

An inhibitor of proteasome $\beta 2$ sites sensitizes myeloma cells to immunoproteasome inhibitors

Sondra Downey-Kopyscinski,¹⁻³ Ellen W. Daily,² Marc Gautier,² Ananta Bhatt,² Bogdan I. Florea,⁴ Constantine S. Mitsiades,³ Paul G. Richardson,³ Christoph Driessen,⁵ Herman S. Overkleeft,⁴ and Alexei F. Kisselev^{2,6}

¹Program in Experimental and Molecular Medicine and ²Department of Medicine and Norris Cotton Cancer Center, Geisel School of Medicine at Dartmouth and Dartmouth-Hitchcock Medical Center, Lebanon, NH; ³Dana-Farber Cancer Institute, Boston MA; ⁴Leiden Institute of Chemistry and Netherlands Proteomics Centre, Leiden University, Leiden, The Netherlands; ⁵Department of Hematology and Oncology, Kantonsspital St. Gallen, St. Gallen, Switzerland; and ⁶Veterans Affairs Medical Center, White River Junction, VT

Key Points

- Immunoproteasome inhibitor ONX-0914 has antimyeloma activity in vitro similar to that of bortezomib and carfilzomib.
- LU-102 sensitizes MM cells to a pharmacologically relevant concentration of ONX-0914, which synergizes with bortezomib in vivo.

Proteasome inhibitors bortezomib, carfilzomib and ixazomib (approved by the US Food and Drug Administration [FDA]) induce remissions in patients with multiple myeloma (MM), but most patients eventually become resistant. MM and other hematologic malignancies express ubiquitous constitutive proteasomes and lymphoid tissue-specific immunoproteasomes; immunoproteasome expression is increased in resistant patients. Immunoproteasomes contain 3 distinct pairs of active sites, $\beta 5i$, $\beta 1i$, and $\beta 2i$, which are different from their constitutive $\beta 5c$, $\beta 1c$, and $\beta 2c$ counterparts. Bortezomib and carfilzomib block $\beta 5c$ and $\beta 5i$ sites. We report here that pharmacologically relevant concentrations of $\beta 5i$ -specific inhibitor ONX-0914 show cytotoxicity in MM cell lines similar to that of carfilzomib and bortezomib. In addition, increasing immunoproteasome expression by interferon- γ increases sensitivity to ONX-0914 but not to carfilzomib. LU-102, an inhibitor of $\beta 2$ sites, dramatically sensitizes MM cell lines and primary cells to ONX-0914. ONX-0914 synergizes with all FDA-approved proteasome inhibitors in MM in vitro and in vivo. Thus, immunoproteasome inhibitors, currently in clinical trials for the treatment of autoimmune diseases, should also be considered for the treatment of MM.

Introduction

Multiple myeloma (MM) is a plasma cell malignancy with a median survival of approximately 7 years.^{1,2} The proteasome inhibitors bortezomib, carfilzomib, and ixazomib are critical components of MM treatment regimens. Although initial response rates with these treatments are high, the majority of patients eventually become resistant and succumb to the disease, underlining a need for new treatments.

MM cells express constitutive proteasomes and immunoproteasomes. The constitutive proteasomes are expressed ubiquitously through the body, whereas immunoproteasomes are highly expressed in cells and tissues of the immune system^{3,4} and constitute 30% to 90% of the total proteasomes in MM cells.^{5,6} A decrease in the expression of immunoproteasomes correlates with a better response to bortezomib in patients,⁷ whereas patients with relapsed/refractory MM show increased immunoproteasome activity.⁸ Thus, immunoproteasome inhibition may be the key to increasing proteasome inhibition (and thereby enhancing MM cell death) in patients with relapsed/refractory MM.

Both types of proteasomes have 3 pairs of active sites, the $\beta 5c$ (PSMB5, or chymotrypsin-like), $\beta 1c$ (PSMB6, or caspase-like), and the $\beta 2c$ (PSMB7, or trypsin-like) sites in the constitutive proteasome and the $\beta 5i$ (PSMB8, LMP7), $\beta 1i$ (PSMB9, LMP2), and the $\beta 2i$ (PSMB10, LMP10, MECL1) sites in the immunoproteasome.⁹ Bortezomib, carfilzomib and ixazomib are potent inhibitors of the $\beta 5i$ and $\beta 5c$ sites. Previous studies have shown that specific inhibition of $\beta 5i$ is not sufficient to kill myeloma cells⁶;

however, it is not known whether coinhibition of $\beta 1i$ and $\beta 2i$ sites will make an inhibitor cytotoxic. We developed LU-102, a specific cell-permeable inhibitor of $\beta 2$ sites and found that it dramatically sensitizes myeloma and solid tumor cells to bortezomib and carfilzomib,^{10,11} restores sensitivity of primary cells from bortezomib- and carfilzomib-resistant myeloma patients to these agents, and synergizes with carfilzomib in murine models of myeloma.¹² Combined inhibition of $\beta 5$ and $\beta 2$ sites may increase mechanism-based toxicity (eg, gastrointestinal, renal, and cardiac toxicities) because of increased inhibition of protein breakdown in these tissues; however, replacing bortezomib and carfilzomib with an immunoproteasome inhibitor should reduce these adverse effects because expression of immunoproteasomes in these tissues is low. Mice lacking all 3 immunoproteasomes subunits are viable.¹³

Although several immunoproteasome inhibitors have been tested against MM cells, their specificity at active doses was not confirmed,^{5,14-17} and the effect of combined inhibition of $\beta 5i$ and $\beta 2$ sites has not been explored. $\beta 5i$ inhibitor ONX-0914 (PR-957) has *in vivo* activity in murine models of many different autoimmune disorders,¹⁸⁻²² in which selective killing of auto-antibody plasma cells is believed to contribute to efficacy. A derivative of ONX-0914, KZR-616, is currently being developed for the treatment of autoimmune diseases. It recently completed a successful phase 1a study in healthy volunteers (ACTRN12616001040459)²³ and seems to bypass the toxic effects (eg, gastrointestinal toxicities, neurotoxicity). Therefore, the possibility of repositioning KZR-616 for the treatment of MM must be explored.

