Antileukemic Activity and Mechanism of Drug Resistance to the Marine Salinispora tropica Proteasome Inhibitor Salinosporamide A (Marizomib)

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ABSTRACT

Salinosporamide A (NPI-0052, marizomib) is a naturally occurring proteasome inhibitor derived from the marine actinobacterium Salinispora tropica, and represents a promising clinical agent in the treatment of hematologic malignancies. Recently, these actinobacteria were shown to harbor self-resistance properties to salinosporamide A by expressing redundant catalytically active mutants of the 20S proteasome \( \beta \)-subunit, reminiscent of \( \beta \)5-associated catalytic subunits point mutations identified in cancer cells with acquired resistance to the founding proteasome inhibitor bortezomib (BTZ). Here, we assessed the growth inhibitory potential of salinosporamide A in human acute lymphocytic leukemia CCRF-CEM cells, and its 10-fold (CEM/BT27) and 123-fold (CEM/BT2Z20) bortezomib-resistant sublines harboring \( \beta \)5MB5 mutations. Parental cells displayed sensitivity to salinosporamide A (IC\( _{50} \) = 5.1 nM), whereas their bortezomib-resistant sublines were 9- and 17-fold cross-resistant to salinosporamide A, respectively. Notably, combination experiments of salinosporamide A and bortezomib showed synergistic activity in CEM/BT2200 cells. CEM cells gradually exposed to 20 nM salinosporamide A (CEM/S20) displayed stable 5-fold acquired resistance to salinosporamide A and were 3-fold cross-resistant to bortezomib. Consistent with the acquisition of a \( \beta \)5MB5 point mutation (M45V) in CEM/S20 cells, salinosporamide A displayed a markedly impaired capacity to inhibit \( \beta \)5-associated catalytic activity. Last, compared with parental CEM cells, CEM/S20 cells exhibited up to 2.5-fold upregulation of constitutive proteasome subunits, while retaining unaltered immunoproteasome subunit expression. In conclusion, salinosporamide A displayed potent antileukemic activity against bortezomib-resistant leukemia cells. \( \beta \)-Subunit point mutations as a common feature of acquired resistance to salinosporamide A and bortezomib in hematologic cells and \( S. \) troptica suggest an evolutionarily conserved mechanism of resistance to proteasome inhibitors.

Introduction

The proteasome has emerged as an important clinical target for the treatment of hematologic malignancies. A decade ago, the reversible proteasome inhibitor bortezomib was approved for the treatment of relapsed/refractory and newly diagnosed multiple myeloma (MM) and mantle cell lymphoma (Kane et al., 2003), and is an emerging treatment strategy for acute leukemia (Messinger et al., 2012; Niewerth et al., 2013a). However, relevant clinical disadvantages of bortezomib relate to its unsuitability for oral administration, its toxicity profile comprising peripheral neuropathy, and the emergence of drug resistance phenomena (Kale and Moore, 2012). Salinosporamide A (NPI-0052, marizomib) is a naturally occurring proteasome inhibitor derived from the marine sediment actinomycete Salinispora tropica and Salinispora arenicola (Felting et al., 2003; Gulder and Moore, 2010). This inhibitor, which belongs to the class of \( \beta \)-lactones, is a novel cancer treatment option since it is orally bioactive (Chauhan et al., 2005) and irreversibly inhibits all three proteolytic activities of the proteasome. In contrast, the founding proteasome inhibitor bortezomib reversibly and preferentially inhibits chymotrypsin-like activity and, to a lesser extent, the caspase-like activity, but not the trypsin-like activity (Miller et al., 2007), of the proteasome. Consistent with this inhibition profile, the enhanced potency of salinosporamide A over bortezomib

ABBREVIATIONS: AMC, 7-amino-4-methylcoumarin; BTZ, bortezomib; HDAC, histone deacetylase; MM, multiple myeloma; MTT, 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide; ONX 0914, (S)-3-[4-methoxypheno]-N-[(S)-1-[(R)-2-methoxiran-2-yl]-1-oxo-3-phenyl-propan-2-yl]-2-((S)-2-(2-morpholinoacetamido)propanamido)propanamide; WT, wild-type.

