Relapsed and refractory lymphoid neoplasms and multiple myeloma with a focus on carfilzomib

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Abstract: Proteasomal inhibition revolutionized myeloma therapies in this decade of novel agents. The only US Food and Drug Administration approved proteasome inhibitor so far, bortezomib effectively targets the constitutive proteasome subunit β5 of the 26S proteasome. Bortezomib induces high and quality response rates that are durable. However, myeloma cells acquire resistance to bortezomib through various mechanisms. Further, grade 3/4 peripheral neuropathy is seen in up to a quarter of patients treated with bortezomib. While the recent change in the mode of administration via the subcutaneous route is associated with a lower incidence of grade 3/4 peripheral neuropathy, it remains a major concern. The second generation proteasome inhibitors are promising, with increased preclinical efficacy and a better administration schedule. The current review spotlights the second generation proteasome inhibitors with special focus on the safety and efficacy of carfilzomib, an epoxyketone with lesser peripheral neuropathy, which exhibits irreversible proteasome inhibition. In this article, we review the pharmacology and preclinical activity of carfilzomib in myeloma and various lymphoid neoplasms as well as ongoing clinical trials.

Keywords: myeloma, carfilzomib, second generation, proteasome inhibitor, epoxyketone

Introduction

The proteasome is a validated target in the management of multiple myeloma (MM) and lymphoma. Combinations of proteasome inhibition with other conventional or targeted agents have proven quite successful for both newly diagnosed and relapsed patients. These combinations have significantly improved overall response rates, complete response, progression free survival, and overall survival. This review summarizes the biologic rational for why this pathway is so important in plasma cell disorders as well as second generation agents in development, including the mechanism of proteasomal inhibition (the ubiquitin-proteasome system); various novel proteasome inhibitors (PIs) under evaluation, with a focus on carfilzomib; the preclinical activity of carfilzomib in myeloma and various lymphoid neoplasms; and the efficacy data from the early Phase trials, and concludes by summarizing the ongoing trials with carfilzomib for refractory lymphoid neoplasms and myeloma.

The ubiquitin proteasome system is a multicatalytic proteinase complex that degrades a wide variety of protein substrates within normal and transformed cells to maintain cellular homeostasis. The intracellular proteins that regulate cellular processes such as cell-cycle control, apoptosis, deoxyribonucleic acid (DNA) repair, and response to oxidative stress are controlled by it. Intracellular proteins targeted
for degradation by the proteasome are first ubiquitinated via the ubiquitin conjugation system, which requires the coordinated reactions of three enzymes: the ubiquitin-activating enzyme, ubiquitin-conjugating enzyme, and ubiquitin ligases. Once ubiquitinated, proteins targeted for degradation bind to the 26S proteasome. The 26S proteasome has a molecular mass of 200 kilo daltons (kDa) and contains a 20S proteolytic hollow core structure and two 19S regulatory caps to regulate the entry of target proteins (Figure 1). A 19S regulatory subunit hosts multiple ATPase active sites and ubiquitin binding sites that recognize the ubiquitinated proteins, transferring them to the catalytic core for proteolysis.\(^2,^3\) The 20S core contains two outer rings (α), comprising 7 α subunits (α1–α7), and two inner rings (β), comprising 7 β-subunits (β1–β7). The core has three active enzymatic sites: a chymotrypsin-like (CT-L) on the β5 subunit, trypsin-like (T-L) on the β2 subunit, and a caspase-like (C-L) site on the β1 subunit (Figure 1).\(^4,^5\)

The ubiquitinated proteins are cleaved within the 20S core by one or more of the three separate threonine protease activities – CT-L for hydrophobic residues, T-L for basic residues, and C-L for acidic residues – though the significance of the different proteolytic sites and the efficacy of inhibitors vary with the protein substrate.\(^5\) CT-L activity represents the target for most clinical PIs. Increased levels of CT-L activity and the resultant protein breakdown have been associated with malignancies, suggesting a vulnerable target. It is the most sensitive protease site for inactivation, with resultant accumulation of ubiquitinated proteins and induction of apoptosis.\(^7,^8\)

Proteasomes are present in their constitutive form and an immunoproteasome form, and are predominantly seen in cells of hemopoietic origin. The immunoproteasome is assembled with alternative subunits whose substrate specificity is altered relative to the normal proteasome. The alternative β forms, denoted as β1i (LMP2), β2i (MECL1), and β5i (LMP7), are expressed in response to the exposure to proinflammatory signals, such as cytokines, in particular, interferon gamma.\(^9\) The most currently available PIs target both the constitutive and immunoproteasome, and emerging evidence suggests that dual targeting enhances efficacy (Figure 1).\(^10\)

**Proteasome inhibitors**

Bortezomib (PS-341) is the only PI approved by the US Food and Drug Administration for both newly diagnosed and relapsed myeloma patients as well as relapsed mantle cell lymphoma patients.\(^11\) The introduction of bortezomib containing induction regimens specifically combining with the immunomodulatory drugs thalidomide or lenalidomide has significantly enhanced the overall response rates and the depth of responses.\(^12,^13\) A recent meta-analysis by Nooka et al suggests an improvement in overall survival associated with bortezomib containing inductions not seen with other agents.\(^14\) Through the addition of bortezomib to the induction regimens in transplant-eligible patients with MM, not only was there improvement in the overall response rate (ORR)
and deepening in the magnitude of the responses seen, but there was also the prolonging of progression free survival and overall survival compared with the nonbortezomib containing induction regimens.\textsuperscript{14} In relapsed/refractory MM (R/R MM), bortezomib combination therapies induced responses and prolonged survival in poor risk patients, as defined by the presence of high risk cytogenetic abnormalities.\textsuperscript{13} Without a doubt, bortezomib has revolutionized myeloma therapies in this decade of novel agents. However, adverse side effects, including peripheral neuropathy (PN) and bortezomib-resistance, are inevitable and the currently established dosing of bortezomib administration, either intravenous or subcutaneously, on days 1, 4, 8, and 11 of a 21-day cycle can be arduous.

The incidence of grade (G) 3/4 PN is seen in up to 28\% of the patients\textsuperscript{15} receiving bortezomib and the incidence is greater in the initial course of therapy, but plateaus after five cycles.\textsuperscript{16,17} In the process of inhibiting the proteasome, bortezomib results in the breakdown of some essential proteases, which is presumed to be associated with the observed neurotoxicity. Even though the recent change in the mode of administration via the subcutaneous (SC) route is associated with less incidence of G3-PN,\textsuperscript{18} in 38\% of patients, it continues to remain a major problem given the association of any grade PN. The reduced incidence is thought to be related to lowering the maximum concentration exposure of bortezomib when given subcutaneously, without affecting the efficacy.

Bortezomib is a boronate reversible PI (Table 1) that primarily targets the constitutive proteasome subunit $\beta_5$ of the 26S proteasome (Figure 1). Myeloma cells acquire resistance to bortezomib by modulating the cell signal pathways (eg, decreased proteasome inhibition with high levels of heat shock protein 27), altering the proteasome complex (eg, subunit $\beta_5$ gene mutation and over expression of subunit $\beta_5$ protein, leading to impaired binding of bortezomib),\textsuperscript{19} or escalating alternate methods of protein degradation, thereby efficiently bypassing the proteasome inhibition (clearance of the protein via the aggresome pathway).\textsuperscript{20} The most promising options to overcome the above stated issues are second generation PIs with better schedules of administration,

Table 1 Various novel proteasome inhibitors

| Chemical structure | IC50 (nm) B5/B2/B1/NF-KB | Dissociation half life | Binding site (20S) |
|--------------------|---------------------------|-----------------------|--------------------|
| **Boronates**      |                           |                       |                    |
| Bortezomib (IV/SC) | 2.4–7.9/590–4200/24–74/36–40 | 110 minutes           | $\beta_5$/LMP7     |
|                    |                            |                       | $\beta_1$/LMP2     |
| CEP-18770 (IV)     | 3.8/–>100/100/NR           | Slowly reversible      |                    |
| MLN9708 (PO)       | 3.4/3500/31/62             | 18 minutes            |                    |
| **Epoxyketones**   |                           |                       |                    |
| Carfilzomib (PR-171) (IV) | 6/3600/2400/NR | Irreversible          | $\beta_5$/LMP7    |
| ONX 0912 (PR-047) (PO) | 36/NR/NR/NR | Irreversible          | $\beta_5$/LMP7    |
| **B-lactone (salinosporamides)** |                 |                       |                    |
| Marizomib (NPI-0052) (IV/PO) | 3.5/28/430/13–20 | Irreversible          | $\beta_5$/LMP7    |
|                    |                           |                       | $\beta_1$/LMP2    |
|                    |                           |                       | $\beta_2$/MECL1    |

**Abbreviation:** IV, intravenous; SC, subcutaneous; PO, per os; NR, not reported.
preferably oral, that can circumvent bortezomib-resistance mechanisms. We have summarized a few novel PIs currently under clinical evaluation that have shown activity, even in bortezomib resistant cell lines.

MLN9708
MLN9708 (Millennium Pharmaceuticals) is a second-generation, reversible PI, boronate analog of bortezomib (Table 1) which has good oral bioavailability and hydrolyzes to the active form, MLN2238. Preclinically, in vitro studies have shown improved efficacy of MLN2238 compared to bortezomib in the lymphoma models. In vivo, MLN9708 demonstrated significant antimyeloma activity. Two Phase I studies with MLN9708 in R/R MM as a single agent and one Phase I study in combination with lenalidomide and dexamethasone in newly diagnosed patients were presented at ASH 2011. In the relapsed/refractory Phase I trials, biweekly and weekly dose escalation cohorts were evaluated to establish the maximum tolerated dose (MTD). Both schedules were well tolerated and demonstrated disease stabilization for 12.9 months and 9.5 months in 61% and 45% patients, respectively (Table 2). Fatigue, thrombocytopenia, nausea, and neutropenia were the most common G3 serious adverse events (SAEs). Neutropenia was not observed in newly diagnosed patients at an MTD of 2.97 mg/m², suggesting that heavily pretreated patients may be more prone to neutropenia. MLN9708 in combination with lenalidomide and dexamethasone demonstrated ≥ partial response (≥PR) rates in 100% patients and ≥ very good partial response (≥VGPR) per International Myeloma Working Group uniform response criteria in 60% patients. These results are encouraging for the possibility of a highly efficacious, oral triplet-regimen in the induction therapy for those newly diagnosed with MM.

CEP-18770
CEP-18770 (Cephalon) is another second generation reversible PI that is orally active (Table 1). In myeloma xenograft models, CEP-18770 demonstrated sustained pharmacodynamic activity and potent anti-tumor activity with tumor regressions. Overall median survival was improved in a systemic model of human MM. Additionally, CEP-18770 exhibited a favorable toxicity profile with human bone marrow progenitors and bone marrow-derived stromal cells. A Phase I study of CEP 18770 in patients with solid tumors and NHL was completed. In patients with R/R MM, a Phase I/II study to determine the MTD of CEP-18770 and to evaluate the antitumor activity is currently

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**Table 2** Other proteasome inhibitors in multiple myeloma: safety, tolerability, and efficacy

| Trial | Phase | Agents | MTD | Safety | Response rate (RR) (%) | Response rate (PR) (%) |
|-------|-------|--------|-----|--------|------------------------|------------------------|
| Richardson et al²² | Phase I | Single agent MLN9708 | G3 drug related | G3 drug related | > PR 6 (1) | > PR 6 (1) |
| Kumar et al²³ | Phase I | Single agent MLN9708 | G3 drug related | G3 drug related | > PR 6 (1) | > PR 6 (1) |
| Bardeja et al²⁴ | Newly diagnosed phase I | MLN 9708 | G3 drug related | G3 drug related | > PR 6 (1) | > PR 6 (1) |
| Papadopoulos et al²⁵ | Phase I | ONX 9012 orally D1-5 | G3 drug related | G3 drug related | > PR 6 (1) | > PR 6 (1) |

Abbreviations: AE, adverse events; CR, complete response; D, days; DLT, dose limiting toxicity; G, Grade; MTD, maximum tolerated dose; NR, not reported; PR, partial response; SAESAE, serious adverse events; SD, stable disease; VGPR, very good partial response;percentages in parentheses indicate > grade 3 (G3) or > grade 2 (G2) adverse events.
were the most common adverse events and MTD was not reached. Dose-escalation was started at 30 mg and is currently escalating at 180 mg in 30 mg increments. Stable disease of >3 month duration has been observed in three patients with prostate cancer, liposarcoma, and non-small-cell lung cancer.43 Another Phase I/II study in patients with Waldenstrom’s macroglobulinemia (WM), MM, and mantle cell (MCL)42 is planned, but not open for patient recruitment yet.