KZR-616 is not yet available to us; therefore, we used ONX-0914 as a compound tool to determine of feasibility of inhibition immunoproteasomes for the treatment of MM. Here, we demonstrate that MM cells, which are sensitive to clinically relevant concentrations of carfilzomib and bortezomib, also respond to treatment with pharmacologically relevant concentrations of ONX-0914. Furthermore, we demonstrate that subtoxic doses of the $\beta 2$ inhibitor LU-102 strongly sensitize MM cells to ONX-0914, as observed previously for bortezomib and carfilzomib.^{11,12,24} We also found that ONX-0914 synergizes with inhibitors approved by the US Food and Drug Administration (FDA) *in vitro* as well as *in vivo*.

Materials and methods

Cell lines

KMS-11 cells were purchased from the Health Science Research Resources Bank (Osaka, Japan). NCI-H929 and RPMI-8226 cells were purchased from the American Type Culture Collection. All other cells lines were authenticated by the University of Vermont Human Cell Line Authentication Facility. Cells were cultured in RPMI-1640 (Hyclone) medium supplemented with 10% fetal bovine serum (Hyclone), penicillin (100 μ g/mL), streptomycin (100 U/mL), and the antimycoplasma antibiotic Plasmocin (1.5 μ g/mL; InvivoGen, San Diego, CA). Patient samples were collected in accordance with the Declaration of Helsinki and under the protocol approved by the Dartmouth College Committee on Protection of Human Subjects or approved by the Dana-Farber Cancer Institute Committee on Protection of Human Subjects, and all animal experiments were conducted according to the protocol approved by Dartmouth Institutional Animal Care and Use Committee.

Cell-based assays

Bortezomib, carfilzomib, and ixazomib were purchased from LC Laboratories, and ONX-0914 was purchased from MedKoo. LU-102 was synthesized as described.¹¹ Unless otherwise stated, cell lines were treated with carfilzomib, bortezomib, ONX-0914, and ixazomib for 1 hour and then cultured in the presence or absence of LU-102 for 47 hours; viability was then assessed with Alamar Blue mitochondrial dye conversion assay (Invitrogen or Bio-Rad) as described.²⁵ For flow cytometry, CD138-PE (BD Pharmingen #550805) and Zombie Aqua Fixable Viability Kit (BioLegend #423101) were used. The values on all graphs are averages \pm standard error of the mean of a number of experiments (supplemental Table 1). At least 2 biological replicates were averaged to define the 4-parameter fit of concentration-dependence curves used to determine the half maximal inhibitory concentration.

Cells were lysed with 0.05% digitonin in 50 mM tris(hydroxymethyl)aminomethane (pH 7.5), 250 mM sucrose, 5 mM $MgCl_2$, 1 mM adenosine triphosphate, 0.5 mM EDTA, and 1 mM dithiothreitol. To assay activity of $\beta 5i$, $\beta 5c$, $\beta 1i$, and $\beta 1c$ subunits, 10 μ g of protein were coincubated with 2.5 μ M BODIPY-NC-001 and BODIPY-NC-005-VS (compounds 23 and 24 in Verdoes et al²⁶) for 1 hour at 37°C. To resolve $\beta 2$, $\beta 2i$, $\beta 1$, and $\beta 1i$ subunits, extracts were co-treated with MV-151²⁷ and BODIPY-NC-001.²⁶ Proteasome subunits were separated by sodium dodecyl sulfate-polyacrylamide gel electrophoresis using 0.75-mm-thick 12.5% gels and a Laemmli buffer system. Probe-modified subunits were revealed by fluorescent imaging. Gels were then stained with Coomassie blue dye as a loading control. $\beta 5i$ and $\beta 5c$ activity was determined using the 7-amino-4-methylcoumarin amide (amc) substrates Suc-LLVY-amc ($\beta 5c$ + $\beta 5i$, 100 μ M) and Ac-ANW-amc ($\beta 5i$, 200 μ M)²⁸ as described.^{24,29}

In vivo testing

Male NSG (Nod/Scid/IL-2 receptor γ -chain knockout; The Jackson Laboratory) mice were treated with 100 cgy of radiation (from a cesium irradiator; sublethal dose) based on Mitsiades et al.³⁰ The following day, 2 million MM1.S cells in phosphate-buffered saline were injected into these mice via the tail vein. Bortezomib (0.5 mg/kg) and ONX-0914 (up to 15 mg/kg) were dissolved in 10 mM calcium citrate (pH 6), with 10% Captisol and injected subcutaneously 2 times per week (as indicated in Figure 4D). Animals were euthanized when they began dragging a hind leg. Blood samples were taken, and human immunoglobulin G λ levels were determined by western blot using anti-human λ -chain antibody (Vector, #AI-33070, 1:500), with a fluorescently labeled anti-goat secondary antibody (Rockland, #605-745-002, 1:10000), and they were imaged on an Odyssey (LICOR) scanner.

Results

ONX-0914 is cytotoxic to MM cells that express high levels of $\beta 5i$

To determine whether the immunoproteasome content in cultured MM cells is similar to that of primary MM cells in which 30% to 90% of proteasomes are immunoproteasomes,⁵ we treated extracts with activity-based probes (ie, fluorescently labeled irreversible inhibitors) BODIPY-NC-005-vs and BODIPY-NC-001,²⁶ and then resolved the fluorescently labeled subunits on an sodium

