INTERACTION OF IRINOTECAN (CPT-11) AND ITS ACTIVE METABOLITE 7-ETHYL-10-HYDROXYCAMPTOTHECIN (SN-38) WITH HUMAN CYTOCHROME P450 ENZYMES

NOBUMITSU HANIOKA, SHOGO OZAWA, HIDETO JINNO, TOSHIKO TANAKA-KAGAWA, TETSUJI NISHIMURA, MASANORI ANDO, AND JUN-ICHI SAWADA

Project Team for Pharmacogenetics (N.H., S.O., J.S.), Division of Environmental Chemistry (N.H., H.J., T.T.-K., T.N., M.A.), Division of Pharmacology (S.O.), and Division of Biochemistry and Immunonchemistry (U.S.), National Institute of Health Sciences, Setagaya-ku, Tokyo, Japan

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ABSTRACT:

The inhibition and mechanism-based inactivation potencies of irinotecan (7-ethyl-10-[4-(1-piperidino)-1-piperidino]carbonyloxy-camptothecin; CPT-11) and its active metabolite (7-ethyl-10-hydroxycamptothecin; SN-38) for human cytochrome P450 (P450) enzymes were investigated to evaluate the potential for drug interactions involving CPT-11 using microsomes from insect cells expressing specific human P450 isoforms. The mechanism and potential for interaction were examined by Lineweaver-Burk analysis, and NADPH-, time- and concentration-dependent effects were observed. CPT-11 and SN-38 competitively inhibited CYP3A4 (testosterone 6β-hydroxylation) and CYP2C9 (dilaforac 4α-hydroxylation) activity with Ki values of 129 and 121 μM, respectively. CYP2A6 (coumarin 7-hydroxylation) and CYP2C8 (paclitaxel 6α-deethylation) activity with Ki values being 181 and 156 μM, respectively. On the other hand, CYP1A2 (phenacetin O-deethylation), CYP2B6 (7-ethoxycoumarin O-deethylation), CYP2C8 (paclitaxel 6α-hydroxylation), CYP2C9 (S-mephenytoin 4α-hydroxylation), CYP2D6 (bufuralol 1’-hydroxylation), and CYP2E1 (chlorozoxane 6-hydroxylation) were hardly affected by either compound. Furthermore, CPT-11 and SN-38 were suggested to be mechanism-based inactivators of CYP3A4. The kcat and Kf values of CPT-11 and SN-38 were 0.06 min⁻¹ and 24 μM and 0.10 min⁻¹ and 26 μM, respectively. However, no inactivation of CYP2A6 and CYP2C9 by SN-38 was observed. These results mean that CPT-11 and SN-38 interact with human P450 isoforms, such as CYP2A6, CYP2C9, and CYP3A4, in vitro and imply that the significant drug interactions involving CPT-11 may be caused by a mechanism-based inactivation of CYP3A4 by SN-38 as an active metabolite of CPT-11 rather than competitive inhibition.

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1 Abbreviations used are: CPT-11, 7-ethyl-10-[4-(1-piperidino)-1-piperidino]carbonyloxy-camptothecin; P450, cytochrome P450; SN-38, 7-ethyl-10-hydroxycamptothecin; APC, 7-ethyl-10-[4-N(5-aminopentanoic acid)-1-piperidino]carbonyloxy-camptothecin; NPC, 7-ethyl-10-[4-(1-piperidino)-1-amino]carbonyloxy-camptothecin; HPLC, high-performance liquid chromatography; βα, cytochrome βα, L-754,394, N2(2R)-hydroxy-1S-indany1)-5-(2S)-1,1-dimethylaminocarbonyl)-4-furo(2,3-b)pyridin-9-ylmethyl)piperazin1-yl)-4(S)-hydroxy-2(R)-phenyl-(methyl)pentanamide.

