Pharmacokinetics and Antitumor Efficacy of XMT-1001, a Novel, Polymeric Topoisomerase I Inhibitor, in Mice Bearing HT-29 Human Colon Carcinoma Xenografts

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Abstract

Purpose: To evaluate the pharmacokinetics and tissue disposition of macromolecular camptothecin (CPT) drug conjugate, XMT-1001, and irinotecan (CPT-11) in mice bearing HT-29 xenograft tumors.

Experimental Design: The antitumor efficacy of XMT-1001 was evaluated in the mouse HT-29 human colon carcinoma xenograft model. XMT-1001 was administered intravenously to female athymic nude (nu/nu) mice bearing established HT-29 xenograft tumors (n = 10) at 15, 30, and 60 mg CPT equivalents/kg on weekly or biweekly schedules. The tumor growth inhibition and tumor growth delay endpoints were used for efficacy evaluation. In the pharmacokinetic study, XMT-1001 was administered intravenously at a pharmacologically relevant dose of 60 mg CPT equivalents/kg × 1 via tail vein or an equimolar dose of CPT-11 at 100 mg/kg i.p. × 1. Mice (n = 3 per time point) were euthanized from 0.083 to 336 hours after XMT-1001 administration and from 0.083 to 24 hours after CPT-11. Plasma, tumor, and tissues were collected from all animals. A liquid chromatography–tandem mass spectrometry assay was used to measure XMT-1001, conjugate release products, CPT-20-O-(N-succinimido-glycinate; CPT-SI) and CPT-20-O-(N-succinamidoyl-glycinate; CPT-SA), and CPT.

Results: After XMT-1001 administration, the majority of the plasma exposure is accounted for by conjugated CPT. XMT-1001 exhibited a prolonged exposure of conjugated drug, active conjugate primary release products, CPT-SI and CPT-SA, and active CPT, which was associated with greater antitumor response compared with CPT-11.


Introduction

Camptothecin (CPT) was discovered from the leaf extracts of the Camptotheca acuminata tree (1). In 1965, Wall and colleagues successfully isolated and characterized the structure of CPT and its analogs (2). The pentacyclic structure of CPT contains unique properties, such as an α-hydroxy lactone system in the E-ring and an unsaturated conjugated pyridone in the D-ring. The aqueous solubility of CPT is very low and will only dissolve in a few organic solvents (3). At physiologic pH (pH = 7.4), the E-ring opens rapidly forming the inactive hydroxy acid. On acidification, the hydroxy acid converts back to the active lactone form (2, 4–6).

CPT has significant antitumor efficacy across a broad spectrum of human tumor xenograft models (2, 7, 8). Although antitumor activity was evident in phase I trials with the sodium salt of CPT, which was used to overcome the insolubility of the lactone form of CPT, only modest response rates and severe toxicities were observed in phase II trials (9, 10). Clinical development of the drug was discontinued because of severe hemorrhagic cystitis (11–14). Rapid renal clearance of water soluble CPT–carboxylate from plasma and its conversion, in the acid milieu of the urine, to the active closed lactone form of CPT, was likely the cause of severe bladder toxicity.

More water soluble CPT derivatives, such as irinotecan and topotecan, that were developed subsequently, comprise the important class of antineoplastic agents. Irinotecan and topotecan are used to treat patients with broad spectrum of solid tumors. Although efficacious, these agents have significant toxicity. Topotecan treatment is...
Polymer–drug conjugates, the subclass of carrier-mediated therapeutic agents, offer several advantages over small molecule drugs, including increased aqueous solubility, prolonged blood circulation time, enhanced tumor delivery, and an improved toxicity profile. Camptothecin (CPT), a DNA topoisomerase I inhibitor, is a potent antineoplastic agent and an attractive target for conjugation with hydrophilic polymer carriers capable of improving its solubility, rapid plasma inactivation, and toxicity, which hindered the therapeutic application of the drug.

XMT-1001 is a novel macromolecular CPT conjugate prepared based on a biodegradable hydrophilic stealth polyacetal carrier. XMT-1001 is designed to produce prolonged tumor exposure to conjugated drug and its active release products to improve efficacy and tolerability in comparison to CPT. The improved distribution of XMT-1001 to the tumor and extended localized release of the novel CPT derivative, CPT-20-O-(N-succinimido-glycinate, CPT-SI), as well as CPT itself, are hypothesized to improve safety and efficacy over existing drugs in this class.

