Invitrogen). After G418 selection, the SVT2 pool was sorted for cyno FcRL5 by flow cytometry resulting in the SVT2.MSCV.gD.cyoFcRL5.SP.2 cell line.

Cell viability assay

The *in vitro* efficacy of anti-FcRL5(13G9) ADCs was determined using an ADC dosing titration on OPM2-FcRL5. Before ADC addition, cells were plated in quadruplicate at 75×10^3 per well in 384-well plates in RPMI containing 10% FBS and allowed to attach overnight. Anti-FcRL5(13G9) ADCs or the control anti-GP120 ADCs were added to experimental wells to final concentration of 10, 3.3, 1.1, 0.37, 0.12, 0.041, 0.014, 0.0046, or 0.0015 $\mu\text{g}/\text{mL}$, with "non-drug conjugate" control wells receiving medium alone. After 72-hour incubation at 37°C, cell viability was measured using the CellTiter-Glo Luminescent Cell Viability Assay (Promega Corp). The concentration of anti-FcRL5(13G9) ADCs resulting in the 50% inhibition of cell viability was calculated from a 4-variable curve analysis.

Scatchard analysis

To determine binding affinity (K_d), 0.5 nmol/L ^{125}I labeled Hu Anti-FcRL5(10A8) was competed against unlabeled Hu Anti-FcRL5(10A8), respectively, ranging from 50 to 0.02 nmol/L (12 step 1:2 serial dilution) in the presence of OPM2-FcRL5 or SVT2-MSCV.gD.cyoFcRL5.SP.2 cells. After incubation at 4°C for 4 hours, cells were washed, and cell pellet counts were read by a gamma counter (1470 WIZARD Automatic Gamma Counter; Perkin Elmer). All points were carried out in triplicate and counted for 10 minutes. The average CPM were used for K_d calculation using the New Ligand (Genentech) program. Binding affinity for Hu Anti-FcRL5(13G9) was determined using the same protocol.

Flow cytometry

Bone marrow aspirates were collected from patients during their initial presentation for diagnosis of a suspected plasma cell disorder or follow-up assessment. FcRL5 expression levels were determined on plasma cells within bone marrow aspirates from patients diagnosed as having multiple myeloma ($n = 16$) or monoclonal gammopathy of uncertain significance (MGUS; $n = 11$). Additional data were collected from 7 subjects that were ultimately diagnosed as having no evidence of bone marrow lymphoma (normal controls).

Leukocytes from bone marrow aspirates were prepared via ammonium chloride lysis of erythrocytes. In summary, a volume of the sample (between 0.5 and 1.5 mL) was

incubated with a 10-fold excess of ammonium chloride (8.6 g/L in distilled H₂O; Vickers Laboratories) for 5 minutes at 37°C. The leukocytes were then washed twice in buffer (FACSFlow; Becton Dickinson Biosciences) containing 0.3% bovine serum albumin (BSA; Sigma). Leukocytes were stained with cocktails of Abs for 20 minutes at 4°C and washed twice in buffer before acquisition on a Canto II instrument (Becton Dickinson Biosciences). A minimum of 100,000 events were collected per sample. Fluorescently conjugated antibodies were used in combinations against the following markers: CD45 Pacific Orange (HI30; Invitrogen), CD20 Pacific Blue (B9E9; Beckman Coulter), CD19 PE-Cy7(J3-119; Beckman Coulter), CD38 APC-AF750 (LS198-4-3; Beckman Coulter), CD138 APC (B-B4; Miltenyi), FcRL5 PE (10A8, mouse anti-human FcRL5; Genentech Inc), and CD56 PE (MY31; Becton Dickinson Biosciences).

Data analysis was carried out using FACSDiva software. Plasma cells were defined by strong CD138 and CD38 expression, CD45 Lo with light scatter characteristics of large mononuclear cells. Pan B cells were identified as CD19+CD138-, CD45 Hi with lymphoid light scatter characteristics. The median fluorescence intensity (MFI) for each antibody was derived for both cell populations: total plasma cells and pan B cells. MFIs for FcRL5 were normalized by subtraction of the MFI of the appropriate conjugated isotype antibody (CD34PE) in Tube 2 within the same gated population. The isotype antibodies used in the panel were specific to non-B-cell markers.

Internalization studies

OPM2 wild type or OPM2-FcRL5 were incubated on ice for 1 hour in complete carbonate-independent medium (Gibco) or at 37°C in growth media containing 3 µg/mL murine or humanized anti-FcRL5(10A8) or isotype controls (murine anti-gD tag or trastuzumab hIgG1, respectively) and lysosomal protease inhibitors (10 µg/mL leupeptin and 5 µmol/L pepstatin; Roche). Cells were then washed twice, fixed with 3% paraformaldehyde (Electron Microscopy Sciences), quenched with 50 mmol/L NH₄Cl (Sigma), permeabilized with 0.4% saponin/2% FBS/1% BSA, then incubated with 2 µg/mL Cy3 anti-mouse or anti-human (Jackson ImmunoResearch). Where indicated, lysosomes were co-stained with 1:1,000 mouse anti-human LAMP1 (Becton Dickinson Biosciences) and detected with FITC-anti-mouse (Jackson ImmunoResearch). Cells were resuspended in 20 µL carbonate-independent medium and adhered to polylysine (Sigma)-coated slides before mounting coverslips in DAPI-containing VectaShield (Vector Laboratories). Slides were imaged by epifluorescence microscopy using a ×100 objective on a DeltaVision (Applied Precision LLC) microscope powered by SoftWoRx (version 3.4.4) software. Figures were compiled using Photoshop CS (Adobe Systems, Inc.).

Antibody conjugation

MCC-DM1 (Immunogen, Inc), MC-MMAF (Seattle Genetics, Inc), and MC-vc-PAB-MMAE (Seattle Genetics,

Inc) ADCs were prepared as previously described (10, 11). *N*-succinimidyl-3-(2-pyridyldithio)-butyrate-DM4 (SPDB-DM4; Immunogen, Inc) conjugates were prepared using purified antibody in 50 mmol/L potassium phosphate at pH 7.5 containing 50 mmol/L NaCl and 2 mmol/L EDTA. SPDB was dissolved in 100% ethanol and added to the protein solution in ratios of 6 to 8 moles of SPDB to 1 mole of antibody to achieve a final drug:antibody ratio of 3–4:1. The linker conjugation reaction was carried out at room temperature for 90 minutes followed by the addition of 1.7-fold excess DM4 over SPDB and an overnight reaction. The conjugates were purified using gel filtration, ion exchange chromatography, or dialysis.

Animal studies

All animal studies were carried out in compliance with National Institutes of Health guidelines for the care and use of laboratory animals and were approved by the Institutional Animal Care and Use Committee at Genentech, Inc.