Address correspondence to: Dr. Nobumitsu Hanioka, Division of Environmental Chemistry, National Institute of Health Sciences, 1-18-1 Kamiyoga, Setagaya-ku, Tokyo 158-8501, Japan. E-mail: hanioka@nihs.go.jp

Irinotecan (7-ethyl-10-[4-(1-piperidino)-1-piperidino]carbonyloxy-camptothecin; CPT-11) (Fig. 1) is a semisynthetic water-soluble derivative of camptothecin, with a heterocyclic ring structure isolated from the Chinese tree Camptotheca acuminata (Sawada et al., 1991). CPT-11 has been shown to have strong antitumor activity through inhibition of topoisomerase I (Creemers et al., 1994; Pommier et al., 1994). After intravenous administration, CPT-11 is metabolized by carboxylesterases in the liver and small intestine to an active metabolite, 7-ethoxy-camptothecin (SN-38) (Fig. 1), which is 100- to 1000-fold more potent than CPT-11 as a topoisomerase I inhibitor in various in vitro system (Creemers et al., 1994; Pommier et al., 1994; Mathijssen et al., 2001). SN-38 is further conjugated by UDP-glucuronosyltransferases primarily in liver to an inactive β-glucuronide

clinical activity against several other types of solid tumors (Slichenmyer et al., 1993; Wiseman and Markham, 1996). This article is available online at http://dmd.aspetjournals.org

Fig. 1. Chemical structures of CPT-11 and SN-38.
derivative and excreted into urine and bile (Rivory, 2000; Mathijsen et al., 2001). Hydrolysis of SN-38 glucuronide by the intestinal microflora can occur and allows possible recycling of SN-38 in humans (Rivory, 2000; Mathijsen et al., 2001). However, CPT-11 unexpectedly causes severe toxicity of leukopenia or diarrhea, and it has been suggested that these side effects are due to an accumulation of SN-38 in various tissues (Rothenberg, 1997; Mathijsen et al., 2001).

Another pathway of CPT-11 metabolism consists of a cytochrome P450 (P450)-mediated oxidation of the bipiperidine side chain attached to the core structure (Haaz et al., 1998a,b; Rivory, 2000). The main metabolites resulting from this pathway have been identified as the aminopentane carboxylic acid and primary amine derivatives of CPT-11, namely APC and NPC, respectively (Rivory, 2000; Santos et al., 2000; Slatter et al., 2000). Although these metabolites have been regarded to have little cytotoxicity like CPT-11, NPC but not APC can be converted into SN-38 by hepatic carboxylesterases and, as such, may contribute to the overall production of the pharmacologically active species (Rivory, 2000). P450 consists of a superfamily of heme-containing monoxygenases and is responsible for the metabolism of many drugs, environmental chemicals, and endogenous substances (Nelson et al., 1996). Although the number of individual isoforms that have been identified and characterized is increasing, the drug metabolism in humans is handled mainly by CYP1, CYP2, and CYP3 (Spatschegger and Jaeger, 1995; Nelson et al., 1996). In the case of CPT-11, CYP3A4 has been suggested to be the predominant isoform in oxidative metabolism (Haaz et al., 1998a,b; Santos et al., 2000). By contrast, the products and isoforms involved in the P450-mediated metabolism of SN-38, the active metabolite of CPT-11, in humans have not been identified, although the UDP-glucuronosyltransferase isoforms involved in glucuronidation have (Iyer et al., 1998; Rivory, 2000; Mathijsen et al., 2001).

Clinically relevant drug interactions are often the result of the effects of P450 enzymes during metabolism and can cause severe complications (Muck, 1994). However, there is little information available about the clinical interactions of CPT-11 with other drugs, and there are no reports directly comparing the efficiencies of CPT-11 and SN-38 to interfere with the biological functions of P450 isoforms in humans. In this study to evaluate the potential for in vivo drug interactions involving CPT-11, the inhibition and mechanism-based inactivation potencies of CPT-11 and SN-38 for human P450 isoforms were examined using microsomes from insect cells expressing human P450s.

