Low Systemic Exposure of Oral Docetaxel in Mice Resulting from Extensive First-Pass Metabolism Is Boosted by Ritonavir

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ABSTRACT

P-glycoprotein seems to be the most important factor limiting the oral absorption of paclitaxel. We have now explored the mechanisms responsible for the low oral bioavailability of docetaxel, a structurally related taxane drug. The recovery of 33% of oxidative metabolites and only 39% of unchanged drug in the feces of FVB wild-type mice receiving 10 mg/kg of oral docetaxel indicates that the major part of the oral dose has been absorbed. The feces and bile of mice receiving 10 mg/kg of i.v. docetaxel contained large amounts of metabolites and only minor quantities of unchanged drug, highlighting the importance of metabolism as an elimination route for this drug. In wild-type and P-glycoprotein knockout mice, dose escalation of p.o. administered docetaxel from 10 to 30 mg/kg resulted in a more than proportional increase in plasma levels, which suggested saturation of first-pass metabolism. Moreover, coadministration of 12.5 mg/kg of the HIV protease inhibitor ritonavir, also a strong inhibitor of cytochrome P4503A4 with only minor P-glycoprotein inhibiting properties, increased the plasma levels after oral docetaxel by 50-fold. In vitro transport studies across monolayers of LLC-PK1 cells (parental and transduced with MDR1 or Mdr1a) suggested that docetaxel is a weaker substrate for P-glycoprotein than paclitaxel is. In conclusion, docetaxel is well absorbed from the gut lumen in mice despite the presence of P-glycoprotein in the gut wall. Subsequent first-pass extraction is the most important factor determining its low bioavailability. The inhibition of docetaxel metabolism by ritonavir provides an interesting strategy to improve the systemic exposure of oral docetaxel.

INTRODUCTION

Cytotoxic drugs are administered to patients by mostly i.v. infusion. However, there are several arguments in favor of exploring the oral route for the administration of these drugs, including patients’ preference for oral treatment, facilitated repeated dosing for chronic treatment regimens, and pharmacoeconomic advantages. Frequently, however, the oral route cannot be used because of a low and variable oral bioavailability. Next to pharmaceutical properties of a drug (e.g., dissolution rate, stability within the intestinal tract), both limited passage through the intestinal wall and limited first-pass metabolism are important factors in reducing the oral bioavailability of drugs (1). We have previously shown that P-gp, a cell membrane localized transport protein that was initially discovered to confer multidrug resistance in mammalian cancer cells (2), limits the absorption of p.o. administered paclitaxel (3). This study using mice carrying a homozygous disruption of the Mdr1a gene [Mdr1a (−/−) mice], also demonstrated that the plasma levels of paclitaxel were increased by 6-fold relative to wild-type mice. Moreover, almost 90% of the oral dose was recovered unchanged in the feces of wild-type mice, whereas this was less than 3% in Mdr1a (−/−) mice, which showed that P-gp in the gastrointestinal tract forms an efficient barrier against paclitaxel absorption (3). On the basis of these findings, we have tested the usefulness of compounds that inhibit P-gp function to increase the systemic exposure of p.o. administered paclitaxel in mice and patients. Concomitant administration of the P-gp inhibitors cyclosporin A, SDZ PSC 833, and GF120918 to mice resulted in 7- to 10-fold higher paclitaxel plasma levels (4–6). In patients, the combination of 60 mg/m² of oral paclitaxel and 15 mg/kg of oral cyclosporin A resulted in nearly 7-fold higher plasma levels compared with patients who received paclitaxel alone, thereby reaching potentially therapeutic levels (7, 8). These results with paclitaxel encouraged us to perform (pre)clinical studies investigating the usefulness of cyclosporin A to increase the systemic exposure of p.o. administered docetaxel. Docetaxel is a semisynthetic taxane analogue that is prepared from 10-deacetyl baccatin III, a noncytotoxic precursor isolated from the needles of the European yew tree (Taxus baccata L.). It is currently available as a formulation for i.v. infusion (Taxotere) and has shown activity against lung, head and neck, breast, and ovarian cancer (9). Like paclitaxel, docetaxel is a potent inhibitor of cell replication by blocking the cells in the late G2-M phase of the cell cycle because of inhibition of the microtubule dynamics (10). Thus far, four major metabolites (M-1, M-2, M-3, and M-4; Fig. 1) formed by CYP3A4 have been identified in human feces, which is the major route of elimination of docetaxel and its metabolites (11). We have detected three of these metabolites (M-1, M-2, and M-3) in mouse plasma after i.v. administration of a high dose (33 mg/kg) of docetaxel (12), which indicates that the metabolism of docetaxel in mice and humans occurs through comparable pathways. Docetaxel is also a substrate of P-gp, as was first shown in 1994 by Wils et al. (13) using Caco-2 cell monolayers and was recently confirmed using parental and MDR1-transduced LLC-PK1 cells (14).