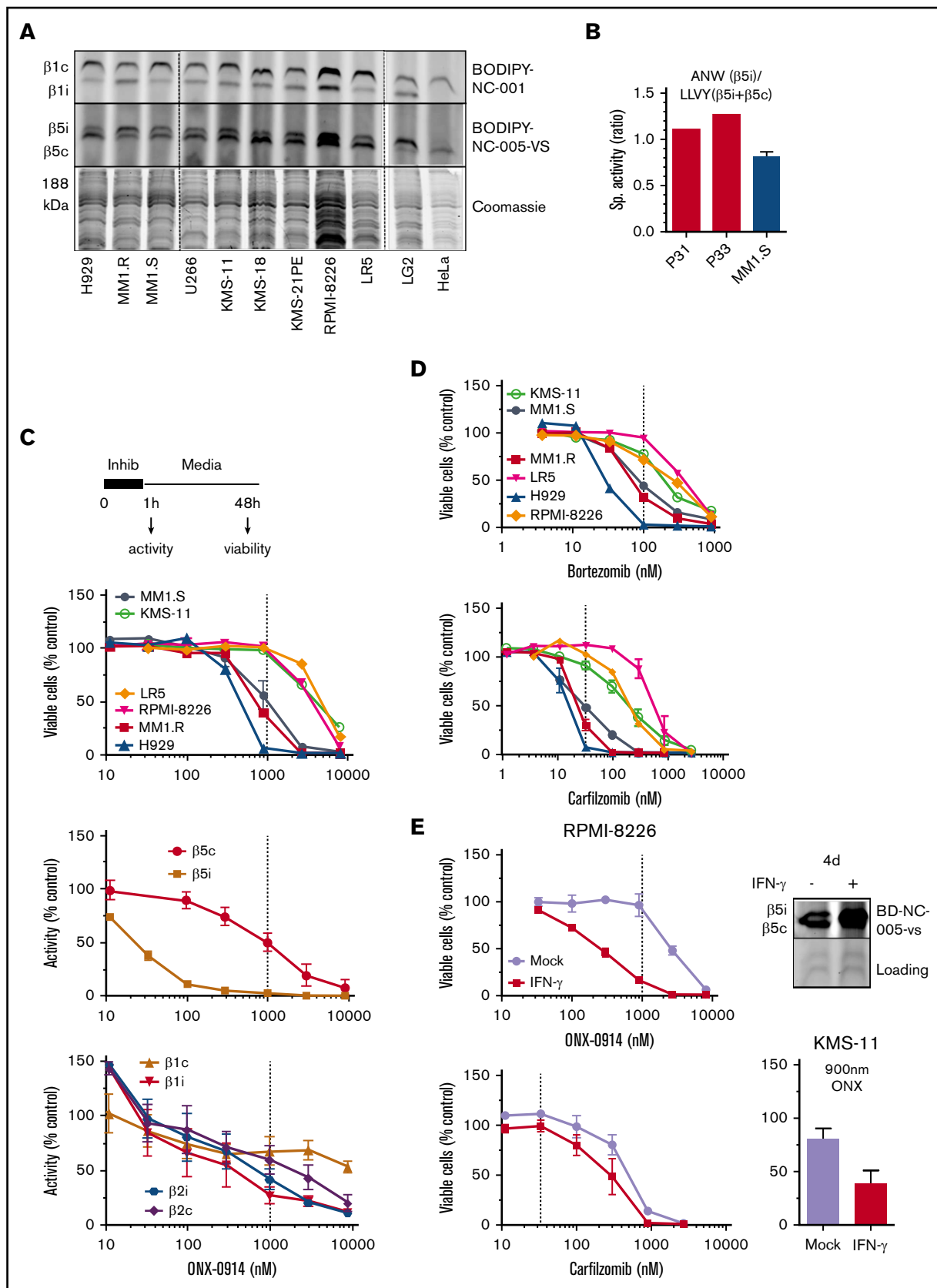


Figure 1. Effect of ONX-0914 on MM cells. (A) Expression of immunoproteasomes in MM cell lines as determined by the activity-based probes. Immortalized B-cell line LG2, which expresses high levels of immunoproteasomes, and HeLa cells, which express little or no immunoproteasomes were used as references ($n = 2$). (B) Cleavage rates

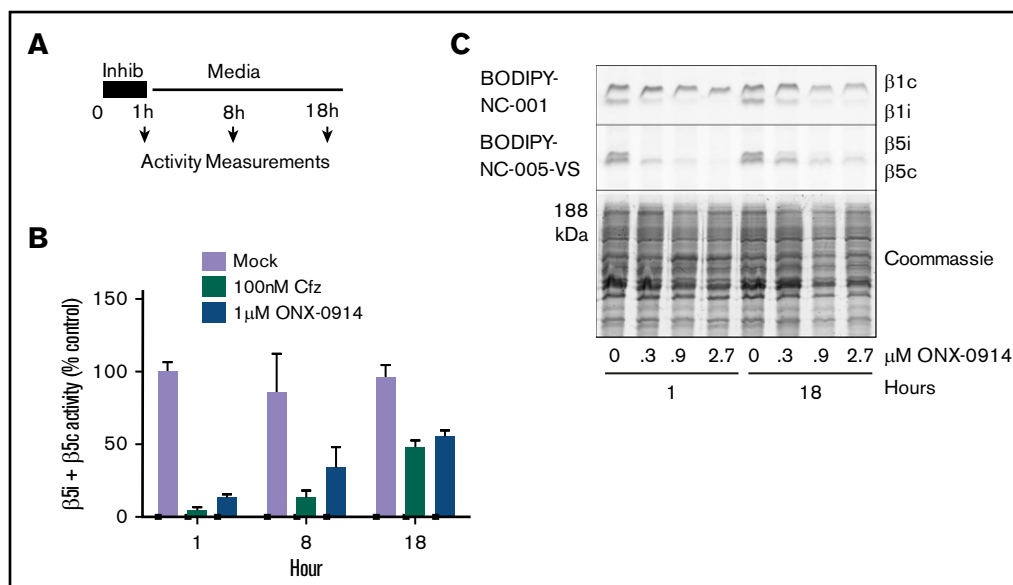


Figure 2. ONX-0914 treated cells upregulate β5c. (A) RPMI-8226 cells were treated as shown. At times indicated, either total β5 (β5i + β5c) activity was measured with Suc-LLVY-amc (n = 2) (B) or individual subunits were measured with ABPs (n = 2) (C).

dodecyl sulfate-polyacrylamide gel electrophoresis gel (Figure 1A). Most MM cells have almost equal amounts of active β5i and β5c (MM1.S, U266, RPMI-8226) or have a greater amount of β5c (H929, KMS-11, KMS-18, KMS-21-PE, LR5). Thus, cultured MM cells express immunoproteasomes, although they have slightly lower β5i:β5c ratios than the primary myeloma cells reported in the literature⁵ or that we isolated from patients (Figure 1B).