**Carfilzomib**

Carfilzomib (Onyx Pharmaceuticals) is a second generation irreversible epoxyketone analogue of YU-10143 with increased aqueous solubility due to the addition of a NH2-terminal morpholino moiety (Table 1). It inhibits CT-L activity, resulting in sustained proteasomal inhibition. It also exhibits less selectivity for T-L and C-L proteases, which may reduce toxicities that are seen with bortezomib, especially neurotoxicity.16,44,45 We will further review the preclinical and clinical data of carfilzomib in patients with refractory lymphoid neoplasms and R/R MM.

**Preclinical activity of carfilzomib in AML/ALL/CLL**

The functional (antiproliferative and proapoptotic) effects of bortezomib and carfilzomib were compared by Stapnes et al on primary human acute myeloid leukemia (AML) cells in vitro. Both drugs inhibited autocrine- and cytokine-dependent proliferation of primary AML blasts in a dose dependent manner (bortezomib: 21 nmol/l–24.8 nmol/l and carfilzomib: 9.8 nmol/l–10.4 nmol/l). AML cells incubated in the presence of bortezomib or carfilzomib showed an increase in the percentage of apoptotic cells and a decrease in cell viability, suggesting the proapoptotic nature of both drugs. The tested functional effects of bortezomib and carfilzomib were identified in AML blasts, even in the presence of nonleukemic stromal cells, after coculturing leukemia cells with bone marrow stromal cells in the in vitro model. Similar trends were observed with the acute lymphoblastic leukemia (ALL) cells in vitro.60 In combination with PIs, cytotoxic agents used for AML therapy, idarubicin, and cytarabine caused a dose-dependent decrease in cell viability after 18 hours of in vitro incubation relative to the drugs tested alone. Further, HDAC inhibitors (HDACis), such as valproic acid, which are finding a place in AML therapy, when combined with bortezomib (10 nmol/l) caused 79% inhibition, whereas valproic acid alone caused no significant inhibition and bortezomib caused 62% growth inhibition when tested
alone.\(^\text{60}\) Antiproliferative and proapoptotic effects of carfilzomib are greater than bortezomib.

The differential sensitivity of pediatric ALL cells to bortezomib, carfilzomib, ONX 0912, and ONX 0914 was examined for the drug concentrations that are required for 50% cell death (LC\(_{50}\)) and for correlation with the protein expression levels of the constitutive proteasome and immunoproteasome subunits.\(^\text{61}\) LC\(_{50}\) was determined in 29 pediatric ALL and twelve AML patient samples after drug exposure for 4 days using the MTT cytotoxicity assay. ALL cells were significantly more sensitive for bortezomib than AML cells (median LC\(_{50}\) : 6.0 nM vs 14.2 nM, respectively, \(P = 0.002\)). The corresponding sensitivity for carfilzomib (median LC\(_{50}\)) was 4.1 nM and 20.1 nM (\(P = 0.00\)). Expression of constitutive proteasome subunits was higher in AML cells than in ALL cells. LC\(_{50}\) concentrations of carfilzomib significantly correlated with beta 5 and beta 1 expression. ALL cells were more sensitive to PIs than AML. This may be due to lower constitutive proteasome unit expression in these cells. ALL/AML cells display sensitivity to PIs without cross-resistance between them. Carfilzomib is promising for bypassing bortezomib resistant cells.

In the chronic lymphocytic lymphoma (CLL) cells, the mechanism of carfilzomib action is unknown, though preclinical data demonstrated potent cytotoxicity of carfilzomib in primary CLL cells. Gupta et al evaluated the effect of carfilzomib to inhibit the chymotrypsin-like proteasome subunit in CLL cells. Carfilzomib causes CLL cell death ex vivo by a caspase-dependent apoptotic pathway, indicated by Poly (ADP-ribose) polymerase (PARP) cleavage and rescued by the broad caspase inhibitor Boc-D-fmk. Further, the pro-apoptotic protein Noxa is increased following carfilzomib treatment.\(^\text{62}\) Carfilzomib causes apoptosis in primary CLL cells irrespective of p53 status, which is of tremendous clinical significance given resistance to standard therapies and dismal overall survival. Proteasome inhibition as a relevant therapeutic target in CLL requires further exploration.

### Preclinical activity of carfilzomib in lymphoma

Like bortezomib, carfilzomib induces growth inhibition of mantle cell lymphoma cells both in vitro and in vivo. In vitro, the anti-tumor effects of carfilzomib and bortezomib were the same, but in vivo, carfilzomib was well tolerated, significantly inhibited tumor growth, and showed prolonged survival relative to bortezomib-treated mice, indicating the therapeutic potential of carfilzomib in MCL therapy.\(^\text{63}\) In the B-cell lymphoma cell lines that are resistant to rituximab-chemotherapy, carfilzomib showed significant activity.\(^\text{64,65}\) Compared to bortezomib, carfilzomib exhibited greater dose-dependent and time-dependent cytotoxicity against rituximab-chemotherapy cell lines and the primary tumor cells of patients with R/R B-cell lymphoma by up-regulating proapoptotic proteins and inducing G2/M cell cycle arrest. It also demonstrated the ability to overcome chemoresistance in chemotherapy resistant cell lines and potentiated the anti-tumor activity of paclitaxel and gemcitabine, suggesting that the clinical use of carfilzomib can overcome resistance to conventional chemotherapeutic agents. A possible mechanism of sensitizing resistant cells to chemotherapy is the down-regulation of p52. Carfilzomib targets the nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB)-p52 pathway by down-regulating the tumor necrosis factor-receptor family B-cell activating factor (BAFF), resulting in lymphoma cell growth inhibition and apoptosis induction.\(^\text{66}\) Carfilzomib showed single agent activity in WM. Inhibition of CT-L activity was seen in both LMP7 and β5 subunits in WM and immunoglobulin M (IgM) secreting lymphoma cell lines, resulting in increased toxicity in primary WM cells by both activation of caspase-dependent and caspase-independent mechanisms.\(^\text{67}\)

### Carfilzomib and HDAC inhibitors

Histone deacetylase inhibitors reverse histone deacetylation, a process involved in the epigenetic regulation of gene expression, thereby promoting cell death and/or differentiation.\(^\text{46}\) Apoptosis from HDACis occurs through the induction of oxidative injury and disruption of DNA repair, among other processes. Co-administration of HDACis with PIs induces a marked increase in mitochondrial injury and apoptosis. Increased activity is associated with transcription factor NF-κB inactivation, c-Jun NH2-terminal kinase activation, p63 induction, caspase-dependent cleavage of p21CIP1, p27KIP1, and Bcl-2, as well as antiapoptotic protein myeloid cell leukemia sequence 1, X-linked inhibitor of apoptosis, and cyclin D1 downregulation. The combination also induces reactive oxygen species generation that further induces apoptosis.\(^\text{47}\) In myeloma and lymphoma cells, HDACi inhibits cell growth and induces apoptosis as a single agent and is also synergistic with bortezomib.\(^\text{48–50}\) Phase I studies combining vorinostat with bortezomib in R/R MM showed promising antmyeloma activity of the regimen,\(^\text{51}\) which is being further evaluated. Similarly, in MCL, bortezomib-induced apoptosis in human MCL cells was shown to be potentiated with the pan-HDACi, panobinostat.\(^\text{52}\)

Coadministration of carfilzomib, vorinostat, and SNDX-275 was evaluated in MCL cells. At minimally lethal
concentrations, this combination induced a sharp increase in mitochondrial injury and apoptosis in both cell lines and primary MCL cells.\textsuperscript{33} Similar activity was seen in human diffuse large B-cell lymphoma (DLBCL) cells.\textsuperscript{54} Carfilzomib was also tested in combination with HDAC6-specific inhibitor (WT-161) in MCL. This caused induction of the pro-apoptotic transcription factors and synergistically induced apoptosis of cell lines and primary MCL cells.\textsuperscript{33} These results support the basis for combining carfilzomib with HDACi in clinical trials. A Phase I study of carfilzomib in combination with vorinostat in R/R B-cell lymphomas\textsuperscript{59} and a Phase I/II study of carfilzomib, lenalidomide, vorinostat, and dexamethasone in R/R MM\textsuperscript{67} are ongoing. A Phase I study\textsuperscript{58} and a Phase I/II study\textsuperscript{59} of carfilzomib in combination with panobinostat in R/R MM are underway.

Preclinical activity of carfilzomib in myeloma

Carfilzomib is structurally dissimilar to bortezomib\textsuperscript{68} and is less active against nonproteasomal proteases when compared to bortezomib.\textsuperscript{69} This target, which is specificity relative to bortezomib, may also explain the ability of carfilzomib to overcome resistance to bortezomib both in vitro and in vivo.\textsuperscript{70} Carfilzomib inhibits proliferation and induces apoptosis in bortezomib-resistant MM cell lines and in primary MM cells from patients with clinically established resistance to bortezomib and other conventional agents.\textsuperscript{70} The proteasomal binding site affinity and magnitude of proteasomal inhibition of carfilzomib differ from bortezomib in bortezomib sensitive cell lines as well as bortezomib-resistant cell lines.\textsuperscript{71}

Site affinity

Carfilzomib exhibits inhibitory-specificity for 20S catalytic activities. Eighty percent CT-L activity inhibition occurred in the β5 subunit (10 nM), with minimal effects on the C-L or T-L activities at 10-fold higher concentrations.\textsuperscript{70} Bortezomib targets β1 and β1i subunits in addition to the β5 subunits,\textsuperscript{72} but does not inhibit the β2 subunit at clinically relevant concentrations. Interestingly, upregulation of the β2 subunit is observed in bortezomib-resistance and combining specific β2 inhibitors to overcome bortezomib-resistance is a potential strategy.\textsuperscript{73} Kuhn et al demonstrated that exposure to low-dose carfilzomib led to preferential binding specificity for the β5 constitutive 20S proteasome and the β5i immunoproteasome subunits. At higher doses (>1 μM), binding occurred with the β1 and β2 subunits as well as with β1i and β2i.\textsuperscript{70} At doses of carfilzomib that selectively inhibit both CT-L active sites in the β5 and LMP7 subunits, antitumor responses were seen in MM, non hodgkin lymphoma (NHL), and leukemia cells. Individual chemical inhibitors of the CT-L subunits β5 or LMP7 had no antitumor effects, but combining both inhibitors produced an antitumor effect equivalent to carfilzomib.\textsuperscript{74}