Preliminary results showed that the pharmacokinetic handling of paclitaxel and docetaxel appeared to be less similar than anticipated on the basis of their structural similarities. Consequently, we performed a comprehensive pharmacokinetic analysis of docetaxel in mice, with the aim of unraveling the critical biological factors involved in the oral bioavailability of this compound.

MATERIALS AND METHODS

Laboratory Animals

The experiments were performed using female FVB wild-type and Mdr1a/b (−/−) mice (15). All of the mice were between 10 and 17 weeks of age and were housed and handled according to institutional guidelines that comply with Dutch legislation. They were given food (Hope Farms B.V., Woerden, the Netherlands) and acidified water ad libitum.

Drugs and Chemicals

Docetaxel (10 mg/ml) formulated in polysorbate 80/ethanol/saline [20:13: 67 (v/v/v); Taxotere] and docetaxel, pure compound, originated from Aventis.

Received 5/3/02; accepted 9/4/02.

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1 Supported by Grant NK96–1799 from the Dutch Cancer Society.

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3 The abbreviations used are: P-gp, P-glycoprotein; CYP3A4, cytochrome P-450 isoenzyme 3A4, UIC, area(s) under the plasma concentration-time curve(s); HPLC, high-performance liquid chromatography.
Plasma Pharmacokinetic Studies

Plasma originated from the Blood bank (Amsterdam, the Netherlands). Millipore (Milford, MA) was used throughout the experiments. Blank human analytical or Lichrosolv gradient grade. Water obtained by the Milli-Q Plus system (Braun (Emmenbrucke, Germany). Saline was purchased from Salinem (St. Louis, MO) and propyleneglycol was from Bufa B.V. (Uitgeest, the Netherlands). Lyophilized BSA (fraction V) was obtained from Roche (Mijdrecht, the Netherlands). Dormicum from Roche Nederland (Mijdrecht, the Netherlands). 

Blood samples of 120 µl were taken from cannulated animals at serial time-points, and this volume was replaced with drug-free heparinized mouse blood obtained from donor mice.

Plasma was separated by centrifugation at 4°C for 5 min at 3000 × g and stored at −20°C until analysis.

Mass Balance Studies

Combination with Cyclosporin A. Wild-type and Mdr1a/b (−/−) mice (n = 4 per group) were housed in Rucot type M1 metabolic cages (Valkenswaard, the Netherlands) with free access to food and water. After an acclimatization period of 2 days, docetaxel (10 mg/kg) either as single agent or with cyclosporin A (50 mg/kg) was administered p.o. Cyclosporin A was administered at the same time as docetaxel. Feces and urine were collected for up to 96 h.

Combination with Ritonavir. The influence of ritonavir (12.5 mg/kg) was studied in a similar experiment; however, ritonavir was administered 30 min in advance of docetaxel.

i.v. Docetaxel. Docetaxel (10 mg/kg) was administered i.v. as single agent to four wild-type and four Mdr1a/b (−/−) mice.

Feces samples were homogenized at 4°C in 10 volumes of 40 g/liter BSA in water using a Polytron PT1200 homogenizer (Kinematika AG, Littau, Switzerland). Urine samples were diluted 5-fold with drug-free human plasma. All of the samples were stored at −20°C until analysis.

