

Coadministration of Oral Cyclosporin A Enables Oral Therapy with Paclitaxel

Jetske M. Meerum Terwogt,¹ Mirte M. Malingré,
Jos H. Beijnen, Wim W. ten Bokkel Huinink,
Hilde Rosing, Franciska J. Koopman,
Olaf van Tellingen, Martha Swart, and
Jan H. M. Schellens

Department of Medical Oncology, The Netherlands Cancer Institute/
Antoni van Leeuwenhoek Hospital, 1066 CX Amsterdam
[J. M. M. T., M. M. M., J. H. B., W. W. t. B. H., O. v. T., M. S.,
J. H. M. S.]; Department of Pharmacy and Pharmacology, The
Netherlands Cancer Institute/Slotervaart Hospital, 1066 EC
Amsterdam [J. M. M. T., M. M. M., J. H. B., H. R., F. J. K.]; and
Department of Pharmaceutical Analysis and Toxicology, Faculty of
Pharmacy, State University of Utrecht, 3584 CG Utrecht [J. H. B.],
the Netherlands

ABSTRACT

i.v. paclitaxel is inconvenient and associated with significant and poorly predictable side effects largely due to the pharmaceutical vehicle Cremophor EL. Oral administration may be attractive because it may circumvent the use of Cremophor EL. However, paclitaxel, as well as many other commonly applied drugs, has poor bioavailability caused by high affinity for the *mdr1* P-glycoprotein drug efflux pump, which is abundantly present in the gastrointestinal tract. Consequently, inhibition of P-glycoprotein by oral cyclosporin A (CsA) should increase systemic exposure of oral paclitaxel to therapeutic levels. A proof-of-concept study was carried out in 14 patients with solid tumors. Patients received one course of oral paclitaxel of 60 mg/m² with or without 15 mg/kg CsA and with i.v. paclitaxel in subsequent courses. The pharmacokinetics of paclitaxel and its major metabolites were determined during the first two courses. In addition, levels of CsA, Cremophor EL, and ethanol were measured. Bioavailability of oral paclitaxel in combination with CsA was 8-fold higher than after oral paclitaxel alone ($P < 0.001$). Therapeutic concentrations were achieved on average during 7.4 h, which is comparable with an equivalent i.v. dose. The oral combination was well tolerated and did not induce gastrointestinal toxicity or myelosuppression. Cremophor EL plasma levels after oral drug administration were undetectable. In conclusion, coadministration of oral CsA increased the systemic exposure of oral paclitaxel from

negligible to therapeutic levels. The combination enables treatment with oral paclitaxel. Undetectable Cremophor EL levels after oral administration may have a very beneficial influence on the safety of the treatment with oral paclitaxel.

INTRODUCTION

Paclitaxel is an important new antitumor agent widely used in the treatment of advanced breast and ovarian cancer (1–3). However, i.v. administration of paclitaxel is inconvenient for patients and associated with significant and unpredictable side effects (4–6). The current commercially available i.v. formulation consists of a mixture of ethanol and Cremophor EL (polyoxyethyleneglycerol triricinoleate 35), and it is now well established that the latter plays a major role in the hypersensitivity reactions observed after i.v. administration of paclitaxel (7, 8). Cremophor EL is also responsible for the nonlinear tissue distribution of paclitaxel (9). Oral administration of paclitaxel is to be preferred as it may circumvent the use of Cremophor EL. Paclitaxel, however, has poor bioavailability because of its high affinity for the multidrug transporter P-gp,² which is abundantly present in the gastrointestinal tract (10–18). P-gp in the mucosa of the small and large intestine may limit the oral uptake of paclitaxel and mediate direct excretion of the drug in the intestinal lumen (19). This became clear when we investigated the oral uptake of paclitaxel in *mdr1a* (–/–) knockout mice lacking functional P-gp in the gut. In this mouse model, the systemic exposure was 6-fold higher than in wild-type mice. High systemic availability could also be achieved in wild-type mice when paclitaxel was administered p.o. in combination with SDZ PSC 833 or with CsA, both of which are efficacious P-gp inhibitors (10). On the basis of these results, we hypothesized that the systemic exposure in humans after oral administration of paclitaxel might be increased with p.o. administered CsA hopefully to therapeutic plasma drug concentrations. To investigate this, a proof-of-concept study in patients with solid tumors was initiated.

PATIENTS AND METHODS

Patients with a histological proof of cancer for whom no standard therapy of proven benefit existed were eligible for the study. Previous radiotherapy or chemotherapy other than taxoid therapy was allowed as long as the last treatment was at least 4 weeks before study entry, and any resulting toxicities were resolved. Patients had to have acceptable bone marrow (WBC, $>3.0 \times 10^9$ /liter; platelets, $>100 \times 10^9$ /liter), liver (serum bilirubin, ≤ 25 μ mol/liter; serum albumin, ≥ 25 g/liter) and kidney (serum creatinine, ≤ 160 μ mol/liter or clearance, ≥ 50

Received 2/1/99; revised 5/25/99; accepted 5/25/99.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

¹ To whom requests for reprints should be addressed, at The Netherlands Cancer Institute/Slotervaart Hospital, Department of Pharmacy and Pharmacology, Louwesweg 6, 1066 EC Amsterdam, the Netherlands. Phone: 31-20-512-4657; Fax: 31-20-512-4753; E-mail: apjmt@slz.nl.

