Clinical Pharmacokinetics, Metabolism, and Drug-Drug Interaction of Carfilzomib

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ABSTRACT

Carfilzomib, an irreversible proteasome inhibitor, has a favorable safety profile and significant antitumor activity in patients with relapsed and refractory multiple myeloma (MM). Here we summarize the clinical pharmacokinetics (PK), metabolism, and drug-drug interaction (DDI) profile of carfilzomib. The PK of carfilzomib, infused over 2–10 minutes, was evaluated in patients with solid tumors or MM. Metabolites of carfilzomib were characterized in patient plasma and urine samples. In vitro drug metabolism and DDI studies were conducted in human liver microsomes and hepatocytes. A clinical DDI study was conducted in patients with solid tumors to evaluate the effect of carfilzomib on CYP3A activity. Plasma concentrations of carfilzomib declined rapidly and in a biphasic manner after intravenous administration. The systemic half-life was short and the systemic clearance rate was higher than hepatic blood flow. Carfilzomib was cleared largely extrahepatically via peptidase cleavage and epoxide hydrolysis. Cytochrome P450 P450–mediated metabolism played a minor role, suggesting that coadministration of P450 inhibitors or inducers is unlikely to change its PK profile. Carfilzomib showed direct and time-dependent inhibition of CYP3A in human liver microsome preparations and exposure to carfilzomib resulted in reductions in CYP3A and 1A2 gene expression in cultured human hepatocytes. However, administration of carfilzomib did not affect the PK of midazolam in patients with solid tumors, and there were no safety signals indicative of potential drug interactions. We conclude that the rapid systemic clearance and short half-life of carfilzomib limit clinically significant DDI.

Introduction

The proteasome is a multicatalytic protease complex that plays a critical role in mediating the regulated degradation of intracellular proteins. The dipeptide boronate bortezomib (Velcade; Millennium Pharmaceuticals, Inc., Cambridge, MA) is a reversible proteasome inhibitor first approved in 2003 for the treatment of multiple myeloma (MM) and mantle cell lymphoma (Bross et al., 2004) and has validated the proteasome as a therapeutic target in B-cell neoplasms. As a result, several next-generation agents have entered clinical trials (Bennett and Kirk, 2008; Dick and Fleming, 2010). The tetrapeptide epoxoyketone carfilzomib is the first irreversible proteasome inhibitor to have been approved by the US Food and Drug Administration (FDA) for the treatment of relapsed and refractory MM. It differs from bortezomib both in the duration of proteasome inhibition and in its selectivity for the unique class of seven proteases that encompass the proteasome active sites (Demo et al., 2007; Arastu-Kapur et al., 2011). In several phase 2 studies, single-agent carfilzomib has demonstrated significant antitumor activity and a favorable safety profile (Martin et al., 2010; Siegel et al., 2012; Vij et al., 2012). Furthermore, preliminary data suggest that the combination of carfilzomib with lenalidomide and low-dose dexamethasone, with each drug administered at full doses and for an extended duration, was effective and well tolerated in patients with MM (Niesvizvyz et al., 2009). Preclinical studies in rats and monkeys have shown that carfilzomib is rapidly and extensively distributed and potently inhibits proteasome activity in a variety of tissues after i.v. administration (Yang et al., 2011). Carfilzomib has a systemic clearance (CL) greater than hepatic blood flow and a terminal half-life (t1/2) shorter than 30 minutes. The rapid elimination