We then pulse-treated a panel of 6 MM cells with ONX-0914 for 1 hour and determined their viability 48 hours later (Figure 1C). The pulse treatment better mimics the bolus injections currently used in patients than the continuous exposure used in most *in vitro* studies.²⁵ In parallel experiments, we assessed the extent to which ONX-0914 inhibits the different active sites in MM1.S cells (Figure 1C). Although β5i specific at low concentrations (eg, 100 nM), this agent inhibited other subunits of immune and constitutive proteasomes at higher concentrations. ONX-0914 (1 μM) inhibited proteasomes to the same degree as it did in the tissues of treated mice at the maximum tolerated dose.¹⁸ This represents complete inhibition of β5i and ~50% inhibition of β5c, β1i, and β1c (Figure 1C). Therefore, for the remainder of the study, we considered 1 μM ONX-0914 to be a pharmacologically relevant concentration. This concentration was cytotoxic to several cell lines. We have previously reported that a 1-hour pulse with 100 nM bortezomib leads to a clinically achievable 75% inhibition of β5 subunits²⁵ and that 33 nM carfilzomib causes

the clinically achievable ~90% β5 inhibition.²⁴ As with ONX-0914, bortezomib and carfilzomib reduced the viability of MM1.S, MM1.R, and H929 cells, but not of any other cell lines at these clinically relevant concentrations (Figure 1D). Thus, at relevant doses, ONX-0914 has *in vitro* cytotoxicity similar to that of carfilzomib and bortezomib.

Because primary cells have a higher β5i:β5c ratio (Figure 1B), we tested whether increasing the expression of β5i by interferon-γ (IFN-γ) specifically enhances sensitivity to an immunoproteasome inhibitor. Indeed, IFN-γ treatment increased cytotoxicity to ONX-0914, but not to carfilzomib (Figure 1E), indicating that increased expression of immunoproteasomes enhances sensitivity to immunoproteasome inhibitors.

Cells upregulate β5c as they recover from β5i inhibition

With the exception of the few most sensitive MM cell lines, proteasome activity in MM cells recovers after treatment with clinically relevant concentrations of bortezomib.²⁵ A 1-hour pulse treatment of RPMI-8226 cells with subtoxic levels (1 μM) of ONX-0914 or with 100 nM carfilzomib (Figure 2A) causes a similar recovery of total β5 activity (eg, combined β5i and β5c activity) within 18 hours (Figure 2B-C). This recovery is mediated by the transcription factor Nrf1,^{31,32} which regulates the transcription of all constitutive proteasome subunits, but

Figure 1. (continued) of β5i-specific substrate Ac-ANW-amc and of β5c and β5i substrate Suc-LLVY-amc were measured in extracts of primary MM cells isolated from relapsed/refractory patients using EasySep Human CD138 Positive Selection Kit II (STEMCELL Technologies, Catalog #18357), and ANW:LLVY ratio was used as readout of relative β5i expression. (C) ONX-0914 is cytotoxic to MM cells. Top: cells were treated with ONX-0914 for 1 hour followed by Alamar Blue assay 47 hours later (n = 2-3; see supplemental Table 1 for exact number of cells for each cell line). In a parallel experiment, proteasome inhibition was measured by site-specific fluorogenic substrates (middle graph) or activity-based probes (bottom graph) immediately after 1-hour treatment with ONX-0914 (n = 4). Dashed line indicates *in vivo* relevant inhibition (eg, concentration that causes ≥95% of β5i and ~50% of β5c inhibition similar to maximal tolerated dose *in vivo*¹⁸). (D) Clinically relevant concentrations of bortezomib or carfilzomib (n = 2-3) have cytotoxicity similar to that of ONX-0914. Dashed lines indicate clinically relevant doses. Except for KMS-11 (n = 5), bortezomib data are from Figure 1 of Shabaneh et al.²⁵ (E) IFN-γ treatment increases the sensitivity of MM cells to ONX-0914, but not to carfilzomib. Cells were treated with IFN-γ for 5 days and then treated with ONX-0914 (upper left and bottom right) or carfilzomib (bottom left) as in panel C. Upper right panel shows increase in β5i activity after 4 days as measured by BODIPY-NC-005-VS (n = 2-3). Sp., specific.