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was shown in human MM cell lines (Chauhan et al., 2005) and in chronic lymphocytic leukemia patient specimens (Ruiz et al., 2006). Salinosporamide A is currently being evaluated in phase I clinical trials as monotherapy and in combination with dexamethasone in patients with relapsed/refractory MM. A combined interim analysis of two dose-escalation studies showed a distinct toxicity compared with that of bortezomib, with no peripheral neuropathy. Furthermore, out of 15 evaluable patients, three bortezomib-refractory patients reached partial remission (Richardson et al., 2011). Therefore, salinosporamide A may be attractive as a proteasome inhibitor for further combination chemotherapy studies in several malignancies, including acute leukemia. Building on this premise, combination therapy studies bearing minimally cytotoxic concentrations of bortezomib and salinosporamide A exhibited synergistic effects in MM, leukemia, and lymphoma cell lines. Furthermore, this combination significantly decreased viability in tumor cells from five relapsed MM patients (two being bortezomib-resistant) and reduced tumor growth in a human MM xenograft mouse model without any noticeable toxicity (Chauhan et al., 2008). Moreover, a combination of salinosporamide A and histone deacetylase (HDAC) inhibitors showed a synergistic effect in human acute lymphoblastic leukemia cell lines, which is superior to bortezomib combined with an HDAC inhibitor (Miller et al., 2007, 2009). Notwithstanding these promising results, it is conceivable that acquired resistance to salinosporamide A may evolve upon prolonged drug treatment. In this respect, recent studies by Kale et al. (2011) discovered a redundant proteasome β-subunit (Sall) in the 20S proteasome machinery of S. tropica, which conferred 30-fold resistance to salinosporamide A in this species. This mechanism of naturally occurring resistance was explained by molecular alterations involving amino acid substitutions (A49V and M45F) in these β-subunits as a result of point mutations in the Sall gene. Notably, the A49V mutation was defined as the major determinant of salinosporamide A resistance, since the M45F mutant largely retained its proteolytic activity and sensitivity to salinosporamide A inhibition. In vitro biochemical experiments, however, revealed that introduction of the A49V point mutation did not recapitulate the full salinosporamide A resistance phenotype as the original Sall subunit (Kale et al., 2011). Since hematologic tumor cell lines with in vitro acquired resistance to bortezomib have also displayed similar mutations in exon 2 of PSMB5 (Oerlemans et al., 2008; Ruckrich et al., 2009; Ri et al., 2010; Balsas et al., 2012; de Wilt et al., 2012; Franke et al., 2012; Verbrugge et al., 2012), this points to a common mechanism of resistance to proteasome inhibitors.

In the present study, we examined the tumor cell growth inhibitory capacity of salinosporamide A in human CCRF-CEM acute lymphocytic leukemia cells and two of its bortezomib (BTZ)-resistant sublines, CEM/ BTZ7 (10-fold resistant to bortezomib) and CEM/BTZ200 (123-fold resistant). Bortezomib resistance in these lines is due to well established PSMB5 mutations introducing amino acid substitutions C52F or both C52F and A49V in the β5 subunit, respectively (Franke et al., 2012). We further determined whether salinosporamide A cytotoxic activity may be compromised by the development of resistance in hematologic tumor cells in a similar fashion as the naturally occurring resistance mechanism to salinosporamide A in S. tropica. Our findings reveal that salinosporamide A is a potent antileukemic agent to both parental and bortezomib-resistant leukemia cells, hence warranting further clinical evaluation of its suitability as a novel antitumor agent.

**Materials and Methods**

**Drugs and Antibodies.** Salinosporamide A was extracted and purified from S. tropica CNB-440 cultures as previously described (Feling et al., 2003). Bortezomib (Velcade) was provided by Millennium Pharmaceuticals (Cambridge, MA). Antibodies to proteasome subunits β1, β2, β5, β11, and β20 were purchased from Enzo Life Sciences (Farmingdale, NY); antiubiquitin (P4D1) was purchased from Santa Cruz Biotechnology (Santa Cruz, CA); and the IRDye infrared-labeled secondary antibodies were from LI-COR Biosciences (Lincoln, NE). In addition, antiactin (clone C4) was purchased from Millipore (Temecula, CA).