SUPPLEMENTARY MATERIAL

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Introduction

The proteasome is a multicatalytic protease complex that plays a critical role in mediating the regulated degradation of intracellular proteins. The dipeptide boronate bortezomib (Velcade; Millennium Pharmaceuticals, Inc., Cambridge, MA) is a reversible proteasome inhibitor first approved in 2003 for the treatment of multiple myeloma (MM) and mantle cell lymphoma (Bross et al., 2004) and has validated the proteasome as a therapeutic target in B-cell neoplasms. As a result, several next-generation agents have entered clinical trials (Bennett and Kirk, 2008; Dick and Fleming, 2010). The tetrapeptide epoxoyketone carfilzomib is the first irreversible proteasome inhibitor to have been approved by the US Food and Drug Administration (FDA) for the treatment of relapsed and refractory MM. It differs from bortezomib both in the duration of proteasome inhibition and in its selectivity for the unique class of seven proteases that encompass the proteasome active sites (Demo et al., 2007; Arastu-Kapur et al., 2011). In several phase 2 studies, single-agent carfilzomib has demonstrated significant antitumor activity and a favorable safety profile (Martin et al., 2010; Siegel et al., 2012; Vij et al., 2012). Furthermore, preliminary data suggest that the combination of carfilzomib with lenalidomide and low-dose dexamethasone, with each drug administered at full doses and for an extended duration, was effective and well tolerated in patients with MM (Niesvizvyz et al., 2009). Preclinical studies in rats and monkeys have shown that carfilzomib is rapidly and extensively distributed and potently inhibits proteasome activity in a variety of tissues after i.v. administration (Yang et al., 2011). Carfilzomib has a systemic clearance (CL) greater than hepatic blood flow and a terminal half-life (t1/2) shorter than 30 minutes. The rapid elimination
of carfilzomib is mediated primarily by metabolism via peptidase cleavage and epoxide hydrolysis (Yang et al., 2011), making carfilzomib a unique small molecule therapeutic agent.

Here we describe the pharmacokinetic (PK) and metabolic profiles of carfilzomib in patients with either solid tumors or MM. The major elimination pathways of carfilzomib were characterized in vitro using human hepatocytes and ex vivo using human plasma and urine samples. In vitro studies were performed to assess the effects of carfilzomib on the activity of cytochrome P450 enzymes. A clinical drug-drug interaction (DDI) study is presented to evaluate the effect of carfilzomib on the PK of midazolam.

Materials and Methods

All clinical trials were conducted according to Good Clinical Practice standards. The protocol, informed consent, and other relevant study documentation were approved by the appropriate institutional review board at each participating site. All participants provided written informed consent in accordance with federal and institutional guidelines. Analyses of human plasma and urine samples, unless specified otherwise, were done using liquid chromatography–tandem mass spectrometry (LC–MS/MS) methods fully validated according to US FDA guidance in compliance with Good Laboratory Practice. Quality control samples covering concentrations across the calibration range were included in each analytical run to ensure accuracy, precision, and reproducibility. The percentages of deviation from nominal values (accuracy) for all quality control samples were ≤±15% (≤±20% at lower limit of quantification) and the percentages of the coefficient of variation (precision) were ≤±15% (≤±20% at lower limit of quantification). All samples were analyzed within the established stability period for sample collection and storage.

Pharmacokinetic Studies. Plasma samples for PK analysis of carfilzomib were taken from patients participating in an open-label, phase 1b/2, multicenter study with relapsed solid tumors (PX-171-007; Clinical trial reg. no. NCT00531284). Carfilzomib was administered to three patients intravenously within the established stability period for sample collection and storage. Plasma samples were collected on days 1 and 16 of cycle 1 before carfilzomib dosing, at the end of drug administration, and at 5, 15, and 30 minutes, and 1, 2, and 4 hours after the end of administration. Samples were processed by protein precipitation and analyzed using a LC–MS/MS method with a calibration range of 0.300–300 ng/ml for carfilzomib and 0.500–500 ng/ml for metabolites using deuterated analogs as the internal standards. For excretion, urine samples were collected from 0 to 5 hours and from 5 to 24 hours postdosing on day 1 of cycle 1. Samples were processed by protein precipitation and analyzed using a LC–MS/MS method with a calibration range of 0.300–300 ng/ml for carfilzomib and 0.500–500 ng/ml for metabolites using deuterated analogs as the internal standards. For excretion, urine samples were collected from 0 to 5 hours and from 5 to 24 hours postdosing on day 1 of cycle 1. Aconitnine (25% of the sample volume) was added to the bulk urine samples to minimize potential binding of carfilzomib to the collection container. The treated samples were then aliquoted and analyzed over a concentration range of 0.00–2000 ng/ml for carfilzomib and M15, and 10.0–5000 ng/ml for M14.