Intraluminal Stability

The contents of the stomach, small intestine, and cecum of two wild-type mice were collected in separate vials. To each vial was added: 200 µl of saline, 1 µg of docetaxel per 100 mg of intestinal contents, and either 20 µl of saline or 20 µl of a 1-mg/ml solution of NADPH in saline. After vortex mixing, the vials were incubated at 37°C. Samples were taken at 0, 15, and 70 min and stored at −20°C until analysis.

Intraluminal Kinetics

Wild-type mice received docetaxel (10 mg/kg) p.o. Gastrointestinal tissues (stomach, small intestine cut into three pieces of equal length, cecum and colon) including their contents were collected from mice killed at 0.25, 0.5, 1, and 3 h after administration. Liver and gall bladder including the bile were also collected. All of the samples were homogenized at 4°C in 2 ml of 40 g/liter BSA in water as described above and stored at −20°C until analysis.

Biliary and Intestinal Secretion

The gall bladders of groups of four wild-type and Mdr1a/b (−/−) mice were cannulated as described earlier (3). Docetaxel (10 mg/kg) was administered by i.v. injection. Bile was collected up to 90 min after drug administration. Next, the contents of the small intestine, cecum, and colon were collected. Bile samples were diluted with 1 ml of drug-free human plasma. The intestinal contents were homogenized in 2 ml of 4% BSA as described above. All of the samples were stored at −20°C until analysis.

In Vitro Transport Assays

Pig-kidney LLC-PK1 cells and subclones transduced with human MDR1 (LLC-MDR1 cells) or mouse Mdr1a (LLC-Mdr1a cells; Ref. 16) were seeded on Transwell microporous (3.0 µm) polycarbonate membrane filters (Corning, NY) at a density of 1 × 10⁴ cells per well and grown for 3 days in 2 ml of complete M199 medium (Life Technologies, Inc., Breda, the Netherlands). Transport experiments were performed in OptiMEM medium containing 11.7

Fig. 1. Structures of docetaxel and its four known metabolites.
μmol [3H]docetaxel or [3H]paclitaxel (both ~5 kBq per well) at the donor compartment. In some experiments, the P-gp inhibitor LY335979 (17) was added at 0.5 or 5 μM to the apical compartment immediately before docetaxel or paclitaxel, whereas ritonavir was used at concentrations of 0 and 100 μM. Cells were incubated at 37°C in 5% CO₂, and samples of 50 μl were taken every hour, up to 4 h after the start of the experiment. The radioactivity in the samples was counted after mixing with 4 ml of UltimaGold scintillation cocktail (Packard, Meriden, CT) using model Tricarb β-scintillation counter (Packard). Inulin [3H]carboxylic acid (~1 kBq per well) was added to the apical compartment to check the integrity of the cell layer. Wells demonstrating a leakage of more than 1.5%/h were excluded from the analyses.

**Cannulation of the Jugular Vein**

The technique of cannulation of the jugular vein has been developed to allow serial blood sampling from an animal. Details will be described elsewhere.

In short, after anesthesia with 7 ml/kg Hypnorm/Dormicum/water [1:1:2 (v/v/v)], an incision was made in the skin just above the right clavicle. After preparation of the jugular vein, it was ligated at the distal side. A 2 French silicone cannula (Access Technologies, Skokie, IL) filled with heparin solution was inserted until the tip reached into the right atrium. The cannula was fixed to the vessel, tunneled to the head of the animal, fixed to the skin between the ears and further protected by a metal spring surrounded by polyvinyl chloride tubing. After recovery, the animal was placed in a specially designed cage that allowed free movement of the animal. The experiment was started after a recovery period of 2 days after the operation.

**Analytical Methods**

Docetaxel and metabolites in biological samples (plasma, feces, urine, tissue, and intestinal contents homogenates) were determined by HPLC, according to a previously developed assay (18). To allow the quantification of docetaxel in the small plasma samples obtained from cannulated animals, we have developed a HPLC method with a lower limit of detection of 50 ng/ml that requires only 50 μl of sample volumes. Details of this method will be presented elsewhere. In short, after anesthesia with 7 ml/kg Hypnorm/Dormicum/water [1:1:2 (v/v/v)], an incision was made in the skin just above the right clavicle. After preparation of the jugular vein, it was ligated at the distal side. A 2 French silicone cannula (Access Technologies, Skokie, IL) filled with heparin solution was inserted until the tip reached into the right atrium. The cannula was fixed to the vessel, tunneled to the head of the animal, fixed to the skin between the ears and further protected by a metal spring surrounded by polyvinyl chloride tubing. After recovery, the animal was placed in a specially designed cage that allowed free movement of the animal. The experiment was started after a recovery period of 2 days after the operation.