² The abbreviations used are: P-gp, P-glycoprotein; CsA, cyclosporin A; AUC, area(s) under the (concentration-time) curve.

ml/min) functions and a WHO performance status ≤ 2 . Patients were excluded if they suffered from uncontrolled infectious disease, neurological disease, bowel obstruction, or brain metastases. Additional exclusion criteria were concomitant use of known P-gp inhibitors, CYP3A-substrates, H2-receptor antagonists, or proton pump inhibitors. The trial was approved by the ethics committee of the institute, and all of the patients gave written informed consent.

In the first part of the study, it was planned that a small cohort of four evaluable patients would receive paclitaxel p.o. as a single agent at a dose of 60 mg/m² during course 1 and paclitaxel i.v. at a dose of 175 mg/m² administered as a 3-h infusion during course 2. In the second part of the study, it was planned that eight evaluable patients would receive paclitaxel on two randomized occasions. On one occasion, they would receive paclitaxel p.o. at a dose of 60 mg/m² combined with a single oral dose of CsA of 15 mg/kg. This low oral dose was selected for safety reasons because the results in mice indicated increased systemic exposure to paclitaxel after oral administration combined with CsA as compared with i.v. administration of paclitaxel alone. Paclitaxel (Paxene) and CsA (Neoral) were ingested as oral solutions with 100 ml of tap water. Paclitaxel was taken 10 min after CsA. On the other occasion, paclitaxel would be administered as a 3-h infusion at a dose of 175 mg/m² without CsA. The oral and i.v. dosages were administered at 9:00 a.m. after an overnight fast. A standard breakfast was served at 2 h after paclitaxel administration. The i.v. formulation of paclitaxel [Paxene, *i.e.*, paclitaxel (6 mg/ml), dissolved in Cremophor EL and ethanol 1:1 w/v, Baker Norton, Miami, FL] was used for both i.v. and oral administration. On all occasions, patients were premedicated with dexamethasone (20 mg) p.o. 12 and 6 h before, clemastine (1 mg) i.v. 30 min before, and ranitidine (50 mg) i.v. shortly before paclitaxel administration. If it was in their best interest, all of the patients continued on a 3 weekly schedule of i.v. paclitaxel at a dose of 175 mg/m².

Pharmacokinetic monitoring of paclitaxel and its major metabolites (6 α -hydroxypaclitaxel, 3' β -hydroxypaclitaxel and 6 α ,3' β -dihydroxypaclitaxel) was performed during the first two courses. Whole blood samples of 5 ml each were collected at 15 time points up to 48 h after paclitaxel administration. After centrifugation plasma was stored at -20°C and analyzed within 4 weeks using a validated high-performance liquid chromatographic assay (20, 21). Noncompartmental pharmacokinetic methods were applied to interpret the results (22). The AUC of paclitaxel was calculated, using the trapezoidal rule with extrapolation to infinity. To compare the systemic exposure after oral and i.v. administration of paclitaxel, the ratio of the median value of the AUC after oral and i.v. administration was calculated and corrected for the difference in dose, using the following formula:

$$F = \frac{\text{AUC oral paclitaxel}}{\text{AUC i.v. paclitaxel}} \times \frac{175}{60}$$

Other parameters to be assessed were the maximal plasma concentration of paclitaxel (C_{max}), the time to maximal plasma concentration (T_{max}), total plasma clearance after i.v. administration (CL), terminal half-life ($t_{1/2}$) and volume of distribution at steady state [V_{ss} (1, 23)]. The terminal $t_{1/2}$ was calculated as $\ln 2/k$, where k is the rate constant of the terminal phase (h^{-1}) of

Table 1 Patient characteristics

Patient characteristics	No.
Total patients	14
Male/Female	2/12
Median age, years (range)	56 (34–69)
Median WHO performance status (range)	1 (0–2)
Tumor sites	
Ovary	4
Breast	3
Unknown primary	2
Neuroectoderm	1
Rectum	1
Lung	1
Colon	1
Stomach	1
Pretreatment combination	
No pretreatment	1
Surgery	1
Surgery + radiation	1
Surgery + chemotherapy	8
Chemotherapy	1
Surgery + radiation + chemotherapy	2

the plasma concentration-time curve. C_{max} and T_{max} were determined graphically. Statistical analysis of the data were performed using SPSS/PC+ (SPSS/PC+ Advanced Statistics, version 6.1, 1994; Chicago, IL). Nonparametric tests (Mann-Whitney U -test) were used for comparison of the oral and i.v. results.

The AUCs of the metabolic products were determined using the trapezoidal rule without extrapolation to infinity. The C_{max} and the T_{max} are the highest measured values and the T_{det} represents the duration that the metabolites could be detected in plasma. Additionally, relationships between metabolite concentrations and paclitaxel concentrations were evaluated by calculation of the ratios of the mean AUC of the metabolites and the mean AUC of paclitaxel.