Pooled human hepatocytes (XenoTech LLC, Lenexa, KS) suspended in Waymouth Medium (Sigma-Aldrich, St. Louis, MO) were incubated with 1 μM carfilzomib at 37°C in an atmosphere of 5% CO2 at a final viable cell density of approximately 0.5 × 10^6 cells/ml in the presence and absence of known chemical inhibitors for each P450 isofrom. Incubations with specific P450 substrates were also conducted as positive controls. At 0, 15, 30, 60, and 120 minutes, the reactions were quenched by adding 200 μl of acetonitrile containing appropriate internal standards. Concentrations of carfilzomib and major metabolites were determined using a nonvalidated LC–MS/MS method after protein precipitation.

In Vitro P450 Inhibition. Human liver microsomes (HLMs) (XenoTech LLC) pooled from 16 donors of mixed gender were incubated at 37°C in duplicate with varying concentrations of carfilzomib (0.01–10 μM) to determine the inhibitory activity against six major human P450 isofroms (1A2, 2C8, 2C9, 2C19, 2D6, and 3A). The inhibitory potentials of 1A4, M15, and M16 on human CYP3A were assessed at concentrations of 0.04–30 μM. Substrates for the individual P450 isofroms were phenacetin (1A2; Km = 39 μM), amodiaquine (2C8; Km = 6.4 μM), diclofenac (2C9; Km = 5.9 μM), S-mephenytoin (2C19; Km = 36 μM), dexamethasorn (2D6; Km = 7.8 μM), testosterone (3A; Km = 100 μM), and midazolam (3A; Km = 3.8 μM). The microsomal protein concentration was 0.1 mg/ml, except for incubations with midazolam, where a protein concentration of 0.05 mg/ml was used. After 5 minutes, the reactions were quenched by protein precipitation with acetonitrile containing appropriate internal standards, and analyzed using validated LC–MS/MS methods (Rodrigues, 2008).

For IC50 measurements, determination of NADPH dependence and resistance to dilution, the concentrations of probe substrates were prepared to be approximately equal to their Km values. For Km measurements, the concentrations of midazolam were approximately equal to 0.3 × Km, 3 × Km, 6 × Km, and 10 × Km in the absence of carfilzomib or at carfilzomib concentrations ranging from 0.5 to 10 μM.

To determine the inactivation potency of carfilzomib on CYP3A, carfilzomib was preincubated in duplicate at 0, 0.5, 1, 3, 5, and 8 μM with pooled HLMs (2.5 mg/ml for testosterone and 1.25 mg/ml for midazolam) and a NADPH-generating mixture (1 mM NADP, 5 mM glucose-6-phosphate, and 1 U/ml glucose-6-phosphate dehydrogenase) for 0, 5, 10, 20, and 30 minutes. After preincubation, 16-μl aliquots of the mixtures were diluted 25-fold with 50 mM potassium phosphate buffer containing 3 mM MgCl2 and 1 mM EDTA (pH 7.4) and incubated with testosterone (200 μM) or midazolam (40 μM) and NADPH-generating mixture for 5 minutes to measure the residual enzymatic activity.
activity. $K_I$ (a carfilzomib concentration that caused half the maximal rate of inactivation) and $k_{m,act}$ (maximal rate of enzyme inactivation) were determined.