**Pharmacokinetic Analysis**

The AUC, the oral bioavailability and their respective SE values were calculated by noncompartmental methods as described previously (5, 6). The oral bioavailability is quoted “apparent” under the circumstance that oral docetaxel was given together with a modifier of drug uptake or inhibitor of drug metabolism, which may result in a change in the clearance of docetaxel from the body. To determine the “true” bioavailability, the same combination should be investigated with i.v. docetaxel.

**Statistical Analysis**

The unpaired Student t test (two-tailed) was used to compare the pharmacokinetic parameters. A P < 0.05 was considered statistically significant.

**RESULTS**

To support the initiatives for clinical studies with oral docetaxel in the Netherlands Cancer Institute, we performed a preclinical study to evaluate the effects of concomitant oral cyclosporin A on the bioavailability of docetaxel in wild-type and Mdr1a/1b (–/–) mice (Fig. 2). The bioavailability of docetaxel was increased by 6-fold from 3.6% in wild-type mice to 22.7% in Mdr1a/1b (–/–) mice (P < 0.001). There was no difference in the AUC of docetaxel in wild-type and Mdr1a/1b (–/–) mice after i.v. administration of the drug as a single agent (Fig. 2). In wild-type mice, the AUC of oral docetaxel was increased 9-fold from 119 ± 21 ng/ml·h to 1121 ± 145 ng/ml·h by coadministration of cyclosporin A (P < 0.001). Calculated relative to the AUC of docetaxel achieved after i.v. administration of this drug given without cyclosporin A, the apparent oral bioavailability of docetaxel plus concomitant cyclosporin A was 33.9%. However, coadministration of cyclosporin A also increased the AUC of i.v. administered docetaxel by 3-fold, both in wild-type and in Mdr1a/1b (–/–) mice (Fig. 2).

We next performed a mass-balance study in wild-type and Mdr1a/1b (–/–) mice to get additional insight into the disposition of p.o. administered docetaxel with and without cyclosporin A. Hardly any docetaxel was recovered in the feces of Mdr1a/1b (–/–) mice or wild-type mice receiving concomitant cyclosporin A (Table 1). However, in wild-type mice receiving docetaxel as single agent, only 40% of the dose was recovered in the feces as unchanged drug and mainly within the first 8 h after dosing. Moreover, about 30% of the dose was recovered as oxidative metabolites. This result suggests that a substantial uptake of docetaxel from the gastrointestinal tract occurs in...
in vivo elimination of this drug from the body comes from 1 h after drug administration. 5.0% of the dose as docetaxel and 4.3% of the dose as metabolites at anance. This is also supported by the finding that the liver contained by extensive first-pass metabolism and effective hepatobiliary clear-
dation of docetaxel in the intestinal contents, either in the absence or 
degradation of the drug within the gastrointestinal lumen, we studied 
intraluminal kinetics of docetaxel in more detail. Docetaxel was 
administered p.o. to groups of wild-type mice, which were sacrificed 
after 0.25, 0.5, 1, and 3 h. Intestinal tissues (including their contents), 
the liver and gallbladder (with bile) were collected and analyzed for 
docetaxel and metabolites (Fig. 3). Within 1 h, ~90% of the dose of 
docetaxel had already disappeared from the stomach into the small 
estine. At this time, only a very small quantity (~2%) had reached 
the colon, which suggested that excretion in the feces within 1 h after 
administration is negligible. Within 3 h after administration, hardly 
any drug was present in the small intestines, thus showing a very rapid 
disappearance from the major site in which drug uptake usually takes 
place. Given the rapid traversal of docetaxel through the gut, excretion 
of part of the dose will have occurred at this time point. Oxidative 
metabolites were present throughout the intestines. However, the 
finding that the ratio of the metabolites, relative to unchanged do-
cetaxel, remains more or less constant over time throughout the 
estines does not support the model of intraintestinal degradation. 
Moreover, the results from the in vitro experiment showed no degra-
dation of docetaxel in the intestinal contents, either in the absence or 
in the presence of NADPH. Consequently, a more likely explanation 
for our observations is a rapid absorption from the intestines followed 
by extensive first-pass metabolism and effective hepatobiliary clearance. 
This is also supported by the finding that the liver contained 
5.0% of the dose as docetaxel and 4.3% of the dose as metabolites at 1 h after drug administration.