**Cell Culture and Development of a Salinosporamide A-Resistant Cell Line.** Human T-cell acute lymphoblastic leukemia CCRF-CEM cells (American Type Culture Collection, Manassas, VA) were cultured in RPMI 1640 medium containing 2 mM L-glutamine (Invitrogen/Gibco, Carlsbad, CA) supplemented with 10% fetal calf serum (Greiner Bio-One, Alphen a/d Rijn, The Netherlands) and 100 µg/ml penicillin/streptomycin (Invitrogen) in an atmosphere of 5% CO2 and 37°C. Cell cultures were seeded at a density of 3 × 10^5 cells/ml and refreshed twice weekly. The bortezomib-resistant cell line CEM/BTZ200, resistant to 200 nM bortezomib, was developed by stepwise drug selection as described previously (Franke et al., 2012).

Development of the salinosporamide A-resistant cell line CEM/S20 was achieved by exposing CCRF-CEM cells to stepwise increasing concentrations of salinosporamide A from 1 to 20 nM (i.e., 4-fold the IC50 concentration for parental cells) over a period of 6 months.

**Cell Growth Inhibition Assay.** In vitro drug sensitivity was determined using the 4-day MT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide) cell growth inhibition and cytotoxicity assay (van Meerroo et al., 2011). Prior to these experiments, bortezomib- and salinosporamide A-resistant cells were cultured in drug-free medium for at least 4 days. Cells were then exposed to a series of salinosporamide A concentrations (2 nM to 4 µM) and bortezomib concentrations (1 nM to 2 µM) for 4 days. The IC50 value is defined as the drug concentration necessary to inhibit 50% of the cell growth compared with the growth of untreated control cells. For combination experiments, drugs were added simultaneously. Combinations were chosen starting from the IC10 values of both drugs. CalcuSyn software (version 1.1.1 1996; Biosoft, Cambridge, UK) was used to calculate a combination index based on the median-effect principle for each drug combination tested (Chou and Talalay, 1984).

**Proteasome Activity.** An intact cell-based assay was used to determine caspase-like, trypsin-like, and chymotrypsin-like proteasome activities, and was conducted using a Proteasome-Glo assay kit according to the manufacturer’s instructions (Promega, Madison, WI). In brief, cells were exposed to a range of concentrations (1–100 nM) of salinosporamide A for 1 hour at 37°C in a white flat-bottomed 96-well plate (Greiner Bio-One) at a density of 10,000 cells per well in a total volume of 50 µl. After a 15-minute incubation period with luminogenic substrates, luminescence was determined with an Infinite 200 Pro microplate reader (Tecan, Giessen, The Netherlands). Background signal from cell-free medium plus substrate was subtracted from cell measurements. β5, β20, and β11 subunit–specific activities in cell extracts were performed with subunit-specific peptide-AMC (7-amino-4-methylcoumarin) probes as previously described (Niewehr et al., 2014a). The extent of inhibition of catalytic activity was indicated by IC50 values that represent the drug concentration at which 50% maximal relative fluorescence was detected.

**Proteasome Active Site Enzyme-Linked Immunosorbent Assay.** An enzyme-linked immunosorbent assay–based assay (ProCISE) for quantitative assessment of active constitutive and immuno-proteasome subunits was performed as previously described (Parlati et al., 2009). In brief, cell lysate was incubated with a biotinylated
proteasome active site binding probe. The lysate was then denatured, and subunits bound to probe were isolated with streptavidin-conjugated sepharose beads. Individual subunits were probed with subunit-specific primary antibodies, followed by horseradish peroxidase-conjugated secondary antibodies. A chemiluminescent substrate was used to generate signal associated with horseradish peroxidase binding, which was read on a GENios plate reader (Tecan, Männedorf, Switzerland). Absolute values of nanograms of subunit per microgram of total protein were based on a purified proteasome standard curve. Protein quantification was performed utilizing the Pierce BCA Protein Assay (Thermo Scientific, Rockford, IL).

**Western Blotting.** Protein expression of proteasome subunits was determined by Western blotting, as previously described (Franke et al., 2012). Protein bands were quantified by Odyssey software (LI-COR Biosciences), corrected for background, and normalized to β-actin to correct for loading differences within blots.

