Identification and Properties of a Major Plasma Metabolite of Irinotecan (CPT-11)
Isolated from the Plasma of Patients

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ABSTRACT

Irinotecan [7-ethyl-10-[[4-(1-piperidino)-1-piperidino]carbonyloxycamptothecin (CPT-11)] is a promising water-soluble analogue of camptothecin [S. Sawada et al., Chem. & Pharm. Bull. (Tokyo), 39: 1446-1454, 1991]. We have reported previously the presence of an important polar metabolite, in addition to 7-ethyl-10-hydroxycamptothecin (SN-38) 6-glucuronide, in plasma of patients taken from patients undergoing treatment with CPT-11 (L. P. Rivory and J. Robert, Cancer Chemother. Pharmacol. 36: 176-179, 1995; L. P. Rivory and J. Robert, J. Chromatogr., 661: 133-141, 1994). Plasma samples (0.5 ml) containing comparatively large amounts of this metabolite were extracted by solid-phase columns and subjected to high-performance liquid chromatography and mass spectrometry in parallel to fluorometric detection followed by NMR spectrometry of purified fractions. The properties of this metabolite in terms of the inhibition of cell growth, induction of topo I-mediated DNA cleavage, conversion to SN-38, and inhibition of AChE were then examined following its chemical synthesis.

INTRODUCTION

CPT-11, the international proprietary name of which is irinotecan, is a semisynthetic and water-soluble derivative of CPT (Fig. 1; Ref. 1) with promising activity against a broad range of tumor types including pretreated colorectal and cervical cancer (2). CPT-11, which is relatively devoid of activity in vitro (3), is thought to exert its anticancer activity following biotransformation in vivo to the potent topo I poison SN-38 (Fig. 1) and is, therefore, widely considered a produg of SN-38 (3). We previously reported the presence of high concentrations of a 6-glucuronide of SN-38 and another unidentified metabolite in the plasma of patients treated with CPT-11 (4, 5). Given the large interindividual variability in the metabolism and disposition of CPT-11 (6, 7), it is vital that the metabolic pathways of CPT-11 are elucidated. Furthermore, there is some evidence to suggest that metabolism of CPT-11 to metabolites other than SN-38 appears to be extensive in man (8), and this is likely to influence the toxicity and/or activity of CPT-11. In this study, we have identified the other principal circulating metabolite observed previously by using a HPLC and MS system with an electrospray interface coupled to fluorometric detection followed by NMR spectrometry of purified fractions. The synthetic of this metabolite in terms of the inhibition of cell growth, induction of topo I-mediated DNA cleavage, conversion to SN-38, and inhibition of AChE were then examined following its chemical synthesis.

MATERIALS AND METHODS

Chemicals and Reagents. Pure CPT-11, SN-38, and CPT were supplied by Rhône Poulenc Rorer SA (Vitry sur Seine, France). Solvents and reagents were of the highest grade available commercially. ATChl, 5,5'-dithiobis-[2-nitrobenzoic acid] (Ellman’s reagent), and AChE (EC 3.1.1.7) from the electric eel (Torpedo californicus) were obtained from Sigma Chemical Co. (St. Louis, MO). Neostigmine methylsulfate was from Astra Pharmaceuticals Pty., Ltd. (North Ryde, New South Wales, Australia).

Sample Handling and Extraction. Blood samples were collected from patients taking part in Phase I and II studies of CPT-11 (300–600 mg/m²) in Bordeaux and Toulouse, France. Plasma was separated rapidly and kept frozen at −70°C until analysis. Samples were chosen in which relatively high concentrations of the unknown metabolite were present when analyzed by HPLC, as described previously for the presence of total SN-38 6-glucuronide (4, 5). To each 500 µl thawed plasma was added 1 ml of a 50:50 (v/v) mixture of acetonitrile and methanol to precipitate proteins. The tubes were centrifuged in an Eppendorf microfuge (12,000 rpm at 4°C), and the supernatant was transferred to an extraction tube and dried down under a stream of nitrogen. Solid-phase extraction columns (Sep-Pak C-18; Waters, Brisbane, Australia) were conditioned with 10 ml methanol, followed by 10 ml of 10 mM acetic acid. The dried-down residue of the sample was then resuspended in 0.5 ml of 1 mM acetic acid and loaded onto the extraction column, which was then washed with 5 ml of 10 mM acetic acid. The column eluate (5 ml of methanol) was dried down under a stream of nitrogen. The residue was stored at 4°C and reconstituted just prior to analysis by the addition of 10 µl each of methanol and 1 mM acetic acid, followed by 50 µl mobile phase buffer (see below). The sample was vortex mixed and transferred to a small glass vial and centrifuged for 30 s at 10,000 rpm. An aliquot of the supernatant (20 µl) was injected onto the column. The use of acidic conditions during the Sep-Pak extraction of plasma and for reconstitution of residues ensured that camptothecins and metabolites were present in their lactone forms.