**In Vitro P450 Induction.** Human hepatocytes from three donors (BD Biosciences, Woburn, MA) were seeded at a density of approximately $2.0 \times 10^5$ viable cells/cm$^2$ in 24-well collagen I-coated plates and maintained in Williams’ Medium E (Sigma-Aldrich Co. LLC) for 2 days before treatment with solvent control (0.08% dimethyl sulfoxide), carfilzomib (0.1, 0.5, and 2.5 $\mu$M), rifampin (20 $\mu$M, an inducer of CYP3A), or $\beta$-naphthoflavone (20 $\mu$M, an inducer of CYP1A2) for an additional 3 days with daily medium and compound changes. After this, the medium was aspirated and replaced with fresh serum-free hepatocyte assay medium. Cells were incubated in triplicate with 200 $\mu$L of testosterone (200 $\mu$M) or phenacetin (100 $\mu$M), specific substrates for CYP3A and CYP1A2, respectively, for 30 and 60 minutes. The rates of 6β-hydroxytestosterone and acetaminophen formation were measured by LC–MS/MS (Perloff et al., 2009). To test the potential inhibitory effects of carfilzomib on P450 catalytic activity, cells exposed to the positive control inducers were treated with fresh medium containing 2.5 $\mu$M carfilzomib for 30 minutes and washed once with drug-free medium before incubation with probe substrates for CYP1A2 and CYP3A activity measurement. Cellular toxicity assays were carried out using 3-(4,5-dimethyl-2-thiazolyl)-2,5-diphenyl-2H-tetrazolium bromide (MTT; Promega Corporation, Madison, WI), and expression of CYP3A and CYP1A2 mRNA was determined by quantitative polymerase chain reaction (qPCR).

**Clinical Drug Interaction Study.** Patients ($n = 18$) with solid tumors received a single 2-mg oral dose of midazolam on day −7 followed by i.v. administration of carfilzomib at 27 mg/m$^2$ over 2–10 minutes on days 1, 2, 8, 9, 15, and 16 of a single 28-day cycle. Patients also received a 2-mg oral dose of midazolam immediately after carfilzomib on days 1 and 16. Plasma samples were collected predose, at 5, 10, and 30 minutes, and at 1, 2, 3, 4, 6, 8, 12, and 24 hours after the midazolam dose on days −7, 1, and 16. On day 1, an additional plasma sample was collected at the end of carfilzomib dose. Midazolam concentrations in plasma were determined using automated liquid-liquid extraction with methyl tert-butyl ether followed by LC–MS/MS analysis across a calibration range of 0.100–100 ng/ml using d$_4$-midazolam as the internal standard. The PK profile of carfilzomib was determined as described above, using samples obtained on day 1.

PK analyses were performed via noncompartmental methods using WinNonlin 5.2 software (Pharsight Corporation) to determine the midazolam pharmacokinetic parameters: time to $C_{\text{max}}$ ($T_{\text{max}}$), $C_{\text{max}}$, AUC from time 0 to 12 hours (AUC$_{0-12}$), AUC$_{\text{last}}$, AUC$_{\text{inf}}$, and $t_{1/2}$. AUC$_{\text{last}}$ determined on day 16 was used to compare with that on day 1 because plasma samples were not collected at 24 hours postdose on day 16. Descriptive statistics for the plasma concentrations versus time as well as all PK parameters were calculated for each treatment (midazolam alone (day −7) and cotreatment with carfilzomib (days 1 and 16)). Using the geometric linear model procedure in SAS software (version 9.2; SAS Institute Inc.), analysis of variance was performed on the log-transformed AUC$_{\text{last}}$ (for day −7 and day 1 only), AUC$_{\text{inf}}$ (for day −7 and day 16 only), AUC$_{\text{last}}$, and $C_{\text{max}}$ data at the α level of 0.05. Geometric mean ratios of midazolam with and without carfilzomib treatment (i.e., day 1 versus day −7, and day 16 versus day −7) with 90% confidence intervals (90% CIs) were calculated. Based on the analysis of in-transformed data, the point estimates and 90% CIs for the least-squares mean difference between treatments ([day 1] − [day −7]) were exponentiated to obtain point estimates and 90% geometric CIs for the ratio ([day 1]/[day −7]) on the original scale.