**Experimental Procedures**

**Materials.** CPT-11 (lot 115122) and SN-38 (lot 970326) were kindly supplied by Yakult Honsha Co. (Tokyo, Japan). The purity (≥99%) of each compound was confirmed by analytical HPLC. Phenacetin, 4-acetamidophenol, N-acetylcaminophenol, N-phenylanthranilic acid, chlorzoxazone, and 4-nitrophenol were purchased from Aldrich Chemical Co. (Milwaukee, WI). Coumarin, 7-hydroxycoumarin, 7-ethoxycoumarin, corticosterone, glutathione, and deeroxame were purchased from Sigma Chemical Co. (St. Louis, MO). Paclitaxel, diclofenac, and testosterone were obtained from Wako Pure Chemicals and Research (Manchester, UK). 7,13-Diacetyl baccatin III was obtained from Alexis Biochemicals (San Diego, CA), phenobarbital from Tokyo Kasei Kogyo Co. (Tokyo, Japan), and catalase from Calbiochem-Novabiochem Co. (San Diego, CA). NADPH, glucose 6-phosphate, and glucose-6-phosphate dehydrogenase were purchased from Oriental Yeast Co. (Tokyo, Japan). All other chemicals and organic solvents were of the highest quality commercially available. Microsomes from baculovirus-infected insect cells expressing CYP1A2, CYP2A6 + b, CYP2B6 + b, CYP2C8 + b, CYP2C9*1 + b, CYP2C19 + b, CYP2D6*1, CYP2E1 + b, and CYP3A4 + b were obtained from GENTEST. All enzymes were coexpressed with NADPH-cytochrome P450 oxidoreductase. The P450 contents were as described in the data sheets provided by the manufacturer.

**Enzyme Assays.** P450-dependent activities were determined by HPLC, as described previously with some modifications (Chaurat et al., 1997; Busby et al., 1999; Nakajima et al., 1999). The standard incubation mixture contained 50 mM potassium phosphate buffer, pH 7.4, substrate, human P450-expressing microsomes, inhibitor/inactivator, and NADPH-generating system (1.0 mM NADP +, 10 mM glucose 6-phosphate, 2.0 units/ml glucose-6-phosphate dehydrogenase, and 5.0 mM MgCl2) in a final volume of 500 μl. All substrates were dissolved in methanol. CPT-11 and SN-38 as inhibitors/inactivators were dissolved in dimethyl sulfoxide, with the solvent being used as the control. The final concentration of organic solvent (methanol and dimethyl sulfoxide) in the incubation mixture was 0.8% (v/v). The substrate concentrations for the determination of residual P450 activities were set up to be close to the KM value for each enzyme activity obtained in the preliminary kinetic analysis. Substrate and microsomal P450 concentrations for the assays were as follows: CYP1A2, 20 μM phenacetin and 20 pmol of P450/ml; CYP2A6, 0.80 μM coumarin and 5.0 pmol of P450/ml; CYP2B6, 100 μM 7-ethoxycoumarin and 20 pmol of P450/ml; CYP2C8, 5.0 μM paclitaxel and 20 pmol of P450/ml; CYP2C9, 2.0 μM diclofenac and 10 pmol/ml P450; CYP2C19, 20 μM S-mephenytoin and 20 pmol/ml P450; CYP2D6, 1.5 μM bufuralol and 5.0 pmol of P450/ml; CYP2E1, 600 μM chlorzoxazone and 50 pmol of P450/ml; CYP3A4, 50 μM testosterone and 10 pmol of P450/ml. The substrate concentrations for the determination of CYP2A6, CYP2A6, 0.50 to 8.0 μM P450, and 10 to 160 μM for CYP3A4.