Cytotoxicity

Exposing hematologic tumor cell lines to carfilzomib for a brief period of one hour leads to rapid proteasomal inhibition followed by accumulation of polyubiquitinated proteins and induction of apoptotic cell death.\textsuperscript{70} Relative to bortezomib, carfilzomib demonstrated increased apoptosis in the cell line models of MM by 1.5 to 2.0 fold through the intrinsic (caspase-9) and extrinsic pathways (caspase-8 and caspase-3). Proapoptotic signaling via Jun-N-terminal kinase (JNK) phosphorylation was also enhanced with carfilzomib compared to bortezomib. In patient-derived purified CD158+ plasma cells, continuous exposure to escalating doses of carfilzomib induced a dose-dependent proteasome inhibition, as measured by the CT-L activity, decreased cellular viability.\textsuperscript{70}

The timing of proteasomal inhibitory activity with carfilzomib was faster and was observed with a shorter duration of exposure.\textsuperscript{71} One hour following treatment with carfilzomib there was more cytotoxicity than bortezomib for tumor cell lines, specifically hematologic tumor lines.\textsuperscript{71} Rapid induction of apoptosis occurred during this brief exposure, as evidenced by caspase activation detected as early as 5 hours and maximum annexin V staining occurred by 24 hours. The consequent effects of carfilzomib on apoptosis, growth arrest, or stress response pathways by measuring markers (eg, β-catenin, P21) were more pronounced than with bortezomib, which is consistent with the greater effects of carfilzomib on cell viability, apoptosis, and cell cycle progression. Carfilzomib has also been demonstrated to be cytotoxic in bortezomib-resistant tumor cell lines.\textsuperscript{72,73} The authors demonstrated that prolonging the length of exposure from one hour to 6 hours resulted in markedly increased total proteasome inhibition in both bortezomib and carfilzomib, especially in C-L and T-L sites.\textsuperscript{71} Inhibition of multiple proteasome active sites restricted the protein turnover to a greater degree than inhibiting CT-L by itself, suggesting a direction for future studies that combines different proteasomal agents such as bortezomib and carfilzomib, which may result in increased proteasomal inhibition.\textsuperscript{8} Lee et al measured the activity of c20S subunits (β5, β2 and β1) and i20S subunits (LMP7, MECL1, and LMP2). Carfilzomib doses of up to 45 mg/m\textsuperscript{2} showed ≥80% inhibition of CT-L active sites (β5, LMP7) as well as dose-dependent inhibition of MECL1
and LMP2. Carfilzomib inhibited 63% of all active sites of the immunoproteasome at 45 mg/m² and 78% at 56 mg/m². Phase I data from Papadopoulos et al administered carfilzomib at 20/56 mg/m² in patients with relapsed solid tumors, and R/R MM showed encouraging activity with a good safety profile and may provide insight into evaluating whether proteasome inhibition alone would be a predictive marker of clinical response.

Pharmacokinetics
In rat pharmacokinetic (PK) studies with intravenous (IV) administration, carfilzomib was rapidly cleared from the plasma compartment with a half-life of approximately 15 minutes. The estimated steady-state volume of distribution superseded the blood volume, suggesting significant penetration into peripheral tissues. In another PK study, plasma half-life ranged from 5 to 20 minutes and plasma clearance values were 195 to 296 mL/min/kg. Carfilzomib binds to the target rapidly and is irreversible. It clears rapidly, but target binding was shown not to be the major mechanism of clearance. Pretreated controls who received a placebo rather than ONX 0912 to completely inhibit the proteasomal activity (CT-L) showed no significant differences in the PK parameters. The Phase I trial with carfilzomib led by O’Connor et al reported pharmacokinetic parameter estimates for three dose levels (11, 15, and 20 mg/m²). Variability in plasma concentrations of rapid clearance with a half-life < 30 minutes, as seen in the animal experiments, was observed. The steady state volume of distribution showed good peripheral tissue distribution consistent with studies in rats and monkeys. Elimination occurred through multiple clearance pathways.

Pharmacodynamics
In rat pharmacodynamic with IV administration of carfilzomib, one hour following administration, a dose-dependent suppression of CT-L activity was observed in the blood, heart, adrenals, lung, spleen, bone marrow, and liver. The same activity was not suppressed in brain, suggesting that despite rapid entry into cells, the compound does not readily cross the blood–brain barrier. A similar clearance and tissue distribution profile has been reported for bortezomib. The in vivo proteasome active site selectivities in mice confirmed that at doses that induced >80% inhibition of CT-L in blood, bortezomib was able to mediate pronounced inhibition of the CT-L consistent with the active site selectivity profiles observed in cell lines. The CT-L activity in vivo is a function of the total dose of carfilzomib administered, not the maximum plasma concentration. Proteasomal inhibition persists even after the drug is cleared systemically, and rapid clearance may prevent its ability to inhibit nonproteasomal targets and may reduce toxicities. In the human Phase I trial conducted by O’Connor et al, a dose-dependent inhibition of the CT-L proteasome activity in whole blood and peripheral blood mononuclear cells (PBMCs) was seen one hour after carfilzomib dosing. At dose levels > 15 mg/m², >75% proteasome inhibition was seen in whole blood and PBMCs after one dose of carfilzomib, and >90% inhibition after five daily doses. Activity normalized to baseline in PBMCs before the next cycle (every 14 days), but not in whole blood, which is thought to be secondary to the inability of erythrocytes to produce new proteins.

Dosing schedules
In rats, proteasome inhibition and recovery was also examined following two dosing schedules: IV carfilzomib administered for two (QDx2) or five (QDx5) consecutive daily doses. No significant differences were observed in the level of inhibition and the rate of recovery of CT-L activity in bone marrow following either dosing schedules compared with a single dose. However, cumulative inhibition of CT-L in blood following QDx2 was more pronounced than QDx5 dosing, likely due to the inability of erythrocytes to recover activity between doses.

Xenograft models
In the human tumor xenograft models, the antitumor activity of carfilzomib was compared with bortezomib in immunocompromised mice implanted with established xenografts derived from three tumor cell lines (colorectal adenocarcinoma, B cell lymphoma, and Burkitt’s lymphoma). MTD for bortezomib in mouse strains was 1 mg/kg D1 and for carfilzomib was 5 mg/kg. In all three models, at MTD, carfilzomib was more efficacious than bortezomib. Dose-reduction or schedule-alteration of carfilzomib to mimic the bortezomib dosing schedule resulted in decreased efficacy. Both the in vivo and xenograft studies reveal that intensive dosing schedules yield greater proteasomal inhibition in solid tumors and the hematologic tumor models without excessive toxicity.

Animal toxicity studies
In the animal toxicology studies, carfilzomib was administered to rats and monkeys for 5 consecutive days every 2 weeks. A severely toxic dose (dose that causes death or irreversible severe toxicity) in 10% of rodents (STD 10) was 12 mg/m², with greater than 90% proteasome inhibition...
in red blood cells one hour after dosing. A dose-dependent decrease in proteasome activity was demonstrated in animals, and equivalent levels of proteasome inhibition were achieved with administration of carfilzomib as either an IV push or an IV infusion. The dose limiting toxicities (DLTs) in animals included toxicity to the gastrointestinal tract, bone marrow, pulmonary, and cardiovascular systems. Carfilzomib did not cross the blood–brain barrier, with similar results reported in rat PD studies by Demo et al. Neurotoxicity or behavioral abnormalities were not seen immediately or at 6 to 9 months. In the chronic toxicity studies, carfilzomib at clinical doses was tolerable. DLTs included effects on the gastrointestinal, renal, pulmonary, and cardiovascular systems. As with bortezomib, transient neutrophilia and cyclical thrombocytopenia was seen, which was likely due to a reversible effect on megakaryocytes. Animal toxicity studies supported the tolerability of carfilzomib at doses achieving excellent proteasome inhibition. Based on the animal studies, two Phase I clinical trials in R/R hematological malignancies, PR-171-001 and PR-171-002, with two dosing schedules from the xenograft models (QDx2 and QDx5) were completed.

**Carfilzomib monotherapy: phase I trials**

PX-171-001 evaluated the safety and efficacy of carfilzomib in R/R hematologic malignancies, with a dose schedule of carfilzomib administered as an IV push consecutively on days 1–5 every 14 days in eight dose groups (1.2, 2.4, 4, 6, 8.4, 11, 15, and 20 mg/m²); 29 patients (10-MM, 15-NHL, 3-HL, and 1-WM) were enrolled on the study. The median number of 14-day cycles per patient was 4.8, and the mean cumulative carfilzomib exposure was 233 mg/m². No DLTs were observed in the initial seven dose groups (1.2–15 mg/m²), but one of three patients in the eighth dose group at 20 mg/m² level experienced G3 febrile neutropenia. One of two additional patients enrolled in the same group also experienced prolonged G4 thrombocytopenia with central nervous system (CNS) progression. The 15 mg/m² dose level was determined to be the MTD. Hematological toxicities were less common and included G2 anemia (G2-3 and G3: two patients) and thrombocytopenia (G1-2 and G4: two patients). Nonhematologic toxicities, mainly G1-2 gastrointestinal symptoms, were seen (mild to moderate nausea, 48%; diarrhea, 35%; and constipation, 21%). Respiratory symptoms (cough, 28%; dyspnea, 28%; and exertional dyspnea, 21%) were common. The responses seen include one unconfirmed CR (uCR) in an MCL patient, one PR in an MM patient, two minor responses (MR) – one in an MM patient and one in a WM patient – and SD in a third of patients in the study.

An alternative dosing schedule of carfilzomib administration was tested by dosing carfilzomib on 2 consecutive days, as opposed to the split dosing schedule. In PX-171-002, during the dose escalation (1.2 to 27 mg/m²) portion of the trial, 37 subjects received carfilzomib on days 1, 2, 8, 9, 15, and 16 of a 28-day cycle. At 15 mg/m², maximal proteasome inhibition (80%) was achieved one hour after dosing. At and beyond this dose level, among the 16 patients enrolled, five durable responses (134 to 392 days) occurred (four PRs and one MR in an MM patient). Six patients had SD (two MM patients and four lymphoma patients). The responses were rapid in onset, beginning in some subjects after one to two doses. DLTs at 27 mg/m² were hypoxia, thrombocytopenia, (G2–G4), and elevated creatinine (G2). In the PX-171-001 study, the most common reason for discontinuation of the study was the inability to maintain the scheduled dosing among patients who completed at least six cycles of treatment. PX-171-002 demonstrated that consecutive biweekly dosing (days 1, 2, 8, 9, 15, and 16 of a 28-day cycle) of carfilzomib at doses of 20 mg/m² leads to sustained proteasome inhibition and is well tolerated. Due to the encouraging safety profile of proteasomal inhibition and the clinical efficacy of carfilzomib as a single agent in the Phase I studies, Phase II studies of carfilzomib (PX-171-003 and PX-171-004) were initiated in patients with R/R MM.

**Carfilzomib monotherapy: phase II trials**

Two Phase II clinical studies evaluated carfilzomib in MM patients: PX-171-003-A0 (N = 46) in relapsed and refractory MM and PX-171-004 (N = 129) in relapsed MM. In both studies, patients received carfilzomib 20 mg/m² IV on days 1, 2, 8, 9, 15, and 16 every 28 days for up to twelve cycles. In the PX-171-003-A0 trial, patients received a median of three cycles and 13 patients completed ≥ six cycles. The most common adverse events were fatigue, anemia, thrombocytopenia, nausea, upper respiratory infections, increased creatinine, and diarrhea. PN occurred in < 10% of patients with one G3 in a patient with pre-existing G2 PN. The treatment-emergent PN rate was low with G3/4 2.2%, despite the fact that 78% of patients had G1/2 PN at enrollment. The response rate in PX-171-003-A0 was 18% PR, 7% MR, and 41% SD in R/R MM patients; 80% of patients achieved response during the first cycle. Of note, five of the 23 patients with bortezomib-refractory disease achieved an MR or PR.
The median time to progression was 5.1 months, with a duration of response (DOR) of 7.4 months. One of the MM patients achieved a PR when the dose was escalated to 27 mg/m² after the patient began to progress on 20 mg/m². Subsequently, a “stepped up” dosing schedule incorporated a higher dose of 20/27 mg/m² in order to maximize the clinical benefit of carfilzomib. Patients were enrolled in a stepped up dosing on PX-171-003-A1 and received 20 mg/m² for the first cycle and 27 mg/m² thereafter.