As defined in the protocol, no clinically significant change in midazolam exposure was to be concluded if the 90% geometric CI of the ratio ([day 1]/[day −7]) and ([day 16]/[day −16]) of least-squares means from the analysis of variance of the In-transformed AUC$_{\text{last}}$ ([day 1]/[day −7]) only, AUC$_{\text{inf}}$ ([day 16]/[day −7]) only, AUC$_{\text{last}}$, and $C_{\text{max}}$ were entirely within the standard equivalence range of 80–125%. Interactions were described as strong, moderate, or weak if AUC alterations were >5-fold, 2- to 5-fold, or 1.25- to 2-fold, respectively.

**Results**

**Pharmacokinetics and Metabolism of Carfilzomib.** After i.v. administration of a dose of 20 mg/m$^2$ to patients with solid tumors, carfilzomib concentrations declined rapidly with time in a biphasic manner, and the majority of the drug was eliminated from the plasma compartment within 30 minutes (Fig. 1; Table 1). Plasma CL was 146 ± 22 and 136 ± 53 l/h on days 1 and 16, respectively, exceeding hepatic blood flow (Kwon, 2001). Similar to results from an earlier in vitro rat blood partitioning experiment (Yang et al., 2011), preliminary data showed that carfilzomib had a low blood to plasma ratio in human blood (data not shown), indicating that the blood clearance is higher than the plasma clearance. These results suggest a significant contribution of extrahepatic mechanisms to carfilzomib elimination. No accumulation of carfilzomib was detected between doses, and exposure to carfilzomib was not changed upon repeat dosing. Carfilzomib was extensively protein bound in the plasma; plasma protein binding was 97.6–98.2%, independent of carfilzomib concentration across 21.6–7841 ng/ml and was not affected by the status of renal function (data not shown). Pooled plasma and urine samples derived from a phase 1 trial (Alsina et al., 2012) were used to determine the metabolic fate of carfilzomib after administration. A total of 15 metabolites were identified in human plasma and urine samples (Supplemental Table 1). The major metabolites (M14, M15, and M16) were derived from peptide cleavage and epoxide hydrolysis of carfilzomib and their MS/MS spectra are shown in Fig. 2. P450-mediated metabolites detected only at very low levels. This correlated with the in vitro study in which the rate of carfilzomib metabolism in human hepatocytes was unaffected by the addition of inhibitors of the major P450 enzymes (Supplemental Table 2). Fourteen of the metabolites detected in human plasma and urine were also detected in animal studies, with only M6, a sulfated tyrosine detected at low levels in human urine samples, not observed in animal samples (Yang et al., 2011). M14, M15, and M16 were detectable in plasma immediately after carfilzomib administration (Fig. 3). In patients with normal renal function

**TABLE 1**

<table>
<thead>
<tr>
<th>Pharmacokinetic Parameters of carfilzomib after intravenous administration to patients with solid tumors at 20 mg/m$^2$</th>
<th>Cycle 1 Day 1</th>
<th>Cycle 1 Day 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\text{max}}$ (ng/ml)</td>
<td>2760 ± 520</td>
<td>3707 ± 1953</td>
</tr>
<tr>
<td>AUC$_{\text{last}}$ (h·ng/ml)</td>
<td>238 ± 36</td>
<td>301 ± 180</td>
</tr>
<tr>
<td>AUC$_{\text{inf}}$ (h·ng/ml)</td>
<td>238 ± 36</td>
<td>301 ± 180</td>
</tr>
<tr>
<td>$t_{1/2}$ (h)</td>
<td>1.0 ± 0.6</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>CL (l/h)</td>
<td>146 ± 22</td>
<td>136 ± 53</td>
</tr>
</tbody>
</table>

Data are presented as mean ± S.D. ($n = 3$).
Fig. 2. MS/MS spectra of carfilzomib and its major metabolites (M14, M15, and M16). (A) Carfilzomib. (B) M14. (C) M15. (D) M16. All x-axes are m/z, and all y-axes are relative intensity.
Carfilzomib is a potent, irreversible inhibitor of the chymotrypsin-like activity of the proteasome that displays rapid tissue distribution, high systemic clearance, and a short half-life in animal models.