Conjugation of CPT and other CPTs, including irinotecan and SN-38, to polymer carriers have also been explored with the theoretical advantages of greater solubility, longer duration of exposure, selective delivery of entrapped drug to the site of action, superior therapeutic index, and the potential to overcome resistance associated with the small molecule antitumor agent (15, 16). The pharmacokinetics of these agents is dependent upon the carrier and not the parent drug until the drug is released from the carrier. The drug that remains linked to a conjugate or polymer or encapsulated in liposomes or nanoparticles is an inactive prodrug, and thus the drug must be released from the carrier to be active. Whether the drug needs to be released outside the cell in the tumor extracellular fluid or within the cell depends on the formulation of the carrier and the mechanism of release. After the drug is released from the carrier, the pharmacokinetics of the drug are the same as after administration of the noncarrier form of the drug. Thus, the pharmacology and pharmacokinetics of these agents are complex, and detailed studies must be carried out to evaluate the disposition of the conjugated or encapsulated form of the drug and the released active drug in plasma, tumor, and tissue (15).

Conventional small molecule anticancer agents have a low molecular weight resulting in rapid whole-body tissue distribution following systemic administration, as well as rapid diffusion out of these tissues, resulting in a relatively short residence time of the drug at the targeted site of action (i.e., tumor). In addition, small molecule drugs have the potential for exerting a pharmacologic toxic effect in normal tissues. The development of polymer conjugates as a method for drug delivery was based on the discovery that macromolecular molecules greater than 40 kDa produced prolonged plasma and tumor exposures and were able to evade renal clearance (17–21). The plasma, tumor, and tissue pharmacokinetics of conjugated drug is dictated by the characteristics of the conjugate, such as size, surface charge, architecture, dose, and route of administration (15, 16). Conjugates, liposomes, and nanoparticles attain high intratumoral concentrations due to the enhanced permeability and retention (EPR) effect in tumors and tumor vasculature (18–22). For conjugate, liposomal, or nanoparticle anticancer agents that do not contain an active targeting moiety (monoclonal antibody, ligand, and others) on the surface of the carrier to be effective for the treatment of solid tumors, they must extravasate through the leaky vasculature of the tumor and release active drug into the extracellular matrix. Once inside the tumor, small molecule drug is released from the conjugate, liposome, or nanoparticle and diffuses into the cell to elicit a cytotoxic response.

Several macromolecular CPT prodrugs tested in phase I/II trials have shown improvement in systemic exposure to CPT and provided the evidence of significant antitumor activity. Clinical development of some of these conjugates were not pursued further, partially due to bladder toxicity, which was likely related to high levels of excretion of CPT in the urine (23). The conjugates of irinotecan and SN-38, although not associated with bladder toxicity, have other toxicities, such as diarrhea (24–27).

XMT-1001 is designed to improve the safety profile compared with other CPT analogs by combining a passive tumor targeting of macromolecular prodrug with a hydrolytic dual phase drug release mechanism leading to distribution of the drug in a low soluble, less toxic, and more stable prodrug form, which can potentially reduce bladder and gastrointestinal toxicities while enhancing efficacy. Unlike many conjugated CPT analogs which rely upon slow hydrolysis or enzymatic cleavage of the CPT-20-O-ester bond to release CPT in one step, XMT-1001 uses a CPT-20-O-(N-succinimidoyl-glycinate) linkage, which generates CPT in 2 steps via well-defined small molecule drug intermediates (Fig. 1). XMT-1001 is a water soluble macromolecular conjugate of CPT. In this novel polymer prodrug, CPT is conjugated with an approximately 60 kDa biodegradable hydrophilic polyacetal, poly-1-(hydroxymethyl)-ethylene hydroxymethylformal] (PHF; ref. 28). In contrast to other polymer–CPT conjugates, such as IF-101 (or CRLX-101) or pegamotecan (EZN-246; ref. 29), which directly release CPT from the conjugate, XMT-1001 was specifically designed to release a novel, active CPT analog, CPT-20-O-(N-succinimidoyl-glycinate; CPT-SI), as its primary release product. In this first step, intramolecular cyclization occurs to release the highly lipophilic, lactone stabilized CPT-SI.
(ED\textsubscript{50} in HT-29 cells 30 nmol/L), which can be further hydrolyzed to the more soluble CPT-20-O-(N-succinimido-glycinate; CPT-SA). In these 2 small molecule prodrugs, the CPT-20-O-glycine-ester bond can be further hydrolyzed to provide the active lactone form of CPT (ED\textsubscript{50} in HT-29 cells = 15 nmol/L). The intent of designing XMT-1001 to release primarily the lipophilic, lactone-stabilized CPT-SI, as opposed to CPT itself, was to minimize the plasma levels of CPT and thereby avoid the renal clearance, bladder accumulation, and associated severe bladder toxicity of CPT itself.