HPLC. HPLC separation was carried out using a microbore C18 column (250 × 1 mm, 5 µm; Alltech, Brisbane, Australia). The mobile phase used was a mixture of methanol and 10 mM ammonium acetate buffer adjusted to pH 5.5 with glacial acetic acid delivered at 50 µl/min by an ABI 140B (Perkin-Elmer, Brisbane, Australia) syringe pump as follows. After equilibrating the column with 45% methanol, the sample was injected and the content of methanol was increased linearly to 65% over a period of 40 min and to 80% over the following 20 min. A 40-min column wash step (100% methanol) followed by NMR spectrometry of purified fractions. The properties of this metabolite in terms of the inhibition of cell growth, induction of topo I-mediated DNA cleavage, conversion to SN-38, and inhibition of AChE were then examined following its chemical synthesis.

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followed. The bulk of the outflow of the column was directed to a Waters 470 fluorimeter (5-μl flow cell) with the excitation and emission wavelengths set at 355 and 515 nm, respectively (5), and the data were collected with MAX-IMA software (Waters).

The remaining column outflow (approximately one-seventh) was directed into a PE SCIEX API III triple quadrupole mass spectrometer (Perkin Elmer, Australia), where it was vaporized at atmospheric pressure, and ions were introduced via an electrospray interface. The OR and interface voltages were set at 100 and 4200 V, respectively, when collecting Q1 data in the positive ion mode. Multiple ion scans were collected for m/z values ranging from 200 to 800 atomic mass units over the duration of the chromatogram.

NMR. The outflow of the fluorescence detector corresponding to the peak of the principal unknown metabolite was collected following each injection of patient plasma extract. The total collection, representing the extracts of 6–7 ml plasma, was dried down and reconstituted in a small volume of 1 mM HCl and reinjected onto the HPLC column under isocratic conditions with 50:50 (v/v) methanol and 1 mM HCl. The peak of interest was again collected and dried down to a pale yellow powdery residue. This was reconstituted in 400 μl deuterated methanol. 1H NMR spectra were obtained using a Bruker DMAX spectrometer operating at 600.13 MHz for proton observation. A double presaturation of methanol and water was processed. The structure determined by NMR was synthesized, and the details of the procedure used are to be published elsewhere. This synthesized compound eluted at the same time as the original peak using the HPLC conditions described above.

Cell Culture and Growth Inhibition Assay. The KB human epidermoid carcinoma cell line was obtained from the American Type Culture Collection (Rockville, MD). Cells were grown as monolayers in a humidified atmosphere (37°C) containing 5% CO2 in DMEM containing 2 mM L-glutamine. 200 lU/ml of penicillin and 200 μg/ml streptomycin, 50 μg/ml gentamicin, and 50 μg/nastatin were supplemented with 10% (v/v) heat-inactivated FCS. Experiments were carried out with exponentially growing cells, as described previously (9). Cells were seeded in 96-well microculture plates (104 cells/ml) in the presence of SN-38, and the incorporation of dye, which reflects the percentage of cell growth relative to the untreated control cells. The IC50 was estimated from semilogarithmic plots of cell growth versus drug concentration.