Further evidence that metabolism plays an important role in the 
elimination of this drug from the body comes from in vitro experi-
ments with i.v. administered docetaxel. In animals with a cannulated 
bile duct, the fraction of the dose that was recovered as metabolites in 
bile was 27.0% in wild-type mice and almost 50% in Mdr1a/1b (−/−) 
mice, whereas only 3–4% of unchanged drug was recovered in both 
of the mouse strains. The results of a mass balance study showed that, 
in both wild-type and Mdr1a/1b (−/−) mice, only a very small 
fraction of the dose was recovered in the feces as unchanged docetaxel 
(4.6 and 0%, respectively), whereas relatively large amounts of known 
metabolites were recovered in both of the mouse strains (42.6 and 
25.6%, respectively).

The in vitro transport characteristics of docetaxel and paclitaxel 
were compared using monolayers of LLC-MDR1 and LLC-Mdr1a 
cells. The difference between transport in the basolateral-to-apical and 
apical-to-basolateral direction (sometimes used to indicated active 
transport) was smaller for docetaxel than for paclitaxel (Fig. 4). An 
accurate measurement of the Km was not feasible because of the 
relatively low aqueous solubility of paclitaxel and docetaxel. The 
hinhibition of docetaxel transport over the LLC-MDR1 cell line was 
achieved using 0.5 μM LY335979, whereas a concentration of 5 μM 
was needed to inhibit transport of paclitaxel. The inhibiting properties 
of LY335979 were slightly lower in the LLC-Mdr1a cell line; how-
ever, when 5 μM was enough to inhibit docetaxel transport, it was not 
sufficient to inhibit paclitaxel transport completely. When the active 
component of transport of docetaxel and paclitaxel is fully inhibited, 
the residual apical-to-basolateral diffusion of both compounds appears 
to be about equal, which indicates no major differences in their 
membrane permeability. The potential participation of another trans-
porter besides P-gp was excluded by the finding that vectorial trans-
port of both drugs over the parental LLC-PK1 monolayers (by endo-
genous porcine P-gp (16), was fully inhibited at 0.5 μM LY335979.

To further investigate the linearity of uptake after oral administra-
dion of docetaxel, we performed a dose-escalation study in wild-type 
and Mdr1a/1b (−/−) mice. An increase of the oral dose from 10 to 20 
and 30 mg/kg in wild-type mice resulted in AUCs of 161 ± 49, 
916 ± 127, and 2539 ± 279 ng/ml·h and, in Mdr1a/1b (−/−) mice, 
resulted in AUCs of 574 ± 112, 1625 ± 214, and 3705 ± 441 
ng/ml·h, respectively, thus showing a more than proportional increase. 
This can be caused by the saturation of uptake and/or metabolism, 
with the latter probably being the more important factor, given the 
already substantial uptake at the lowest dose level.

Metabolism of docetaxel in humans occurs mainly via CYP3A4 
and, in mice, probably through similar reactions using the CYP3a 
pathway (19, 20). We have, therefore, tested the effects of ritonavir, 
a very strong inhibitor of CYP3A4, on the oral bioavailability of 
docetaxel. Administration of ritonavir results in a major increase in

Table 1. Fecal excretion of unchanged drug and metabolites after oral administration of docetaxel (10 mg/kg) with or without concomitant oral cyclosporin A (50 mg/kg) to wild-type and Mdr1a/1b (−/−) mice.