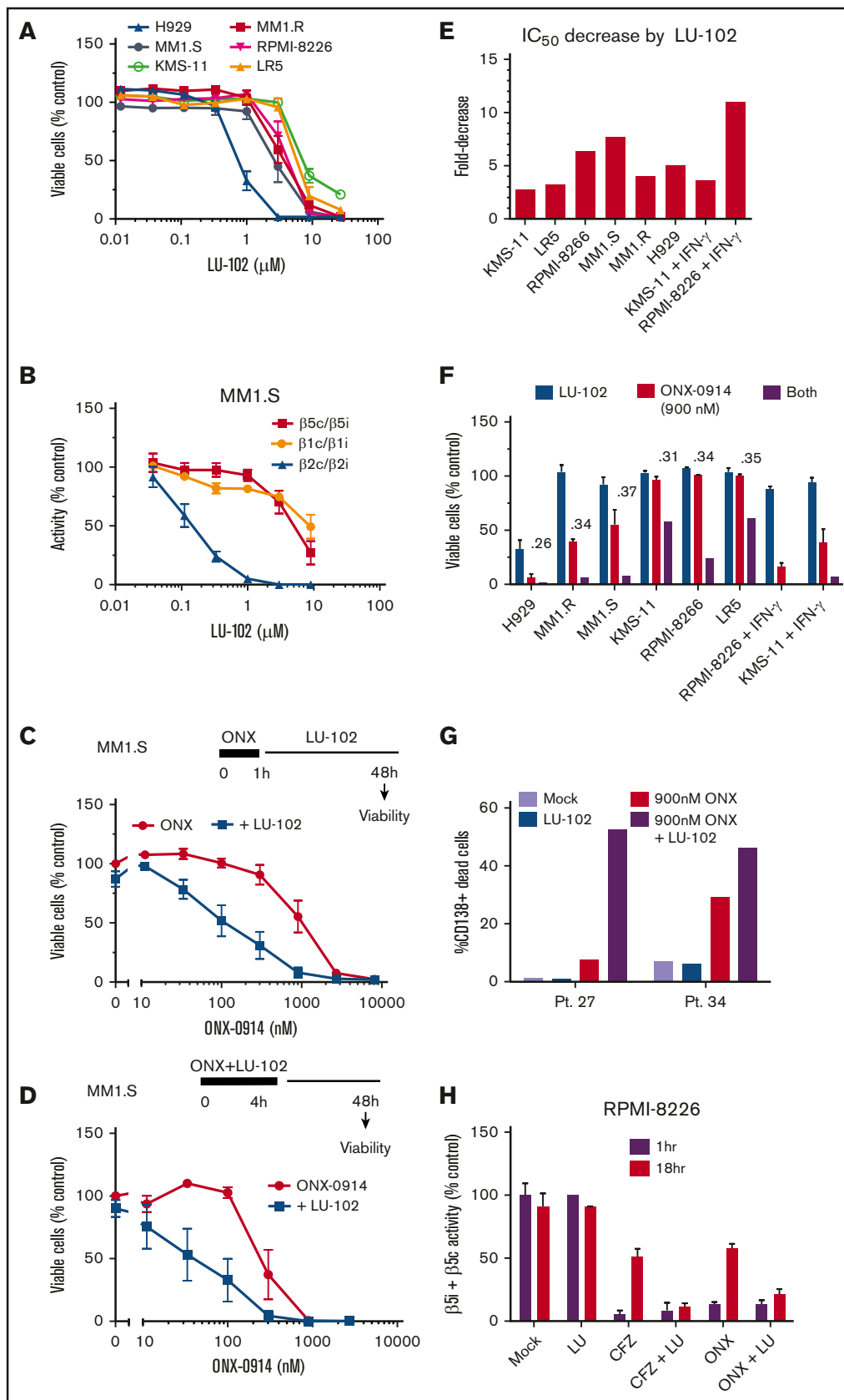


Figure 3. Addition of LU-102 sensitizes cells to in vivo relevant concentrations of ONX-0914. (A) Effect of 48-hour treatment with LU-102 on viability of MM cells as determined by Alamar Blue ($n = 2-4$). (B) Inhibition of proteasome in MM1.S cells after 2-hour treatment as determined by the Proteasome-Glo

not of $\beta 5i$ (PSMB8) and other immunoproteasome subunits.³³ We conclude that $\beta 5c$ -dependent recovery of proteasome activity can desensitize MM cells to $\beta 5i$ inhibitors, suggesting that an agent that blocks recovery should be able to increase the efficacy of immunoproteasome inhibitors.

LU-102 sensitizes cells to clinically relevant concentrations of ONX-0914

We have shown that LU-102, the $\beta 2c$ and $\beta 2i$ inhibitor, dramatically sensitizes MM cells to bortezomib and carfilzomib,^{11,12} and that the mechanism of such sensitization involves inhibition of the Nrf1-dependent recovery of proteasome activity.¹⁰ On the basis of this phenomenon, we next tested whether LU-102 sensitizes cells to ONX-0914. When used as a single agent, LU-102 did not cause cell death at $\beta 2c/\beta 2i$ -specific concentrations (Figure 3A-B), except in the H929 cells that are highly sensitive to all proteasome inhibitors. However, subtoxic $\beta 2$ -specific concentrations of LU-102 dramatically sensitized MM cell lines to ONX-0914 (Figure 3C-D; supplemental Figure 1A), decreasing the half maximal inhibitory concentration by threefold to eightfold (Figure 3E) and reducing viability of all cell lines treated for 1 hour with the pharmacologically relevant 0.9 μ M ONX-0914 (Figure 3F). LU-102-induced decrease in viability was similar in magnitude to the reduction seen in carfilzomib-treated cells (supplemental Figure 1). The cells treated with IFN- γ were especially sensitive to the combined treatments. Importantly, LU-102 synergized with ONX-0914 in inducing death of CD138⁺ cells from MM patients (Figure 3G). As expected, LU-102 blocked the recovery of $\beta 5$ activity after treatment with either carfilzomib or ONX-0914 (Figure 3H). Thus, LU-102 is a potent sensitizer of MM cells to ONX-0914.

Addition of ONX-0914 to FDA-approved inhibitors overcomes resistance

Our previous data indicate that inhibition of the $\beta 5i$ site is most effective when $\beta 5c$ sites are also partially inhibited. These conditions are achieved by combining ONX-0914 with lower subtoxic doses of carfilzomib or bortezomib. Because such combinations can be introduced into clinical trials more rapidly than LU-102, we combined ONX-0914 and the FDA-approved proteasome inhibitors. ONX-0914 synergized with bortezomib, carfilzomib, and ixazomib in MM1.S (Figure 4A) and RPMI-8226 (Figure 4B) cell lines.

We decided to determine whether this synergistic interaction can be recapitulated in an orthotopic murine model of MM, in which MM cells form tumors in bone marrow if they are injected via the tail vein into irradiated immunodeficient mice.³⁰ Bortezomib was chosen over carfilzomib for this study because initial clinical trials are performed in heavily pretreated patients, and phase 1 trial candidates are more

likely to be refractory to bortezomib than to carfilzomib. The onset of paraplegia and the presence of immunoglobulin G λ -light chain levels in the serum were used as readouts for tumor growth. Bortezomib treatment alone slightly but significantly increased the overall survival in the experimental model compared with vehicle-injected mice (Figure 4C). Although ONX-0914 treatment alone did not increase survival, the combination of ONX-0914 and bortezomib delayed the appearance of λ -light chains in blood and significantly increased the overall survival compared with the vehicle group and the bortezomib-only group without obvious signs of additional toxicity. Thus, ONX-0914 synergizes with bortezomib *in vivo*.

Discussion

Our data provide a strong rationale for the use of a combination therapy that includes immunoproteasomes and $\beta 2$ inhibitors. ONX-0914 is the precursor of KZR-616, which is currently being developed for the treatment of autoimmune disorders and for which a phase 1 trial in healthy volunteers has been successfully completed.²³ Although KZR-616 was not available to us, the active site inhibition profile for it resembles that for ONX-0914, which has been used in our work (Christopher Kirk, Kezar Life Sciences, oral communication, 18 April 2017). Because $\beta 2$ inhibitors are at the early stages of preclinical development, an increase in overall survival of mice treated with bortezomib and ONX-0914 suggests that combinations of KZ-616 with one of the FDA-approved proteasome inhibitors will yield the fastest route to the clinic.