In PX-171-003-A1, a Phase Ib trial, a total of 266 patients were enrolled and 257 were response-evaluable. The ORR was 24% with a median DOR of 7.4 months. Of the 229 patients that had available cytogenetics, 71 had one cytogenetic abnormality. Among these patients, the ORR was very similar to standard risk patients and achieved an ORR of 28%, with a median DOR of seven months. Median overall survival was 15.5 months. The most common treatment-emergent AEs ≥ G3 SAEs were mostly hematologic events; 27 patients completed twelve cycles and continued on the extension protocol of PX-171-010. Notably, durable responses were achieved in 36% of patients with bortezomib and immunomodulatory drug refractory MM and those with unfavorable cytogenetics. This long-term follow up did not demonstrate any cumulative toxicities.

In PX-171-004, R/R MM patients received 20 mg/m² carfilzomib in cohort 1 (n = 94) and stepped up dosing with 20 mg/m² for the first cycle and 27 mg/m² thereafter in cohort 2 (n = 70). The study included patients who had never received bortezomib treatment (n = 129) and patients who had received prior bortezomib (n = 35). The subset of patients that were bortezomib treated had an ORR of 18%. Median DOR was 9 months and median time to progression (TTP) was 5.3 months. Among the nonbortezomib patients, 80% received a transplant in cohort 1 and 67% received a transplant in cohort 2. At baseline, 52% had a PN of any grade, 15% patients had unfavorable cytogenetics, and another 15% had creatinine clearance (CrCl) < 50 mL/min. Altogether, the median number of cycles received was >6.5 in both groups. Response rates for cohorts 1 and 2 were ORR 42% and 52%; ≥VGPR rates were 17% and 29%; and CR was 3% and 2%, respectively. In patients with unfavorable cytogenetics, the ORR was 36.8%. The median duration of response was 13.1 (7.2-NE) months in cohort 1 and not reached in cohort 2 at a median follow up of 13.8 months. Median progression free survival was 8.3 months. The most common G3/4 toxicities were lymphopenia (14%/19%), anemia (12%/17%), thrombocytopenia (15%/11%), neutropenia (12%/14%), pneumonia (14%/11%), fatigue (12%/1%), and dyspnea (5%/6%). G1/2 PN was seen in 14% and 19% of patients and G 3/4 in 2% and 0%. AEs led to discontinuation of the drug in 22% and 10% of patients, with 29% and 42% of patients completing twelve cycles. The median TTP was 7.6 and 5.3 months in these two groups, respectively. Carfilzomib can induce very high levels of response in patients who have not previously been treated with bortezomib, and even in bortezomib-treated patients, substantial anti-tumor activity was observed. Notably, disease control was achieved in 65% of patients with progressive MM upon entering the study. Patients that had undergone > twelve cycles had good tolerability, and cumulative toxicity has not been observed.

PX-171-005 is a Phase II trial that evaluated the safety and efficacy of carfilzomib in R/R MM patients with varying degrees of renal insufficiency. A quarter of the total enrolled patients (n = 39) had normal (CrCl 80 mL/min), mild (50–79), moderate (30–49), and severe (<30) renal functions. Patients received carfilzomib at a dose of 15 mg/m² IV on days 1, 2, 8, 9, 15, and 16 every 28 days for cycle 1, escalating to 20 mg/m² in cycle 2 and to 27 mg/m² in cycle 3. G3/4 AEs included anemia, thrombocytopenia, fatigue, increased creatinine, and mental status changes. Carfilzomib was dissociated with t 3/4 at 30–60 minutes and undetectable in plasma within three hours. Proteasome inhibition ranged from 75%–89% at one hour post-dose at doses of 15–20 mg/m². Thirteen patients achieved ≥MR and another 13 patients achieved SD (37% each). Dose adjustments were not required, suggesting manageable toxicity in renal failure patients.

PX-171-007 is a Phase Ib/2 study in R/R MM and relapsed solid tumors, designed to evaluate a 30-minute infusion of carfilzomib using a modified stepped-up dosing regimen, based on preclinical safety data showing that a slower infusion was better tolerated than a 2 to 10 minute infusion. MTD of 56 mg/m² was given on days 1, 2, 8, 9, 15, and 16 of a 28-day cycle. Of a total of 33 patients (four at 36 mg/m²; three at 45 mg/m²; 24 at 56 mg/m²; and two at 70 mg/m²), five received ≥ten cycles, suggesting tolerability to a prolonged infusion schedule at higher doses. DLTs occurred in two patients treated at 70 mg/m². The ORR of the MTD cohort (56 mg/m²) was 60% (stringent complete response (sCR) 5%; VGPR 20%, PR 35%; MR 5%; and SD 20%) with ≥G3 AEs in the 20/56 mg/m² cohort with thrombocytopenia (38%), anemia (21%), and hypertension (13%). Proteasomal inhibition of chymotrypsin-like activity in PBMCs was ≥95% at ≥56 mg/m² compared to >80% at 20 mg/m². These encouraging data support prolonging infusion times, which enables higher dose tolerability and a higher magnitude of proteasome inhibition. Table 3 summarizes...
| Trials | Type/disease | Drugs | Dose and schedule (every 28 days) | Results | SAE | Comments |
|--------|--------------|-------|----------------------------------|---------|-----|----------|
| PX-171-001 | Phase I (Hematologic malignancies) | CFZ | 1.2–20 mg/m² days 1–5 every 14 days | uCR 4% (MCL); PR 4% (MM) MR 4% (MM); MR 4% (WM) SD 33% | Nausea, vomiting, diarrhea, cough, dyspnea | 9 SD patients with mean DOT 116 days |
| O’Connor et al 2007 | | | | | | |
| N = 27 | | | | | | |
| PX-171-002 | Phase I (Hematologic malignancies) | CFZ | 1.2–27 mg/m² on days 1, 2, 8, 9, 15, 16 | PR 11% (MM) MR 3% (MM) SD 16% (6% MM; 10% NHL) | Hypoxia, thrombocytopenia; elevated creatinine | 6 SD patients with DOT 134–392 days |
| Alsina et al 2008 | | | | | | |
| N = 37 | | | | | | |
| PX-171-003-A0 | Phase II (R/R myeloma) | CFZ | CFZ: 20 mg/m² on days 1, 2, 8, 9, 15, 16 | >PR 18%; MR 26%; SD 41% median TTP 5.1 m; median DOR 7.4 m | Anemia, thrombocytopenia, neutropenia, fatigue, URTI; dyspnea | Expanded to protocol PX-171-003-A1 |
| Jagannath et al 2009 | | | | | | |
| N = 46 | | | | | | |
| PX-171-003-A1 | Phase II | CFZ | Cohort 1: 20/27 mg/m² | >PR 24%; median DOR-7.4 m | Anemia, thrombocytopenia neutropenia | 27 patients continued on expansion protocol PX-171-010 |
| Siegel et al 2009 | | | | | | |
| N = 257 | | | | | | |
| PX-171-004 | Phase II (R or R myeloma; bortezomib naïve) | CFZ | Cohort 1: 20/20 mg/m² | Cohort 1: ORR 42%; CR 3%; VGPR 14% | Median DOR: 13.1 m; TTP 8.3 m in cohort 1 |
| Vij et al 2009 | | | | | | |
| N = 129 | | | | | | |
| PX-171-005 | Phase II (R/R myeloma with renal impairment) | CFZ | CFZ: 15/20 mg/m² escalation to 27 mg/m² on days 1, 2, 8, 9, 15, 16 | CBR 37% (PR 23%; MR 14%); SD 37% | Fatigue, anemia, diarrhea, nausea, thrombocytopenia, constipation | Proteasome inhibition 1 hour post-dose: 75%–89% |
| Badros et al 2010 | | | | | | |
| N = 39 | | | | | | |
| PX-171-006 | Phase IIb/II (R/R myeloma) | CRd | CFZ: 2027 mg/m² on days 1, 2, 8, 9, 15; lenalidomide 25 mg on days 1–21; dex 40 mg days 1, 8, 15, 22 | ORR 78% (PR 38%; VGPR 22%; CR/sCR 18%) | Neutropenia, anemia, thrombocytopenia | |
| Wang et al 2010 | | | | | | |
| N = 52 | | | | | | |
| PX-171-007 | Phase II (Newly diagnosed myeloma) | CRd | CFZ: 16 mg/m² on days 1, 2, 8, 9, 15, 16; lenalidomide 25 mg on days 1–21; dex 40 mg on days 1, 8, 15, 22 | ORR 94% (sCR/CR/In CR 53%; >VGPR 65%); sCR/CR/InCR increased to 79% after 12 cycles | Anemia, neutropenia, thrombocytopenia, dyspnea, hyperglycemia, thrombocytopenia, anemia, neutropenia, fatigue, nausea, pyrexia, dyspnea | Unfavorable CTG: ORR 100%; CR 56% |
| Jakubowiak et al 2010 | | | | | | |
| N = 53 | | | | | | |
| PX-171-008 | Phase IIb/II | CFZ | CFZ: 20/27 mg/m² escalation to 36, 45, 56, or 70 mg/m² (stepped-up dosing) on days 1, 2, 8, 9, 15, 16 | ORR for 20/56 mg/m² cohort 60% | Median DOR was 8.0 m and median PFS was 7.0 m | At 56 mg/m², >75% total immunoproteasome activity inhibited |
| Papadopoulos et al 2010 | | | | | | |
| N = 33 | | | | | | |
| PX-171-009 | Phase II (Relapsed/refractory MM) | CTd | CFZ: 20 mg/m² on days 1, 2, 8, 9, 15, 16; thalidomide 200 mg daily; dex 40 mg on days 1, 8, 15, 22 | ORR 84% (PR 38%; VGPR 29%; CR/sCR 16%) | PN < G2 24% | ORR for del 17p 60%; TTS: G3 4%; GI < G2 4% G3 4% |
| Sonneveld et al 2010 | | | | | | |
| N = 45 | | | | | | |

Abbreviations: CBR, clinical benefit response; C1, cycle 1; CFZ, carfilzomib; CR, complete response; CRd, Carfilzomib, lenalidomide, dexamethasone; CTD, Carfilzomib, thalidomide, dexamethasone; CTG, cytogenetic; dex, dexamethasone; DOrr, duration of response; DOT, duration of therapy; GI, gastrointestinal; MCL, mantle cell lymphoma; MM, multiple myeloma; MR, minor responses; nCR, near complete response; ORR, overall response rate; PFS, progression free survival; PN, peripheral neuropathy; PR, partial response; R/R, MM, relapsed/refractory MM; RR, response rate; sCR, stringent complete response; SD, stable disease; TTS, tumor lysis syndrome; TTP, time to progression; uCR, unconfirmed complete response; URTI, Upper respiratory tract infection; VGPR, very good partial response; WM, Waldenstrom’s macroglobulinemia.
the efficacy, safety, and tolerability of carfilzomib in Phase I/II trials.