<table>
<thead>
<tr>
<th>Mouse strain</th>
<th>Cyclosporin</th>
<th>Docetaxel</th>
<th>Metabolites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td>–</td>
<td>38.6 ± 2.0</td>
<td>32.7 ± 2.8</td>
</tr>
<tr>
<td>Wild-type</td>
<td>+</td>
<td>5.4 ± 1.3</td>
<td>37.3 ± 2.0</td>
</tr>
<tr>
<td>Mdr1a/1b(−/−)</td>
<td>–</td>
<td>1.4 ± 0.6</td>
<td>45.2 ± 2.9</td>
</tr>
<tr>
<td>Mdr1a/1b(−/−)</td>
<td>+</td>
<td>0.1 ± 0.1</td>
<td>25.8 ± 4.6</td>
</tr>
</tbody>
</table>

Data are expressed as percentage of administered dose ± SE (n = 4).

Fig. 3. Intraluminal kinetics of docetaxel. Fractions of docetaxel (black bars) and metabolites (hatched bars), expressed as percentage of administered dose (mean ± SE; n = 4 animals per time point) found in segments of the intestines at 0.25, 0.5, 1, and 3 h after oral administration of 10 mg/kg of docetaxel to wild-type mice.
administered dose is recovered as unchanged drug in the feces of wild-type mice (3). In line with paclitaxel, the oral bioavailability of docetaxel was very low and coadministration of cyclosporin A increased the AUC of docetaxel by 9-fold. However, after i.v. administration of docetaxel to Mdr1a/1b (−/−) mice, there was no difference in its plasma clearance as compared with wild-type mice, whereas the clearance of paclitaxel was reduced by 50% in Mdr1a/1b (−/−) mice (3). Moreover, although the bioavailability of docetaxel was 6-fold higher in Mdr1a/1b (−/−) mice, it was still only 23%. Interestingly, we recovered only about 40% of the p.o. administered dose in the feces of wild-type mice as unchanged drug, and we also detected about 30% of oxidative metabolites. On the basis of the in vitro degradative experiment in intestinal juices and the in vivo intraluminal kinetics, these observations could not be explained by degradation of docetaxel within the gastrointestinal lumen. Hence, these results seem to indicate a substantial uptake of docetaxel despite the presence of P-gp in the intestinal wall, which would imply that docetaxel is a weaker substrate of P-gp than paclitaxel is. The results of in vitro transport studies strongly support this idea.

The rapid disappearance of docetaxel from the gut lumen and the short t\textsubscript{max} in plasma both imply that the uptake of docetaxel occurs readily. Effective first-pass extraction and metabolic breakdown, subsequently followed by hepatobiliary excretion of unchanged drug and metabolites into the gut lumen, could thus explain the low docetaxel plasma levels. The important role of hepatic metabolism in the disposition of docetaxel is highlighted by the large amounts of metabolites recovered from the bile after i.v. administration of docetaxel to mice with cannulated gallbladders. Similarly, the fecal recovery of unchanged drug after i.v. administration of docetaxel was negligible. Given these results, we have tested the effects of the protease inhibitor

the plasma levels of docetaxel in wild-type and Mdr1a/1b (−/−) mice (Fig. 5). Calculated relative to the AUC of i.v. administered docetaxel without ritonavir, the systemic exposure in wild-type mice increased about 50-fold from 123 ± 39 ng/mlh to 6,043 ± 1,572 ng/mlh (P = 0.013) and in Mdr1a/1b (−/−) mice from 574 ± 112 ng/mlh to 33,322 ± 1,753 ng/mlh (P < 0.003). A mass balance study performed with this combination showed that 65.3% of unchanged docetaxel and 3.6% of metabolites were recovered in the feces of wild-type mice, whereas in Mdr1a/1b (−/−) mice, this was 5.5 and 46.0%, respectively (Table 2). The influence of ritonavir on the transport characteristics of docetaxel was studied in vitro over LLC-MDR1 and LLC-Mdr1a cells. It was found that a concentration of 100 μM had no effect on the vectorial transport of docetaxel (Fig. 6), which suggested that ritonavir is not a very potent P-gp inhibitor.

**DISCUSSION**

This study shows that the presence of P-gp in the epithelial cells lining the gastrointestinal tract is not able to prevent the uptake of docetaxel from the intestinal lumen of mice. However, subsequent and very efficient first-pass metabolism, probably by CYP3a enzymes, results in very low plasma levels and, thus, in a low bioavailability. The HIV protease inhibitor ritonavir, a very effective inhibitor of human CYP3A4, dramatically increases the systemic exposure to docetaxel by 50-fold.