To successfully translate these findings in the clinic, upregulation of constitutive proteasomes in response to $\beta 5i$ inhibition, which we detected independently (Figure 2) and which 2 other laboratories also detected,^{17,34} must be addressed. We suggest that immunoproteasome inhibitors should be combined with agents that, like LU-102, block the recovery of activity. Expression of constitutive proteasomes is upregulated by Nrf1. Nrf1 activation involves ubiquitin, VCP ATPase, and proteolytic activation by DDI2, an aspartic protease similar to HIV protease.^{31,32,35-37} Inhibitors of VCP1³⁸ and of E1 ubiquitin-activating enzyme³⁹ are undergoing clinical trials, and it should not be difficult to develop DDI2 inhibitors.

The content of immunoproteasomes varies among patients with MM,⁵ and we clearly show that increased immunoproteasome expression selectively sensitizes cells to immunoproteasome inhibitors. Therefore, all clinical trials of immunoproteasome inhibitors in myeloma or hematologic malignancies should involve patient stratification. In addition to the enzyme-linked immunosorbent assay-based ProCISE assay developed by ONYX,⁶ we have developed several subunit-specific assays^{26,40} that can be adopted for clinical use.

Figure 3. (continued) assay ($n = 3$) (Promega). (C) MM1.S cells were treated with ONX-0914 for 1 hour, and then treated with 1 μ M LU-102 for 47 hours ($n = 3$). (D) MM1.S cells were cotreated for 4 hours with ONX-0914 and 3 μ M LU-102 ($n = 2$). (E) Cells were treated by ONX-0914, followed by LU-102 (250 nM in H929 and MM1.R, 1 μ M in all others) for 47 hours ($n = 2-6$), and half maximal inhibitory concentrations of MM cells was determined from dose-response curves (supplemental Figure 1). (F) Viability of cells treated with 900 nM ONX-0914 in experiment shown in panel E. Numbers are combination indexes (CIs). (G) Primary cells isolated from plural effusions of bortezomib-refractory patients were treated with 0.9 μ M ONX-0914 for 4 hours with or without 2 μ M LU-102, and viability of CD138⁺ cells was determined by flow cytometry at 48 hours using PE Mouse Anti-Human CD138 and Zombie Aqua Fixable Viability antibodies. (H) LU-102 blocks the recovery of $\beta 5i/\beta 5c$ activity over time after 1-hour treatment. Total $\beta 5$ activity was measured with Proteasome-Glo in RPMI-8226 cells, either immediately after 1-hour treatment with 1 μ M ONX-0914 or 100 nM carfilzomib or after a 17-hour recovery in the presence or absence of 1 μ M LU-102 ($n = 2$). Pt., patient.