The final reaction mixture consisted of 0.9 mg microsomal protein in 0.2 M Tris buffer containing 0.1% SDS. The samples were electrophoresed at 2 V/cm for 5 min in a thermostated agitating water bath (37°C), and the reaction was initiated by the addition of CPT-11. In preliminary experiments, we have observed different rates of hydrolysis for the two forms of CPT-11, and the drug was added, therefore, as either the lactone or ring-opened carboxylate. Samples (50 μl) were taken every 10 min over a 1-h incubation and assayed for total SN-38 concentrations by HPLC, as described previously (5). Two independent experiments were performed. We verified these observations using purified human liver carboxylesterase as described recently (13). Briefly, incubations of the metabolite and CPT-11 (50 μM) with purified human liver carboxylesterase (EC 3.1.1.1) were carried out in PBS (pH 7.4) at 37°C using 2 μM enzyme. The substrates were always equilibrated in the reaction buffer at room temperature prior to the initiation of the reaction and were present, therefore, as a mixture of the lactone and ring-opened carboxylate forms. Samples were withdrawn during the steady-state phase of the reaction and analyzed for total concentrations of SN-38 by HPLC. These concentrations were corrected for the presence of SN-38 as a contaminant of the synthesized metabolite (~0.4%) in both types of study. The possible inhibitory effects of the metabolite on the conversion of CPT-11 to SN-38 were investigated in both systems by the coinoculation of the metabolite and CPT-11 at equal concentrations (microsomes, 10 and 25 μM; purified enzyme, 50 μM). These experiments were performed in triplicate.

Inhibition of AChE. CPT-11 and other CPT analogues featuring nitrogenous substitutions at C10 have been shown to be inhibitors of AChE in vitro (14). Therefore, the inhibition of AChE by CPT-11 and the metabolite was studied using the prototypic enzyme from the electric eel. Incubations of AChE were carried out with neostigmine methylsulfate for comparative purposes. A modification of the method of Ellman et al. (15) was used. Briefly, the formation of thionitrobenzenesulphonamide (λ = 412 nm) at 30°C in 0.1 M phosphate buffer (pH 7.3; 0.3 mM 5,5'-dithiobis(2-nitrobenzoic acid)) with a Uvikon 810 spectrophotometer (Kontron, Schlesien, Switzerland) following the addition of ATChl at a final concentration corresponding to the Km of AChE under the same conditions (2.83 mM) and 0.05 units of AChE. A preincubation of the drug with AChE for 3 min prior to the addition of ATChl was required to achieve a maximal effect for neostigmine. In the case of the metabolite and CPT-11, however, there was no increased effect with preincubation; therefore, none was used.

RESULTS

The HPLC and MS conditions were optimized with the pure standards of CPT, SN-38, and CPT-11 as their lactones. Lower OR voltages were applied to the CPT-11 metabolite, which was synthesized, and the details of the procedure used are to be published elsewhere.

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5 L. P. Rivory, M-C. Haaz, and J. Robert, unpublished observations.
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Fig. 2. Fluorescence (A) and total ion count (B) traces obtained with the HPLC and MS analysis of an extract of 0.5 ml plasma. This sample was taken 30 min after infusion from a 47-year-old patient receiving 600 mg/m² CPT-11 in a first cycle for a colonie tumor. Peaks in A: 1. SN-38 β-glucuronide; 2. APC; 3. SN-38; 4. CPT-11.

(40 V) were found to yield lower signal clarity, and the camptothecins were detected partially as dimers and acetate adducts under such Q1 conditions. Furthermore, as can be seen in Fig. 2, A and B, the high OR used (100 V) resulted in fragmentation characteristic of the loss of CO₂ (−44), although this was more pronounced for SN-38 and CPT than for CPT-11. The neutral loss of 44 atomic mass units was found to be a useful property, which in addition to the fluorescence trace, was used to detect several metabolites in addition to the readily identifiable SN-38 β-glucuronide, SN-38, and CPT-11 (Fig. 2A, peaks 1, 3, and 4, respectively) in extracts of patient plasma. CPT-11 also yielded fragments consistent with loss of the distal piperidine (m/z, 502) and the loss of CO₂ from this species. The principal unknown metabolite was well resolved from the other peaks and yielded spectra with a major peak at m/z 619 and, as for the standards, significant fragmentation (Fig. 3C).