The early pharmacokinetic and biodistribution studies conducted with dual-labeled PHF–CPT conjugate (\textsuperscript{111}In-labeled PHF and \textsuperscript{3}H-labeled CPT) confirmed improved plasma exposure to conjugated drug and preferential tumor and tissue accumulation of polymer carrier and CPT. The level of tumor accumulation of CPT reported in this study was significantly higher than was expected on the basis of prior studies using polymer carrier accumulation, indicating that both conjugated drug and drug released in circulation as lipophilic prodrugs CPT-SI and CPT-SA, and CPT contribute to intratumoral drug accumulation. Preclinical XMT-1001 pharmacokinetic studies in rats and dogs confirmed a prolonged plasma exposure of XMT-1001, CPT-SI, CPT-SA, and CPT (30). However, the pharmacokinetic disposition of XMT-1001, CPT-SI, CPT-SA, and CPT in tumor and tissues have not been evaluated.

The objectives of this study were to evaluate the plasma, tumor, and tissue pharmacokinetics and antitumor response of XMT-1001 in female \textit{nu/nu} mice bearing HT-29 human colon carcinoma xenografts. New sample processing methods were developed for quantitative determination of conjugated CPT (XMT-1001) and primary conjugate release products, CPT-SI and CPT-SA; and CPT in tumor and tissues.

**Materials and Methods**

**Chemicals and reagents**

XMT-1001 (6% weight/weight of CPT), CPT-20-O-(N-succinimido-glycinate; CPT-SI), and CPT-20-O-(N-succinamidoyl-glycinate; CPT-SA) were supplied by Mersana Therapeutics, Inc. CPT was purchased from Boehringer Ingelheim. CPT-11 and SN-38 were purchased from Sigma-Aldrich. Topotecan was supplied by Dr. Reddy’s Laboratories.

**Animal care**

All mice were handled in accordance with animal care and use procedures set forth in the Guide for the Care and Use of Laboratory Animals with respect to restraint, husbandry, surgical procedures, feed, and fluid regulation, and veterinary care (31). Animals were fed an irradiated NIH-31 modified 6% mouse/rat Sterilizable Diet (Teklad/Harlan Laboratories, Inc.) consisting of 18.0% crude protein, 6.0% crude fat, and 5.0% crude fiber and had access to water \textit{ad libitum} (reverse osmosis, 1 ppm Cl). They were housed on irradiated Enrich-o’cobs laboratory enrichment bedding.

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Figure 1. Dual-phase release of CPT from XMT-1001 occurs via lipophilic intermediates, CPT-20-O-(N-succinimido-glycinate; CPT-SI) and CPT-20-O-(N-succinamidoyl-glycinate; CPT-SA). Hydrolysis of intermediates results in formation of an active lactone form of CPT.
Individual tumor volumes ranged from 63.0 to 172.0 mm³ and were implanted subcutaneously into the flank of female athymic nude (nu/nu) mice (Harlan Laboratories, Inc.). The HT-29 tumors were harvested when they reached 500 to 1,000 mm³ and were implanted as approximately 1-mm³ fragments subcutaneously in the right flank of female athymic nude (nu/nu) mice by aseptic techniques. The target tumor volumes of the pharmacokinetic and efficacy studies were 150 to 300 mm³ and 100 to 150 mm³, respectively. Tumor volume was calculated using the following formula:

\[
\text{tumor volume (mm}^3\text{)} = (w^2 \times l)/2, \text{in which } w = \text{width and } l = \text{length in mm of the tumor}\]

**Pharmacokinetic study**

On day 29 following subcutaneous tumor implantation, mice (approximately 10 weeks of age) were pair matched and weighed. The tubes were placed in a Precellys 24 (Omni International, Inc.). Tumor and tissues were weighed in these 2-mL tubes. A volume of 3 mL 10% (w/v) trypsin was added per 1 g of tumor or tissue (32, 33).

**Tissue homogenization procedure**

Tumor and tissue samples from female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts were removed from the −80°C freezer and thawed on ice. Standard 2 mL screw-top tubes were filled with 15 mL of 1.4-mm and two 2.8-mm ceramic zirconium oxide beads (Omni International, Inc.). Tumor and tissues were weighed in these 2-mL tubes. A volume of 3 mL 10% (n/v) trypsin was added per 0.9 mL of plasma to prevent ex vivo conversion of XMT-1001 to the conjugate release products CPT-SI, CPT-SA, and CPT. Tumor, liver, skeletal muscle, spleen, brain, pancreas, kidney, lung, and peritoneal fat tissues were collected from each mouse. Plasma, tumor, and tissues were placed in cryopreservation vials and preserved by snap freezing using liquid nitrogen. They were stored at −80°C until analysis.