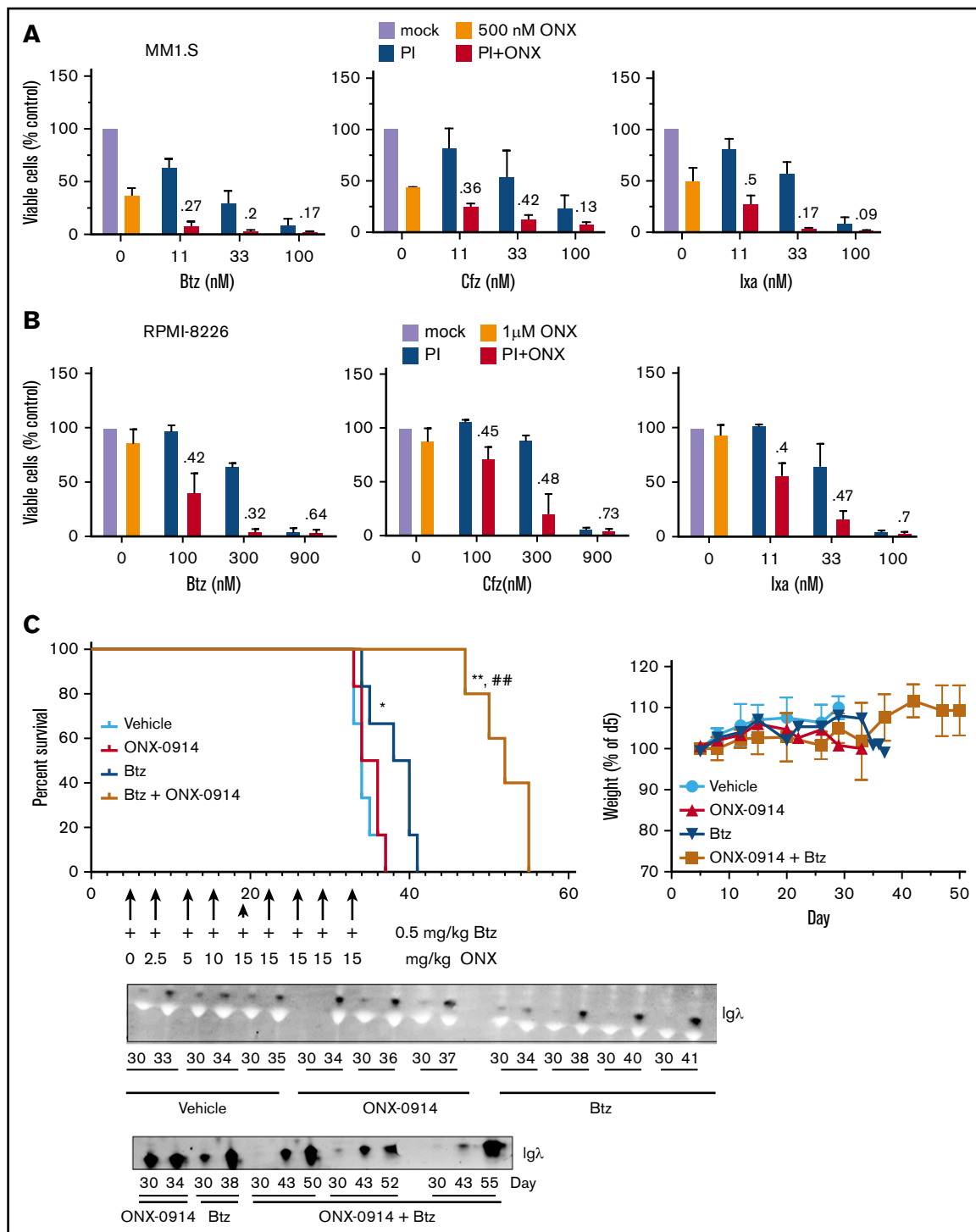


Figure 4. ONX-0914 is synergistic with FDA-approved inhibitors. (A-B) ONX-0914 is synergistic with bortezomib (Btz), carfilzomib (Cfz), and ixazomib (Ixa) in MM1.S (A) and RPMI-8226 (B) cells ($n = 2$). Numbers on the graph are CIs. (C) ONX-0914 and bortezomib have synergistic activity in orthotopic mouse model of MM. NSG mice (6 per group) were injected intravenously with MM1.S cells and then treated as shown. Weight at euthanasia is not included on the right graph because animals lose weight as a result of disease progression. Error bars indicate standard error of the mean. Bottom: 1 μ L of serum samples was assayed for human Ig λ by western blot. The latest sample was taken at euthanasia. * $P < .05$ when compared with vehicle group; ** $P < .005$ when compared with vehicle group; ### $P < .005$ when compared with bortezomib only group. PI, proteasome inhibitor.

In summary, this work provides a strong rationale for the development of immunoproteasome inhibitors in the treatment of patients with MM and also raises the possibility that these

agents will be of therapeutic value for the treatment of other hematologic malignancies that also express high levels of immunoproteasomes.^{41,42}

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Authorship

Contribution: S.D.-K., B.I.F., C.D., H.S.O., and A.F.K. designed the research; S.D.-K., E.W.D., and A.F.K. performed the research; S.D.-K., E.W.D., B.I.F., C.D., H.S.O., and A.F.K. analyzed the data; S.D.-K., B.I.F., and A.F.K. wrote the paper; and A.B., M.G., P.G.R., and C.S.M. provided patient samples.

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ORCID profiles: S.D.-K., 0000-0003-4203-3583; B.I.F., 0000-0001-7114-2266; C.D., 0000-0002-1124-7303; H.S.O., 0000-0001-6976-7005.

Correspondence: Alexei F. Kisselev, Auburn University, Pharmacy Research Building, 720 S Donahue Dr, Auburn, AL 36849; e-mail: afk0006@auburn.edu.

References

1. Kumar SK, Dispenzieri A, Lacy MQ, et al. Continued improvement in survival in multiple myeloma: changes in early mortality and outcomes in older patients. *Leukemia*. 2014;28(5):1122-1128.
2. Anderson KC. Progress and paradigms in multiple myeloma. *Clin Cancer Res*. 2016;22(22):5419-5427.
3. Noda C, Tanahashi N, Shimbara N, Hendil KB, Tanaka K. Tissue distribution of constitutive proteasomes, immunoproteasomes, and PA28 in rats. *Biochem Biophys Res Commun*. 2000;277(2):348-354.
4. Guillaume B, Chapiro J, Stroobant V, et al. Two abundant proteasome subtypes that uniquely process some antigens presented by HLA class I molecules. *Proc Natl Acad Sci USA*. 2010;107(43):18599-18604.
5. Singh AV, Bandi M, Aujay MA, et al. PR-924, a selective inhibitor of the immunoproteasome subunit LMP-7, blocks multiple myeloma cell growth both in vitro and in vivo. *Br J Haematol*. 2011;152(2):155-163.
6. Parlati F, Lee SJ, Aujay M, et al. Carfilzomib can induce tumor cell death through selective inhibition of the chymotrypsin-like activity of the proteasome. *Blood*. 2009;114(16):3439-3447.
7. Zhang XD, Baladandayuthapani V, Lin H, et al. Tight junction protein 1 modulates proteasome capacity and proteasome inhibitor sensitivity in multiple myeloma via EGFR/JAK1/STAT3 signaling. *Cancer Cell*. 2016;29(5):639-652.
8. Dytfeld D, Luczak M, Wrobel T, et al. Comparative proteomic profiling of refractory/relapsed multiple myeloma reveals biomarkers involved in resistance to bortezomib-based therapy. *Oncotarget*. 2016;7(35):56726-56736.
9. Huber EM, Basler M, Schwab R, et al. Immuno- and constitutive proteasome crystal structures reveal differences in substrate and inhibitor specificity. *Cell*. 2012;148(4):727-738.
10. Weyburne ES, Wilkins OM, Sha Z, et al. Inhibition of the proteasome $\beta 2$ site sensitizes triple-negative breast cancer cells to $\beta 5$ inhibitors and suppresses Nrf1 activation. *Cell Chem Biol*. 2017;24(2):218-230.
11. Geurink PP, van der Linden WA, Mirabella AC, et al. Incorporation of non-natural amino acids improves cell permeability and potency of specific inhibitors of proteasome trypsin-like sites. *J Med Chem*. 2013;56(3):1262-1275.
12. Kraus M, Bader J, Geurink PP, et al. The novel $\beta 2$ -selective proteasome inhibitor LU-102 synergizes with bortezomib and carfilzomib to overcome proteasome inhibitor resistance of myeloma cells. *Haematologica*. 2015;100(10):1350-1360.
13. Kincaid EZ, Che JW, York I, et al. Mice completely lacking immunoproteasomes show major changes in antigen presentation. *Nat Immunol*. 2011;13(2):129-135.
14. Kuhn DJ, Hunsucker SA, Chen Q, Voorhees PM, Orlowski M, Orlowski RZ. Targeted inhibition of the immunoproteasome is a potent strategy against models of multiple myeloma that overcomes resistance to conventional drugs and nonspecific proteasome inhibitors. *Blood*. 2009;113(19):4667-4676.
15. Santos RLA, Bai L, Singh PK, et al. Structure of human immunoproteasome with a reversible and noncompetitive inhibitor that selectively inhibits activated lymphocytes. *Nat Commun*. 2017;8(1):1692.
16. Wehenkel M, Ban JO, Ho YK, Carmony KC, Hong JT, Kim KB. A selective inhibitor of the immunoproteasome subunit LMP2 induces apoptosis in PC-3 cells and suppresses tumour growth in nude mice. *Br J Cancer*. 2012;107(1):53-62.
17. Niewerth D, van Meerloo J, Jansen G, et al. Anti-leukemic activity and mechanisms underlying resistance to the novel immunoproteasome inhibitor PR-924. *Biochem Pharmacol*. 2014;89(1):43-51.