Concentrations of CsA (in whole blood), Cremophor EL (in plasma), and ethanol (in plasma) at different time points were measured according to validated methods. Concentrations of CsA and Cremophor EL were measured at the time points corresponding with the time points of the paclitaxel sampling, and ethanol concentrations were measured at three separate time points: 15 min, 30 min, and 1 h after oral administration of paclitaxel with CsA. Cremophor EL was quantified using a high-performance liquid chromatographic assay, as described previously (24) with minor modifications. CsA was measured with a fluorescence polarization immuno assay (Ref. 25, Abbott TDx-FLx, Amstelveen, the Netherlands), and ethanol was quantitatively determined by gas chromatography.

RESULTS

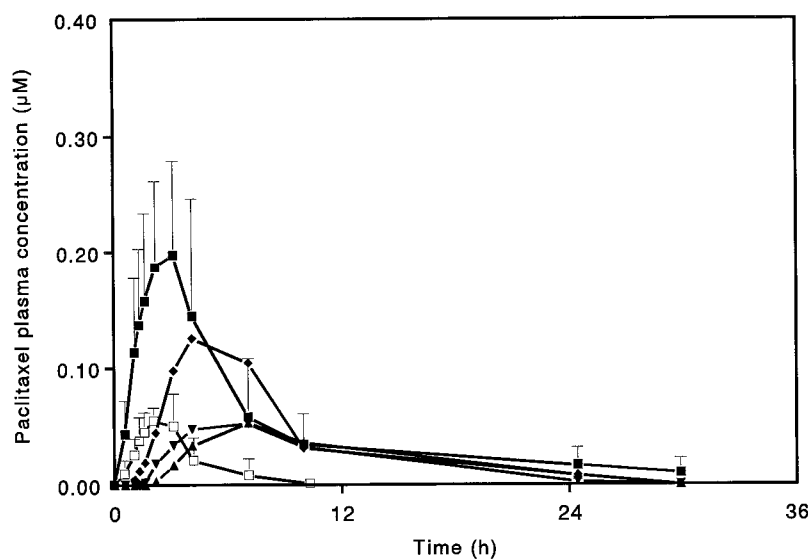
In total, 14 patients were enrolled in the study. Patient characteristics are outlined in Table 1. Three patients went off-study before they had received paclitaxel i.v. in a second course because of rapid disease progression. Five patients received oral paclitaxel at a dose of 60 mg/m² without CsA during the first course, and three of them received i.v. paclitaxel during course 2 and subsequent courses. Five other patients received oral paclitaxel at a dose of 60 mg/m² in combination with CsA

Table 2 Pharmacokinetics of paclitaxel: main pharmacokinetic parameters of paclitaxel represented as means (\pm SD) after oral administration of a dose of 60 mg/m² without and with administration of CsA and after a 3-h i.v. infusion of a dose of 175 mg/m²

Pharmacokinetic parameter	PART I		PART II	
	oral (n = 5)	i.v. (n = 3)	oral + CsA (n = 9)	i.v. (n = 8)
AUC ($\mu\text{M} \cdot \text{h}$)	0.2 (\pm 0.1)	16.4 (\pm 4.3)	1.7 (\pm 0.9) ^a	17.1 (\pm 3.7)
C _{max} (μM)	0.1 (\pm 0.0)	4.5 (\pm 0.9)	0.2 (\pm 0.1) ^a	4.7 (\pm 1.0)
T _{max} (h)	2.4 (\pm 0.6)	3.0 (\pm 0.1)	2.4 (\pm 0.8)	3.1 (\pm 0.2)
T > 0.1 μM (h)		15.0 (\pm 3.8)	3.7 (\pm 2.3)	17.2 (\pm 3.5)
T > 0.05 μM (h)	1.2 (\pm 0.9)	22.2 (\pm 3.3)	7.4 (\pm 4.4) ^a	28.1 (\pm 8.9)

^a $P < 0.001$ compared with oral paclitaxel without CsA.

Fig. 1 Plasma concentration versus time curves of oral paclitaxel with (■) and without CsA (□) represented as means (\pm SD), and plasma concentration-time curves of the major metabolites after oral paclitaxel. ▲, 6 α ,3'p-dihydroxypaclitaxel; ▼, 3'p-hydroxypaclitaxel; ◆, 6 α -hydroxypaclitaxel.