The presence of the 393 and 227 fragments indicate that the addition of 32 mass units to the principal unknown metabolite ([M+1] = 619), relative to CPT-11, occurs on the bipiperidino moiety. Specifically, the signal at m/z 502 indicates that the distal piperidine is the site of metabolism (Fig. 3C). Spectra obtained from collision-associated dissociation experiments using argon did not provide further structural information regarding this compound (data not shown), which was suspected to be either a bi-hydroxylated or ring-opened carboxylate metabolite. The purified metabolite yielded NMR spectra with the aromatic part very similar to that of CPT-11 (δ = 8.24, d, J = 8 Hz; δ = 8.04, s; δ = 7.67, d, J = 8 Hz), and the two methylenes at δ = 5.4 and 5.6 (AB system) and δ = 5.38 (A₂ system) indicated that no modification occurred on the camptothecin moieties. The two α protons of the proximal piperidine residue were also clearly identified at δ = 4.55 and 4.37, as well as two of the β protons at δ = 2.24. On the other hand, three signals at δ = 1.9 (m, 4H), δ = 2.3 (t, 2H), and δ = 3.1 (t, 2H) characteristic of a n-butyl chain suggested that scission of the distal piperidine had occurred at the level of a N-C bond of this ring and that the metabolite was APC (Fig. 1). Another four metabolites were detected, which eluted in proximity to SN-38 (Fig. 2A). Three of these yielded [M+1] ions with m/z of 603, indicating monohydroxylation of CPT-11 and the fourth ([M+1] = 519) had a pattern of fragmentation suggesting a N-dealkylated metabolite of APC. These metabolites require further characterization to be certain of their identity.

Fig. 3. Mass spectra collected from the peaks of SN-38 (A), CPT-11 (B), and APC (C). Insets, proposed fragmentation.
The cytotoxic potential of APC was assessed by a cell growth inhibition assay using the KB human epidermoid cell line. For comparative purposes, CPT-11 and SN-38 were evaluated in parallel. Under the experimental conditions used (4 days of continuous exposure), APC was found to be a weak inhibitor of cell proliferation. The IC$_{50}$ found (mean ± SD; n = 4) was 2.1 ± 0.09 µg/ml, whereas those of CPT-11 and SN-38 were 5.5 ± 0.4 and 0.01 ± 0.002 µg/ml, respectively.

In vivo, topo I enables normal replication and transcription to be carried out by relaxing the supercoiling of DNA (2). Topo I cleaves and reseals one strand of the DNA duplex through a transesterification reaction that leads to the formation of transient covalent complexes between nicked DNA and topo I. These intermediate complexes are often referred to as “cleavable,” because they are transformed into permanent single-stranded breaks following the addition of protein denaturants. Because the camptothecins greatly stabilize these intermediate complexes by inhibiting the religation step of topo I, the evaluation of topo I-mediated DNA cleavage offers a sensitive and selective system for determining the potency of camptothecin analogues. To test the topo I-mediated activity of APC, we used such a DNA cleavage assay, and the cleavage products were separated by alkaline agarose gel electrophoresis. An autoradiograph of a gel from a typical experiment is shown in Fig. 4. Purified topo I produced only a strong enhancement of DNA cleavage compared with the enzyme alone, which was not present in the absence of topo I (data not shown). The cleavage resulted in the reduction of the intensity of the band corresponding to the DNA substrate and the appearance of an increasing proportion of fragments with lower molecular weights. The relative potency of the three compounds could be estimated by inspection of the autoradiograph and comparison of the concentrations of drugs required to cause a similar extent of cleavage, as determined from the intensity of the band corresponding to the DNA substrate as a percentage of total lane absorbance. APC at 10 µg/ml produced cleavage (%A, 19.7) equivalent to a concentration of CPT-11 of between 10 (%A, 35.3) and 100 µg/ml (%A, 18.3), suggesting that APC is more potent than CPT-11. However, this interpretation should be made carefully, given that SN-38 was found to be a minor contaminant of the synthesized APC. In any case, the cleavage observed at the highest concentration of APC was less intense than that observed with the lowest concentration of SN-38 (0.1 µg/ml), indicating that APC is at least 100-fold less active than SN-38 in the stabilization of topo I-cleavable complexes.

APC was found to be an extremely poor substrate of human liver microsomes in either its lactone or ring-opened carboxylate forms. Indeed, no significant release of SN-38 could be measured (Fig. 5). Similar observations were made with purified human liver carboxylesterase (Fig. 6), which appears to be the principal CPT-11-converting enzyme of human liver (13). APC did not inhibit the biotransformation of CPT-11 by microsomes (data not shown) or by human liver carboxylesterase (Fig. 6) when present in concentrations equal to those of CPT-11.