**DNA Sequencing Analysis.** Sequencing analysis of proteasome subunits PSMB6 (β1), PSMB7 (β2), and exon 2 of PSMB5 (β3) was performed as previously described (Franke et al., 2012).

### Results

**Sensitivity of Bortezomib-Sensitive and -Resistant Hematologic Cell Lines to Salinosporamide A.** To assess the antileukemic activity of salinosporamide A, its cell growth inhibitory effects were determined in the human T-cell acute lymphoblastic leukemia cell line CCRF-CEM, and its 10-fold (CEM/BTZ27) and 123-fold (CEM/BTZ200) bortezomib-resistant sublines, as compared with the sensitivity of these cell lines to bortezomib (Fig. 1, A and B; Table 1). Parental CCRF-CEM cells displayed a remarkable sensitivity to salinosporamide A (IC\textsubscript{50} = 5.1 ± 1.7 nM). CEM/BTZ7 cells (harboring a single mutation C52F) with low levels of bortezomib resistance displayed 9-fold cross-resistance to salinosporamide A (IC\textsubscript{50} = 47.4 ± 4.0 nM), whereas CEM/BTZ200 cells (harboring the mutations A49V and C52F) displayed 17-fold cross-resistance to salinosporamide A (IC\textsubscript{50} = 87.9 ± 12 nM). Thus, given the 123-fold resistance to bortezomib in CEM/BTZ200 cells, salinosporamide A retained appreciable activity in these highly bortezomib-resistant cells.

**Synergistic Activity of Salinosporamide A and Bortezomib Drug Combinations in Bortezomib-Resistant Cells.** Next, combined exposure to a wide range of salinosporamide A and bortezomib concentrations showed no synergistic effects for these two drugs in parental CEM cells (Fig. 2A). Conversely, CEM/BTZ200 cells exposed to minimally cytotoxic concentrations of each agent, e.g., 39.5 nM salinosporamide A (IC\textsubscript{50} = 87.9 nM) and 158 nM bortezomib (IC\textsubscript{50} = 419 nM), achieved 82% growth inhibition, whereas no significant growth inhibition was observed using either of these agents alone at these low concentrations. Consistently, combination indices indicated synergy for all four combinations that achieved more than 50% cell growth inhibition (Fig. 2B).

**Proteasome Subunit Catalytic Activity Inhibition Profiles of Salinosporamide A.** To examine the inhibitory potency of salinosporamide A against the β subunit–associated catalytic activities of the proteasome in hematologic cells, parental CEM cells and CEM/BTZ200 cells were exposed to a range of salinosporamide A concentrations for 1 hour. Salinosporamide A was effective in inhibiting all three proteolytic activities in both parental CEM and CEM/BTZ200 cells. For parental CEM cells, a most pronounced inhibition by salinosporamide A was observed for β\textsubscript{5}/β\textsubscript{5i}-associated chymotrypsin-like activity (EC\textsubscript{50}: 1.1 nM) and equipotency for β\textsubscript{1}-associated caspase-like activity (EC\textsubscript{50}: 15.7 nM), as well as for β\textsubscript{2}/β\textsubscript{2i}-associated trypsin-like activities (EC\textsubscript{50}: 14.2 nM) (Fig. 3A). Notably, the inhibitory potential of salinosporamide A was superior to that of bortezomib, which achieved 50% inhibition of chymotrypsin-like activity, caspase-like activity, and trypsin-like activity at 7.3, 33.8, and >100 nM bortezomib, respectively (Supplemental Fig. 1). In direct comparison with parental CEM cells, 1.4–2.5-fold higher concentrations of salinosporamide A were necessary to inhibit the three catalytic proteasome activities in the bortezomib-resistant CEM/BTZ200 cells, with EC\textsubscript{50} values of 1.6, 21.3, and 36.9 nM for chymotrypsin-like, caspase-like, and trypsin-like activities, respectively (Fig. 3B). Nonetheless, near complete inhibition of all three activities was accomplished in bortezomib-resistant cells at 100 nM salinosporamide A, similar to parental cells (Fig. 3B).