at a dose of 15 mg/kg at the first course, and, in four patients, this was followed by i.v. administration of paclitaxel during course 2 and subsequent courses. The remaining four patients started with i.v. paclitaxel during the first course, followed by oral paclitaxel and CsA during the second course. During all of the subsequent courses, paclitaxel was administered i.v. Table 2 summarizes the main pharmacokinetic parameters. The mean AUC in patients who received oral paclitaxel in combination with CsA was 1.7 $\mu\text{M}\cdot\text{h}$ (\pm 0.9), which is approximately 8-fold higher than the mean AUC of 0.2 $\mu\text{M}\cdot\text{h}$ (\pm 0.1) in patients who received oral paclitaxel without CsA ($P < 0.001$; Fig. 1). The mean AUC in the five patients who started with oral paclitaxel + CsA was not significantly different from the mean AUC in the four patients who received oral paclitaxel + CsA at the second course. The dose-corrected ratio of mean AUC values of oral paclitaxel and i.v. paclitaxel was 0.036 and of oral paclitaxel + CsA and i.v. paclitaxel 0.282, respectively. However, because of the nonlinear pharmacokinetics of paclitaxel caused by Cremophor EL effects, this calculation results in an underestimation of the true bioavailability (9, 26). In a dose-finding study performed by Huizing *et al.*, a mean AUC of i.v. paclitaxel at a dose of 100 mg/m² of 5.8 h $\cdot\mu\text{M}$ was reported (23). Recalculation of the above ratios applying the dose-adjusted AUC found by Huizing *et al.* provided values of 0.059 for the ratio of oral paclitaxel:i.v. paclitaxel and 0.474 for the ratio of

oral paclitaxel + CsA:i.v. paclitaxel. The mean time of the paclitaxel plasma concentration above a previously defined level of 0.05 μM was 1.2 (\pm 0.9) h after oral paclitaxel and 7.4 (\pm 4.4) h after oral paclitaxel plus CsA ($P < 0.001$). The mean duration of plasma levels above 0.1 μM was 3.7 (\pm 2.2) h after oral paclitaxel with CsA, and this threshold was not reached after oral paclitaxel alone. *CL* after i.v. paclitaxel was 13 (\pm 3) liter/m²/h in three patients who had received oral paclitaxel without CsA at the first course and 12 (\pm 2) liter/m²/h in the eight other patients [not statistically significant (*NS*)]. The terminal $t_{1/2}$ of i.v. paclitaxel in the two groups of patients was 17.7 (\pm 2.7) h ($n = 3$) and 16.3 (\pm 10.5) h [$n = 8$ (*NS*)]. The difference in V_{ss} was also not statistically significant in the two groups of patients and was 69 (\pm 27) liter/m² ($n = 3$) and 86 (\pm 62) liter/m² ($n = 8$). The i.v. pharmacokinetic data are in good agreement with earlier observations (1, 23).

Plasma metabolite concentrations after i.v. paclitaxel as well as after oral paclitaxel with CsA showed large interpatient variability. After oral administration of paclitaxel alone, metabolites could not be detected. The mean pharmacokinetic parameters of the metabolites after oral administration of paclitaxel with CsA and after i.v. administration are represented in Table 3. After oral administration with CsA, the mean peak plasma concentration ratios of 6 α -hydroxypaclitaxel, 3'p-hydroxypaclitaxel, and 6 α ,3'p-dihydroxypaclitaxel to paclitaxel were 0.78,

Table 3 Pharmacokinetics of paclitaxel metabolites: main pharmacokinetic parameters of 6 α -hydroxypaclitaxel, 3'p-hydroxypaclitaxel, and 6 α ,3'p-dihydroxypaclitaxel in plasma, represented as means (\pm SD)

	<i>n</i>	<i>T</i> _{det} (h)	<i>T</i> _{max} (h)	<i>C</i> _{max} (μ M)	AUC (μ M · h)	Ratio AUC metabolite: AUC paclitaxel
6 α -hydroxypaclitaxel						
oral paclitaxel + CsA	9	11.7 (\pm 7.9)	4.2 (\pm 1.8)	0.18 (\pm 0.11)	1.25 (\pm 1.23)	0.87
i.v. paclitaxel	8	7.4 (\pm 9.0)	3.2 (\pm 0.2)	0.37 (\pm 0.34)	1.05 (\pm 1.29)	0.06
3'p-hydroxypaclitaxel						
oral paclitaxel + CsA	9	6.8 (\pm 6.8)	4.1 (\pm 1.3)	0.03 (\pm 0.02)	0.22 (\pm 0.22)	0.16
i.v. paclitaxel	8	7.6 (\pm 8.8)	3.3 (\pm 0.2)	0.14 (\pm 0.11)	0.56 (\pm 0.71)	0.03
6 α ,3'p-dihydroxypaclitaxel						
oral paclitaxel + CsA	9	10.7 (\pm 8.3)	6.4 (\pm 2.0)	0.06 (\pm 0.04)	0.62 (\pm 0.59)	0.44
i.v. paclitaxel	8	5.7 (\pm 9.5)	3.7 (\pm 0.5)	0.18 (\pm 0.31)	0.67 (\pm 1.38)	0.04

0.14, and 0.26, respectively. After i.v. administration, these values were 0.08, 0.03, and 0.04. For the AUCs, these ratios were 0.87, 0.16, and 0.44 after oral administration with CsA and 0.06, 0.03, and 0.04 after i.v. administration. Significant increases in metabolite:paclitaxel ratios were observed after oral administration compared with i.v. administration ($P < 0.001$). All three of the metabolites could be detected in plasma for only a limited period of time.