**Efficacy study**

On day 29 following subcutaneous tumor implantation, mice (approximately 10 weeks of age) were pair matched and weighed. The tubes were placed in a Precellys 24 (Omni International, Inc.). Tumor and tissues were weighed in these 2-mL tubes. A volume of 3 mL 10% (w/v) trypsin was added per 1 g of tumor or tissue (32, 33).

**Tissue homogenization procedure**

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Two separate assays were developed to measure XMT-1001, and CPT-SI, CPT-SA, and CPT in plasma, tumor, and tissue on the basis of previous studies (30). SN-38 was used as an internal standard (IS) for both assays. For XMT-1001, 100 μL of acidified plasma, tumor, or tissue homogenate was protein precipitated using 300 μL of acetonitrile. The samples were centrifuged and the acetonitrile supernatant containing CPT-SI, CPT-SA, and CPT was discarded. The pellet samples were then centrifuged and the supernatant was decanted into clean tubes and evaporated under nitrogen in TurboVap. Samples were reconstituted in 100 μL of acidic mobile phase containing acetonitrile:methanol:water:formic acid (25:25:50:0.1, v:v:v:v) and analyzed by liquid chromatography and tandem mass spectroscopy (LC/MS-MS). CPT-SI, CPT-SA and CPT, and IS were extracted from 100 μL of acidified mouse plasma, tumor, or tissue homogenate by protein precipitation with 300 μL of acetonitrile. The sample was centrifuged and the acetonitrile supernatant containing CPT-SI, CPT-SA, CPT, and IS was removed. The acetonitrile supernatant was evaporated, reconstituted with 100 μL of acidic mobile phase containing acetonitrile:methanol:water:formic acid (25:25:50:0.1, v:v:v:v), and analyzed by LC/MS-MS.

Briefly, the LC/MS-MS method consisted of reversed phase chromatography with triple quadrupole detection. The injection volume was 10 μL and solvent flow rate was 0.7 mL/min on a Chromolith SpeedRod RP-18e (50 × 4.6 mm, 2-μm particle size) analytical column. Mobile phase A consisted of water and formic acid [100:0.1(v:v)] and mobile phase B consisted of acetonitrile, methanol, and formic acid (50:50:0.1(v:v:v)). Peak detection was achieved using a Thermo TSQ Quantum Ultra mass spectrometer operating in electron spray positive ion (ESI+) mode (Spray voltage: 3,000 V, Vaporizer temperature: 500°C). XMT-1001, CPT-SI, CPT-SA, and CPT were detected using selected reaction monitoring using a transition of 349.156 → 305.200, 488.210 → 331.150, 506.216 → 331.130, and 349.156 → 305.200, respectively. The retention times for XMT-1001, CPT-SI, CPT-SA, CPT, and SN-38 (IS) under the above conditions were 3.44, 3.61, 3.37, 3.44, and 3.36 minutes, respectively. Quantitation was achieved by comparing the observed peak area ratios of analyte (XMT-1001, CPT-SI, CPT-SA, or CPT) and IS (SN-38) of the samples to a regression curve determined from drug-fortified plasma, tumor, or tissue standards. The standard curves of XMT-1001 and CPT-SA, and CPT in plasma, tumor, and tissue homogenates showed linearity over the concentration range of 3 to 900 ng/mL and 3 to 3,000 ng/mL, respectively. Obtained XMT-1001 plasma and tissue concentrations were reported in CPT equivalents. The acceptable criterion for precision and accuracy was 15% deviation from the nominal, except at the lower limit of quantitation where 20% deviation was acceptable, in accordance with the U.S. Food and Drug Administration Guidance for Industry on Bioanalytical Method Validation.

Sample processing and high-performance liquid chromatography assay for CPT-11

On the basis of our prior studies, a high-performance liquid chromatography (HPLC) with fluorescence detection assay was used to measure total (lactone + hydroxy acid) form of CPT-11 and SN-38 (35, 36). Topotecan (TPT) was used as the IS. A volume of 100 μL of acidified plasma, tumor, or tissue homogenate was protein precipitated using methanol. A volume of 30 μL of supernatant was directly injected on the HPLC. Quantitation was achieved by comparing the observed peak area ratios of analyte (CPT-11 and SN-38) and IS (TPT) of the samples to a regression curve determined from drug-fortified plasma, tumor, or tissue standards. The standard curve of CPT-11 and SN-38 in plasma, tumor, and tissue homogenates showed linearity over the concentration range of 3 to 1,000 ng/mL.

