Effect of Interleukin-2 on Intestinal P-glycoprotein Expression and Functionality in Mice

CELINE VEAU, LAURENCE FAIVRE, SYLVIANE TARDIVEL, MIREILLE SOURSAC, HELENE BANIDE, BERNARD LACOUR, and ROBERT FARINOTTI

Unite Propre de Recherche de l’Enseignement Supérieur 2706 (C.V., L.F., S.T., M.S., H.B., B.L., R.F.); Laboratoire du Métabolisme Minéral des Mammifères, Ecole Pratique Hautes Etudes-Physiologie, Faculté de Pharmacie, Châtenay-Malabry (S.T., B.L.); and Service de Pharmacie Clinique et des Biomatériaux, Hôpital Bichat, Paris, France (R.F.)

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ABSTRACT

P-glycoprotein (Pgp), an active drug transporter expressed in enterocytes, can reduce intestinal absorption of drugs. Until now, interleukin-2 (IL2) has been reported as a Pgp modulator only in vitro. The present study examines the effects in vivo of IL2 after chronic treatment on intestinal Pgp protein expression and activity. This work also describes the effects of IL2 on the oral bioavailability of a Pgp substrate (digoxin) and of a Pgp/CYP3A cosubstrate (saquinavir). Human recombinant interleukin-2 (rIL2), administered to mice at 9 million international units/kg by intraperitoneal route twice daily for 4 days, led to a decrease in intestinal Pgp protein expression evaluated by Western blot with C219 antibody. In an in vitro everted gut sac model, rIL2 pretreatment decreased the Pgp-mediated transport of rhodamine 123 across mouse intestine by 37%. Moreover, rIL2 pretreatment markedly raised the area under the curve of orally administered digoxin from 3.5 ± 0.5 to 9.7 ± 1.5 mg min l−1 as a consequence of the reduction in intestinal Pgp activity. rIL2 treatment increased saquinavir bioavailability from 2.5 to 4.5%, showing that first-pass metabolism is not affected and that Pgp by itself has only a moderate effect on saquinavir oral bioavailability. In conclusion, rIL2 pretreatment reduces intestinal Pgp protein expression and activity in mice. However, the effect of such a treatment on drug bioavailability depends on the extent of their metabolism by CYP3A.

P-glycoprotein (Pgp) is an active drug transporter belonging to the ATP-binding cassette transporter family with a very wide substrate range. It is abundant in the apical membrane of many pharmacologically important epithelial barriers, such as the intestinal epithelium and the blood-brain barrier (Thiebaut et al., 1987; Lum and Gosland, 1995). In the intestine, Pgp transports its substrates in an outward (extracellular) direction, thus limiting their absorption from the intestinal lumen and contributing to the low bioavailability of such drugs (Terao et al., 1996; Wacher et al., 1996). In humans, Pgp is encoded by MDR1. In mice, mdr1a is the major RNA transcript expressed in small intestine (Schinkel et al., 1994).

The bioavailability of some drugs is also decreased by metabolism via a phase I metabolism involving cytochrome P450. CYP3A, extensively expressed in liver and in intestine of humans and rodents, is the main subfamily responsible for phase I metabolism of such drugs (Wacher et al., 1996). A sticking overlap of substrate specificity for CYP3A and Pgp has been observed (Wacher et al., 1995; Schuetz et al., 1996). Furthermore, Pgp and CYP3A share many inhibitors such as cyclosporin A, ketoconazole, and ritonavir. Hence, in most human and animal studies, simultaneous inhibition of Pgp and CYP3A by these compounds increases the bioavailability of Pgp/CYP3A cosubstrates (Kempf et al., 1997; Salphati and Benet, 1998).

Digoxin is a Pgp substrate poorly metabolized in humans and mice. Digoxin is considered as a reference substrate to test intestinal Pgp functionality in vivo (Greiner et al., 1999; Kawahara et al., 1999; Hoffmeyer et al., 2000). In humans, drug-drug interactions involving modulation of intestinal Pgp have been reported with digoxin: itraconazole or atorvastatin, two Pgp inhibitors, increase digoxin area under the curve (Sachs et al., 1993; Boyd et al., 2000). In mice, digoxin absorption is markedly increased in the absence of mdr1a (Mayer et al., 1996; Kawahara et al., 1999).

Saquinavir, a protease inhibitor used in combination in the treatment of HIV infection, has a very low bioavailability (4%) due to an extensive first-pass metabolism and an efflux by intestinal Pgp (Kim et al., 1998). In humans, saquinavir is...
strongly metabolized by CYP3A4 (Noble and Faulds, 1996; Fitzsimmons and Collins, 1997).

Recently, interleukin-2 (IL2) has been used as immunomodulator in HIV treatment. This cytokine plays a central role in immune response by stimulation of Natural Killer cells and cytotoxic T-lymphocyte activity. Drug-drug interactions between human recombinant interleukin-2 (rIL2) and protease inhibitors have been reported previously (Piscitelli et al., 1998). A decrease in Pgp protein expression associated with a decrease in its mRNA by IL2 has been reported in human colon carcinoma cells (Stein et al., 1996). Therefore, IL2 could modify intestinal Pgp function in vivo and influence pharmacokinetics of Pgp substrates.

The aim of this study was to investigate the effects of IL2 pretreatment in mice on the activity and expression of intestinal Pgp, both at the mRNA and protein levels. These effects were correlated to the bioavailability of two Pgp substrates: digoxin (poorly metabolized) and saquinavir (strongly metabolized). Protein expression was estimated by Western blot using C219 as Pgp antibody. mRNA mdr1a expression was quantified by RT-PCR. To estimate Pgp activity, we used an in vitro model of everted gut sacs with rhodamine 123 as substrate for the transporter. Pharmacokinetics of digoxin was investigated after oral administration as reference. Bioavailability of saquinavir was investigated after oral and intravenous administration in mice.