Whole blood CsA concentrations were measured in seven patients. Maximum CsA concentrations ranged from 2.1 mg/liter to 4.7 mg/liter (mean, 3.0 mg/liter) and were reached at 3–4 h after intake. The concentrations 10 h after intake ranged from 0.3–1.3 mg/liter (mean, 0.7 mg/liter). Cremophor EL levels in plasma after oral administration of paclitaxel with or without CsA were lower than the lower limit of quantitation of the assay of 0.05% (24). Ethanol concentrations were measured in seven patients, and the highest detected ethanol concentration in plasma was 0.1‰, which was found in three patients 13 min after paclitaxel intake.

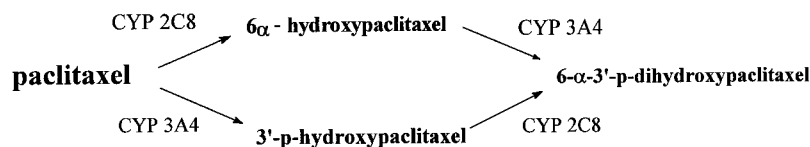
Paclitaxel in the oral formulation with or without CsA had a bitter taste but was very well tolerated. No significant side effects were seen after one course of oral paclitaxel with or without CsA. A pattern of toxicity common to paclitaxel developed after two to three i.v. courses. CTC grade 2 myalgia was observed in 7 (50%) of 14 patients, and grade 1 neurotoxicity was also seen in 7 (50%) patients. Granulocytopenia grade 3 developed in two (14%) patients. All of the patients developed alopecia, which was grade 1 in eight (57%) patients and grade 2 in one (7%) patient. Stomatitis grade 2 was seen in 1 patient and flushing grade 2 in another patient. Mild nausea grade 1 (4 patients) and vomiting grade 1 (3 patients) were observed but only after i.v. paclitaxel. At present, 5 of the 14 patients are still on study. A total of 61 courses of paclitaxel have been administered, 14 of which were oral. The median number of courses per patient was four (range, one to eight).

DISCUSSION

The results presented above prove that the coadministration of a P-gp inhibitor significantly increases the systemic exposure of p.o. administered paclitaxel. Paclitaxel administered p.o. as a single agent without CsA exhibits poor apparent bioavailability of only 4% of the exposure after i.v. administration. Coadministration of CsA increased the systemic exposure of paclitaxel up to 28%. However, the true oral bioavailability may be sig-

nificantly underestimated because paclitaxel clearly shows pronounced nonlinear pharmacokinetics due to the presence of Cremophor EL (9, 26). Recalculation of these figures using the AUC of i.v. paclitaxel at a lower dose (23), which is more realistic for comparison purposes, resulted in an apparent bioavailability of 47% after administration of oral paclitaxel with CsA. An important pharmacokinetic parameter is the time-period of exposure above a certain paclitaxel threshold concentration. Earlier data indicate a strong positive relationship between the duration of the paclitaxel plasma concentration above 0.05 μ M or 0.1 μ M and pharmacological activity (23, 26). The frequently applied i.v. dose of paclitaxel of 175 mg/m² resulted in a time-period above 0.05 μ M of 28.1 (\pm 8.9) h. Even at the low oral dose of 60 mg/m² applied in our study, plasma concentrations higher than 0.05 μ M were achieved during 7.4 (\pm 4.4) h. Our preclinical data obtained in wild-type and P-gp-negative *mdr1a* knockout mice, combined with these first clinical results, reveal that CsA increases the absorption of paclitaxel by effectively blocking P-gp in the gut. A second mechanism that may contribute to the increased systemic exposure is an inhibition of paclitaxel metabolism by CsA, because paclitaxel and CsA are both substrates for the cytochrome P₄₅₀ (CYP) 3A4-isozymes (27, 28). The three main metabolites of paclitaxel are 6 α -hydroxypaclitaxel, 3'p-hydroxypaclitaxel, and 6 α ,3'p-dihydroxypaclitaxel and are formed via CYP 2C8, CYP 3A4, and both CYP 2C8 and 3A4, respectively (Fig. 2; Ref. 29). All of the metabolites showed reduced *in vitro* cytotoxicity as compared with paclitaxel (30). Competition for CYP 3A4 by CsA may result in altered ratios between the metabolite levels. This hypothesis was supported by our data. Oral administration of paclitaxel with CsA resulted in an increase in the AUC ratio metabolite:paclitaxel for all three of the metabolites. However, a relative larger increase (15-fold) in the AUC ratio 6 α -hydroxypaclitaxel:paclitaxel is observed in comparison with the AUC ratios of 3'p-hydroxypaclitaxel:paclitaxel and 6 α ,3'p-dihydroxypaclitaxel:paclitaxel (a 5- and 11-fold increase, respectively). Increased metabolism of paclitaxel after oral administration can be explained by the relatively higher amount of paclitaxel passing the liver (first-pass effect). Additionally, metabolism of paclitaxel in the intestinal wall may contribute to the increased metabolite levels. Increased metabolism after oral administration may indeed result in diminished levels of the active drug and, possibly, reduced efficacy. However, in our

Fig. 2 Major metabolic pathways of paclitaxel.



opinion, the achieved gain in increased uptake outweighs the possible loss by the increased metabolism.