A closer examination of subunit-specific catalytic activities of the β\textsubscript{5}, constitutive proteasome subunit and β\textsubscript{5i} and β\textsubscript{1i} immunoproteasome subunits showed that β\textsubscript{5} activity was less efficiently inhibited by salinosporamide A in cell extracts of bortezomib-resistant CEM/BTZ7 cells (EC\textsubscript{50}: 1.6 nM) and CEM/BTZ200 cells (EC\textsubscript{50}: 21.3 nM) as compared with parental CEM cells (EC\textsubscript{50}: 0.96 nM). In contrast, inhibition of immunoproteasome subunit β\textsubscript{5i} catalytic activity was only slightly less effective in bortezomib-resistant cell lines [EC\textsubscript{50} CEM/wild-type (WT): 0.79 nM, CEM/BTZ7: 1.4 nM, CEM/BTZ200: 1.3 nM]. Last, the inhibitory capacity of salinosporamide...
A was equally potent in inhibition of $\beta_{1i}$ immunoproteasome subunit catalytic activity in parental and CEM/BTZ7 cells (EC$_{50}$ CEM/WT: 4.1 nM, CEM/BTZ7: 4.7 nM) but 2-fold less potent for CEM/BTZ200 cells (EC$_{50}$: 8.4 nM) (Supplemental Fig. 2). Sensitivity profiling of CEM/S20 cells compared with parental CEM cells and bortezomib-resistant CEM/BTZ7 and CEM/BTZ200 cells was performed for salinosporamide A and bortezomib. An overview of PSMB5 mutations (exon 2) in the indicated cell lines is provided.

Characterization of Salinosporamide A-Resistant Cells. We, as well as others, have previously reported that chronic exposure of leukemic cells to proteasome inhibitors induces acquired drug resistance (Oerlemans et al., 2008; Franke et al., 2012; Niewerth et al., 2014b). Given that actinomycete S. tropica harbors intrinsic resistance to salinosporamide A by a similar mechanism as acquired resistance to proteasome inhibitors including bortezomib in leukemic cells (Kale and Moore, 2012), we set out to explore the acquisition of resistance to salinosporamide A in cultured CEM leukemic cells by stepwise gradual increments. Resistance emerged gradually over a period of 6 months with CEM cells adapting to growth in the presence of 20 nM salinosporamide A (CEM/S20). These cells exhibited an IC$_{50}$ value of 23.2 ± 1.3 nM salinosporamide A, being 5-fold resistant relative to parental cells (Fig. 4A). In addition, CEM/S20 cells displayed 3-fold cross-resistance to bortezomib (IC$_{50}$: 10.8 ± 2.7 nM vs. 3.4 ± 0.9 nM; Fig. 4B). Resistance to salinosporamide A in CEM/S20 cells was stable when cells were cultured in drug-free medium for a month (not shown).

In keeping with previous studies from our laboratory establishing that chronic exposure of leukemic cells to bortezomib results in the acquisition of point mutations in exon 2 of PSMB5 (encoding the S1 pocket of $\beta_3$) (Oerlemans et al., 2008; Franke et al., 2012), PSMB5 of CEM/S20 cells was also sequenced, revealing a point mutation at nucleotide position A310G that introduced a methionine to valine shift at position 45 (M45V) (Table 1). An identical point mutation was recently identified in bortezomib-resistant 8226/PR8 harboring the M45V mutation (Fig. 5A). These results were corroborated by Western blot analysis (Fig. 5B). Last, the inhibitory capacity of salinosporamide A against subunit-specific proteasome 5i and 2i (Fig. 5A). These results were corroborated by Western blot analysis (Fig. 5B). Last, the inhibitory capacity of salinosporamide A against subunit-specific proteasome

### Table 1

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<th>PSMB5 Exon 2</th>
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Adapted from Franke et al. (2012).
catalytic activities in cell extracts of salinosporamide A–resistant CEM cells revealed a 22-fold lower potency of salinosporamide A in achieving half-maximal inhibition of β5 activity in CEM/S20 cells compared with parental cells, whereas β5i and β1i immunoproteasome activities were similarly inhibited in CEM/S20 cells as in parental CEM cells (Fig. 6). To substantiate these results, we analyzed the accumulation of polyubiquitinated proteins in CEM/WT cells and CEM/S30 cells upon exposure to salinosporamide A. These results (Supplemental Fig. 3) illustrate proficient accumulation of polyubiquitinated proteins in CEM/WT cells after 24-hour exposure to 10 nM salinosporamide A, whereas CEM/S30 displayed minimal accumulation of polyubiquitinated proteins when exposed to their selective concentration. Only upon addition of salinosporamide A concentrations that exert a β5 catalytic activity inhibitory effect did these resistant cells reveal accumulation of polyubiquitinated proteins.