To establish subcutaneous xenograft models, the tumor cells (2×10^7 cells in 0.2 mL Hank's Balanced Salt Solution; Hyclone) were inoculated subcutaneously into the flanks of female CB17 ICR SCID mice (7 to 16 weeks of age from Charles Rivers Laboratories). When mean tumor size reached the desired volume, the mice were divided into groups of 7 to 10 mice with the same mean tumor size and dosed intravenously (i.v.) via the tail vein with ADCs or antibodies.

Bortezomib (Velcade) was obtained from Millennium Pharmaceuticals, Inc., and dissolved in 0.9% sodium chloride at the appropriate concentration before drug injection. Mice were dosed by intravenous injection at 1 mg/kg twice weekly for 2 weeks.

Lenalidomide (Revlimid) was supplied by the ECA International Corporation and dissolved in dimethyl sulfoxide (DMSO). Immediately before use, lenalidomide was further diluted in 0.5% methylcellulose and 0.2% Tween 80, and administered intraperitoneally into mice at 50 mg/kg once a day for 13 days.

The SCID-rab model was carried out as previously described (12). To establish SCID-rabbit bone model, the tibia, humerus, ulna, and radius were harvested from New Zealand White rabbits (3 to 4 weeks of age from Myrtle Rabbitry), and fractionated into fragments (1 to 2 cm³ size). The bone fragments were then surgically engrafted into the flanks of female CB17 ICR SCID mice (6 to 8 weeks of age from Harlan Sprague Dawley). At 6 to 8 weeks post bone engraftment, the LD cells (1×10^6 cells in 50 µL PBS; ref. 13) were injected directly into the engrafted bone. The LD line was maintained by serial passage because of poor *in vitro* growth. Blood samples were taken periodically to assess tumor burden by measuring the amount of human lambda light chain in serum. When the amount of human lambda light chain reached the desired serum level, mice were randomized into groups of 8 to 10 with the same mean serum concentration and received weekly intravenous injections of ADCs for 2 weeks.

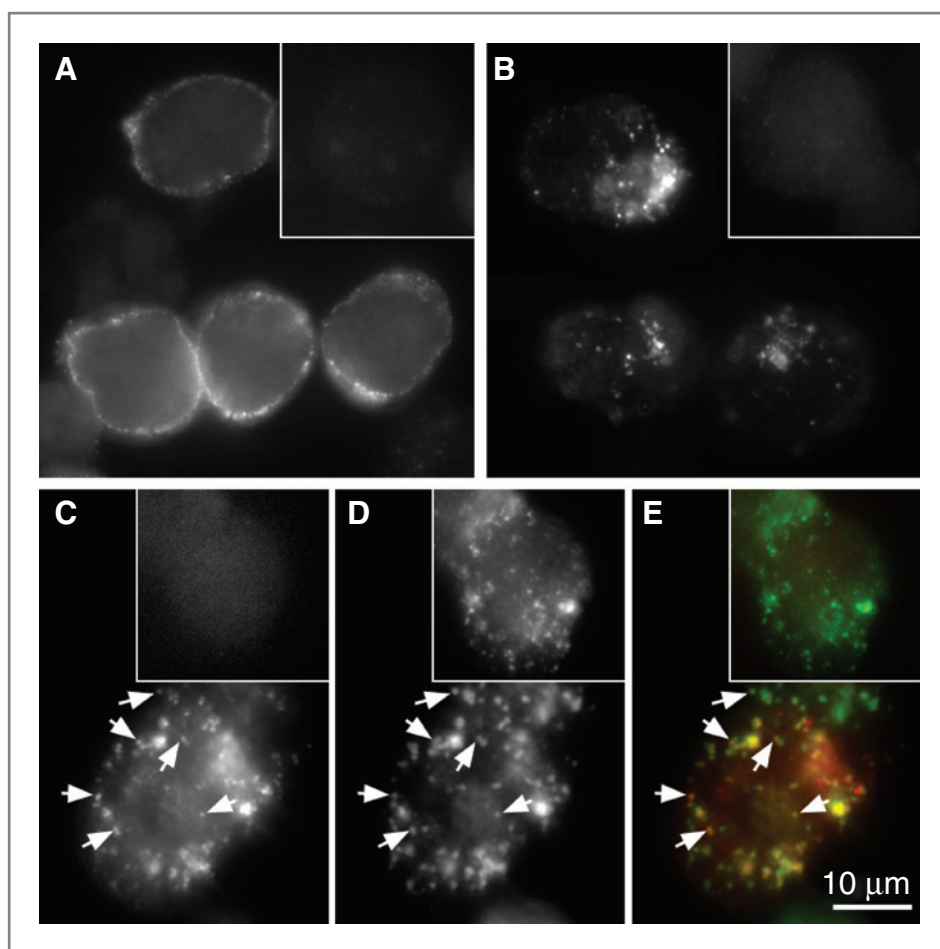


Figure 2. Anti-FcRL5 is internalized upon cell binding. Anti-FcRL5 (m10A8) surface binding (A) or 2-hour uptake at 37°C (B) in FcRL5-OPM2 cells (insets show lack of signal in OPM2 wild-type cells) detected with Cy3-anti-mouse. C–E, following 13-hour internalization of h10A8 (or isotype control, insets) detected with Cy3-anti-human (C and red channel in merge), OPM2-FcRL5 cells were co-stained with the lysosomal marker mouse anti-LAMP1 (D and green channel in merge) followed by FITC anti-mouse. Colocalization is evident from the yellow color in the merged panel (E), a subset of which is highlighted with arrows. Scale bar, 10 μ m.

controls were statistically significant, with the prob > chi-squared values being 0.0092 and 0.0164, respectively, as determined using the Wilcoxin (Kruskal–Wallis) test. Within the same subjects, we found that CD19+ B lymphocytes had either low or barely detectable FcRL5 expression across all subjects tested (data not shown).

Furthermore, it appears that FcRL5 staining in combination with CD38 staining can identify plasma cells or multiple myeloma cells as effectively as the CD38/CD138 combination, currently used. The percentages of cells found in the CD138/CD38 gate were replicated with the CD38/FcRL5 and the CD138/FcRL5 combinations (Fig. 1B). Moreover, in samples that are CD138^{Hi}CD38^{Hi}, 100% of the cells from the FcRL5/CD38++ population were also CD138^{Hi}, indicating that the FcRL5/CD38 marker combination does not pick up non-plasma cells (Fig. 1B). These observations indicate that the addition of FcRL5 to the current CD138 and CD38 plasma cells markers could only improve the diagnostic sensitivity and accuracy of multiple myeloma cell detection, especially with aberrant immunophenotypes or should technical difficulties interfere with their detection.

One of the major obstacles of immunotherapy for multiple myeloma, especially with ADCs, is the selection

of a suitable surface antigen. The fact that FcRL5 is elevated in multiple myeloma or MGUS compared with normal plasma cells, and that its levels are low on pan B cells, render FcRL5 an excellent target for immunotherapy.