The reaction was initiated by the addition of the NADPH-generating system after a 1-min preincubation at 37°C. After incubation for 20 min (CYP2C8 and CYP2C19), 15 min (CYP1A2, CYP2C9, and CYP2E1), or 10 min (CYP2A6, CYP2D6, and CYP3A4) at 37°C, the reaction was terminated by the addition of 2.5 ml of ethyl acetate (CYP1A2, CYP2C8, CYP2C9, CYP2E1, and CYP3A4), 20 μl of 2.0 M phosphoric acid and 2.5 ml of β-t-butyl methyl ether (CYP2C9) and 20 μl of 2.0 M phosphoric acid (CYP2A6, CYP2B6, and CYP2D6). Samples for the determination of CYP1A2, CYP2C8, CYP2C9, CYP2C19, CYP2E1, and CYP3A4 activities were spiked with internal standards (5.0 nmol of 3-acetamidophenol for CYP1A2, 2.0 nmol of 7,13-diacetyl baccatin III for CYP2C8, 2.0 nmol of N-phenylanthranilic acid for CYP2C9, 2.0 nmol of phenobarbital for CYP2C19, 5.0 nmol of 4-nitrophenol for CYP2E1, and 5.0 nmol of corticosterone for CYP3A4) and vigorously vortexed for 2 min. After centrifugation at 2000g for 10 min, the organic phase was evaporated to dryness under a gentle stream of nitrogen at 35°C. The residues were dissolved in 200 μl of methanol/water (50:50, v/v) and analyzed by HPLC. Samples for determination of CYP2A6, CYP2B6, and CYP2D6 activities were centrifuged at 6000g for 20 min. The supernatant was filtered with a polytetrafluoroethylene membrane filter with a 0.2 μM pore size (Millipore, Bedford, MA) and analyzed by HPLC.

**HPLC Analysis.** HPLC analysis was performed using a Shimadzu SCL-10A system controller (Kyoto, Japan) consisting of three LC-10AD pumps, an SPD-10AV UV-VIS detector, a CTO-10A column oven, a DGU-14A degasser, and a C-R7A chromatopac system controller (Kyoto, Japan) consisting of three LC-10AD pumps, an SPD-10AV UV-VIS detector, a CTO-10A column oven, a DGU-14A degasser, and a C-R7A chromatopac integrator. The samples were cooled at 4°C, and 20-μl aliquots were injected into an Inertsil ODS-80A column (150 × 4.6-mm i.d.; GL Sciences, Tokyo, Japan). The column was kept at 40°C. The calibration curves were established using authentic metabolites. The analytical conditions under which the products did not overlap with interfering peaks originating from inhibitors/inactivators and their metabolites were examined in a preliminary study.