**Discussion**

The present study is the first to show that PSMB5 mutations underlie a common molecular mechanism of in vitro acquired resistance of hematologic tumor cells to the marine proteasome inhibitor salinosporamide A as the intrinsic natural resistance mechanism of the salinosporamide A–producing actinomycete *S. tropica* (Kale et al., 2011). This finding demonstrates that PSMB5 mutations have an evolutionary ancestor in conferring proteasome inhibitor resistance. Point mutations in the PSMB5 gene introducing single amino acid substitutions in the β5 subunit were previously found in bortezomib-resistant leukemic cell lines (Lu et al., 2008; Oerlemans et al., 2008; Ri et al., 2010; Franke et al., 2012; Verbrugge et al., 2012), bortezomib-resistant JY lymphoblastoid cells (Verbrugge et al., 2013), and in nonsmall-cell lung cancer cells (de Wilt et al., 2012), all pointing to this subunit as a key determinant in mediating drug resistance to proteasome inhibitors.

Human CEM/BTZ7 leukemia cells with low-level (10-fold) bortezomib resistance due to a C52F mutation in the β5 subunit were 9-fold cross-resistant to salinosporamide A. A β5 subunit–associated C52F mutation has been reported in bortezomib-resistant leukemia cells and lung cancer cells (de Wilt et al., 2012; Franke et al., 2012). Notably, a G52S mutation was observed in the Sα subunit of *S. tropica* with intrinsic resistance to salinosporamide A, but its exact contribution to the resistance phenotype was not further defined (Kale et al., 2011). Based on crystallography studies by Groll et al. (2006a), amino acid position 52 did not emerge as being critical in proteasome inhibitor binding; however, studies from our laboratory identified that a C52F mutation did result in repulsion of bortezomib from the S1 pocket, which negatively affects binding affinity (Franke et al., 2012). Acquisition of an additional mutation (A49V) was found in CEM/BTZ200 cells, which display high-level (123-fold) resistance to bortezomib and 17-fold cross-resistance to salinosporamide A. Notably, both the β5 subunit of CEM/BTZ200 and the Sα subunit of *S. tropica* harbor exactly the same A49V substitution to confer acquired resistance to bortezomib and intrinsic resistance to salinosporamide A, respectively (Kale et al., 2011; Franke et al., 2012). These results indicate that C52F and A49V mutations both contribute to bortezomib and salinosporamide A resistance.

Crystal structure studies of salinosporamide A in complex with the 20S proteasome revealed that all three catalytic subunits (chymotrypsin-like/β5, trypsin-like/β2, and caspase-like/β1) were occupied by the compound (Groll et al., 2006b). Indeed, assessment of proteasome catalytic activity in parental and bortezomib-resistant CEM cells showed that...
salinosporamide A inhibited all three proteasome activities at lower concentrations than bortezomib. In parental cells, caspase- and trypsin-like activities were similarly inhibited (ED\textsubscript{50} 15.7 and 14.2 nM, respectively), whereas in CEM/ BTZ200 cells, trypsin-like activity was even better inhibited by salinosporamide A than caspase-like activity (ED\textsubscript{50} 21.3 and 36.9 nM, respectively). Kisselev et al. (2003) established that inhibition of the caspase-like sites stimulates the trypsin-like activity. Since trypsin-like activity in CEM/BTZ200 cells lacks targeting by bortezomib (Supplemental Fig. 1B), it is conceivable that residual trypsin-like activity is a compensatory mechanism, which preserves sufficient proteasome activity. The synergistic effect of bortezomib in combination with salinosporamide A in these bortezomib-resistant cells may therefore be explained by complementary inhibition of trypsin-like activity by salinosporamide A in an irreversible and more prolonged fashion. In this respect, salinosporamide A and bortezomib were reported to trigger different apoptosis pathways, which may also add to their synergistic effect (Chauhan et al., 2008).