Validation of FcRL5 as an ADC target for the treatment of multiple myeloma

The expression pattern of FcRL5 indicated that it would be a good target for the use of antibody or ADC therapy for the treatment of multiple myeloma. To validate this hypothesis, we sought to identify cell lines where we could test potential anti-FcRL5 therapies. We identified 10 cell lines that expressed FcRL5 RNA but found none that expressed significant amounts of surface FcRL5. We have observed a similar downregulation of other FcRL family proteins on cultured cells compared with the primary tissue expression levels (data not shown). To circumvent this problem, we developed 2 transgenic multiple myeloma cell lines, OPM2-FcRL5 and EJM-FcRL5, which stably express surface FcRL5 (see methods). During growth, in both *in vitro* and as xenograft models, OPM2-FcRL5 and EJM-FcRL5 cells express levels of surface FcRL5 that are equivalent to the higher end and the

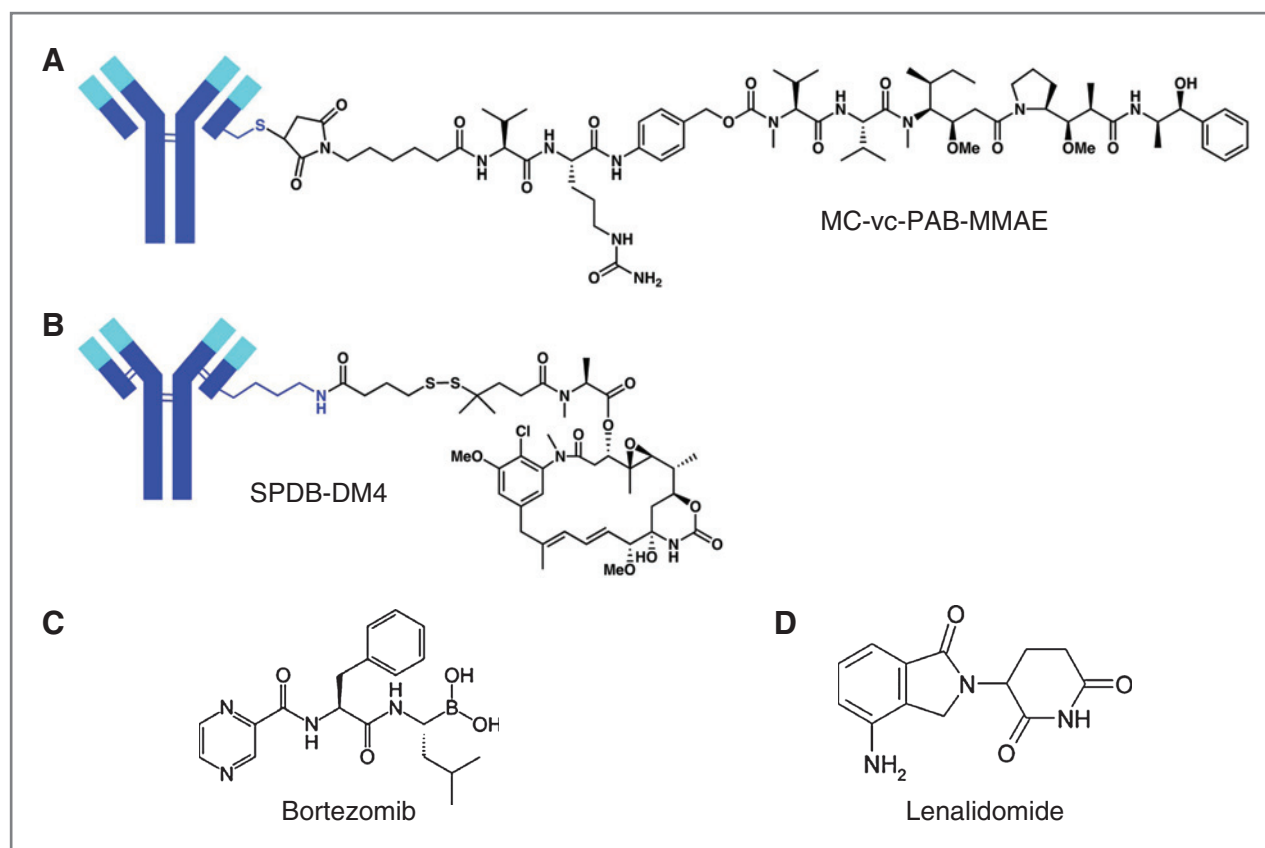


Figure 3. Structures of key small molecules. A and B, structure of MC-vc-PAB-MMAE attached to an interchain disulfide bond (A) and SPDB-DM4 attached to antibody lysine (B). The drug-to-antibody ratio for the ADCs was 3.4. Only 1 linker drug is shown for clarity. C, structure of bortezomib (Velcade). D, structure of lenalidomide (Revlimid).

mean levels of expression found in multiple myeloma patient cells, respectively (data not shown).

Internalization upon antibody binding can be a key feature that determines whether a target will be more suited to a naked antibody approach that uses antibody-dependent cell cytotoxicity (ADCC) and requires an extended duration of antibody binding on the cell surface, as compared with an ADC therapy where internalization to facilitate drug delivery is desirable. Anti-FcRL5 antibody bound specifically to OPM2-FcRL5 cells versus controls (Fig. 2A) and was internalized within 2 hours (Fig. 2B). By 13 hours, anti-FcRL5 was almost completely delivered to lysosomes, as detected by colocalization with LAMP1 (Fig. 2C–E). Uptake was specific, because an isotype control antibody gave no signal (Fig. 2C–E insets) and no anti-FcRL5 signal was seen in OPM2 cells lacking FcRL5 (insets in A, B; data not shown). These data show that anti-FcRL5 is well internalized upon binding and, thus, has properties that would make it an appropriate target for ADCs.

We sought to further test our hypothesis that FcRL5 would make a good target for ADCs by testing the effectiveness of 4 ADC formats, all of which use potent inhibitors of microtubule polymerization as the active drug. We tested maytansinoid conjugates linked to the antibody

through the ϵ -amino group of lysine with an uncleavable thioester linker (MCC-DM1) or a hindered disulfide reducible linker (SPDB-DM4). In addition, we tested the monomethylauristatins linked to antibody cysteines with an uncleavable maleimidocaproyl (MC) linker (MC-MMAF) and a protease cleavable linker (MC-vc-PAB-MMAE; see ref. 14 and Fig. 3 for detailed descriptions of these linker drugs).