The product (4-acetamidophenol) for CYP1A2 was eluted isocratically with 20 mM phosphate buffer, pH 5.4/methanol/acetonitrile (90:7.3, v/v/v) for 15 min, followed by a 15-min linear gradient to 20 mM phosphate buffer, pH 5.4/methanol/acetonitrile (62:14:24, v/v/v), and held for 20 min at a flow rate of 1.1 ml/min. UV detection was performed at 245 nm. The product (7-hydroxycoumarin) for CYP2A6 and CYP2B6 was eluted isocratically with 20 mM sodium perchlorate, pH 2.5/methanol (68:32, v/v) for 10 min, followed by a 10-min linear gradient to 20 mM sodium perchlorate, pH 2.5/methanol/acetonitrile (53:32:15, v/v/v), and held for 20 min at a flow rate of 1.1 ml/min.
Fluorometric detection was performed at a 330-nm excitation and 454-nm emission. The product (6a-hydroxyxpaclitaxel) for CYP2C8 was eluted isocratically with water/methanol/acetonitrile (52:12:36, v/v/v) at a flow rate of 1.2 ml/min. UV detection was performed at 230 nm. The product (4’-hydroxycyclophene) for CYP2C9 was eluted isocratically with 20 mM phosphate buffer, pH 6.5/methanol/acetonitrile (65:22:13, v/v/v) for 20 min, followed by a 10-min linear gradient to 20 mM phosphate buffer, pH 6.5/methanol/acetonitrile (54:33:13, v/v/v), and held for 20 min at a flow rate of 1.2 ml/min. UV detection was performed at 280 nm. The product (4’-hydroxymephenytoin) for CYP2C19 was eluted isocratically with 20 mM potassium dihydrogenphosphate/methanol/acetonitrile (50:26:24, v/v/v), and held for 20 min at a flow rate of 1.2 ml/min. UV detection was performed at 280 nm. The product (1’-hydroxybufuralol) for CYP2D6 was eluted isocratically with 20 mM sodium perchlorate, pH 2.5/methanol/acetonitrile (63:34:3, v/v/v) for 10 min, followed by a 10-min linear gradient to 20 mM potassium dihydrogenphosphate/methanol/acetonitrile (63:34:3, v/v/v) for 20 min, followed by a 10-min linear gradient to 20 mM sodium phosphate buffer, pH 6.5/methanol/acetonitrile (65:22:13, v/v/v) for 20 min, followed by a 10-min linear gradient to 20 mM potassium dihydrogenphosphate/methanol/acetonitrile (50:26:24, v/v/v), and held for 20 min at a flow rate of 1.2 ml/min. UV detection was performed at 254 nm. The product (6-hydroxychlorzoxazone) for CYP2E1 was eluted isocratically with 50 mM acetic acid/methanol/acetonitrile (73:25:2, v/v/v) for 30 min, followed by a 10-min linear gradient to 20 mM potassium dihydrogenphosphate/methanol/acetonitrile (50:26:24, v/v/v), and held for 20 min at a flow rate of 1.2 ml/min. UV detection was performed at 280 nm. The product (1’-hydroxybufuralol) for CYP2D6 was eluted isocratically with 20 mM sodium perchlorate, pH 2.5/methanol/acetonitrile (63:34:3, v/v/v) for 10 min, followed by a 10-min linear gradient to 20 mM sodium phosphate buffer, pH 6.5/methanol/acetonitrile (54:33:13, v/v/v), and held for 20 min at a flow rate of 1.0 ml/min. Fluorometric detection was performed at a 252-nm excitation and 297-nm emission. The product (6-hydroxychlorzoxazone) for CYP2E1 was eluted isocratically with 50 mM potassium dihydrogenphosphate/methanol/acetonitrile (73:25:2, v/v/v) for 20 min, followed by a 10-min linear gradient to 20 mM potassium dihydrogenphosphate/methanol/acetonitrile (50:26:24, v/v/v), and held for 20 min at a flow rate of 1.1 ml/min. UV detection was performed at 295 nm. The product (6β-hydroxytestosterone) for CYP3A4 was eluted isocratically with water/methanol (58:42, v/v) for 20 min, followed by a 20-min linear gradient to water/methanol/acetonitrile (48:46:6, v/v/v), and held for 20 min at a flow rate of 1.0 ml/min. UV detection was performed at 254 nm. The intra- and interday precisions did not exceed 10% of any of the assays.

**Inhibition Experiments.** P450-dependent activities in the absence and presence of CPT-11 or SN-38 were measured according to the method described in the previous sections. The inhibitor concentrations were set at 100 μM. For the determination of the inhibition type and Ki values, Lineweaver-Burk plots were constructed. Michaelis-Menten parameters (Km and Vmax values) were estimated using EnzymeKinetics v.1.4 (Trinity Software, Camp- ton, NH). The Ki values were calculated from the following equations (Voet and Voet, 1990): for competitive inhibition, \( K_i = K_m[I]/(K_m - K_m') \), and for mixed inhibition, \( K_i = K_m V_{\text{max}}'[I]/(K_m' V_{\text{max}} - K_m' V_{\text{max}}') \), where [I] is the inhibitor concentration, and \( K_m' \) and \( V_{\text{max}}' \) are the Michaelis-Menten parameters in the presence of inhibitor.

**Inactivation Experiments.** Human P450-expressing microsomes were preincubated at 37°C for 20 min with CPT-11 or SN-38 at 100 μM in the presence of the NADPH-generating system. After preincubation, typical substrates were added, and the corresponding P450 activities were measured according to the method described in the previous sections. For the determination of kmixed and Ki values, human P450-expressing microsomes were preincubated at 37°C in the presence of the NADPH-generating system with varying concentrations (0, 25, 50, and 100 μM) of CPT-11 or SN-38. At selected time intervals (0, 10, 20, 40, and 60 min for CYP2A6 and CYP2C9 and 0, 5, 10, 20, and 30 min for CYP3A4), aliquots (100 μl) were withdrawn and diluted 5-fold into a prewarmed (37°C) incubation system containing NADPH-generating system and typical substrates in 50 mM potassium phosphate buffer, pH 7.4, and the corresponding P450 activities were measured according to the method described in the previous sections. The kmixed (initial rate constant for inactivation) values were obtained as slopes of an initial linear phase plotting logarithm of the residual activity against the preincubation time (Waley, 1985). The kmixed and Ki values were estimated by a nonlinear regression analysis using Prism v.3.0a (GraphPad Software, San Diego, CA). The effects of trapping agents on the inactivation of CYP3A4 were determined by incubating 100 μM CPT-11 or SN-38 together with glutathione (2.0 mM), deferoxamine (100 μM), or catalase (1000 units/ml) at 37°C for 20 min in the preactivation step.