The mechanism that determines the low oral bioavailability of docetaxel is different from what we had expected, based on our experience with oral paclitaxel. The oral uptake of the latter, a structurally closely related taxane drug, is almost completely inhibited by P-gp in the intestinal wall, because virtually the complete p.o.
Ritonavir, a very effective inhibitor of CYP3A4, the key enzyme responsible for the metabolic breakdown of docetaxel in humans (21). Ritonavir increased the systemic exposure of oral docetaxel dramatically by 50-fold (Fig. 5). The inhibition of P-gp by ritonavir does not seem to contribute to this effect. Although several studies have suggested that ritonavir may act as a P-gp inhibitor (22–26), ritonavir was not potent enough to inhibit P-gp mediated transport of docetaxel. Moreover, there was no evidence for an increased uptake of docetaxel from the gastrointestinal tract when given with ritonavir. The fecal excretion of unchanged docetaxel in wild-type and animals receiving docetaxel as single agent, which may be caused by the strong inhibition of docetaxel metabolism resulting in a larger hepatobiliary excretion of unchanged drug.

Our results thus show that both P-gp and metabolism cause the low oral bioavailability of docetaxel with the latter, however, being the major determinant. It is well established that there is a striking overlap between substrates of P-gp and CYP3A4 (27–31). Bennet et al. (29) and Zhang and Bennet (31) have proposed a model in which P-gp and CYP3A4 cooperate as a barrier against the drug uptake from the gut lumen, with P-gp limiting the access of the drug to CYP3A4, thus preventing the saturation of the latter. Docetaxel appears to be an excellent model compound for this so-called “gate-keeper” theory. It was found that P-gp is moderately efficient in preventing the intestinal uptake of docetaxel at a dose of 10 mg/kg, with about 40% of the unchanged drug being recovered in the feces. However, of the 60% of the dose that is absorbed from the intestines, only 4% managed to bypass metabolism and reach the systemic circulation. When P-gp was absent, as in Mdr1a/1b (−/−) mice, a higher uptake of only about 2-fold from the gut resulted in about a 6-fold higher systemic plasma level. Moreover, a similar nonproportional increase was observed with increasing doses, whereas docetaxel displayed linear pharmacokinetics in mice after i.v. administration in the same dose range (18). Consequently, these results reflect the saturation of enzymes involved in first-pass metabolism with an increasing supply of drug.

In patients, the combination of oral cyclosporin A and docetaxel has proven to be very effective because it increased the apparent bioavailability of docetaxel from 8 to 90% (32). The reasons for the rather modest effect of cyclosporin A on the bioavailability of docetaxel in mice are not clear. Cyclosporin A acts as a double-edged sword, inhibiting both P-gp and CYP3A4 (33), and it may be that cyclosporin A is more effective in inhibiting human CYP3A4 than it is in murine CYP3A. Our experiments show that ritonavir is a very effective inhibitor of metabolism of docetaxel in mice. In HIV patients, ritonavir is now commonly used as a booster for saquinavir and indinavir oral bioavailability, and studies have shown that a low oral so-called “baby” dose of 100 mg is already sufficient to increase the bioavailability to therapeutic plasma levels (34, 35). Moreover, the use of ritonavir seems to be safe, even when taken for a long period of time, as is common in anti-HIV therapy. Consequently, the clinical use of ritonavir as a booster for the oral bioavailability of docetaxel appears to be an attractive alternative over concomitant cyclosporin A. Moreover, boosting with ritonavir may even reduce the costs of therapy, because it is likely that dose reductions of docetaxel are required when using ritonavir.

In conclusion, our study shows that both the P-gp and the CYP3A metabolizing enzymes determine the low oral bioavailability of docetaxel in mice with the CYP3A, however, being quantitatively most important. Ritonavir boosts the systemic exposure of docetaxel extensively and provides a promising combination for further testing in patients.

ACKNOWLEDGMENTS

We gratefully acknowledge the excellent biotechnical assistance of Ton Schrauwers.

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