The anti-FcRL5-MC-vc-PAB-MMAE, anti-FcRL5-MC-MMAF, and anti-FcRL5-SPDB-DM4 ADCs had similar efficacy *in vitro*, whereas anti-FcRL5-MCC-DM1 appeared less potent in comparison (Fig. 4A). *In vivo*, only the cleavable linker ADCs, namely anti-FcRL5-MC-vc-PAB-MMAE and anti-FcRL5-SPDB-DM4, showed strong antitumor efficacy (Fig. 4B); however, all the FcRL5 conjugates showed significant activity compared with vehicle and its corresponding control conjugates. In addition, the activity of the FcRL5 conjugates is significantly different from each other (Supplementary Fig. S1). Unconjugated anti-FcRL5 antibodies did not have any efficacy *in vitro* or *in vivo* (Fig. 5A and data not shown), consistent with their rapid internalization and lack of ADCC induction. These data indicate that FcRL5 is a potential target for the treatment of multiple myeloma with ADCs containing cleavable linkers.

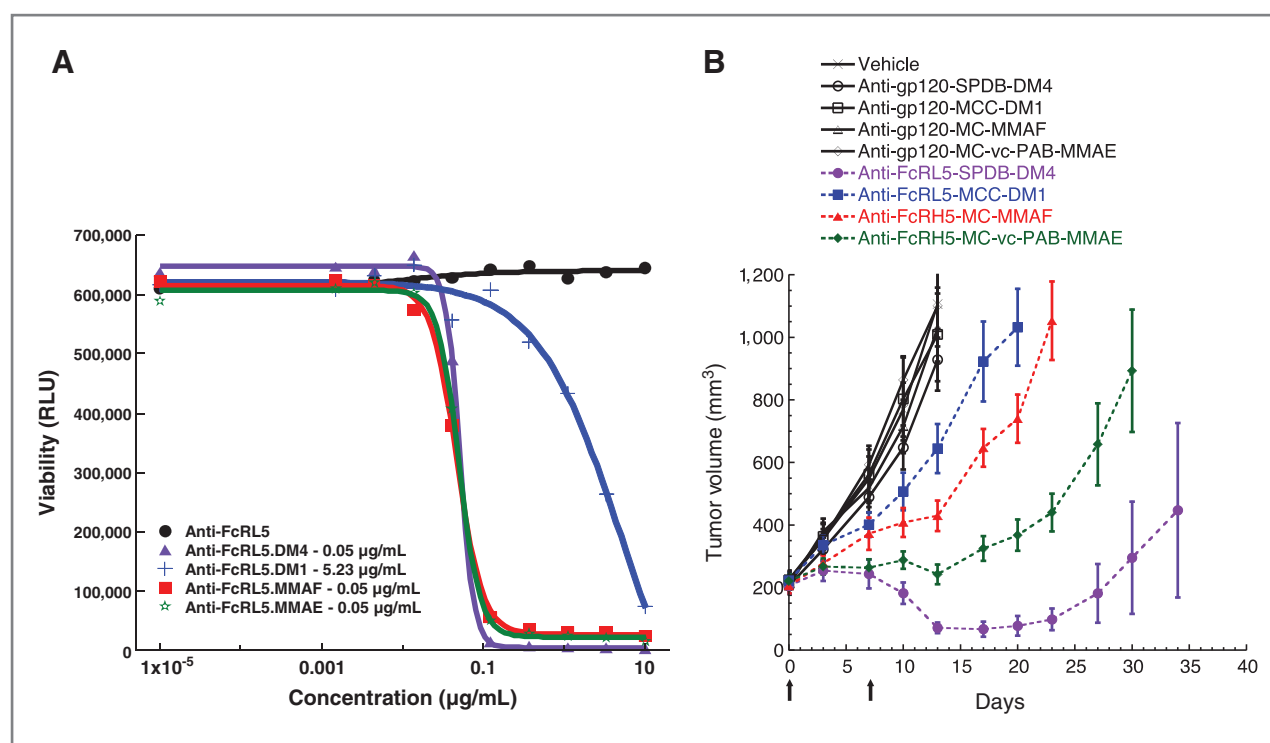


Figure 4. Efficacy of anti-FcRL5 ADCs with different linker drugs. **A**, *in vitro* killing of OPM2-FcRL5 cells with unconjugated anti-FcRL5(13G9) and anti-FcRL5 (13G9) ADCs conjugated to different linker drugs and their IC_{50} s as indicated. **B**, *in vivo* efficacy of OPM2-FcRL5 tumors with an average starting volume of 215 mm^3 . Groups of 7 mice were *i.v.* dosed 2 times as indicated (arrows) with 10 mg ADC/kg mouse. Anti-gp120 is an isotype control antibody conjugated to the various linker drugs in a similar manner as anti-FcRL5. Error bars represent SEM. RLU, relative luciferase units.

Generation of anti-FcRL5 ADCs suitable for treatment of humans

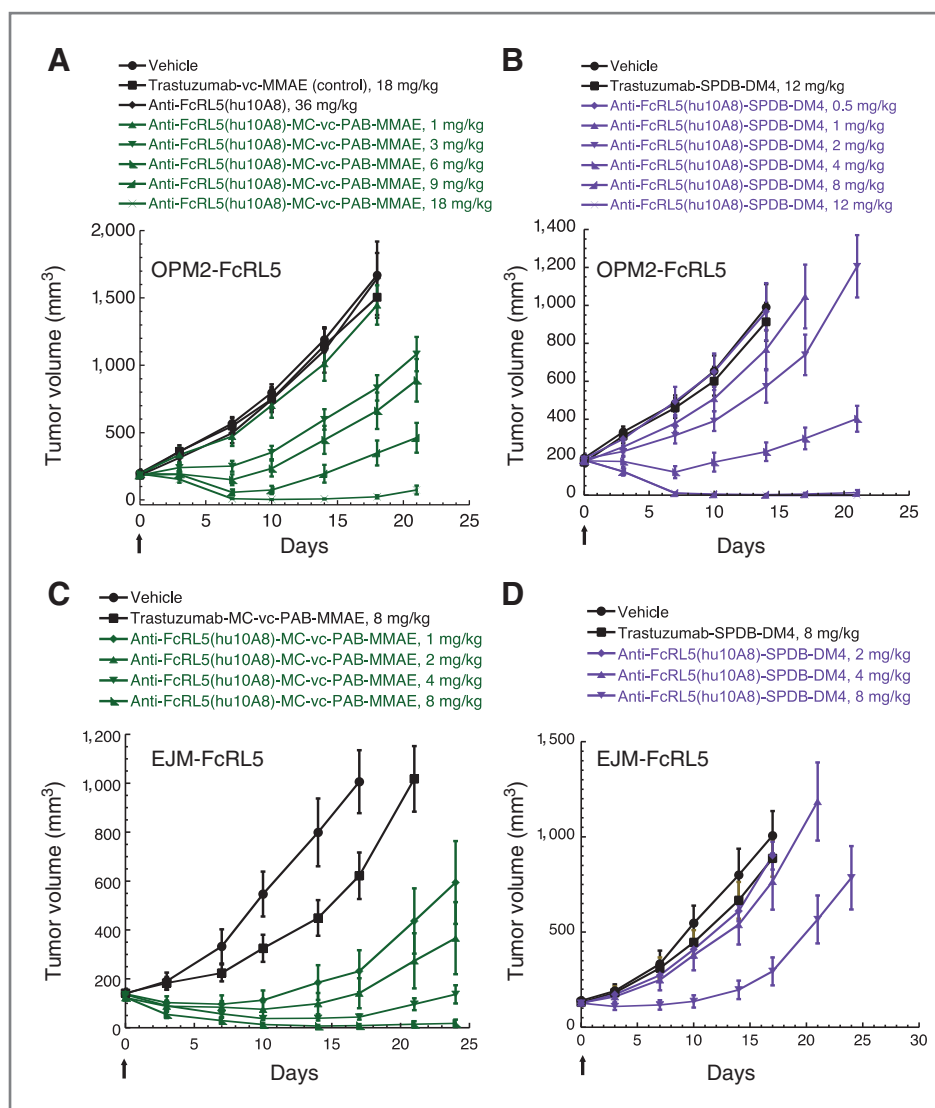
To generate ADCs suitable for the treatment of humans, we tested our anti-FcRL5 antibodies for cross-reactivity to cynomolgus monkeys with the goal of having FcRL5 ADCs that would be suitable for target-dependent safety studies in non-human primates (NHP). We found that both anti-FcRL5(13G9) and anti-FcRL5(10A8) cross-reacted with cynomolgus monkey FcRL5 with high affinity (data not shown). Anti-FcRL5(13G9) and anti-FcRL5(10A8) were humanized using previously described methods to generate anti-FcRL5(hu13G9) and anti-FcRL5(hu10A8) (9). These humanized antibodies that cross-react to cynomolgus monkey could serve as a basis for anti-FcRL5 antibody therapies to be tested in NHP for safety and subsequently used in humans in the clinic.