**Statistics.** All reported values are the mean ± S.D. of three separate experiments in duplicate. Similar results were obtained in all experiments.

**Results**

**Inhibition of Human P450 Activities by CPT-11 and SN-38.** The inhibitory effects of CPT-11 and SN-38 on the activity of each P450 isoform were examined (Fig. 2). Although we attempted to determine the IC50 values of CPT-11 and SN-38, no 50% inhibitory effect up to a concentration of 100 μM was observed for any P450 isoform (data not shown). Additionally, the solubility of SN-38 in the reaction mixture was very low (<120 μM). Therefore, CPT-11 and SN-38 were used at a single concentration (100 μM) in this study. Both CPT-11 and SN-38 effectively inhibited CYP3A4 activity by 28 and 30%, respectively. SN-38 also inhibited CYP2A6 and CYP2C9 activities by 27 and 31%, although the inhibition potency was not as strong as that for CYP3A4 activity. However, CYP1A2, CYP2B6, CYP2C8, CYP2C19, CYP2D6, and CYP2E1 activities were unaffected by either compound.

To obtain further information on the type of inhibition and Ki values of CPT-11 for CYP3A4 activity and SN-38 for CYP2A6, CYP2C9, and CYP3A4 activities, Lineweaver-Burk plots were constructed (Table 1). The inhibitory pattern of SN-38 for CYP2A6 and CYP2C9 activities exhibited a mixture of competitive and noncompetitive components, with K values of 181 and 156 μM, respectively. On the other hand, CYP3A4 activity was competitively inhibited by CPT-11 and SN-38, with K values of 129 and 121 μM, respectively (Fig. 3).

**Mechanism-Based Inactivation of Human P450 Enzymes by CPT-11 and SN-38.** The possibility that CPT-11 and SN-38 are mechanism-based inactivators of human P450 enzymes was examined (Fig. 4). CYP2A6 and CYP2C9 activities were decreased 27 and 29% by SN-38, respectively. CYP3A4 activity was notably decreased by both CPT-11 and SN-38 (60 and 82%, respectively). The efficiency of SN-38 against CYP3A4 activity was greater than that of CPT-11. The other P450 enzymes were not affected by either compound.

Furthermore, inactivation constants for CYP2A6, CYP2C9, and CYP3A4 were calculated from the rates of reduction in enzyme activity over various preincubation times with increasing concentrations of CPT-11 and SN-38 (Table 2). An NADPH-, time-, and concentration-dependent inactivation of CYP3A4 by CPT-11 and SN-38 was observed (Fig. 5). The inactivation by SN-38 proceeded more rapidly than that by CPT-11. The kmixed and Ki values of CPT-11 and SN-38 were 0.06 min⁻¹ and 24 μM, and 0.10 min⁻¹ and 26 μM, respectively. However, CYP2A6 and CYP2C9 were not inactivated by SN-38.

The protective effects of trapping agents, such as glutathione (a
Discussion

Although CPT-11 is a useful anticancer agent for numerous malignancies, such as colon and lung cancers, it can cause severe leukopenia or diarrhea due to an accumulation of SN-38, the active metabolite of CPT-11, in various tissues (Rothenberg, 1997). CPT-11 is clinically administered either alone or in combination with other drugs, including anticancer agents. However, coadministration often causes drug interactions leading to harmful side effects (Muck, 1994). Thus, the prediction or evaluation of the potential for drug interactions is an important aspect of individualized drug therapy. One of the most important mechanisms of drug interactions is the decrease of hepatic metabolism catalyzed by P450 enzymes (Guengerich, 1997). In the present study, the selectivity of inhibition or mechanism-based inactivation of CYP3A4 by CPT-11 and SN-38 was also evaluated (Table 3). All of the exogenously added trapping agents failed to prevent CYP3A4 from being inactivated by CPT-11 and SN-38.