**In Vitro Inhibition and Induction Potential of Carfilzomib on Human P450s.** The epoxyketone pharmacophore of carfilzomib has the potential to covalently interact with and inhibit P450 enzymes. Carfilzomib’s potential to alter the exposure of concomitantly administered medications was assessed in vitro. In the P450 inhibition study using HLMs, the IC$_{50}$ values for CYP1A2, 2C8, 2C9, 2C19, and 2D6 were $>10$ $\mu$M (7194 $\text{ng/ml}$), the maximum concentration tested. This was greater than the mean $C_{\text{max}}$ values from the clinical studies described above. In contrast, carfilzomib acted as a direct inhibitor of CYP3A (Fig. 4A). The effects of carfilzomib were more pronounced when midazolam (IC$_{50}$: 1.7 $\mu$M) was used as the CYP3A substrate relative to testosterone (>10 $\mu$M) and the inhibition was competitive. The inhibitory effect of carfilzomib on human CYP3A was time-dependent. When carfilzomib was preincubated with HLMs for 30 minutes, the IC$_{50}$ value decreased from 1.7 to 0.49 $\mu$M when using midazolam as the substrate, and from >10 to 0.97 $\mu$M when testosterone was used as the substrate. This time-dependent inhibition required NADPH as a cofactor and was resistant to dilution. This suggests that carfilzomib is an irreversible or quasi-reversible inhibitor of CYP3A (Supplemental Fig. 1) and the time-dependent inhibition is not due to direct reaction of the epoxyketone with CYP3A. The $K_i$ was determined to be 11 $\mu$M and the $k_{\text{inact}}$ was 0.10 min$^{-1}$ using both substrates.

Based on the in vitro inhibition results and the data on the exposure of carfilzomib in patients, we estimated the ratio of intrinsic clearance values (R values) of a CYP3A probe substrate in the absence and presence of carfilzomib using a basic model (US Food and Drug Administration, 2012). The R1 value for direct inhibition was approximately 4.5–5.7 using a total maximum plasma concentration of 5.9–8.0 $\mu$M (unpublished data; Supplemental Fig. 2) with a carfilzomib dose of 27 $\text{mg/m}^2$. The calculated R2 value for time-dependent inhibition ranged from 84 to 540 using the maximum carfilzomib plasma concentration (above), the values of $k_{\text{inact}}$ and $K_i$ measured in this study, and the reported $K_{\text{deg}}$ values for CYP3A4 (Yang et al., 2008).

Neither of the major circulating metabolites, M14 and M15, showed either direct or time-dependent inhibition of CYP3A at concentrations up to 30 $\mu$M, whereas M16 showed time-dependent inhibition of CYP3A as the IC$_{50}$ value decreased from >30 to 1.8 $\mu$M in the absence or presence of a 30-minute preincubation (data not shown). The effect of carfilzomib on the activity and expression of CYP1A2 and 3A was evaluated by treating cultured primary human hepatocytes with varying concentrations of carfilzomib. CYP3A activity was decreased in a concentration-dependent manner after 3 days of treatment (Fig. 4B). At a carfilzomib concentration of 2.5 $\mu$M, CYP3A4 activity decreased by 45–96%, and CYP1A2 activity dropped to below the limit of quantification in two of three hepatocyte cultures. Exposure to Rifampin (20 $\mu$M) or β-naphthoflavone (20 $\mu$M), known inducers of CYP3A and CYP1A2, resulted in 14–50-fold or 9–47-fold induction of enzyme activity, respectively. In addition, cell viability was unaffected by the exposure to carfilzomib (data not shown), demonstrating that the cell cultures were suitable for assessment of P450 induction. When rifampin-treated hepatocyte cultures were incubated with carfilzomib at 2.5 $\mu$M for 30 minutes, only a 14–23% decrease in CYP3A activity was observed, suggesting that reduced enzymatic activity in human hepatocytes upon carfilzomib treatment of 3 days was unlikely to be due to enzyme inhibition.