A plausible explanation for the relative larger increase in 6 α -hydroxypaclitaxel levels may be that competitive inhibition of CYP 3A4 by CsA results in relatively less formation of 3'-p-hydroxypaclitaxel and 6 α ,3'-p-dihydroxypaclitaxel. Consequently, metabolism of paclitaxel by CYP 2C8 is favored, resulting in increased formation of 6 α -hydroxypaclitaxel. Thus, as CsA interferes with CYP-mediated metabolism of paclitaxel, decreased elimination by inhibition of the metabolic enzymes may contribute to the observed increase in systemic exposure. In addition, Sparreboom *et al.* (19) showed that direct intestinal excretion of paclitaxel, another important route of drug elimination, is significantly diminished in the absence of P-gp. At present, it is unknown whether involvement of other factors, including drug release from the pharmaceutical formulation (dissolution), modification of biliary excretion, and drug degradation in gastrointestinal fluids, may contribute to the extent of the systemic exposure of p.o. administered paclitaxel.

The single oral dose of 15 mg/kg of CsA resulted in C_{\max} and trough values that are in the therapeutic range for immunosuppression and may be associated with toxicity, in particular renal dysfunction. However, the available studies of CsA, pharmaceutically formulated in Neoral, are limited (31) and, more importantly, this side effect is mainly associated with CsA when given on a chronic treatment basis. No renal toxicity, or any other side effect clearly associated with the single CsA administration, was observed. The CsA concentrations found in our study were higher than we expected, possibly because of competition for CYP-mediated metabolism by paclitaxel.

Cremophor EL levels could not be detected after oral administration of paclitaxel (dissolved in Cremophor EL-ethanol) as a single agent nor when coadministered with CsA (formulated in alcohol and α -tocopherol). This may be very beneficial for the safety profile of oral paclitaxel because Cremophor EL plays a pivotal role in the hypersensitivity reactions associated with i.v. paclitaxel administration (4–8). The maximum measured ethanol levels of 0.1% are not clinically relevant. Besides a bitter taste, paclitaxel in the oral formulation at a dose of 60 mg/m² was very well tolerated without induction of gastrointestinal or bone marrow toxicity. The main side effects were alopecia and myalgia CTC grade 1 or 2, which developed after 2–3 courses of i.v. paclitaxel. Regarding the nearly uneventful oral administration of the dose of 60 mg/m², oral doses can be escalated or given b.i.d. to prolong exposure at therapeutic levels. The ultimate goal is to test whether at least equal activity of oral paclitaxel can be obtained, as compared with i.v. paclitaxel, but with better safety. However, coadministration of a P-gp inhibitor may increase paclitaxel levels in brain and heart tissue and may, therefore, enhance the risk of central neurotox-

icity or cardiac toxicity³ (32). Neither in our clinical study nor in animal studies did we observe signs of central neurotoxicity or cardiac toxicity, at least not at the dosages that were used. Furthermore, oral administration opens the opportunity to explore therapeutic activity and safety on a chronic daily treatment schedule. Finally, the concept of modulation of P-gp may well be applied to other drugs, including noncytotoxic agents, which have a high affinity for P-gp and are associated with poor oral bioavailability, *e.g.*, HIV protease inhibitors (33). The knowledge presently gained by the extensive analysis of *mdr1a* knockout mice has proven to be extremely valuable to the development of new strategies to further optimize drug treatment (34, 35). The improvement of systemic exposure of oral paclitaxel and other drugs as well as the development of an optimal pharmaceutical formulation for oral administration are presently investigated in our institute. On the basis of these early results, oral administration of paclitaxel in combination with CsA may be a realistic alternative to the current treatment modalities. In summary, we have demonstrated for the first time in cancer patients the proof of the concept of efficient oral uptake of paclitaxel, made possible by concomitant administration of the P-gp blocker CsA.

ACKNOWLEDGMENTS

We thank the nurses of the clinical ward for their dedicated contribution to the study and our clinical colleagues for their active support. Paclitaxel (Paxene) was kindly supplied by Baker Norton Pharmaceutical Inc., Miami, FL.

REFERENCES

- Huizing, M. T., Keung, A. C., Rosing, H., van der Kuij, V., ten Bokkel Huinink, W. W., Mandjes, I. M., Dubbelman, A. C., Pinedo, H. M., and Beijnen, J. H. Pharmacokinetics of paclitaxel and metabolites in a randomized comparative study in platinum-pretreated ovarian cancer patients. *J. Clin. Oncol.*, *11*: 2117–2135, 1993.
- Huizing, M. T., Sewberath Misser, V. H., Pieters, R. C., ten Bokkel Huinink, W. W., Veenhof, C. H., Vermorken, J. B., Pinedo, H. M., and Beijnen, J. H. Taxanes: a new class of antitumor agents. *Cancer Invest.*, *13*: 381–404, 1995.
- McGuire, W. P., Hoskins, W. J., Brady, M. F., Kucera, P. R., Partridge, E. E., Look, K. Y., Clarke-Pearson, D. L., and Davidson, M. Cyclophosphamide and cisplatin compared with paclitaxel in patients with stage III and stage IV ovarian cancer. *N. Engl. J. Med.*, *334*: 1–6, 1996.
- Weiss, R. B. Hypersensitivity reactions. *Semin. Oncol.*, *19*: 458–477, 1992.