Pharmacokinetic analysis

The pharmacokinetics of XMT-1001 and CPT-11 in plasma, tumor, and tissue were analyzed by noncompartmental analysis using WinNonlin Professional Edition version 5.2.1 (Pharsight Corp.). The area under the concentration versus time curve (AUC) was calculated using the linear up/log down rule. AUC from 0 to t (AUC0–t) and AUC from 0 to infinity (AUC0–∞) were calculated. AUC0–∞ was reported if the percent extrapolation was 20% or less. The maximum concentration (Cmax), time of Cmax (tmax), last measured concentration (Clast), and time of Clast (tlast) were determined by visual inspection of the concentration versus time curve. Distribution half-life (t1/2), and elimination half-life (t1/2), time it takes for concentration to reach one-half of its original value during drug distribution and elimination phases, respectively, were calculated for XMT-1001.

Statistical analysis

Statistical analyses and graphical presentations of statistical analyses were carried out using Prism for Windows version 3.03 (GraphPad Software, Inc.). MTV was assessed between treatment and control groups using the Mann–Whitney U test. The log-rank test was used to compare the TTE of individual mice in each group (except those deaths determined to be NTR) between treatment and control groups. Statistical significance was determined using 2-tailed tests with α = 0.05. OS curves showing the percentage of mice remaining in the study as a function of time were constructed using TTE data by the Kaplan–Meier method.

Results

Efficacy and toxicity of XMT-1001 and CPT-11

Tumor response parameters are presented in Table 1. Mean tumor growth curves and Kaplan–Meier plot are
Table 1. Tumor response parameters of female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts following administration of CPT-11 and XMT-1001

<table>
<thead>
<tr>
<th>Dose</th>
<th>Treatment Route</th>
<th>Frequency</th>
<th>MTV (n) mm³</th>
<th>TGI (%)</th>
<th>Regressions Median TTE (range)</th>
<th>P&lt;sub&gt;0&lt;/sub&gt;</th>
<th>P&lt;sub&gt;II&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>—</td>
<td>—</td>
<td>446 (10)</td>
<td>—</td>
<td>—</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CPT-11</td>
<td>50 i.p.</td>
<td>twice weekly × 5</td>
<td>36 (10)</td>
<td>92</td>
<td>0.0001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>100 i.p.</td>
<td>once weekly × 5</td>
<td>209 (10)&lt;sup&gt;II&lt;/sup&gt;</td>
<td>53</td>
<td>0.0052</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>50 i.p.</td>
<td>once weekly × 5</td>
<td>320 (10)</td>
<td>28</td>
<td>0.0892</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>XMT-1001</td>
<td>15 i.v.</td>
<td>twice weekly × 5</td>
<td>135 (10)</td>
<td>70</td>
<td>&lt;0.0001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>biweekly × 5</td>
<td>40 (10)&lt;sup&gt;II&lt;/sup&gt;</td>
<td>91</td>
<td>&lt;0.0001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>once weekly × 5</td>
<td>279 (10)</td>
<td>37</td>
<td>0.1051</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>once weekly × 5</td>
<td>239 (10)&lt;sup&gt;II&lt;/sup&gt;</td>
<td>46</td>
<td>0.0029</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>once weekly × 5</td>
<td>126 (9)&lt;sup&gt;II&lt;/sup&gt;</td>
<td>72</td>
<td>0.0015</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>once weekly × 5</td>
<td>135 (10)&lt;sup&gt;II&lt;/sup&gt;</td>
<td>70</td>
<td>&lt;0.0001</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Abbreviations: MTV (n), median tumor volume (number of animals assessed); TFS, tumor-free survivor.
<sup>a</sup>Mann-Whitney U test.
<sup>b</sup>Log-rank test.

Plasma, tumor, and tissue disposition of XMT-1001, CPT-SI, CPT-SA, and CPT

Plasma, tumor, and tissue concentration profiles of XMT-1001, CPT-SI, CPT-SA, and CPT are presented in Fig. 3. Pharmacokinetic parameters of XMT-1001, CPT-SI, CPT-SA, and CPT are presented in Table 2.