Although emergence of bortezomib resistance in myeloma patients is growing as a clinically relevant issue (Petrucci et al., 2013), the onset of acquired resistance to salinosporamide A is largely unexplored, let alone any underlying molecular basis. Here, we delineated the mechanism underlying acquired resistance to salinosporamide A in CEM/S20 cells that were 22-fold resistant to salinosporamide A. Strikingly, salinosporamide A resistance in CEM/S20 cells shared common features with mechanisms of acquired resistance to bortezomib (Oerlemans et al., 2008; Franke et al., 2012) and immunoproteasome inhibitor PR-924 (Niewerth et al., 2014b). These include upregulation of constitutive proteasome β subunits (Franke et al., 2012) as a first compensatory mechanism to relieve proteasome inhibitor selective pressure, as well as acquisition of a mutation (M45V) in PSMB5. Consistent with a genetic alteration in CEM/S20 cells, salinosporamide A resistance was stable when CEM/S20 cells were cultured in the absence of salinosporamide A for more than a month. Since inhibition of constitutive β\textsubscript{5} is required for the growth inhibitory activity of proteasome inhibitors (Singh et al., 2011; Niewerth et al., 2014b), active site mutations in the β\textsubscript{5} subunit are the most evident to be induced after chronic exposure to proteasome inhibitors. The mutation found in the CEM/S20 cells is likely to inflict a negative impact on the binding affinity of salinosporamide A, as was previously observed for bortezomib (Franke et al., 2012). Indeed, this notion is supported by the marked loss of salinosporamide A inhibitory potency of β\textsubscript{5}-dependent catalytic activity in cell extracts of CEM/BTZ200 cells (Supplemental Fig. 2) and CEM/S20 cells (Fig. 6) versus parental cells. It is noteworthy that, other than for constitutive proteasome subunits, expression of immunoproteasome subunits β\textsubscript{5i}, β\textsubscript{2i}, and β\textsubscript{1i} was essentially unaltered in salinosporamide A–resistant CEM cells. None of these subunits harbored mutations. Remarkably, salinosporamide A displayed great potency in inhibiting the catalytic activities of the β\textsubscript{5i} and β\textsubscript{1i} subunits, both of parental cells and CEM/S20 cells (Fig. 6). Nonetheless, proficient immunoproteasome inhibition by salinosporamide A had no apparent impact on preventing the onset of salinosporamide resistance in CEM/S20 cells. This notion is in line with the observations by Parlati et al. (2009) and our laboratory (Niewerth et al., 2014b) that growth inhibitory effects of selective immunoproteasome inhibitors require concomitant inhibition of constitutive proteasome subunits. When, for example, constitutive β\textsubscript{5} subunits harbor mutations hampering bortezomib or salinosporamide A active site binding, this property will largely dictate the resistance level. This also implies that, by upregulating the immunoproteasome at the expense of the constitutive proteasome, cells may gain sensitivity to proteasome inhibition. Indeed, recent studies by our laboratory (Niewerth et al., 2014a) showed that upregulation of cellular immunoproteasome subunit content, e.g., by exposure to interferon-γ, allowed partial sensitization of bortezomib-resistant hematologic cells to ONX 0914 [(S)-3-(4-methoxyphenyl)-N-[(S)-1-((R)-2-methyloxiran-2-yl)-1-oxo-3-phenylpropan-2-yl]-2-((S)-2-(2-morpholinoacetamido)propanamido)propanamide], a selective immunoproteasome inhibitor.

Surprisingly, whereas Met45 (compared with Ala49) mutations did little in contribution to the natural resistance to salinosporamide A in S. tropica (Kale et al., 2011), M45V emerged as the dominant mutation conferring resistance to salinosporamide A in CEM/S20 cells. In fact, Met45 has been characterized to undergo conformational changes upon binding of bortezomib (Groll et al., 2006a) or immunoproteasome inhibitor ONX 0914 (Huber et al., 2012) to the β\textsubscript{5} active site binding pocket. Within the S1 pocket, Met45 facilitates favorable hydrophobic interactions with the P1 side chain of salinosporamide A (Groll et al., 2006b; Kale and Moore, 2012). Hence, Met45 mutations may impact these interactions by restricting
in CEM leukemia cells, we showed that the PR-924–resistant MM cell line 8226/PR7 harboring the M45V mutation (Niewerth et al., 2014b) was markedly cross-resistant to salinosporamide A.