18. Muchamuel T, Basler M, Aujay MA, et al. A selective inhibitor of the immunoproteasome subunit LMP7 blocks cytokine production and attenuates progression of experimental arthritis [published correction appears in *Nat Med*. 2009;15(11):1333]. *Nat Med*. 2009;15(7):781-787.
19. Ichikawa HT, Conley T, Muchamuel T, et al. Beneficial effect of novel proteasome inhibitors in murine lupus via dual inhibition of type I interferon and autoantibody-secreting cells. *Arthritis Rheum*. 2012;64(2):493-503.
20. Kalim KW, Basler M, Kirk CJ, Groettrup M. Immunoproteasome subunit LMP7 deficiency and inhibition suppresses Th1 and Th17 but enhances regulatory T cell differentiation. *J Immunol*. 2012;189(8):4182-4193.
21. Basler M, Dajee M, Moll C, Groettrup M, Kirk CJ. Prevention of experimental colitis by a selective inhibitor of the immunoproteasome. *J Immunol*. 2010;185(1):634-641.
22. Basler M, Mundt S, Muchamuel T, et al. Inhibition of the immunoproteasome ameliorates experimental autoimmune encephalomyelitis. *EMBO Mol Med*. 2014;6(2):226-238.
23. Lickliter J, Anderl J, Kirk CJ, Wang J, Bomba D. KZR-616, a selective inhibitor of the immunoproteasome, shows a promising safety and target inhibition profile in a phase I, double-blind, single (SAD) and multiple ascending dose (MAD) study in healthy volunteers [abstract]. *Arthritis Rheumatol*. 2017;69(S10). Abstract 2587.
24. Mirabella AC, Pletnev AA, Downey SL, et al. Specific cell-permeable inhibitor of proteasome trypsin-like sites selectively sensitizes myeloma cells to bortezomib and carfilzomib. *Chem Biol*. 2011;18(5):608-618.
25. Shabaneh TB, Downey SL, Goddard AL, et al. Molecular basis of differential sensitivity of myeloma cells to clinically relevant bolus treatment with bortezomib. *PLoS One*. 2013;8(2):e56132.
26. Verdoes M, Willems LI, van der Linden WA, et al. A panel of subunit-selective activity-based proteasome probes. *Org Biomol Chem*. 2010;8(12):2719-2727.
27. Verdoes M, Florea BI, Menendez-Benito V, et al. A fluorescent broad-spectrum proteasome inhibitor for labeling proteasomes in vitro and in vivo. *Chem Biol*. 2006;13(11):1217-1226.
28. Blackburn C, Gigstad KM, Hales P, et al. Characterization of a new series of non-covalent proteasome inhibitors with exquisite potency and selectivity for the 20S beta5-subunit. *Biochem J*. 2010;430(3):461-476.
29. Britton M, Lucas MM, Downey SL, et al. Selective inhibitor of proteasome's caspase-like sites sensitizes cells to specific inhibition of chymotrypsin-like sites. *Chem Biol*. 2009;16(12):1278-1289.
30. Mitsiades CS, Mitsiades NS, Bronson RT, et al. Fluorescence imaging of multiple myeloma cells in a clinically relevant SCID/NOD in vivo model: biologic and clinical implications. *Cancer Res*. 2003;63(20):6689-6696.
31. Steffen J, Seeger M, Koch A, Krüger E. Proteasomal degradation is transcriptionally controlled by TCF11 via an ERAD-dependent feedback loop. *Mol Cell*. 2010;40(1):147-158.
32. Radhakrishnan SK, den Besten W, Deshaies RJ. p97-dependent retrotranslocation and proteolytic processing govern formation of active Nrf1 upon proteasome inhibition. *eLife*. 2014;3:e01856.
33. Sha Z, Goldberg AL. Proteasome-mediated processing of Nrf1 is essential for coordinate induction of all proteasome subunits and p97. *Curr Biol*. 2014;24(14):1573-1583.
34. Winter MB, La Greca F, Arastu-Kapur S, et al. Immunoproteasome functions explained by divergence in cleavage specificity and regulation. *eLife*. 2017;6.
35. Sha Z, Goldberg AL. Reply to Vangala et al: Complete inhibition of the proteasome reduces new proteasome production by causing Nrf1 aggregation. *Curr Biol*. 2016;26(18):R836-R837.
36. Lehrbach NJ, Ruvkun G. Proteasome dysfunction triggers activation of SKN-1A/Nrf1 by the aspartic protease DDI-1. *eLife*. 2016;5.
37. Koizumi S, Irie T, Hirayama S, et al. The aspartyl protease DDI2 activates Nrf1 to compensate for proteasome dysfunction. *eLife*. 2016;5.
38. Le Moigne R, Aftab BT, Djakovic S, et al. The p97 inhibitor CB-5083 is a unique disrupter of protein homeostasis in models of multiple myeloma. *Mol Cancer Ther*. 2017;16(11):2375-2386.
39. Hyer ML, Milhollen MA, Ciavarri J, et al. A small-molecule inhibitor of the ubiquitin activating enzyme for cancer treatment. *Nat Med*. 2018;24(2):186-193.
40. de Bruin G, Xin BT, Kraus M, et al. A set of activity-based probes to visualize human (immuno)proteasome activities. *Angew Chem Int Ed Engl*. 2016;55(13):4199-4203.
41. Niewerth D, Franke NE, Jansen G, et al. Higher ratio immune versus constitutive proteasome level as novel indicator of sensitivity of pediatric acute leukemia cells to proteasome inhibitors. *Haematologica*. 2013;98(12):1896-1904.
42. Kraus M, Rückrich T, Reich M, et al. Activity patterns of proteasome subunits reflect bortezomib sensitivity of hematologic malignancies and are variable in primary human leukemia cells. *Leukemia*. 2007;21(1):84-92.