nucleophilic-trapping agent), deferoxamine (a free-iron scavenger), and catalase (a scavenger of reactive oxygen species), on the inactivation of CYP3A4 by CPT-11 and SN-38 were also evaluated (Table 3). All of the exogenously added trapping agents failed to prevent CYP3A4 from being inactivated by CPT-11 and SN-38.
interaction of human P450 enzymes by CPT-11 and SN-38 was investigated using microsomes from insect cells expressing P450s. To this end, we used nine P450-dependent activities as markers of P450 isoforms that mainly catalyze xenobiotics. The P450-dependent activities were phenacetin O-deethylation for CYP1A2, coumarin 7-hydroxylation for CYP2A6, 7-ethoxycoumarin O-deethylation for CYP2B6, paclitaxel 6α-hydroxylation for CYP2C8, diclofenac 4'-hydroxylation for CYP2C9, 5-mephenytoin 4'-hydroxylation for CYP2C19, bufuralol 1'-hydroxylation for CYP2D6, chlorozoxazone 6-hydroxylation for CYP2E1, and testosterone 6β-hydroxylation for CYP3A4 (Wrighton and Stevens, 1992; Wrighton et al., 1993; Busby et al., 1999).

It has been reported that the most predominant P450 isoform involved in the oxidative metabolism of CPT-11 is CYP3A4 (Haaz et al., 1998a,b; Santos et al., 2000). The present results showed that CPT-11 effectively inhibits only CYP3A4 activity among the P450 isoforms tested, through competitive inhibition. SN-38, however, inhibited CYP2A6, CYP2C9, and CYP3A4 activities with a mixed or competitive type of inhibition. These observations may suggest that not only CYP3A4 but also CYP2A6 and CYP2C9 contribute to SN-38 metabolism. However, the inhibitory effects of CPT-11 and SN-38 on these P450 activities were not so strong; the Ki values (121–181 μM) were higher than the Km values (18–111 μM) for the formation of APC and NPC in P450-mediated metabolism of CPT-11 using microsomes from human livers and mammalian cells expressing CYP3A4 in previous reports (Haaz et al., 1998a,b; Santos et al., 2000). On the other hand, Haaz et al. (1998a,b) have found that the oxidative metabolism of CPT-11 in human liver microsomes is remarkably inhibited by drugs such as loperamide and ondansetron, which are mainly metabolized by CYP3A4. The reason for the discrepancy between our results and previous reports may be a difference in the marker enzyme reactions, source of the enzyme, and/or CYP3A4 properties. Like CYP3A4, CYP2A6 and CYP2C9 also catalyze many drugs used clinically, such as tegafur, warfarin, and phenytoin (Rendic and Di Carlo, 1997). To predict drug interactions involving CPT-11, therefore, it is necessary to identify the rate and metabolites of the oxidative metabolism of SN-38 in humans and the P450 isoforms that are involved.