Unlike CPT-11, APC was a weak inhibitor of AChE, with an IC$_{50}$ of approximately 45 µM. The corresponding IC$_{50}$ values for CPT-11 and neostigmine were 0.19 and 0.053 µM, respectively (Fig. 7). SN-38 did not have any detectable activity over a comparable range of concentrations.

DISCUSSION

It has been noted that the kinetics of CPT-11 and its active metabolite SN-38 display large interindividual variations (6, 7), and the role of variable metabolism and disposition of CPT-11 on antitumoral
activity and systemic toxicity is unclear. The contribution of the biotransformation to SN-38 appears to be a minor metabolic route for CPT-11, with plasma, bile, and urine levels generally one to two orders of magnitude lower for SN-38 than for CPT-11 (6–8). Furthermore, the total proportion of the dose recovered as SN-38 plus CPT-11 in the urine is on the order of 20–50% (6–8), which suggests that a hitherto unknown metabolic route exists for CPT-11 (8). This has been suspected, because we discovered a major circulating fluorescent metabolite in the plasma of patients (4, 5), but the small amounts of plasma available precluded the direct identification of this metabolite until now. The use of electrospray HPLC and MS in combination with fluorescence detection and NMR has enabled us to identify this compound with only 6–7 ml patient plasma. The conditions used here appear suitable for the studies of the metabolism of other camptothecin analogues.

Recently, we reported a preliminary study of the pharmacokinetics of APC in patients in whom we observed large interindividual variation in the concentrations of this metabolite (16). In all patients, however, the plasma APC concentrations were greater than for SN-38 except for late time points (12–24 h after infusion). On the other hand, they were generally lower than for CPT-11, although in some patients, the reverse was true 2–3 h after the end of the infusion. These particular plasma samples were the ones selected for the present study. The plasma kinetics of APC and their relationship to the other known metabolites of CPT-11 are to be published in detail elsewhere.

APC is most likely a product of cytochrome P450-mediated metabolism (17) and appears to be metabolized further to a N-dealkylated metabolite. Other metabolites were observed, which suggests that several metabolic pathways, which are possibly interrelated (e.g., monohydroxylation as an intermediate step toward piperidine ring opening), are active in the elimination of CPT-11. Unfortunately, the concentrations of these other metabolites were considerably lower than APC, preventing their characterization using the same methodology.

It is noteworthy that APC was not significantly converted to SN-38 by human liver microsomes or human liver carboxylesterases. Although CPT-11 is itself only moderately transformed in comparison to avid substrates such as p-nitrophenylacetate (13, 18), it appears that APC will not act directly as a prodrug of SN-38 in vivo. Studies carried out with human liver carboxylesterase have shown that the rate of enzymatic hydrolysis of a range of acylsalicylic acids increases dramatically with the length of the acyl chain (19). Likewise, the conversion of SN-38 prodrugs by the rat serum CPT-11-converting enzyme is greatly influenced by the structure of the C10 side chain (18). Specifically, the rate of hydrolysis of 4-(N-dialkylamino)-1-piperidino esters of CPT-11 is dependent on the hydrophobicity of the alky substitution, with the 4-(N-dibutylamino)-1-piperidino analogue being cleaved at almost twice the rate of CPT-11 (18). Thus, a probable reason for the negligible rate of APC conversion to SN-38 is the considerable hydrophilicity of the side chain of APC compared with CPT-11.

APC was found to be a poor inhibitor of cell growth in culture, with an IC_{50} comparable to that of CPT-11. Like CPT-11, APC was only a weak inducer of topo I-mediated DNA cleavage in vitro. This is likely to be due to the presence of the bulky substitution. In both systems, APC was found to be approximately 100-fold less active than the active metabolite SN-38. However, APC differed significantly from CPT-11 as far as inhibition of acetylcholinesterase was concerned. Therefore, it is unlikely that APC plays a direct role in the activity and toxicity profile of CPT-11. Nevertheless, because the exact mechanism for the tardive diarrhea associated with CPT-11 remains to be determined, an involvement of APC in this toxicity cannot be ruled out. In any case, the presence of APC in the plasma of patients is evidence of an important route of metabolism, in addition to the conversion of CPT-11 to SN-38 by carboxylesterase and the conjugation of the latter to glucuronic acid. The route of metabolism involving the production of APC may be an important source of variability in the disposition of CPT-11 in patients.

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REFERENCES

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