Following administration of XMT-1001, conjugated CPT plasma concentration reached C<sub>max</sub> within 15 minutes and then declined biexponentially over 7 days. The majority of conjugated CPT, responsible for more than 95% of XMT-1001 exposure, was cleared from the plasma in the first 48-hour post administration with a t<sub>1/2</sub> of 4.0 hour; the rest of the exposure (approximately 5%) was cleared with a t<sub>1/2</sub> of 30.9 hours.

The plasma concentrations of CPT-SI, CPT-SA, and CPT following administration of XMT-1001 reached C<sub>max</sub> within 15 minutes and declined over 24 hours. Estimated t<sub>1/2</sub> values for CPT-SI, CPT-SA, and CPT were comparable with t<sub>1/2</sub> values for conjugated CPT ranging from 2.1 to 3.0 hours. The AUC<sub>C100</sub> for CPT-SI, CPT-SA, and CPT were relatively minor components in plasma as compared with AUC values observed for conjugated CPT (1.48%, 1.27%, and 0.24% for CPT-SI, CPT-SA, and CPT, respectively).

The tumor concentration profiles for conjugated CPT and release product showed gradual accumulation of conjugated CPT, and the low water soluble CPT-SI...
and CPT and rapid accumulation of water soluble CPT-SA. The distribution phase for all CPT derivatives was completed by 24 hours. Intratumoral concentrations of drug-related compounds declined gradually over a 2-week period. High intratumoral concentrations of conjugated CPT (approximately 1,000 ng/mL) and CPT-SI (30 ng/mL) were observed at the last sample time at 336 hours.

Relative tumor exposure to lipophilic CPT-SI and CPT was 4.2- and 2.5-fold higher than their relative plasma exposure, indicating longer retention of the low water soluble prodrug CPT-SI in the tumor. The ratio of tumor AUC to plasma AUC for conjugated CPT and conjugated release products, CPT-SI, CPT-SA, and CPT were 15%, 65%, 14%, and 38%, respectively. This indicated significant tumor distribution and accumulation of CPT prodrugs and, especially, for therapeutically active lipophilic CPT-SI and CPT.

The extended tissue retention and high exposure of XMT-1001 and conjugated drug release products, CPT-SI, CPT-SA, and CPT were also observed in the liver, spleen, kidney, muscle, fat, lung, and pancreas. The lowest exposure of CPT and its prodrugs were observed in the brain.

Plasma, tumor, and tissue disposition of CPT-11 and SN-38

Plasma, tumor, and tissue concentration versus time profiles of CPT-11 and SN-38 are depicted in Fig. 4. Following administration of CPT-11, plasma CPT-11, and SN-38 concentrations reached Cmax within 30 minutes. CPT-11 and SN-38 plasma concentrations rapidly declined over 24 hours. Pharmacokinetic parameters of CPT-11 and SN-38 are presented in Table 2. There were high exposures of CPT-11 and SN-38 observed in the plasma, tumor, liver, spleen, kidney, muscle, fat, lung, and pancreas. The lowest exposure of CPT-11 and SN-38 was observed in the brain.

Discussion

The optimal pharmacokinetic characteristics of polymer conjugate nanoparticle anticancer agents includes an extended blood or plasma circulation time, enhanced tumor delivery, and release of active drug from the carrier into the tumor extracellular matrix (15, 16, 22, 37, 38). Preliminary pharmacokinetics of XMT-1001 in rats and dogs reported an extended plasma circulation time of conjugated drug, yet the full extent of tumor and tissue...
Figure 3. Individual and mean concentration versus time profiles of: XMT-1001 (A), CPT-SI (B), CPT-SA (C), and CPT (D) in plasma, tumor, and tissue of female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts following administration of XMT-1001 at 60 mg/kg (CPT equivalents) i.v. Mean concentration at each time point is represented by a (●).
Table 2. Noncompartmental pharmacokinetic parameters following administration of XMT-1001 and CPT-11 in mice bearing HT-29 human colon carcinoma xenografts