Drug metabolism catalyzed by P450 enzymes can be inhibited by other mechanisms in addition to competitive inhibition. One example is the inactivation of P450 by the metabolite of a drug that covalently binds to the enzyme to form a complex with P450, leading to irreversible inhibition (Silverman, 1988). In this case, as the drug has to be metabolically activated by an enzyme and covalently binds to the same enzyme, inactivation affects only the P450 isoform that is involved in the drug metabolism. However, it has not been determined whether CPT-11 and/or its metabolites are further activated by P450 enzymes to form active metabolites that inhibit P450-dependent drug oxidation in humans. Therefore, we also examined the possibility that CPT-11 and SN-38 are mechanism-based inactivators of human P450 enzymes. It was clearly shown that CYP3A4 is inactivated by CPT-11 and SN-38 in an NADPH-, time-, and concentration-dependent manner. The inactivation by SN-38 was more extensive than that by CPT-11. In addition, glutathione, deferoxamine, and catalase did not prevent or slow the inactivation of P450 enzymes, supporting this possibility, because a lack of prevention by these agents is one of the characteristics of mechanism-based inactivation. The inactivation kinetics of human CYP3A4 by mechanism-based inactivators have been reported previously. For example, the values of km and Ki have been estimated as 0.39 min⁻¹ and 46 μM for gestodene (Gueneguerich, 1990), 1.62 min⁻¹ and 7.5 μM for L-754,394 (human immunodeficiency virus-1 protease inhibitor) (Chiba et al., 1995), 0.59 min⁻¹ and 22 μM for delavirdine (Voorman et al., 1998), 0.09 min⁻¹ and 4.7 μM for mifepristone (He et al., 1999), 0.06 to 0.17 min⁻¹ and 16 to 19 μM for erythromycin (Kanamitsu et al., 2000), 0.06 min⁻¹ and 13 μM for amiodarone (Ohyama et al., 2000), and 0.07 min⁻¹ and 3.3 μM for diltiazem (Yeo and Yeo, 2001), respectively. The ki values of CPT-11 and SN-38 for CYP3A4 activities obtained in this study were comparable to those of mifepristone, erythromycin, amiodarone, and diltiazem, whereas the values were much lower than those of gestodene, L-754,394, and delavirdine. CYP2A6 and CYP2C9 were not inactivated by SN-38, although they were subject to mixed-type inhibition. This may imply that the decrease in CYP2A6 and CYP2C9 activities is not due to the formation of a metabolic intermediate complex. Accordingly, it is possible that CPT-11 and SN-38 are moderate mechanism-based inactivators of human CYP3A4.

The mechanism-based inactivation requires more attention than competitive inhibition because the inhibitory effects remain after the elimination of the inhibitor from blood and tissue. It has been reported that the terminal elimination half-life of CPT-11 in plasma after intravenous administration is 14 to 15 h, and the value of SN-38 increases 1.7- to 2.1-fold relative to CPT-11 (Sparreboom et al., 1998; Kehrer et al., 2000; Slatter et al., 2000). Furthermore, the excretion rate of SN-38 into urine and bile has been reported to be clearly slower than that of unchanged CPT-11, although the total urinary and fecal excretion as free/conjugated forms is 6.5 to 12% of the dose (Sparreboom et al., 1998; Slatter et al., 2000). These findings may mean that SN-38 is extensively distributed and accumulated in the tissues and that the metabolite rather than parent drug causes drug interactions. However, although the Ki values of CPT-11 and SN-38 for CYP3A4 activities obtained in this study differed from the plasma concentration of CPT-11 and its metabolites (0.17–7.5 μM) (Sparreboom et al., 1998; Kehrer et al., 2000), we could not identify the relationship between in vitro and in vivo data.

In conclusion, we studied the selectivity of the inhibition or inactivation of human P450 isoforms by CPT-11 and its active metabolite SN-38. CPT-11 and SN-38 blocked CYP3A4 activity and CYP2A6, CYP2C9, and CYP3A4 activities, respectively, through competitive or mixed-type inhibition. The Ki values were >100 μM, suggesting that the drug interactions involving CPT-11 caused by competitive inhibition are clinically insignificant. However, a moderate mechanism-based inactivation of CYP3A4 by CPT-11 and SN-38 was observed (SN-38 > CPT-11). Therefore, our findings imply that significant drug interactions involving CPT-11 results from a mechanism-based inactivation of CYP3A4 by SN-38 as an active metabolite of CPT-11 rather than competitive inhibition. The pharmacokinetic interactions of CPT-11 based on the induction of CYP3A4 by anticonvulsants and micelle encapsulation of anticancer agents in formulation vehicles have been reported (Friedman et al., 1999; van Zuylen et al., 2001). Further studies are underway in our laboratory to clarify the relationship between the metabolic profile of CPT-11 and the inhibition or inactivation selectivity of P450 isoforms and to predict in vivo interactions of CPT-11 from in vitro data for the suitable use of CPT-11 in combination with other drugs.

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References