**Carfilzomib in combination with lenalidomide and dexamethasone**

PX-171-006 was an ongoing Phase II study in patients with relapsed MM in which carfilzomib is administered in combination with lenalidomide and dexamethasone (CRd). Carfilzomib was administered at 20 mg/m² on days 1 and 2 of cycle 1; 27 mg/m² was thereafter administered on days 1, 2, 8, 9, 15, and 16; lenalidomide was administered at 25 mg per os (PO) on days 1–21; and 40 mg dexamethasone PO was administered on days 1, 8, 15, and 22 of a 28-day cycle. Among the 52 patients enrolled, no DLTs were reported and 11.5% of the patients had SAEs (6/52). Hematologic AEs including G3/4 neutropenia (n = 12), anemia (n = 8), and thrombocytopenia (n = 8) were manageable. The ORR was 78% (CR/sCR 18%; VGPR 22%; PR 38%; MR 2%; and SD 8%) and prolonged administration of this regimen with manageable toxicities was possible (14–23 months). Based on these results, a large Phase III trial, ASPIRE, comparing CRd and Rd (PX-171-009) was initiated in July 2010 and is currently accruing patients with a final accrual goal of 700 patients.

Another Phase I/II study with CRd studied frontline therapy in MM. Transplant eligible candidates received four cycles of CRd (carfilzomib 20/27/36 mg/m² on days 1, 2, 8, 9, 15, and 16; lenalidomide 25 mg on days 1–21; and dexamethasone 40/20 mg on days 1, 8, 15, and 22 of a 28-day cycle); patients then underwent stem cell harvest and received four more cycles of CRd (dexamethasone reduced to 20 mg on days 1, 8, 15, and 22 of a 28-day cycle), followed by a maintenance phase from cycle 9 (reduced to 20 mg on days 1, 8, 15, and 22 of a 28-day cycle) onward until disease progression or toxicity. Transplant ineligible patients received eight cycles of CRd and proceeded to the maintenance phase from cycle 9 until disease progression or toxicity. In Phase II, CRd was administered at the maximum planned dose (carfilzomib 36 mg/m² on days 1, 2, 8, 9, 15, and 16; lenalidomide 25 mg on days 1–21, and dexamethasone 40/20 mg on days 1, 8, 15, and 22 of a 28-day cycle). Evaluating toxicities from cycles 1–8, the most common G1/2 hematological toxicity was thrombocytopenia and the most common nonhematological toxicity was hyperglycemia. Most common G3/4 hematological toxicities included anemia and neutropenia. Dose reductions were required in 31% of patients (carfilzomib 14%; lenalidomide 22%; and dexamethasone 4%). No G3/4 PN was seen among the cohort, but G1/2 PN was seen in 22% of patients. The ORR was 94% with ≥VGPR rates of 65% and sCR/CR/nCR rates of 53%. Patients with unfavorable cytogenetics (deletion 13 by metaphase, hypodiploidy, t(4;14), t(14;16), or deletion 17p) had ≥VGPR rates of 75% and sCR/CR/nCR rates of 56%. Given that the median change in M-protein from cycle 1 day 1 (C1D1) to C3D1 was 82%, most patients achieved the initial cytodestruction by C3. Continuing the same dose of lenalidomide at 25 mg until C4 and further lowering the doses of lenalidomide after stem cell harvesting may decrease the incidence of hematological toxicities associated with this combination. The study design also signifies the importance of maintenance regimens, as 24 of 27 patients continued CRd maintenance beyond cycle 9, and most patients did not require dose modifications. After twelve cycles or more, 100% of patients achieved ≥VGPR rates favoring this regimen, making it an excellent option for frontline therapies in myeloma. Together, these results suggest that the combination of CRd is active and well tolerated with no significant overlapping toxicities. Importantly, lenalidomide-associated neutropenia and thrombocytopenia do not appear to be exacerbated by concurrent treatment with carfilzomib, even up to 27 mg/m², suggesting that carfilzomib will combine well with other anti-cancer agents.

**Carfilzomib in combination with thalidomide and dexamethasone**

The European Myeloma Network evaluated the combination of carfilzomib with thalidomide and dexamethasone (Carthadex) as induction and consolidation therapy in transplant eligible patients with MM based on the VTD (bortezomib/thalidomide/dexamethasone) data from Cavo et al, resulting in the highest CR rate after induction and after high dose therapy and transplant in Phase III trials. The study evaluated 45 patients for response and safety with the combination of carfilzomib 20 mg/m² on days 1 and 2 and 27 mg/m² on days 8, 9, 15, and 16, and thalidomide 200 mg daily and dexamethasone 40 mg on days 1, 8, 15, and 22 of a 28-day cycle. After four such cycles, patients were harvested and received high dose chemotherapy with melphalan 200 mg/m². Post-transplant, in the consolidation phase, patients received four more cycles of CTd (carfilzomib 27 mg/m² on days 1, 2, 8, 9, 15, and 16; thalidomide 50 mg daily; and dexamethasone 40 mg on days 1, 8, 15, and 22 of a 28-day cycle). Two SAEs were reported in cycle 1. One patient progressed at cycle 4 and another progressed at the time of stem cell harvest. This combination resulted in an ORR of 84%, and 16% patients achieved CR/sCR. It is very
well tolerated, with G1/2 PN in 24% patients and no G3 PN. Dose reductions for thalidomide were done for one of seven patients with G1 PN and three of nine patients with G2 PN. 4% tumor lysis syndrome (TLS) was observed. The ORR for high risk patients (del17p) was 60% and inferior in standard risk patients; however, it is premature to come to conclusions, given the small sample size. Overall, the combination is well tolerated, but the incidence of PN may be further reduced with second and third generation immunomodulatory drugs.

### Safety data of carfilzomib

The selectivity of carfilzomib for the proteasome is regarded as the major reason for the low rates of PN relative to bortezomib. Safety data have been compiled for 526 patients enrolled in the trials PX-171-003-A0, PX-171-003-A1, PX-171-004, and PX-171-005. Overall, 94 (19%) patients received ≥twelve cycles of carfilzomib with a mean (SD) 5.7 (4.2) cycles. Almost all patients experienced a treatment-emergent AE; the most common AEs of any grade were fatigue, anemia, and nausea. The most frequently reported nonhematological AEs occurring in ≥30% of patients included fatigue (55%), nausea (45%), dyspnea (35%), diarrhea (33%), and pyrexia (30%). The most common ≥G3 nonhematological AE occurring in ≥10% of patients was pneumonia (11%). More than 50% patients were treated at 20/27 mg/m², and fewer than 10% required dose reduction. 18% of patients completed ≥twelve cycles and are participating in an ongoing Phase II study (PX-171-010) to monitor long-term safety. No evidence of cumulative toxicity was seen in these heavily pretreated patients with R/R MM.

### Hematological safety

Since the majority of patients with R/R MM exhibit therapy-related myelosuppression, hematological safety data for MM patients is of essential importance. The most frequently reported hematological AEs occurring in ≥30% of patients included anemia (47%) and thrombocytopenia (36%). The most common ≥G3 hematological AEs occurring in ≥10% of patients were thrombocytopenia (23%), anemia (22%), lymphopenia (18%), and neutropenia (10%). Platelet counts predictably decreased and reached a nadir by day 8 of a 28-day treatment cycle and returned to normal by the first day of the next cycle. There was no evidence of cumulative thrombocytopenia. There were no G5 hematological events and no G4 or 5 bleeding reactions associated with thrombocytopenia. Febrile neutropenia was reported in 1% of patients.

### PN

Overall PN was reported in 14% of patients across all studies. Although 378 (72%) patients had baseline PN (≥G2), only 13% reported treatment-emergent symptoms during the study. Seven (1.3%) patients experienced maximum G3 PN AEs, and no ≥G4 events were reported; one patient (0.2%) discontinued treatment due to a PN AE and five patients (1%) required dose modification or discontinuation due to PN. Martin et al evaluated the efficacy and tolerability of carfilzomib in R/R MM patients with a baseline PN of G1-2 from the Phase Ib trial (PX-171-003-A1); 206 (77%) had PN G1-2 at study entry. The >PR rate was 24% and the median DOR was 7.4 months for these heavily pretreated R/R MM patients (median lines of therapy were 13 and median disease duration was 5.9 years) in both the overall and PN-baseline cohorts. These results suggest that PN has no impact on the depth or durability of responses, or on the tolerability of carfilzomib and that it can safely be administered in heavily pretreated R/R MM patients.

### Special considerations

#### Unfavorable cytogenetics

Jakubowaik et al evaluated the outcomes of patients with high risk cytogenetics from the PX-171-003-A1 trial for Phase II patients with R/R MM with carfilzomib as a single agent (20/27 mg/m² administered on days 1, 2, 8, 9, 15, and 16 every 28 days). Unfavorable cytogenetic were defined as the presence of any of del13 or hypodiploidy by metaphase cytogenetic (CTG) analysis and/or del17p13, t(4;14), and t(14;16) by fluorescence in situ hybridization. Of the 234 patients, CTG data were available for 203 patients (87%) and fluorescence in situ hybridization data were available for 210 patients (90%); both were available for 178 patients (76%). 75 patients had ≥one unfavorable cytogenetic feature. The ORR for patients with unfavorable CTG was 30%, compared to 23% for patients with no CTG abnormalities. The DOR and TTP were seven months and four months, respectively, for patients with unfavorable CTG, and eight months and five months, respectively, for patients with no CTG abnormality. DOR for patients with t(14;16) was 5.6 months and 4.6 months for patients with del17p, suggesting that DOR may be shorter in heavily pretreated patients in whom del17p is consistently prevalent. Response rates were similar to patients with no CTG abnormality, with the exception of a lower rate for t(14;16); however, data are limited to three patients.