Next, we conjugated anti-FcRL5(hu10A8) to SPDB-DM4 and MC-vc-PAB-MMAE and tested the 2 resultant ADCs at several dose levels in our 2 xenograft models. In the OPM2-FcRL5 model, a single dose of anti-FcRL5(hu10A8)-MC-vc-PAB-MMAE or anti-FcRL5(hu10A8)-SPDB-DM4 resulted in complete tumor remission (Fig. 5A and B). Substantial responses included complete remissions with anti-FcRL5(hu10A8)-MC-vc-PAB-MMAE in the EJM-FcRL5 model (Fig. 5C and D). In contrast, the unconjugated anti-FcRL5(hu10A8) or the negative control trastuzumab ADCs had very little, if any, effect on tumor growth, which indicates that the activity seen with the

anti-FcRL5 ADCs was due to the target-specific delivery of cytotoxic drugs to the tumors, rather than ADCC. Interestingly, the EJM-FcRL5 model responded better than OPM2-FcRL5 to the FcRL ADCs despite having a lower expression level of FcRL5. In addition, anti-FcRL5-SPDB-DM4 was more effective than anti-FcRL5-MC-vc-PAB-MMAE in the OPM2-FcRL5 model, whereas their efficacy was switched in the EJM-FcRL5 model. These data show that anti-FcRL5 ADCs have excellent preclinical efficacy in xenograft models of multiple myeloma and that, even in cases where one anti-FcRL5 ADC is not effective, another one can be.

To further explore the effectiveness of our anti-FcRL5 ADCs we tested anti-FcRL5-SPDB-DM4 in a xenograft model that better recapitulates the biology of multiple myeloma cells, such as the stromal-multiple myeloma cell interactions and naturally expressed FcRL5. We used a SCID-rab model in which bone grafts were established subcutaneously in SCID mice and subsequently injected with human LD tumor cells (12, 13). LD cells express FcRL5 and are dependent on stromal cells for survival. When co-cultured *in vitro* with stromal cells, LD cells could be maintained, but lost their FcRL5 expression, which led us to maintain them by serial passage in the *in vivo* SCID-rab bone multiple myeloma model. Because the cells secrete IgA1, we monitored tumor growth by using ELISA for human lambda light chain (huIg). When the average serum huIg concentration reached

Figure 5. Efficacy of anti-FcRL5 (hu10A8) ADCs at various dose levels. A, anti-FcRL5(hu10A8)-MC-vc-PAB-MMAE inhibited the growth of OPM2-FcRL5 tumors with an average starting volume of 190 mm³. Groups of 9 mice were i.v. dosed once as indicated (arrow) with 1, 3, 6, 9, or 18 mg ADC/kg mouse. B, anti-FcRL5(hu10A8)-SPDB-DM4 inhibited the growth of OPM2-FcRL5 tumors with an average starting volume of 185 mm³. Groups of 9 mice were i.v. dosed once as indicated (arrow) with 0.5, 1, 2, 4, 8, or 12 mg ADC/kg mouse. C, anti-FcRL5(hu10A8)-MC-vc-PAB-MMAE inhibited the growth of EJM-FcRL5 tumors with an average starting volume of 134 mm³. Groups of 8 mice were i.v. dosed once as indicated (arrow) with 1, 2, 4, or 8 mg ADC/kg mouse. D, anti-FcRL5 (hu10A8)-SPDB-DM4 inhibited the growth of EJM-FcRL5 tumors with an average starting volume of 130 mm³. Groups of 8 mice were i.v. dosed once as indicated (arrow) with 2, 4, or 8 mg ADC/kg mouse. Error bars represent SEM.



594 ng/mL, the mice were grouped out and treated. Mice treated with vehicle and control ADC continued to have an increase in serum huIg, whereas the anti-FcRL5-SPDB-DM4-treated mice showed a reduction in the serum human Ig that later increased after treatment had stopped (Fig. 6). These data show that, even in a higher *in vivo* model of multiple myeloma, supported by host stromal interactions, anti-FcRL5 ADCs can be effective.