³ J. van Asperen, A. Sparreboom, O. van Tellingen, and J. H. Beijnen. Cremophor EL masks the effect of *mdr1a* P-gp on the plasma pharmacokinetics of paclitaxel in mice, submitted for publication.

5. Rowinsky, E. K., and Donehower, R. C. Paclitaxel (Taxol). *N. Engl. J. Med.*, 332: 1004–1014, 1995.
6. Nannan Panday, V. R., Huizing, M. T., ten Bokkel Huinink, W. W., Vermorken, J. B., and Beijnen, J. H. Hypersensitivity reactions to the taxanes paclitaxel and docetaxel. *Clin. Drug Invest.*, 14: 418–427, 1997.
7. Lorenz, W., Reimann, H. J., Schmal, A., Dormann, P., Schwarz, B., Neugebauer, E., and Doenicke, A. Histamine release in dogs by Cremophor EL and its derivatives. *Agents Actions*, 7: 63–67, 1977.
8. Dorr, R. T. Pharmacology and toxicology of cremophor EL diluent. *Ann. Pharmacother.*, 28: S11–S14, 1994.
9. Sparreboom, A., van Tellingen, O., Nooijen, W. J., and Beijnen, J. H. Nonlinear pharmacokinetics of paclitaxel in mice results from the pharmaceutical vehicle Cremophor EL. *Cancer Res.*, 56: 2112–2115, 1996.
10. van Asperen, J., van Tellingen, O., Sparreboom, A., Schinkel, A. H., Borst, P., Nooijen, W. J., and Beijnen, J. H. Enhanced oral bioavailability of paclitaxel in mice treated with the P-glycoprotein blocker SDZ PSC 833. *Br. J. Cancer*, 76: 1181–1183, 1997.
11. Fujita, H., Okamoto, M., Takao, A., Mase, H., and Kojima, H. Pharmacokinetics of paclitaxel in experimental animals. Part I. Blood level (Japanese). *Kan to Kagaku Ryoho*, 21: 653–658, 1994.
12. Eisman, J. L., Eddington, N. D., Leslie, J., MacAuley, C., Sentz, D. L., Zuhowski, M., Kujawa, J. M., Young, D., and Egorin, M. J. Plasma pharmacokinetics and tissue distribution of paclitaxel in CD₂F₁ mice. *Cancer Chemother. Pharmacol.*, 34: 465–471, 1994.
13. Dano, K. Active outward transport of daunomycin in resistant Ehrlich ascites tumor cells. *Biochim. Biophys. Acta*, 323: 466–483, 1973.
14. Inaba, M., and Sakuri, Y. Enhanced efflux of actinomycin D, vincristine and vinblastine in Adriamycin-resistant subline of P388 leukemia. *Cancer Lett.*, 8: 111–115, 1979.
15. Schinkel, A. H., Smit, J. J., van Tellingen, O., Beijnen, J. H., Wagenaar, E., van Deemter, L., Mol, C. A., van der Valk, M. A., Robanus-Maandag, E. C., te Riele, H. P., Berns, A. J., and Borst, P. Disruption of the mouse *mdr1a* P-glycoprotein gene leads to a deficiency in the blood-brain barrier and to increased sensitivity to drugs. *Cell*, 77: 491–502, 1994.
16. Thiebaut, F., Tsuruo, T., Hamada, H., Gottesman, M. M., Pastan, I., and Willingham, M. C. Cellular localization of the *multidrug-resistance* gene product P-glycoprotein in normal human tissues. *Proc. Natl. Acad. Sci. USA*, 84: 7735–7738, 1987.
17. Cordon-Cardo, C., O'Brien, J. P., Casals, D., Rittman-Grauer, L., Biedler, J. L., Melamad, M. R., and Bertino, J. R. *Multi drug resistance* gene (P-glycoprotein) is expressed by endothelial cells at blood-brain barrier sites. *Proc. Natl. Acad. Sci. USA*, 86: 695–698, 1989.
18. Borst, P., and Schinkel, A. H. Genetic dissection of the function of mammalian P-glycoproteins. *Trends Genet.*, 13: 217–222, 1997.
19. Sparreboom, A., Van Asperen, J., Mayer, U., Schinkel, A. H., Smit, J. W., Meijer, D. K., Borst, P., Nooijen, W. J., Beijnen, J. H., and van Tellingen, O. Limited oral bioavailability and active epithelial excretion of paclitaxel (Taxol) caused by P-glycoprotein in the intestine. *Proc. Natl. Acad. Sci. USA*, 4: 2031–2035, 1997.
20. Sparreboom, A., van Tellingen, O., Nooijen, W. J., and Beijnen, J. H. Determination of paclitaxel and metabolites in mouse plasma, tissue, urine and faeces by semi-automated reversed-phase high-performance liquid chromatography. *J. Chromatogr. B. Biomed. Appl.*, 664: 383–391, 1995.