In the other Phase II study on patients with R/R MM (PX-171-004), CTG and fluorescence in situ hybridization...
| Trials | Carfilzomib in combination with | Dose and schedule (every 28 days) | Primary endpoints | Secondary endpoints | Start date | Planned completion date |
|--------|--------------------------------|----------------------------------|------------------|---------------------|------------|------------------------|
| Phase I (relapsed AML/ALL) | N = 18 | Single agent | CFZ: phase I schedule | MTD; G2 PN; G3 toxicities | RR; correlative studies | 09/2010 | 04/2013 |
| Phase I (relapsed/ refractory lymphoma) | N = 24 | Vorinostat (SAHA) | CFZ: regular schedule + SAHA PO BID D1, 2, 3, 8, 9, 10, 15, 16, 17 | MTD; safety; tolerability | Response | 01/2011 | 09/2011 |
| CLL, SLL, PLL | N = 36 | Single agent | CFZ: regular schedule | DLT; MTD safety and toxicity profile | Efficacy; PK; PD; correlatives | 10/20 | 08/2013 |
| T-cell lymphoma | N = 12 | Single agent | CFZ: regular schedule | DLT; MTD; NF-K B activation in tumor tissue | 06/2011 | 12/20/14 |
| Phase I | N = 30 | Lenalidomide | CFZ: D1, 2, 8, 15, 16 for C1–12 and D1, 2, 15, 16 for C12+ | MTD | Efficacy; PK | 08/2008 | 08/2012 |
| Phase I (relapsed/ refractory myeloma) | N = 45 | Pomalidomide | CFZ: regular schedule + Pom D1–21 + Dex 40 mg D1, 8, 15, 22 | Safety; tolerability | RR; TTP; PFS; OS | 11/2011 | 10/2014 |
| Refractory to bortezomib | N = 45 | Lenalidomide | CFZ: 20 mg/m² for C1 and escalated to 27, 36, and 45 mg/m² during C2–4 | Safety; tolerability | CT; MT; Efficacy | 04/2011 | 04/2013 |
| B: IMiD regimen | N = 50 | Vorinostat (SAHA) | CFZ: 20 mg/m² for C1 and escalated to 27, 36, and 45 mg/m² during C2–4 | | SAE; MTD | ORR; TTNT; TTP; DOR | 04/2011 | 03/2013 |
| (NCT012797764) | N = 50 | Lenalidomide | CFZ: 20 mg/m² for C1 and escalated to 27, 36, and 45 mg/m² during C2–4 | | MTD | CBR; PFS; OS; DOR; tolerability | 10/2010 | 03/2013 |
| (NCT01279694) | N = 32 | Melphalan | CFZ: D1, 2, 8, 9, 22, 23, 29, 30 + Melphalan: 6 mg/m² and prednisone: 60 mg/m² D1–4 q 42 D | MTD | | 06/2010 | 03/2013 |
| (NCT01496118) | N = 54 | Vorinostat (SAHA) | CFZ: 20 mg/m² for C1 and escalated to 27, 36, and 45 mg/m² during C2–4 | | RR | TTP; PFS; OS | 12/20/10 | 01/2014 |
| (NCT01301807) | N = 58 | Panobinostat | Regular schedule + panobinostat 15 mg PO D1, 3, 5, 8, 10, 12 | MTD | | 08/2010 | 03/2014 |
| (NCT01246063) | N = 53 | PLD | CFZ: phase I schedule + PLD: 30 mg IV D 8 | MTD | Efficacy; toxicity | 06/2011 | 11/2015 |
| (NCT01372540) | N = 76 | ARRY-520 | CFZ: phase I schedule + Argy-520: 0.75 mg/m³ IV D1, 2, 15 and Dex: 4 mg PO D1, 2, 8, 9, 15, 16 | MTD | Efficacy; toxicity | 05/20/12 | 05/2015 |
| Phase VII (newly diagnosed myeloma) | N = 45 | Cyclophosphamide | CFZ: regular schedule + Cyclophosphamide: D1, 8, 15 + Dex D1, 8, 15, 22 + thalidomide: D1–28 | MTD | VGPR | CR; TTTF; DOR; PFS; OS; SAE | 03/20/10 | 01/2015 |
| NCT Number | Study Name | Design | Treatment | Schedule | Endpoints | N | Start Date | End Date |
|-----------|------------|--------|-----------|----------|-----------|---|-------------|----------|
| NCT01029054 | Lenalidomide and Dexamethasone | Phase I (WM) | Lenalidomide and Dexamethasone | CFZ: D1,2, 8, 9, 15, 16 C1–8; D1, 2, 15, 16 for C9+. Lenalidomide: PO 25 mg D1-21. Dex: 40 mg on D1, 8, 15, 22 for C1–4, 20 mg C5–8, 10 mg C9+ | Safety; MTD; efficacy | 25 | 09/2009 | 06/2015 |
| NCT01470196 | Rituximab (R) and Dexamethasone | Phase I (WM): Waldenstrom’s Macroglobulinemia | Rituximab (R) and Dexamethasone | CFZ: 20 mg/m² D1, 2, 8, 9 of C1, 36 mg/m² D1, 2, 8, 9 of C2–6 + R: 375 mg/m² IV D2,9 + Dex 20 mg D1, 2, 8, 9 | RR; PN incidence; safety; tolerability; TTP | 30 | 10/2011 | 12/2013 |
| NCT00884312 | Single agent CFZ | Phase II (relapsed/refractory myeloma) | Single agent CFZ | CFZ 56 mg/m² D1, 2, 8, 9, 15, 16 | RR Safety; long term efficacy | 100 | 04/2009 | 04/2012 |
| NCT01351623 | Single agent CFZ | Phase II (relapsed/refractory myeloma) | Single agent CFZ | CFZ 56 mg/m² D1, 2, 8, 9, 15, 16 | RR Safety; PFS, TTP, DOR | 44 | 05/2011 | 05/2013 |
| NCT01346787 | Single agent CFZ & Cyclophosphamide | Phase II (newly diagnosed myeloma) | Single agent CFZ & Cyclophosphamide | CFZ 20 mg/m² D1, 2 of C1; 36 mg/m² D 8, 9, 15, 16 of C1 and subsequent doses + Cyclophosphamide 300 mg/m² D1, 8, 15 + Dex 40 mg D1, 8, 15, 22 | Toxicity; efficacy | 53 | 07/20/11 | 04/2015 |
| NCT01402284 | Lenalidomide and Dexamethasone | Phase II (relapsed/refractory myeloma) | Lenalidomide and Dexamethasone | CFZ: regular schedule C1–12; 27 mg/m² D1, 2, 15, 16 C13–18 | Toxicity including; PN BR; PFS; OS; OR, DOR | 45 | 07/2011 | 09/2015 |
| NCT01080391 | CRd vs Rd | Phase III (relapsed/refractory myeloma) | CRd vs Rd | CFZ: regular schedule C1–9; 27 mg/m² D1, 2, 15, 16 C10-18 | PFS | 700 | 07/2010 | 03/2014 |
| NCT01302392 | Single agent vs BSC | FOCUS (PX-171-011) | Single agent vs BSC | CFZ: regular schedule C1–9; 27 mg/m² D1, 2, 15, 16 C10-18 | OS PFS; RR; DCR; SAE | 302 | 09/2010 | 01/2015 |

Notes: Phase I schedule: carfilzomib (CFZ) in Phase I studies is administered IV over 30 minutes at 20 mg/m² on days 1 and 2, and at 27 mg/m² on days 8, 9, 15, and 16; dose escalation to 20 mg/m² occurs on days 1 and 2, and to 36 mg/m² on days 8, 9, 15, and 16; dose escalation to 20 mg/m² occurs on days 1 and 2, and to 45 mg/m² on days 8, 9, 15, and 16 every 28 days. Regular Schedule: Carfilzomib is administered on days 1, 2, 8, 9, 15, and 16 every 28 days.

Abbreviations: BR, best response; BSC, best supportive care; CBR, clinical benefit response; CR, complete response; CRd: CFZ, carfilzomb; lenalidomide, and dexamethasone; D, day; DOR, duration of clinical response; Dex, dexamethasone; DLT, dose limiting toxicity; DOR, duration of response; GEP, gene expression profiling; IMid, immunomodulatory agent; MTD, maximum tolerated dose; N, total number of patients; OS, overall survival; PD, pharmacodynamics; PFS, progression free survival; PK, pharmacokinetics; PLD, pegylated liposomal doxorubicin; PN, peripheral neuropathy; Rd, lenalidomide and dexamethasone; RR, response rate; SAE, serious adverse events; TTNT, time to next therapy; TTP, time to progression; VGPR, very good partial response.
data were available for 122 nonbortezomib patients. The ORR for the entire cohort was 48% (the ORR for patients with favorable vs unfavorable CTG was 51% and 37%). The unfavorable CTG group comprising 19 (15%) patients had only seven responses.

In the CRd frontline study, no significant differences in response rates were observed in the unfavorable CTG group vs the favorable CTG group (ORR 100% vs 91%; >VGPR 75% vs 61%; and CR 56% vs 52%). In the other frontline trial CTd, no significant differences in response rates were observed in the unfavorable CTG group vs the favorable CTG group (90% vs 88%; and >VGPR 55% vs 59%). These results demonstrate that carfilzomib may overcome the poor prognostic outcomes portended by unfavorable cytogenetics; however, the DOR and TTP are of extreme importance in this patient group because they tend to relapse early. The results of the ongoing carfilzomib maintenance therapy in this high risk group are of significant interest.

**Elderly patients**

In the PX-171-004 study of R/R MM patients, ORR for patients <65 and >65 was 59% and 38%, respectively. Other confounding variables of unfavorable cytogenetics, prior lines of therapy in older patients, and renal functions have not been adjusted for these results. In the frontline setting, as in CRd, where 43% of patients were >65 years old, ORR was 94%, suggesting that elderly patients derive the same benefit as younger patients.

**Renal failure**

From the safety data of 526 patients from the PX-171-003-A0, PX-171-003-A1, PX-171-004 and PX-171-005 trials, 71% had baseline renal dysfunction (CrCl <50 mL/min). Transient worsening of renal function (defined as a ≥2 fold increase in serum creatinine from baseline that normalizes during the study period) was reported in 6% of patients. Worsening of renal functions was observed in 7% of patients, and among these patients, 2% discontinued the study due to a renal AE; 87% of patients had no episodes of worsening renal function. Based on the pooled analyses and the results from PX-0171-005, carfilzomib dose and schedule need not be adjusted for baseline renal dysfunction, including in patients with severe renal dysfunctions.

**Dose response**

A comparison of efficacy based on dose response was analyzed from the results of PX-171-003-A0 (20 mg/m²) and PX-171-003-A1 (20/27 mg/m²); and PX-171-004-cohort 1 (20/27 mg/m²) and PX-171-004-cohort 2 (20/27 mg/m²), based on the increased ORR observed in the comparator arms 003-A1 vs 003-A0 as well as in 004-cohort 2 vs 004-cohort 1. A pooled multivariate model was designed to establish the dose–response relationship using the above Phase II studies. Using multivariate logistic regression analysis, the authors demonstrated that the odds of achieving >PR for a given patient treated with 27 mg/m² were 4.08-fold higher than for a patient receiving 20 mg/m². Also of interest in this analysis is the increment per-cycle odds of >PR, which were 1.12-fold for each 1 mg/m² increase in carfilzomib dose. It is of theoretical interest to analyze the dose-toxicity analysis in the group of interest. Ongoing studies (PX-171-007) are currently evaluating higher dosing regimens in relapsed solid tumors and R/R MM.

**Speed of response**

Prior studies with carfilzomib suggested that initial responses occur rapidly, and the depth of response improves with continued treatment. An exploratory analysis to evaluate the time to initial response was completed using patient data from two Phase II clinical trials, PX-171-003-A1 (257 patients) and PX-171-004 (bortezomib-naive patients, 135; bortezomib treated, 35 patients). The speed of responses was rapid across all groups. The median time to achieve a PR was 1.9, 1.7, and 1.4 months in PX-171-003-A1, PX-171-004, (bortezomib-naive), and PX-171-004 (bortezomib treated) patients, respectively. Similar results were observed in the upfront CRd trial, with a 42% reduction in paraprotein 2 weeks after initiating therapy, a 68% reduction after cycle 1, and an 82% reduction after cycle 3. A similar trend was observed in the other upfront trial CTd with response rates after cycle 1 (67% PR; 9% VGPR; and 2% CR), improving with subsequent cycles (after cycle 2 [50% PR; 30% VGPR; and 10% CR]; after cycle 3 [36% PR; 39% VGPR; and 11% CR], and after cycle 4 [25% PR; 35% VGPR; and 25% CR]).

**Duration of treatment**

Neurotoxicity is a major limitation for the long-term administration of bortezomib. In the preclinical chronic animal toxicology studies, carfilzomib did not cause neurotoxicity with long-term administration of 6 to 9 months. Patients treated on PX-171-002, PX-171-003, PX-171-004, and PX-171-005 were included in the analysis to evaluate long-term tolerability. Ten percent of patients in studies PX-171-003 and PX-171-005 and approximately 24% of patients in PX-171-004 completed twelve cycles of carfilzomib therapy, and 42 patients enrolled in the expanded protocol (PX-171-010). The median duration of treatment in this cohort was 14 months;
one patient continued treatment for longer than 27 months. Cumulative toxicities were not observed; four drug-related SAEs included infection, dyspnea, bronchitis, and asthenia. PN was not seen. The maintenance carfilzomib offered sustained disease control and resulted in excellent long-term tolerability, which is a promising maintenance regime.