Combining ADC with current drug treatments of multiple myeloma

Multiple myeloma is a difficult disease to treat; it is incurable and no single new treatment is likely to cure patients. Thus, it is important to establish whether anti-FcRL5 ADCs could combine with current therapies to improve treatment outcomes. We tested our 2 anti-FcRL5 ADCs in combination with bortezomib in the OPM2-FcRL5 xenograft model. Biweekly doses of 1 mg/kg bortezomib (the maximum tolerated dose in this model)

had similar efficacy as a single dose of 4 mg/kg of the anti-FcRL5-SPDB-DM4 or anti-FcRL5-MC-vc-PAB-MMAE, which slowed tumor growth without substantially regressing the tumors. However, the combination of anti-FcRL5-SPDB-DM4 and bortezomib resulted in 8 of 9 complete tumor remissions (Fig. 7A). Bortezomib plus anti-FcRL5-SPDB-DM4 showed significant activity compared with bortezomib alone ($P < 0.0001$; Supplementary Fig. S2), whereas bortezomib plus control-SPDB-DM4 did not ($P = 0.081$). Anti-FcRL5-MC-vc-PAB-MMAE plus bortezomib resulted in 3 of 9 complete tumor remissions (Fig. 7B). Anti-FcRL5-MC-vc-PAB-MMAE alone showed the same activity as bortezomib alone ($P = 0.7383$). The combination was significantly more efficacious than either single agent alone ($P < 0.0001$; Supplementary Fig. S3). In addition, we tested the combination of anti-FcRL5-MC-vc-PAB-MMAE and lenalidomide in the OPM2-FcRL5 xenograft model. Thirteen daily doses of 50 mg/kg lenalidomide (the maximum tolerated dose in this model) had

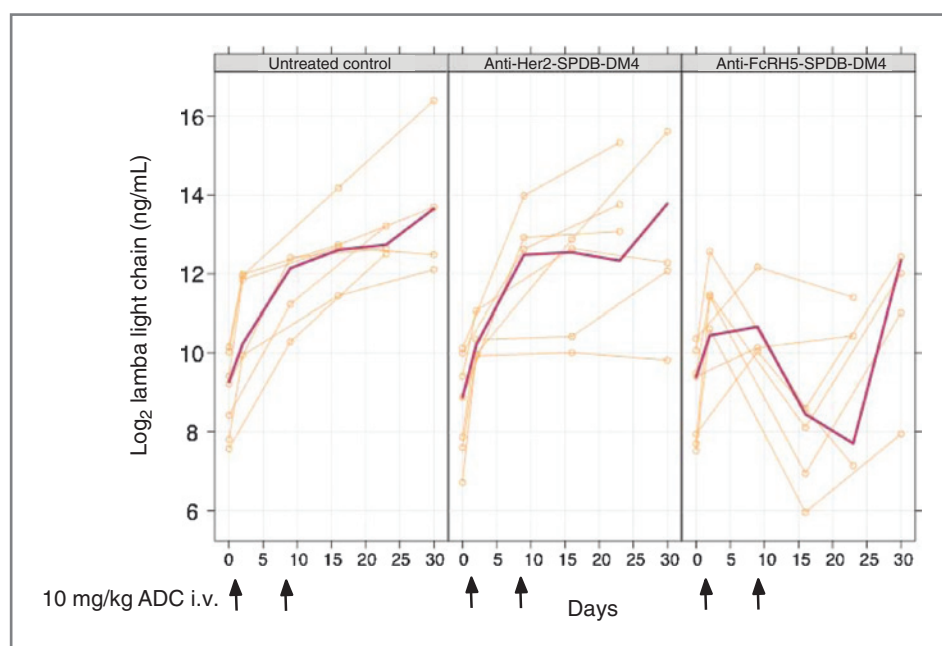


Figure 6. Anti-FcRL5-SPDB-DM4 is effective in the SCID-rab/LD model of MM. Anti-FcRL5-SPDB-DM4-treated mice showed reducing human Ig (hulg) serum level in the SCID-rab LD model with an average starting hulg concentration of 594 ng/mL. Groups of 6 to 8 mice were i.v. dosed 2 times as indicated (arrows) with 10 mg ADC/kg mouse. The red line represents the average concentration.

similar efficacy as a single dose of 6 mg/kg anti-FcRL5-MC-vc-PAB-MMAE (Fig. 7C); in both cases tumor growth slowed but there was no substantial regression of the tumors. The combination at the same doses caused regression of the tumors resulting in 8 of 8 tumors having partial remission. Anti-FcRL5-MC-vc-PAB-MMAE alone showed the same activity as lenalidomide alone ($P = 0.5453$) and the combination was more effective than either single agent alone ($P < 0.0001$; Supplementary Fig. S4).

Mice receiving single-agent anti-FcRL5 ADCs continued gaining weight over time, when tracked along with the vehicle group. In contrast, mice receiving bortezomib or lenalidomide had between 5% and 10% weight loss. In addition, the combination groups had 5% to 10% weight loss, indicating that anti-FcRL5 ADCs combined well with bortezomib or lenalidomide, and did not appear to exacerbate the weight loss caused by bortezomib or lenalidomide.

These data show that anti-FcRL5 ADCs, when used in combination with current treatments, can lead to substantially improved therapeutic outcomes.

Discussion

In this work, we examined FcRL5 as a target for antibody-based therapies. Our data characterizing FcRL5 as a marker indicate that the addition of FcRL5 to the current CD138 and CD38 plasma cell markers can further improve the diagnostic sensitivity and accuracy of multiple myeloma cell detection, especially in cases with aberrant immunophenotypes or when technical difficulties interfere with detection.

We detected FcRL5 expression on plasma cells from the vast majority of patients with multiple myeloma, which, combined with its restricted expression pattern and prevalence, led us to the conclusion that FcRL5 could be a target for antibody-based therapies for multiple myeloma.

One aspect of FcRL5 biology that could slightly complicate the use of anti-FcRL5 antibody therapies is that there is a soluble form of FcRL5 in circulation that is elevated in patients with multiple myeloma (15). This circulating form of FcRL5 could interfere with antibody-based therapies at low doses of antibody therapy or in the first few treatments.

Our results indicate that, while unmodified anti-FcRL5 antibodies are not effective therapeutically, anti-FcRL5 ADCs show promising antitumor efficacy in multiple preclinical models. We report on 2 anti-FcRL5 ADCs suitable for further testing in NHPs and use in humans. The linker drugs we have used, MC-vc-PAB-MMAE and SPDB-DM4, show promise in the context of other ADCs in early clinical trials. Brentuximab vedotin (SGN-35, anti-CD30-MC-vc-PAB-MMAE) is currently under development for the treatment of Hodgkin lymphoma (16) and CDX-011 (Anti-GPNMB MC-vc-PAB-MMAE) for the treatment of breast cancer and melanoma. In both cases, the maximum tolerated dose is ~ 1.8 mg/kg every 3 weeks with the primary dose-limiting toxicities being diarrhea and leukopenia and, in the case of CR011, target-mediated skin toxicities (17). nBT062 (anti-CD138-SPDB-DM4) is being tested for the treatment of multiple myeloma. CD138 is found on the basolateral surface of epithelial cells, vascular smooth muscle cells, and the endothelium (ref. 18 and references therein). nBT062 has shown promising preclinical activity in xenograft models of multiple myeloma (19, 20) and, on the basis of these data, a phase 1 clinical trial was started where patients were treated every 3 weeks at 7 dose levels ranging from 10 to 200 mg/m². The skin, eye, and gastrointestinal tract are the target organs for toxicity at high doses (21). The ocular toxicity is probably not target dependent as this has been observed with other ADCs containing the SPDB-DM4 linker drug