Collectively, the current and other studies (Ruckrich et al., 2009; Franke et al., 2012; Niewerth et al., 2014b) point to upregulation of β5 subunit expression as the primary response mechanism to proteasome inhibition, which may set the stage for acquisition of mutations following prolonged bortezomib exposure. PSMB5 mutations have not yet been recorded in human clinical specimens derived from patients receiving proteasome inhibitor–based therapy (Politou et al., 2006; Shuqing et al., 2011; Lichter et al., 2012). This might be explained by the fact that current treatment strategies do not implement maintenance therapy with proteasome inhibitors; however, with the introduction of orally available proteasome inhibitors without emerging peripheral neuropathy, this will likely be investigated soon. Indeed, in The Netherlands, the role of ixazomib citrate as maintenance therapy will be explored. However, common PSMB5 mutations in human in vitro–derived proteasome inhibitor–resistant leukemia cells and in S. tropica point toward an evolutionarily conserved resistance mechanism. It should be emphasized that PSMB5 mutations do not represent the sole mechanism of proteasome inhibitor resistance. In fact, multiple mechanisms can be accountable in contributing to either intrinsic or acquired resistance, e.g., drug efflux transporters (Verbrugge et al., 2012), suppression of spliced X-box protein 1 (Leung-Hagesteijn et al., 2013), increased expression of the insulin growth factor receptor (Kuhn et al., 2012), or an impaired balance of constitutive versus immunoproteasome subunit expression (Niewerth et al., 2013b). These mechanisms were mostly revealed in relation to bortezomib resistance and certainly warrant further investigation with respect to salinosporamide A.

In conclusion, salinosporamide A displayed potent antileukemic activity, even in bortezomib-resistant cells, and was synergistic with bortezomib in these cells. The oral availability and promising results from early-phase clinical trials may hold potential for therapeutic interventions in leukemia. Given the potential emergence of acquired resistance to salinosporamide A, its optimal application will most likely come in the form of combination therapy with bortezomib or other agents, e.g., lenalidomide (Chauhan et al., 2010) and HDAC inhibitors (Miller et al., 2009).

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Authorship Contributions

Participated in research design: Niewerth, Riethoff, Jansen, Cloos, Kale, Moore.

Conducted experiments: Niewerth, Riethoff, van Meerloo, Anderl.

Contributed new reagents or analytic tools: Anderl, Moore, Kale.

Performed data analysis: Niewerth, Riethoff, van Meerloo, Anderl.

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References

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Molecular Pharmacology

Antileukemic activity and mechanism of drug resistance to the marine *Salinispora tropica* proteasome inhibitor salinosporamide A (marizomib)

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Supplemental figures

Figure S1. Impact of salinosporamide A compared to bortezomib on proteasome catalytic activity in parental and bortezomib-resistant CEM cells. Chymotrypsin-like, caspase-like, and trypsin-like proteasome activity was analyzed by Proteasome-Glo assay in intact (A) parental CEM/WT cells, and (B) bortezomib-resistant CEM/BTZ200 cells after 1-hour exposure to salinosporamide A (Sal A) or bortezomib (BTZ). Results are presented relative to untreated controls and represent the mean (± standard deviation) of three independent experiments.

Figure S1
A
CEM/WT

B
CEM/BTZ200
Figure S2. Impact of salinosporamide A on proteasome catalytic activity in parental and bortezomib-resistant CEM cells. β5, β5i, and β1i-associated catalytic activity in cell extracts of CEM/WT, CEM/BTZ7, and CEM/BTZ200 cells was assessed after 1-hour exposure to salinosporamide A. Results depicted represent the mean (± standard deviation) of 3 separate experiments.
Figure S3. Accumulation of ubiquitinated proteins in parental CEM and salinosporamide A-resistant CEM cells after salinosporamide A exposure. Western blot analysis of accumulation of polyubiquitinated proteins in untreated cells, after 24h exposure to salinosporamide A (10 nM for CEM/WT, 30 nM and 60 nM for CEM/S30).