Exposure to carfilzomib resulted in a concentration-dependent decrease in gene expression relative to solvent controls, with >95% decrease for CYP3A (three donors) and an approximately 40% decrease for CYP1A2 (one donor) at 2.5 $\mu$M (Fig. 4C). In contrast, exposure of cells to known P450 inducers resulted in increases in gene expression proportional to the changes in enzymatic activity.

Because carfilzomib demonstrated an inhibitory effect on midazolam metabolism in HLMs and reduced CYP3A activity and expression in human hepatocytes, a drug interaction study in patients with solid tumors was conducted to determine whether carfilzomib administration would alter the exposure of a CYP3A substrate in a physiologic setting. Of 18 patients enrolled, 17 received at least 1 dose of carfilzomib, and 12 patients completed a full cycle of administration. Fig. 4D depicts the mean plasma concentration versus time profiles for midazolam in samples taken before carfilzomib administration and on days 1 and 16 of cycle 1 of carfilzomib dosing. Table 2 lists the PK parameters of midazolam. The 90% geometric CI of the ratios of midazolam exposure before carfilzomib dosing (day −7) and after a single dose of carfilzomib (day 1) fell within the equivalence range of 80–125% (Supplemental Table 5), indicating that there was no clinically significant effect of carfilzomib on the PK of midazolam. Similarly, repeat dosing of carfilzomib failed to demonstrate a major impact on midazolam exposure. Administration of carfilzomib to these patients resulted in systemic clearance similar to those described above (Supplemental Fig. 2). In addition, no safety signals suggesting an overexposure to midazolam arose during the cycle of coadministration of the two compounds, providing further supporting evidence for a lack of a drug interaction (Supplemental Table 6).

**Discussion**

Carfilzomib is a potent, irreversible inhibitor of the chymotrypsin-like activity of the proteasome that displays rapid tissue distribution, high systemic clearance, and a short half-life in animal models.
In patients with MM, significant antitumor activity and a favorable safety profile have been reported (Martin et al., 2010; Siegel et al., 2012). However, the presence of a reactive pharmacophore makes an assessment of the PK, metabolism, and drug interactions of carfilzomib essential to understanding the practical clinical use of this promising new agent. The data presented here extend earlier preclinical findings and show that carfilzomib’s characteristic PK profile results in a lack of drug interactions in patients.
In animals, after single doses of up to 48 mg/m², carfilzomib displayed rapid clearance from plasma and a nearly instantaneous formation of metabolites (Yang et al., 2011). Consistent with these observations, carfilzomib displays high systemic clearance and a short half-life in patients with solid tumors. A similar PK profile was also observed in patients with hematologic malignancies (O’Connor et al., 2009; Alsina et al., 2012) and MM having varying degrees of renal dysfunction (Niesvizky et al., 2011). The rapid clearance of carfilzomib is primarily mediated by metabolism instead of renal excretion. On the other hand, potent proteasome inhibition (Connor et al., 2009) due to the electrophilic functional group. In HLMs, carfilzomib induced direct and time-dependent inhibition in hepatocyte cultures. Finally, carfilzomib and M16 in addition, carfilzomib also decreased CYP3A mRNA expression in cultured human hepatocytes. The clinical drug interaction study was therefore designed to assess both the effect of single- and repeat-dose administration of carfilzomib on CYP3A in solid tumor patients. The results of this study indicated that carfilzomib does not significantly alter the PK of midazolam after either single- or repeat-dose administration. Because midazolam is a highly sensitive CYP3A substrate (US Food and Drug Administration, 2012), it is reasonable to conclude that carfilzomib would not be expected to interact with other CYP3A substrates in vivo. Taken together, the results of the present study suggest that carfilzomib can be administered with other medications that are substrates of P450 enzymes without altering their exposure.