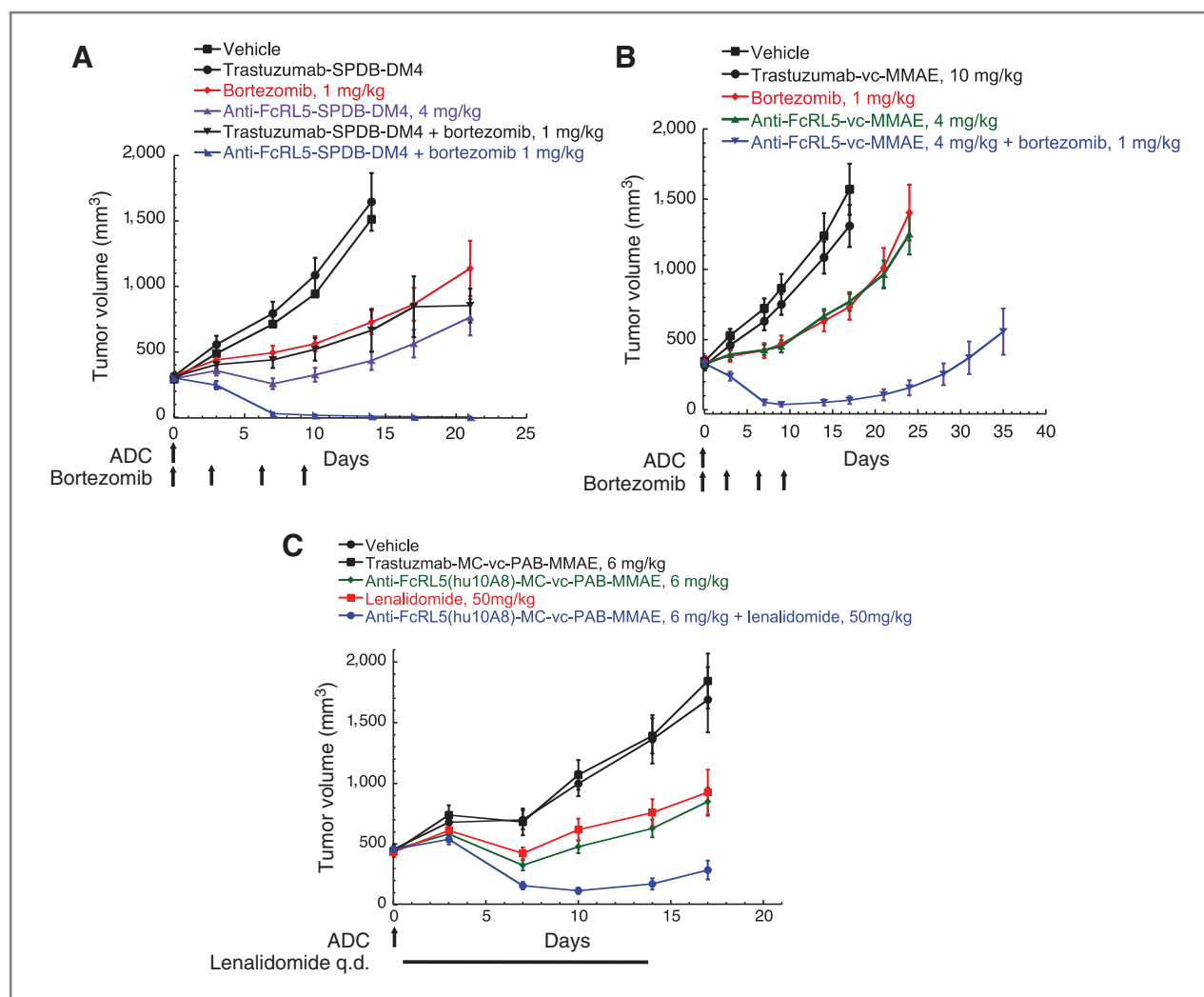


Figure 7. Anti-FcRL5 ADCs showed greater activity when combined with standard of care therapeutics. OPM2-FcRL5 cell line (2×10^7) was injected into mice, and the resulting tumors were treated with: A, a single dose of 4 mg anti-FcRL5-SPDB-DM4/kg mouse or twice weekly doses as indicated (arrows) of 1 mg bortezomib/kg mouse as single-agent or in combination. Average starting volume was 306 mm³ for the groups of 9 mice. B, a single dose of 4 mg anti-FcRL5-MC-vc-PAB-MMAE/kg mouse or twice weekly doses as indicated (arrows) of 1 mg bortezomib/kg mouse as single-agent or in combination. Average starting volume was 331 mm³ for the groups of 9 mice. C, a single dose of 6 mg anti-FcRL5-MC-vc-PAB-MMAE/kg mouse and daily doses as indicated (line) of 50 mg lenalidomide/kg mouse as single-agent or in combination. Average starting volume was 446 mm³ for the groups of 8 mice. Error bars represent SEM.

(e.g., SAR3419; ref. 22). However, the skin and GI toxicity could be due to target expression in these tissues. In the 20 evaluable patients, 7 showed clinical benefit and 2 showed an objective response.

In addition to nBT062, an ADC targeting CD56, IMGN901 (huN901-DM1), is in phase 1 clinical trials. IMGN901 (huN901-DM1) is a humanized anti-CD56 antibody with a linker cleavable by disulfide reduction (SPP) attached to the maytansinoid DM1. CD56 is expressed in NK cells, a subpopulation of T lymphocytes, neural tissue, and muscle. Although CD56 is not found in normal plasma cells, it is expressed in 70% of multiple myeloma (23). In the current phase 1 trial, patients with CD56⁺ relapsed or refractory multiple myeloma received a single intravenous infusion of IMGN901 on 2 consecutive weeks

every 3 weeks at doses ranging from 40 to 140 mg/m². Headache, fatigue, and neuropathy were the major adverse events and 1 of the 25 patients showed a partial response. That patient had been on treatment for more than a year (24).

FcRL5 offers advantages over other ADC targets for the treatment of multiple myeloma because the normal tissue expression of FcRL5 is limited to B cells and plasma cells and it is found on most, if not all, multiple myeloma. A broader expression pattern can lead to damage of normal tissues and more rapid clearance of the ADC due to the antigen acting as a sink, limiting the therapeutic potential of the ADC. FcRL5-ADCs can overcome these problems and deliver the therapeutic agent selectively to the tumor, thus increasing the therapeutic index. The promising

clinical data with other ADCs using MC-vc-PAB-MMAE and SPDB-DM4, combined with our preclinical efficacy data in several multiple myeloma preclinical models, clearly show that both anti-FcRL5-MC-vc-PAB-MMAE and anti-FcRL5-SPDB-DM4 are potentially effective ADCs for the treatment of multiple myeloma, both as single agents and especially in combination with currently approved multiple myeloma therapeutics.