<table>
<thead>
<tr>
<th>Matrix</th>
<th>XMT-1001</th>
<th>CPT-SI</th>
<th>CPT-SA</th>
<th>CPT-SA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AUC&lt;sub&gt;∞&lt;/sub&gt; (ng/mL h)</td>
<td>t&lt;sub&gt;max&lt;/sub&gt; (h)</td>
<td>C&lt;sub&gt;max&lt;/sub&gt; (ng/mL)</td>
<td>AUC&lt;sub&gt;∞&lt;/sub&gt; (ng/mL h)</td>
</tr>
<tr>
<td>Plasma</td>
<td>3,626,518.70</td>
<td>0.1</td>
<td>792,726.80</td>
<td>53,653.10</td>
</tr>
<tr>
<td>Tumor</td>
<td>541,536.8</td>
<td>0.1</td>
<td>101,666.60</td>
<td>34,695.40</td>
</tr>
<tr>
<td>Liver</td>
<td>2,897,487.2</td>
<td>1</td>
<td>189,528.0</td>
<td>8,303.70</td>
</tr>
<tr>
<td>Muscle</td>
<td>379,821.70</td>
<td>2</td>
<td>8,610.80</td>
<td>570.9</td>
</tr>
<tr>
<td>Spleen</td>
<td>1,786,496.9</td>
<td>0.5</td>
<td>40,257.40</td>
<td>25,452.30</td>
</tr>
<tr>
<td>Brain</td>
<td>40,641.70</td>
<td>0.3</td>
<td>8,610.80</td>
<td>570.9</td>
</tr>
<tr>
<td>Pancreas</td>
<td>226,834.10</td>
<td>2</td>
<td>15,266.70</td>
<td>7,416.60</td>
</tr>
<tr>
<td>Kidney</td>
<td>1,107,174.0</td>
<td>0.5</td>
<td>48,946.80</td>
<td>41,486.00</td>
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<tr>
<th>Matrix</th>
<th>CPT-11</th>
<th>SN-38</th>
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<td></td>
<td>AUC&lt;sub&gt;∞&lt;/sub&gt; (ng/mL h)</td>
<td>t&lt;sub&gt;max&lt;/sub&gt; (h)</td>
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<tr>
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<td>Fat</td>
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NOTE: Pharmacokinetic parameters of XMT-1001, CPT-SI, CPT-SA, and CPT in female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts following the administration of XMT-1001 at 60 mg/kg (CPT equivalents) i.v. × 1 via tail vein, (A). Pharmacokinetic parameters of CPT-11 and SN-38 in female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts following the administration of CPT-11 at 100 mg/kg i.p. × 1, (B).
nanoparticle drugs are cleared from normal tissues. The decreased clearance of polymer conjugates by impaired lymphatic drainage in tumor results in the retention of these formulations at high concentrations for extended periods of time in the tumor (18). Normal tissue vasculature without the abnormal and disorganized qualities of tumor vasculature selectively excludes polymer conjugates from penetration and accumulation. This reduces localization of these drugs in normal tissue and the associated toxicities. Another primary driving force for the accumulation of polymer conjugate nanoparticles in the tumor is the prolonged plasma circulation time exhibited by macromolecular drugs larger than 40 kDa (39–41). This size is sufficient for macromolecular drugs to escape the threshold for renal clearance and to remain in the plasma compartment until further distribution or metabolism. Factors that affect the EPR effect include vehicle-related (plasma residence time, conjugate, or liposome size, conjugate, or liposome architecture), tumor-related (size, type, and microenvironment) and external mediators (radiation, bradykinin antagonist, cyclooxygenase inhibitor, and nitric oxide scavenger; refs. 17–21).

Following the administration of XMT-1001 at 60 mg/kg i.v. %1 or CPT-11 at 100 mg/kg i.p. %1 to female nude (nu/nu) mice bearing HT-29 human colon carcinoma xenografts, the plasma exposure of XMT-1001 was 27.5-fold greater than CPT-11 at the equimolar dose. XMT-1001 exhibited a 7-fold increase in duration of exposure in plasma (168 hours) compared with CPT-11 (24 hours). After administration of XMT-1001, 97.0% of CPT remained conjugated to the polymer in plasma. Duration of exposure of the lipophilic, active primary release product of XMT-1001, CPT-SI, as well as the secondary release product, CPT-SA, and active drug CPT in plasma were 24 hours. The duration of exposure of the active metabolite of CPT-11, SN-38, was also 24 hours.

The tumor exposure of XMT-1001 was 2.7-fold greater than that of CPT-11. Moreover, the duration of exposure of XMT-1001 (336 hours) was 14-fold greater than that of CPT-11 (24 hours). CPT-SI, CPT-SA, and CPT (6.4%, 1.2%, and 0.6%, respectively) represented 8.2% of the exposure in the tumor following XMT-1001 administration, whereas SN-38 represented 12.3% of the exposure following CPT-11 administration. However, released CPT from XMT-1001 resulted in a 1.6-fold higher exposure in tumor than that of SN-38 from CPT-11. XMT-1001 release products and SN-38 had similar durations of exposure (24 hours) in the tumor. The overall degree of tumor penetration and exposure is best described by the ratio of tumor to plasma exposures of XMT-1001, CPT-SI, CPT-SA, and CPT. The ratio of tumor to plasma exposure of conjugate and conjugate release products following the administration of XMT-1001 is 0.157.