The lack of clinically significant drug interactions of carfilzomib with CYP3A may be attributed to the pharmacokinetic properties of carfilzomib. First, the drug is rapidly metabolized after i.v. administration with a short systemic half-life. The mean plasma concentration at 5 minutes postinfusion was approximately 20% of the mean Cmax and was further reduced to <1% by 30 minutes. Although the true intracellular hepatic concentration of carfilzomib is unknown, the exposure of P450 enzymes to intact carfilzomib is likely to be of a short duration. Furthermore, the major circulating metabolites, M14 and M15, are not inhibitors of CYP3A. Second, the NADPH-dependent oxidative metabolic pathway(s) responsible for time-dependent inhibition of CYP3A by carfilzomib and M16 in HLMs were not significant in vivo. This is supported by the lack of time-dependent inhibition in hepatocyte cultures. Finally, carfilzomib is highly bound to plasma proteins, further limiting the potential exposure of P450 enzymes to the free drug. Indeed, the level of proteasome inhibition in liver after i.v. administration of carfilzomib to rats was less than that seen in blood and other organs (Demo et al., 2007). Therefore, carfilzomib is unlikely to result in decreased mRNA expression of P450 isoforms in vivo as was seen in cultured hepatocytes.

In summary, carfilzomib displays high systemic clearance, a short half-life, and rapid metabolism largely via extrahepatic peptidase cleavage and epoxide hydrolysis. P450-mediated metabolism does not play an important role in the elimination of carfilzomib; therefore,

<table>
<thead>
<tr>
<th>Pharmacokinetic Parameter</th>
<th>Day −7 (n = 17)</th>
<th>Day 1 (n = 17)</th>
<th>Day 16 (n = 12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cmax (ng/ml)</td>
<td>16.3 ± 7.6</td>
<td>15.7 ± 6.2</td>
<td>16.0 ± 7.7</td>
</tr>
<tr>
<td>AUC0−12 (hr·ng/ml)</td>
<td>49.8 ± 30.9</td>
<td>47.3 ± 26.4</td>
<td>48.4 ± 23.0</td>
</tr>
<tr>
<td>AUC0−12 (hr·ng/ml)</td>
<td>42.5 ± 23.2</td>
<td>40.3 ± 19.1</td>
<td>48.4 ± 23.0</td>
</tr>
<tr>
<td>Tmax (h)</td>
<td>0.5 ± 0.2</td>
<td>0.7 ± 0.3</td>
<td>0.8 ± 0.7</td>
</tr>
<tr>
<td>t1/2 (h)</td>
<td>6.6 ± 2.2</td>
<td>6.3 ± 1.9</td>
<td>5.5 ± 1.5</td>
</tr>
</tbody>
</table>

Note: n = 11 on day 16 for AUC0−12 and t1/2.
coadministration of carfilzomib with drugs that are potent P450 inhibitors or inducers is unlikely to alter its PK profile. Although exposure to carfilzomib resulted in modest inhibition of CYP3A activity in vitro in HLMs and caused a decrease in P450 gene expression in human hepatocytes, clinically significant drug interaction was not noted in a study specifically designed to determine the effect of carfilzomib on CYP3A activity. Carfilzomib is a proteasome inhibitor with a distinct pharmacokinetic profile relative to bortezomib that may allow greater opportunity for general use in combination with other medications with less cause for concern regarding DDI.

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Wrote or contributed to the writing of the manuscript: Wang, Yang, Kirk, Alsina, Badros, Papadopoulos, Infante.

References