Disclosure of Potential Conflicts of Interest

A. Rawstron has honoraria from Speakers Bureau of Roche and GlaxoSmithKline and is a consultant/advisory board member for Celgene, Biogen Idec, and BD Biosciences. No potential conflicts of interest were disclosed by the other authors.

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References

- Carter PJ, Senter PD. Antibody–drug conjugates for cancer therapy. *Cancer J* (Sudbury, Mass) 2008;14:154–69.
- Polakis P. Arming antibodies for cancer therapy. *Curr Opin Pharmacol* 2005;5:382–7.
- Polson AG, Ho WY, Ramakrishnan V. Investigational antibody–drug conjugates for hematological malignancies. *Expert Opin Investig Drugs* 2011;20:75–85.
- Davis RS, Ehrhardt GR, Leu CM, Hirano M, Cooper MD. An extended family of Fc receptor relatives. *Eur J Immunol* 2005;35:674–80.
- Dement-Brown J, Newton CS, Ise T, Damdinsuren B, Nagata S, Tolnay M. Fc receptor-like 5 promotes B cell proliferation and drives the development of cells displaying switched isotypes. *J Leukoc Biol* 2012;91:59–67.
- Hatzivassiliou G, Miller I, Takizawa J, Palanisamy N, Rao PH, Iida S, et al. IRTA1 and IRTA2, novel immunoglobulin superfamily receptors expressed in B cells and involved in chromosome 1q21 abnormalities in B cell malignancy. *Immunity* 2001;14:277–89.
- Polson AG, Zheng B, Elkins K, Chang W, Du C, Dowd P, et al. Expression pattern of the human FcRH/IRTA receptors in normal tissue and in B-chronic lymphocytic leukemia. *Int Immunol* 2006;18:1363–73.
- Inoue J, Otsuki T, Hirasawa A, Imoto I, Matsuo Y, Shimizu S, et al. Overexpression of PDZK1 within the 1q12-q22 amplicon is likely to be associated with drug-resistance phenotype in multiple myeloma. *Am J Pathol* 2004;165:71–81.
- Carter P, Presta L, Gorman CM, Ridgway JB, Henner D, Wong WL, et al. Humanization of an anti-p185HER2 antibody for human cancer therapy. *Proc Natl Acad Sci U S A* 1992;89:4285–9.
- Doronina SO, Toki BE, Torgov MY, Mendelsohn BA, Cerveny CG, Chace DF, et al. Development of potent monoclonal antibody auristatin conjugates for cancer therapy. *Nat Biotechnol* 2003;21:778–84.
- Polson AG, Yu SF, Elkins K, Zheng B, Clark S, Ingle GS, et al. Antibody–drug conjugates targeted to CD79 for the treatment of non-Hodgkin's lymphoma. *Blood* 2007;110:616–23.
- Yata K, Yaccoby S. The SCID-rab model: a novel *in vivo* system for primary human myeloma demonstrating growth of CD138-expressing malignant cells. *Leukemia* 2004;18:1891–7.
- Li X, Pennisi A, Zhan F, Sawyer JR, Shaughnessy JD, Yaccoby S. Establishment and exploitation of hyperdiploid and non-hyperdiploid human myeloma cell lines. *Br J Haematol* 2007;138:802–11.
- Ducry L, Stump B. Antibody–drug conjugates: linking cytotoxic payloads to monoclonal antibodies. *Bioconjug Chem* 2010;21:5–13.
- Ise T, Nagata S, Kreitman RJ, Wilson WH, Wayne AS, Stetler-Stevenson M, et al. Elevation of soluble CD307 (IRTA2/FcRH5) protein in the blood and expression on malignant cells of patients with multiple myeloma, chronic lymphocytic leukemia, and mantle cell lymphoma. *Leukemia* 2007;21:169–74.
- Bartlett NL, Grove LE, Kennedy DA, Sievers EL, Forero-Torres SA. Objective responses with brentuximab vedotin (SGN-35) retreatment in CD30-positive hematologic malignancies: a case series. *J Clin Oncol* 2010 (suppl; abstr 8062).
- Burris H, Saleh M, Bendell J, Hart L, Rose A, Dong Z, et al. A phase (Ph) I/II study of CR011-VcMMAE, an antibody–drug conjugate, in patients (Pts) with locally advanced or metastatic breast cancer (MBC) [abstarct]. In: *Proceedings of the 32nd Annual CTRC-AACR San Antonio Breast Cancer Symposium*; 2009 Dec 10–13; San Antonio, TX. Philadelphia (PA): AACR; 2009. Abstract nr 6096.
- Barclay AN, Brown M, Law SKA, McKinght AJ, Tomlinson MG, Anton van der Merwe P. *The leucocyte antigen facts book*. San Diego, CA: Academic Press; 1997.
- Keda H, Hideshima T, Fulciniti M, Lutz RJ, Hiroshi Y, Okawa Y, et al. The monoclonal antibody nBT062 conjugated to cytotoxic maytansinoids has selective cytotoxicity against CD138 positive multiple myeloma cells *in vitro* and *in vivo*. *Clin Cancer Res* 2009;15:4028–37.
- Polson AG, Sliwkowski MX. Toward an effective targeted chemotherapy for multiple myeloma. *Clin Cancer Res* 2009;15:3906–7.
- Chanan-Khan AA, Jagannath S, Heffner LT, Avigan D, Lee KP, Lutz RJ, et al. Phase I study of BT062 given as repeated single dose once every 3 weeks in patients with relapsed or relapsed/refractory multiple myeloma. *ASH Annual Meeting Poster session Abstracts* 2009;114:1862.
- Younes A, Gordon L, Kim S, Romaguera J, Copeland AR, de Castro Farial S, et al. Phase I multi-dose escalation study of the anti-CD19 maytansinoid immunoconjugate SAR3419 administered by intravenous (IV) infusion every 3 weeks to patients with relapsed/refractory B-cell non-hodgkin's lymphoma (NHL). *ASH Annual Meeting Abstracts* 2009;114:585.
- Chanan-Khan AA, Jagannath S, Munshi NC, Schlossman RL, Anderson KC, Lee K, et al. Phase I study of huN901-DM1 (BB-10901) in patients with relapsed and relapsed/refractory CD56-positive multiple myeloma. *ASH Annual Meeting Abstracts* 2007;110:1174.
- Chanan-Khan A, Wolf J, Gharibo M, Jagannath S, Munshi NC, Anderson KC, et al. Phase I study of IMG901, Used as monotherapy, in patients with heavily pre-treated CD56-positive multiple myeloma - a preliminary safety and efficacy analysis. *ASH Annual Meeting Abstracts* 2009;114:2883.