XMT-1001 distributed to the liver, spleen, and kidney with resulting exposures of CPT-SI, CPT-SA, and CPT. This tissue distribution corresponds to the known mechanisms of clearance of conjugates, liposomes, and nanoparticles (12). The liver and spleen are part of the mononuclear disposition of XMT-1001 had not been evaluated. This is the first study evaluating the plasma, tumor, and tissue pharmacokinetics and antitumor efficacy of XMT-1001 and its release products CPT-SI, CPT-SA, and CPT, in mice bearing HT-29 human colon carcinoma xenografts. The results of this study suggest that XMT-1001 provides pharmacokinetic advantages in plasma and tumors when compared with CPT-11. In addition, the results of our study are consistent with the improved antitumor efficacy and therapeutic index of XMT-1001 compared with CPT-11.

The theory behind the improved tumor localization of XMT-1001 revolves around the phenomenon known as enhanced permeability and retention (EPR; ref. 39). It is believed that polymer conjugate nanoparticles use the EPR effect of the tumor microenvironment as a means of passive tumor targeting (17–21). The vasculature of tumors, unlike normal vasculature, comprises poorly aligned and defective endothelial cells lacking innervation and smooth muscle cells, as well as upregulated vascular permeability enhancing factors, each facilitating the transport of the polymer conjugate nanoparticle across tumor capillaries (18). In addition, tumors also exhibit an impaired lymphatic drainage, which is the mechanism by which small molecule and
phagocyte system (MPS), and their role is to filter large particles from the blood. Monocytes, macrophages, and dendritic cells serve as scavengers of the MPS removing circulating large particles from the blood and as well as in other tissues and facilitate their transport to end organs of the MPS for removal (16).

Previously, XMT-1001 showed effectiveness against human colon (LS174T) and ovarian (A2780) carcinoma xenografts (42). In this study, the antitumor response of XMT-1001 seems to be dose and schedule dependent. The best overall response was observed in the treatment group that received XMT-1001 at 30 mg/kg i.v. twice weekly × 5. This regimen resulted in 5 CR and 5 PR at day 100. XMT-1001 (60 mg/kg) administered once weekly was also more effective in controlling tumor growth compared with higher doses of CPT-11 (100 mg/kg once weekly) on the same regimen.

Results from the phase I clinical trial of XMT-1001 also support the design of XMT-1001 to release primarily the lipophilic, active lactone-stabilized analog CPT-SI and avoid the severe bladder toxicity associated with CPT. In contrast to clinical results with alternative CPT–polymer conjugates, such as pegamotecan, which release CPT directly and are associated with this toxicity (23, 43), results from clinical studies have shown that XMT-1001 is not associated with hemorrhagic cystitis (44). Compared to CPT and irinotecan, XMT-1001 also has an improved therapeutic index in human tumor xenograft models (45). In addition, conjugates of irinotecan and SN-38 commonly cause significant diarrhea, although not causing hemorrhagic cystitis (23, 46, 47).

The development of conjugate nanoparticles to improve the pharmacokinetic and pharmacodynamic disposition of small molecule anticancer agents is a promising technique to circumvent the less-than-ideal chemical properties of some small molecule agents. This technique also helps to improve the delivery of active drug to tumors in which it can exert its cytotoxic activity, as well as preventing the broad distribution of chemotherapy to normal tissues, where toxicity can occur. XMT-1001, a polymer conjugate of CPT, exhibits prolonged plasma and tumor exposure and improved antitumor efficacy compared with CPT-11 in HT-29 human colon carcinoma xenografts. The results of this study suggest that XMT-1001 has pharmacologic properties that may make it superior to other small molecule CPT analogs. XMT-1001 is currently being evaluated in a phase I clinical trial in patients with advanced stage solid tumors (48).

Disclosure of Potential Conflicts of Interest

A.V. Yurkovetskiy and T.B. Lowinger are employees of and have ownership interest in Mersana Therapeutics, and W.C. Zamboni has received commercial research grant, is a consultant, and is on the advisory board of Mersana Therapeutics. R.J. Fram is a former employee of and has ownership interest in Mersana Therapeutics. The other authors disclosed no potential conflicts of interest.

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References


Pharmacokinetics and Antitumor Efficacy of XMT-1001, a Novel, Polymeric Topoisomerase I Inhibitor, in Mice Bearing HT-29 Human Colon Carcinoma Xenografts

Mark D. Walsh, Suzan K. Hanna, Jeremy Sen, et al.

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