Ongoing trials with carfilzomib as a single agent and in combination with other agents

Studies on carfilzomib as a single agent in relapsed/refractory AML, ALL, CLL, SLL, PLL, and T-cell lymphomas and as maintenance therapy in myeloma as well as a dose-finding study of higher doses of carfilzomib are currently ongoing. A Phase III study with carfilzomib as single agent that compares the best supportive care is ongoing. Dose finding studies in myeloma Phase I studies in combination with immunomodulatory drugs (lenalidomide and pomalidomide), HDACi (panobinostat and vorinostat), and cytoxic therapies (PLD and cytoxan) are currently continuing. In WM, carfilzomib is being evaluated in combination with rituximab and dexamethasone. A large Phase III trial comparing CRd and Rd is also ongoing. Currently ongoing studies are summarized in Table 4.

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References

1. Jung T, Catalol B, Grune T. The proteasomal system. Mol Aspects Med. 2009;30(4):191–296.
2. Rabl J, Smith DM, Yu Y, Chang S-C, Goldberg AL, Cheng Y. Mechanism of gate opening in the 20S proteasome by the proteasomal ATPases. Mol Cell. 2008;30(3):360–368.
3. Liu C-W, Li X, Thompson D, et al. ATP binding and ATP hydrolysis play distinct roles in the function of 26S proteasome. Mol Cell. 2006;24(1):39–50.
4. Braun BC, Glickman M, Kraft R, et al. The base of the proteasome regulatory particle exhibits chaperone-like activity. Nat Cell Biol. 1999;1(4):221–226.
5. Orlowski M, Wilk S. Catalytic activities of the 20S proteasome: a multi-catalytic proteinase complex. Arch Biochem Biophys. 2000;383(1):1–16.
6. Keith DW. Ubiquitination and deubiquitination: targeting of proteins for degradation by the proteasome. Semin Cell Dev Biol. 2000;11(3):141–148.
7. Dorsey BD, Iqbal M, Chatterjee S, et al. Discovery of a potent, selective, and orally Active proteasome inhibitor for the treatment of cancer. J Med Chem. 2008;51(4):1068–1072.
8. Kisselev AF, Callard A, Goldberg AL. Importance of the different peptolytic sites of the proteasome and the efficacy of inhibitors varies with the protein substrate. J Biol Chem. 2006;281(13):8582–8590.
9. Griffin TA, Nandi D, Cruz M, et al. Immunoproteasome assembly: cooperative incorporation of interferon γ (IFN-γ)–inducible subunits. J Exp Med. 1998;187(1):97–104.
10. Dick LR, Fleming PE. Building on bortezomib: second-generation proteasome inhibitors as anti-cancer therapy. Drug Discov Today. 2010;15(5–6):243–249.
11. Kane RC, Farrell AT, Sridhara R, Pazdur R. United States Food and Drug Administration approval summary: bortezomib for the treatment of progressive multiple myeloma after one prior therapy. Clin Cancer Res. 2006;12(10):2955–2960.
12. Richardson PG, Weller E, Lonial S, et al. Lenalidomide, bortezomib, and dexamethasone combination therapy in patients with newly diagnosed multiple myeloma. Blood. 2010;116(5):679–686.
13. Cavo M, Tacchetti P, Patriarca F, et al. Bortezomib with thalidomide plus dexamethasone compared with thalidomide plus dexamethasone as induction therapy before, and consolidation therapy after, double autologous stem-cell transplantation in newly diagnosed multiple myeloma: a randomised Phase 3 study. Lancet. 2010;376(9758):2075–2085.
14. Nooka AK, Kaufman JL, Behera M, et al. The improved efficacy of bortezomib containing induction regimens (BCIR) versus non-bortezomib containing induction regimens (NBCIR) in transplant-eligible patients with multiple myeloma (MM): meta-analysis of Phase III randomized controlled trials (RCTs). ASH Annual Meeting Abstracts. 2011;118(21):3994.
15. Bringenh S, Larrocca A, Rossi D, et al. Efficacy and safety of once-weekly bortezomib in multiple myeloma patients. Blood. 2010;116(23):4745–4753.
16. Argyriou AA, Iconomou G, Kalofonos HP. Bortezomib-induced peripheral neuropathy in multiple myeloma: a comprehensive review of the literature. Blood. 2008;112(5):1593–1599.
17. Windebank AJ, Grisold W. Chemotherapy-induced neuropathy. J Peripher Nerv Syst. 2008;13(1):27–46.
18. Moreau P, Pylpenko H, Grouscki S, et al. Subcutaneous versus intravenous administration of bortezomib in patients with relapsed multiple myeloma: a randomised, Phase 3, non-inferiority study. Lancet Oncol. 2011;12(5):431–440.
19. Oerlemans R, Franke N, Assaraf YG, et al. Molecular basis of bortezomib resistance: proteasome subunit β5 (PSMB5) gene mutation and overexpression of PSMB5 protein. Blood. 2008;112(6):2489–2499.
20. Kumar S, Rajkumar SV. Many facets of bortezomib resistance/susceptibility. Blood. 2008;112(6):2177–2178.
21. Kupperman E, Lee EC, Cao Y, et al. Evaluation of the proteasome inhibitor MLN9708 in preclinical models of human cancer. Cancer Res. 2010;70(5):1970–1980.
22. Richardson PG, Baz R, Wang L, et al. Investigational agent MLN9708, an oral proteasome inhibitor in patients (Pts) with relapsed and/or refractory multiple myeloma (MM): results from the expansion cohorts of a Phase 1 dose-escalation study. ASH Annual Meeting Abstracts. 2011;118(21):301.
23. Kumar S, Bensinger WI, Reeder CB, et al. Weekly dosing of the investigational oral proteasome inhibitor MLN9708 in patients with relapsed and/or refractory multiple myeloma: results from a Phase 1 dose-escalation study. ASH Annual Meeting Abstracts. 2011;118(21):816.
24. Berdeja JG, Richardson PG, Lonial S, et al. Phase 1/2 study of oral MLN9708, a novel, investigational proteasome inhibitor in combination with lenalidomide and dexamethasone in patients with previously untreated multiple myeloma (MM). ASH Annual Meeting Abstracts. 2011;118(21):479.
25. Durie BGM, Harousseau JL, Miguel JS, et al. International uniform response criteria for multiple myeloma. Leukemia. 2006;20(9):1467–1473.
26. Sanchez E, Li M, Steinberg JA, et al. Oral dosing of the novel proteasome inhibitor CEP-18770 shows marked anti-myeloma effects in SCID-Hu models of multiple myeloma. ASH Annual Meeting Abstracts. 2009;114(22):1840.
27. Piva R, Ruggeri B, Williams M, et al. CEP-18770: a novel, orally active proteasome inhibitor with a tumor-selective pharmacologic profile competitive with bortezomib. *Blood*. 2008;111(5):2765–2775.

28. NIH. Phase I study of the proteasome inhibitor CEP 18770 in patients with solid tumours or non-Hodgkin's lymphomas. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2007. Available from: http://clinicaltrials.gov/show/NCT00572617. Accessed February 26, 2012.

29. NIH. Study to determine the maximum tolerated dose and evaluate the efficacy and safety of CEP-18770 in patients with relapsed multiple myeloma refractory to the most recent therapy. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2010. Available from: http://clinicaltrials.gov/show/NCT01023880. Accessed February 26, 2012.

30. NIH. CEP-18770 in combination with lenalidomide and dexamethasone in relapsed or refractory multiple myeloma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT01348919. Accessed February 26, 2012.

31. Sanchez E, Nichols CM, Lam AC, et al. Efficacy and tolerability of CEP-18770 in combination with dexamethasone and lenalidomide using a SCID-Hu model of multiple myeloma (MM). *ASH Annual Meeting Abstracts*. November 18, 2011;118(21):2946.

32. Chauhan D, Hideshima T, Anderson KC. A novel proteasome inhibitor NPI-0052 as an anticancer therapy. *Br J Cancer*. 2006;95:961–965.

33. Singh AV, Lloyd GK, Palladino MA, Chauhan D, Anderson KC. Pharmacodynamic and efficacy studies of a novel proteasome inhibitor NPI-0052 in human plasmacytoma XenoMouse Model. *ASH Annual Meeting Abstracts*. 2008;112(11):3665.

34. Chauhan D, Catley L, Li G, et al. A novel orally active proteasome inhibitor induces apoptosis in multiple myeloma cells with mechanisms distinct from Bortezomib. *Cancer Cell*. 2005;8(5):407–419.

35. Richardson P, Hofmeister C, Jakubowiak A, et al. Phase 1 clinical trial of the novel structure proteasome inhibitor NPI-0052 in patients with relapsed and relapsed/refractory multiple myeloma (MM). *ASH Annual Meeting Abstracts*. 2009;114(22):431.

36. Chauhan D, Singh AV, Ciccarelli B, Richardson PG, Palladino MA, Anderson KC. Combination of novel proteasome inhibitor NPI-0052 and lenalidomide trigger in vitro and in vivo synergistic cytotoxicity in multiple myeloma. *Blood*. 2010;115(4):834–845.

37. NIH. Phase 1 trial of NPI-0052 in patients with advanced solid tumor malignancies or refractory lymphoma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2006. Available from: http://clinicaltrials.gov/show/NCT00396864. Accessed February 26, 2012.

38. NIH. Phase 1 clinical trial of NPI-0052 in patients with relapsed or relapsed/refractory multiple myeloma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2007. Available from: http://clinicaltrials.gov/show/NCT00461045. Accessed February 26, 2012.

39. NIH. Proteasome inhibitor NPI-0052 and vorinostat in patients with non-small cell lung cancer, pancreatic cancer, melanoma or lymphoma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2008. Available from: http://clinicaltrials.gov/show/NCT00667082. Accessed February 26, 2012.

40. Chauhan D, Singh AV, Aujay M, et al. A novel orally active proteasome inhibitor ONX 0912 triggers in vitro and in vivo cytotoxicity in multiple myeloma. *Blood*. 2010;116(23):4906–4915.

41. Papadopoulos K, Mendelson D, Tolcher A, et al. A Phase I, open-label, dose-escalation study of the novel oral proteasome inhibitor (PI) ONX 0912 in patients with advanced refractory or recurrent solid tumors. *J Clin Oncol*. 2011;Suppl 29:Abstr 3075.

42. NIH. Open-label study of the safety and activity of ONX 0912 in patients with hematological malignancies. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT01416428. Accessed February 27, 2012.

43. Elofsson M, Splittgerber U, Myung J, Mohan R, Crews CM. Towards subunit-specific proteasome inhibitors: synthesis and evaluation of peptide α′, β′-epoxyketones. *Chemistry and Biology*. 1999;6(11):811–822.

44. Dikic I, Crosetto N, Calatroni S, Bernasconi P. Targeting ubiquitin in cancers. *Eur J Cancer*. 2006;42(18):3095–3102.

45. Arastu-Kapur S, Ball AJ, Anderl JL, Bennett MK, Kirk CJ. Neuroedegeneration induced by bortezomib exposure in vitro occurs via proteasome independent mechanisms. *ASH Annual Meeting Abstracts*. 2009;114(22):2859.

46. Bolden JE, Peart MJ, Johnston RW. Anticancer activities of histone deacetylase inhibitors. *Nat Rev Drug Discov*. 2006;5(9):769–784.

47. Fuchs O, Provaznikova D, Marinov I, Kuzelova K, Spicka I. Antiproliferative and proapoptotic effects of proteasome inhibitors and their combination with histone deacetylase inhibitors on leukemia cells. *Cardiovasc Hematol Drug Development Targets*. 2009;9(1):62–77.