21. Huizing, M. T., Sparreboom, A., Rosing, H., van Tellingen, O., Pinedo, H. M., and Beijnen, J. H. Quantification of paclitaxel metabolites in human plasma by high-performance liquid chromatography. *J. Chromatogr. B. Biomed. Appl.*, 674: 261–268, 1995.
22. Gibaldi, M., and Perrier, D. Noncompartmental analysis based on statistical moment theory. *In: M. Gibaldi, and D. Perrier, (eds.), Pharmacokinetics*, Ed. 2, pp. 409–417. New York: Dekker, 1982.
23. Huizing, M. T., Giaccone, G., Van Warmerdam, L. J. C., Rosing, H., Bakker, P. J., Vermorken, J. B., Postmus, P. E., van Zandwijk, N., Koolen, M. G., ten Bokkel Huinink, W. W., van der Vijgh, W. J., Bierhorst, F. J., Lai, A., Dalesio, O., Pinedo, H. M., Veenhof, C. H., and Beijnen, J. H. Pharmacokinetics of paclitaxel and carboplatin in a dose escalating and sequencing study in patients with non-small cell lung cancer. *J. Clin. Oncol.*, 15: 317–329, 1997.
24. Sparreboom, A., van Tellingen, O., Huizing, M. T., Nooijen, W. J., and Beijnen, J. H. Determination of polyoxyethyleneglycerol triricinoleate 35 (Cremophor EL) in plasma by precolumn derivatization and reversed-phase high-performance liquid chromatography. *J. Chromatogr. B. Biomed. Appl.*, 681: 355–362, 1996.
25. Chan, G. L., Weinstein, S. S., LeFor, W. W., Spoto, E., Kahana, L., and Shires, D. L. Relative performance of specific and nonspecific fluorescence immunoassay for cyclosporin in transplant patients. *Ther. Drug Monit.*, 14: 42–47, 1992.
26. Gianni, L., Kearns, C. M., Gianni, A., Capri, G., Vigano, L., Lacatelli, A., Bonadonna, G., and Egorin, M. J. Nonlinear pharmacokinetics and metabolism of paclitaxel and its pharmacokinetic/pharmacodynamic relationship in humans. *J. Clin. Oncol.*, 13: 180–190, 1995.
27. Shet, M. S., Fisher, C. W., Holmans, P. L., and Estabrook, R. W. Human cytochrome P450 3A4: enzymatic properties of a purified recombinant fusion protein containing NADPH-P450 reductase. *Proc. Natl. Acad. Sci. USA*, 90: 11748–11752, 1993.
28. Harris, J. W., Rahman, A., Kim, B. R., Guengerich, F. P., and Collins, J. M. Metabolism of Taxol by human hepatic microsomes and liver slices: participation of cytochrome P450 3A4 and an unknown P450 enzyme. *Cancer Res.*, 54: 4026–4035, 1994.
29. Kivistö, K. T., Kroemer, H. K., and Eichelbaum, M. The role of human cytochrome P450 enzymes in the metabolism of anticancer agents: implications for drug interactions. *Br. J. Clin. Pharmacol.*, 40: 523–530, 1995.
30. Sparreboom, A., Huizing, M. T., Boesen, J. J. B., Nooijen, W. J., van Tellingen, O., and Beijnen, J. H. Isolation, purification and biological activity of mono- and dihydroxylated paclitaxel metabolites from human feces. *Cancer Chemother. Pharmacol.*, 36: 299, 1995.
31. Olyaei, A. J., de Mattos, A. M., and Bennett, W. M. Switching between cyclosporin formulations—what are the risks? *Drug Saf.*, 16: 366–373, 1997.
32. Arbus, S. G., Strauss, H., Rowinsky, E., Christian, M., Suffness, M., Adams, J., Oakes, M., McGuire, W., Reed, E., Gibbs, H., Greenfield, R. A., and Montello, M. A reassessment of cardiac toxicity associated with Taxol. *J. Natl. Cancer Inst. Monogr.*, 15: 117–130, 1993.
33. Kim, R. B., Fromm, M. F., Wandel, C., Leake, B., Wood, A. J. J., and Roden, D. M. The drug transporter P-glycoprotein limits oral absorption and brain entry of HIV-1 protease inhibitors. *J. Clin. Invest.*, 101: 289–294, 1998.
34. Schinkel, A. H., Mol, C. A. A. M., Wagenaar, E., van Deemter, L., Smit, J. J., and Borst, P. Multidrug resistance and the role of P-glycoprotein knockout mice. *Eur. J. Cancer*, 31A: 1295–1298, 1995.
35. Borst, P., and Schinkel, A. H. What have we learnt thus far from mice with disrupted P-glycoprotein genes? *Eur. J. Cancer*, 32A: 985–990, 1996.