48. Hideshima T, Richardson PG, Anderson KC. Mechanism of action of proteasome inhibitors and deacetylase inhibitors and the biological basis of synergy in multiple myeloma. *Mol Cancer Ther*. 2011;10(11):2034–2042.

49. Mitsiades CS, Mitsiades NS, McMullan CJ, et al. Transcriptional signature of histone deacetylase inhibition in multiple myeloma: biological and clinical implications. *Proc Natl Acad Sci U S A*. 2004;101(2):540–545.

50. Zhang QL, Wang L, Zhang YW, et al. The proteasome inhibitor bortezomib interacts synergistically with the histone deacetylase inhibitor suberoylanilide hydroxamic acid to induce T-leukemia/lymphoma cells apoptosis. *Leukemia*. 2009;23(8):1507–1514.

51. Badros A, Burger AM, Philip S, et al. Phase I study of vorinostat in combination with bortezomib for relapsed and refractory multiple myeloma. *Clin Cancer Res*. 2009;15(16):5250–5257.

52. Rao R, Fiskus W, Yang Y, et al. Co-treatment with panobinostat enhances bortezomib-induced unfolded protein response, endoplasmic reticulin stress and apoptosis of human mantle cell lymphoma cells. *ASH Annual Meeting Abstracts*. 2008;112(11):887.

53. Dasmahapatra G, Lembersky D, Son MP, et al. Carfilzomib interacts synergistically with histone deacetylase inhibitors in mantle cell lymphoma cells in vitro and in vivo. *Mol Cancer Ther*. 2011;10(9):1686–1697.

54. Dasmahapatra G, Lembersky D, Kramer L, et al. The pan-HDAC inhibitor vorinostat potentiates the activity of the proteasome inhibitor carfilzomib in human DLBCL cells in vitro and in vivo. *Blood*. 2010;115(22):4478–4487.

55. Rao R, Fiskus W, Balusu R, et al. Treatment with histone deacetylase 6-specific inhibitor WT-161 disrupts hsP90 function, abrogates aggresome formation and sensitizes human mantle cell lymphoma cells to lethal ER stress induced by proteasome inhibitor carfilzomib. *ASH Annual Meeting Abstracts*. 2010;116(21):2856.

56. NIH. Study of carfilzomib and vorinostat for relapsed or refractory lymphoma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT01276717. Accessed February 27, 2012.

57. NIH. A study of carfilzomib, lenalidomide, vorinostat, and dexamethasone in relapsed and/or refractory multiple myeloma (QUAD). In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT01297764. Accessed February 27, 2012.

58. NIH. Carfilzomib plus panobinostat in relapsed/refractory multiple myeloma (MM). In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT0130180. Accessed February 27, 2012.

59. NIH. Study of the combination of panobinostat and carfilzomib in patients with relapsed/refractory multiple myeloma. In: ClinicalTrials.gov [website on the Internet]. Bethesda, MD: US National Library of Medicine; 2011. Available from: http://clinicaltrials.gov/show/NCT01496118. Accessed February 27, 2012.

60. Stappes C, Deskandal P, Hatfield K, et al. The proteasome inhibitors bortezomib and PR-171 have antiproliferative and proapoptotic effects on primary human acute myeloid leukemia cells. *Br J Haematol*. 2007;136(6):814–828.
Carfilzomib in relapsed/refractory lymphoid neoplasms and myeloma

61. Newherr D, Franke N, Jansen G, et al. Sensitivity of pediatric acute leukemia cells to bortezomib and epoxetane-based proteasome inhibitors: correlations with proteasome subunit expression. *ASH Annual Meeting Abstracts*. 2011;118(21):1513.

62. Gupta SV, Hertlein EK, Woyach JA, et al. The novel proteasome inhibitor carfilzomib functions independently of p53 to induce potent cytotoxicity in primary chronic lymphocytic leukemia cells and a defective NF-kappaB response. *ASH Annual Meeting Abstracts*. 2011;118(21):3510.

63. Zhang L, Qian J, Ou Z, et al. Carfilzomib, an irreversible proteasome inhibitor induces long-term growth inhibition of mantle cell lymphoma in vivo. *ASH Annual Meeting Abstracts*. 2011;118(21):3740.

64. Gu J, Hernandez-Illarramendi FJ, Kaufman GP, Mavis C, Czuczman MS. Carfilzomib (CFZ): a novel proteasome inhibitor that induces cell cycle arrest and cell death in rituximab-chemotherapy resistant lymphoma and potentiates the anti-tumor activity of chemotherapeutic agents. *ASH Annual Meeting Abstracts*. 2010;116(21):4908.

65. Gu J, Czuczman NM, Kaufman GP, Mavis C, Hernandez-Illarramendi FJ, Czuczman MS. The novel proteasome inhibitor carfilzomib (CFZ) potentiates the anti-tumor activity of chemotherapeutic agents in rituximab-chemotherapy resistant lymphoma through inducing G2/M cell cycle arrest and cell death. *ASH Annual Meeting Abstracts*. 2011;118(21):4970.

66. Pham LV, Tamayo AT, Li C, Lee J, Fayed L, Ford RJ. Chemo-resistance in diffuse large cell lymphoma: novel drug combinations targeting NFAT/NF-kB growth/survival/chemo-resistance signaling pathways in validated novel experimental systems. *ASH Annual Meeting Abstracts*. 2011;118(21):1428.

67. Sacco A, Aujay M, Morgan B, et al. Carfilzomib-dependent selective inhibition of the chymotrypsin-like activity of the proteasome leads to antitumor activity in Waldenstrom's macroglobulinemia. *Clin Cancer Res*. 2011;17(7):1753–1764.

68. Zhou H-J, Aujay MA, Bennett MK, et al. Design and synthesis of an orally bioavailable and selective peptide epoxetane proteasome inhibitor (PR-047). *J Med Chem*. 2009;52(9):3028–3038.

69. Arastu-Kapur S, Anderl JL, Kraus M, et al. Nonproteinosomal targets of the proteasome inhibitors bortezomib and carfilzomib: a link to clinical adverse events. *Clin Cancer Res*. 2011;17(9):2734–2743.

70. Kuhn DJ, Chen Q, Vorhees PM, et al. Potent activity of carfilzomib, a novel, irreversible inhibitor of the ubiquitin-proteasome pathway, against preclinical models of multiple myeloma. *Blood*. 2007;110(9):3281–3290.

71. Demo SD, Kirk CJ, Aujay MA, et al. Antitumor of PR-171, a novel irreversible inhibitor of the proteasome. *Cancer Res*. 2007;67(13):6383–6391.

72. Berkers CR, Verdoes M, Lichtman E, et al. Activity probe for vivo profiling of the specificity of proteasome inhibitor bortezomib. *Nat Meth*. 2005;2(5):357–362.

73. Kraus M, Florea B, Bader J, et al. Selective inhibition of the proteasome’s {beta}2 catalytic subunit alone does not induce cytotoxicity, but resenitizes bortezomib-refractory myeloma cells for bortezomib treatment. *ASH Annual Meeting Abstracts*. 2011;118(21):2915.

74. 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.

75. Lee SJ, Woo TM, Arastu-Kapur S, Wong AF, Renau TE, Kirk CJ. Potent inhibition of multiple proteasome subunits by carfilzomib in multiple myeloma and solid tumor patients. *ASH Annual Meeting Abstracts*. 2011;118(21):5068.

76. Papadopoulos KP, Lee P, Singhal S, et al. A Phase Ib/2 study of prolonged infusion carfilzomib in patients with relapsed and/or refractory (R/R) multiple myeloma: updated efficacy and tolerability from the completed 20/56 mg/m2 expansion cohort of PX-171-007. *ASH Annual Meeting Abstracts*. 2011;118(21):2930.

77. Yang J, Wang Z, Fang Y, et al. Pharmacokinetics, pharmacodynamics, metabolism, distribution, and excretion of carfilzomib in rats. *Drug Metab Dispos*. 2011;39(10):1873–1882.

78. Papadopoulos K, Mendelson D, Tolcher A, et al. A Phase I, open-label, dose-escalation study of the novel oral proteasome inhibitor (PH) ONX 0912 in patients with advanced refractory or recurrent solid tumors. *J Clin Oncol*. 2011;Suppl 29:Abstr 3075.

79. O’Connor OA, Stewart AK, Vallone M, et al. A Phase I dose escalation study of the safety and pharmacokinetics of the novel proteasome inhibitor carfilzomib (PR-171) in patients with hematologic malignancies. *Clin Cancer Res*. 2009;15(22):7085–7091.

80. Orlowski RZ, Stinchcombe TE, Mitchell BS, et al. Phase I trial of the proteasome inhibitor PS-341 in patients with refractory hematologic malignancies. *J Clin Oncol*. 2002;20(2):420–4227.

81. Lonial S, Waller EK, Richardson PG, et al. Risk factors and kinetics of thrombocytopenia associated with bortezomib for relapsed, refractory multiple myeloma. *Blood*. 2005;106(2):3777–3784.

82. Alzina M, Trudel S, Vallone M, Molinuevos C, Kunkel L, Goy A. Phase 1 single agent antitumor activity of twice weekly consecutive day dosing of the proteasome inhibitor carfilzomib (PR-171) in hematologic malignancies. *ASH Annual Meeting Abstracts*. 2007;110(11):411.

83. Jagannath S, Vij R, Stewart K, et al. Final results of PX-171-003-A0, part 1 of an open-label, single-arm, Phase II study of carfilzomib (CFZ) in patients (pts) with relapsed and refractory multiple myeloma (MM). *J Clin Oncol*. 2009;27(Suppl 15s):Abstr 8504.

84. Vij R, Kaufman JL, Jakubowiak AJ, et al. Final results from the bortezomib-naive group of PX-171-004, a Phase 2 study of single-agent carfilzomib in patients with relapsed and/or refractory MM. *ASH Annual Meeting Abstracts*. 2011;118(21):813.

85. Siegel D, Wang L, Orlowski RZ, et al. PX-171-004. An ongoing open-label, Phase II study of single-agent carfilzomib (CFZ) in patients with relapsed or refractory myeloma (MM); updated results from the bortezomib-treated cohort. *ASH Annual Meeting Abstracts*. 2009;114(22):303.

86. Vij R, Siegel D, Kaufman J, et al. Results of an ongoing open-label, Phase II study of carfilzomib in patients with relapsed and/or refractory multiple myeloma (R/R MM). *J Clin Oncol*. 2010;28(Suppl 15s):Abstr 8000.

87. Badros A, Vij R, Martin T, et al. Phase II study of carfilzomib in patients with relapsed/refractory multiple myeloma and renal insufficiency. *J Clin Oncol*. 2010;28(Suppl 15s):Abstr 8128.

88. Wang M, Bensinger W, Martin T, et al. Interim results from PX-171-006, a Phase (Ph) II multicenter dose-expansion study of carfilzomib (CFZ), lenalidomide (LEN), and low-dose dexamethasone (IoDex) in relapsed and/or refractory multiple myeloma (R/R MM). *J Clin Oncol*. 2011;118(21):813.

89. Moreau P, Palumbo A, Stewart A, et al. A randomized, multicenter, Phase (Ph) III study comparing carfilzomib (CFZ), lenalidomide (LEN), and dexamethasone (Dex) to LEN and Dex in patients (Pts) with relapsed multiple myeloma (MM). *J Clin Oncol*. 2011;Suppl 29:Abstr 8025.

90. Martin T, Singhal SB, Vij R, et al. Baseline peripheral neuropathy does not impact the efficacy and tolerability of the novel proteasome inhibitor carfilzomib (CFZ): results of a subset analysis of a Phase 2 trial in patients with relapsed and refractory multiple myeloma (R/R MM). *ASH Annual Meeting Abstracts*. 2010;116(21):3031.