Materials and Methods

Chemicals. rIL2 (18 MIU; Proleukin) was a gift from Chiron Laboratories (Suresnes, France). Saquinavir (200-mg capsules; Invirase) and saquinavir mesylate were from Roche Applied Science (Neuilly-sur-Seine, France). Digoxin Nativel was from Procter & Gamble (Neuilly-sur-Seine, France). Cyclosporin (Sandimmun) was from Novartis (Basel, Switzerland). (Carboxymethyl)cellulose, rhodamine 123, verapamil, probenecid, boric acid, and trifluoroacetic acid were from Sigma-Aldrich (St. Quentin Fallavier, France). Glucose i.p. twice daily for 4 days). Animals were fasted overnight, taken above the caecum, washed with isotonic saline, and everted. It was cut into 5-cm-long segments that were ligated at one end, filled to 10 ml with 5% glucose to obtain a final concentration of 1.8 mM NaCl, 25 mM NaHCO₃, 1.2 mM MgCl₂, 1.25 mM CaCl₂, 11 mM glucose, and 4.7 mM HCl, pH 7.4. The solution was gassed with 95% O₂/5% CO₂ and maintained at 37°C throughout the experiment.

Transport of rhodamine 123 from the serosal to the mucosal side was measured by sampling 500 μl of the external medium every 20 min up to 80 min. The rate of rhodamine 123 transport was expressed as percentage secreted per minute in the mucosal compartment.

In some experiments, inhibitors were added in the mucosal and the serosal sides at the same concentration. Several inhibitors of different intestinal drug transporters were used: verapamil (25 and 250 μM) and cyclosporin A (10 and 50 μM) as Pgp blockers and probenecid (25 and 100 μM) as a multidrug-resistance protein (MRP) blocker. Cyclosporin A was dissolved in a mixture of ethanol/Cremophor EL (0.015 and 0.27%, v/v, respectively, in buffer A). This mixture was also used as vehicle for control experiments. In some experiments, rIL2 (1 μM) was added in the mucosal and the serosal sides, to study the in vitro interaction between rIL2 and rhodamine 123.

Rhodamine 123 concentrations were measured by a reversed phase-high performance liquid chromatography technique with spectrofluorometric detection. It was separated on a C₄ column (3.9 × 150 mm, Nova-Pak; Waters, Saint-Quentin-en-Yvelines, France) using a mixture of acetonitrile and 0.05 M sodium phosphate buffer, pH 2.83 (25:75, v/v) as mobile phase. The flow rate was 1 ml/min (RF-10AS pump; Shimadzu, Kyoto, Japan). Under these conditions, retention time of rhodamine 123 was 10 min. Detection was set at 500 and 525 nm for excitation and emission, respectively, using an RF-551 spectrofluorometer (Shimadzu). Ten microliters of each sample was injected in the chromatographic system. The interday coefficients of variation in the studied concentration range (5–200 nM) were below 10%. The limit of quantification was 1 nM.

Semiquantitative Determination of Pgp Expression by Western Blot. After laparotomy, the intestines of mice were quickly removed and washed with ice-cold isotonic saline containing 1 mM phenylmethylsulfonyl fluoride (PMSF) as protease inhibitor. Mucosa were scraped on ice with a slide glass and homogenized using a glass Teflon potter (20 strokes) in a buffer containing 250 mM sucrose, 50 mM Tris-HCl pH 7.4, 1 mM PMSF, and 0.1 U/ml aprotinin. The homogenates were centrifuged 10 min at 3,000g, and the supernatant was again centrifuged for 30 min at 15,000g. The pellets containing the crude membranes were resuspended in 0.5 ml of a buffer containing 50 mM mannitol, 50 mM Tris pH 7.4, 1 mM PMSF, and 0.1 U/ml aprotinin and stored at ~8°C until use. Protein concentrations were determined using the Bio-Rad protein assay kit (Bio-Rad, Hercules, CA) with bovine serum albumin (BSA; Sigma-Aldrich) as standard.

Crude membrane suspensions were diluted to a final protein concentration of 0.5 μg/ml/1% Triton and placed at 4°C during 30 min for solubilization of Pgp. A volume of 10 μl of loading buffer (240 mM Tris-HCl pH 6.8, 8% SDS, 40% glycerol, 0.1% bromphenol blue, and 0.2% mercaptoethanol) was added to 40 μl of each solubilized sample. Ten micrograms of protein was separated on a 7.5% SDS-polyacrylamide gel. After electrophoresis, the proteins were electroblotted with a nitrocellulose membrane. The membrane was blocked in phosphate-buffered saline containing 0.05% Tween 20 (PBST) and 3% skimmed milk for 2 h at room temperature and washed two times for 5 min in PBST. The primary monoclonal antibody C219 (DAKO, Glostrup, Denmark), diluted 200-fold in PBST-1% BSA, was incubated overnight at 4°C. After washing in PBST buffer, secondary polyclonal antibody, mouse anti-IgG peroxidase conjugate (Bioys, France) was diluted 800-fold in PBST-1% BSA, was incubated at room temperature for 2 h. Pgp protein in crude membranes was detected by chemiluminescence using enhanced chemiluminescence detection ID software (Eastman Kodak, Rochester, NY).

Because IL2 is a Pgp substrate, it could interact with Pgp, masking adequate revelation by C219 in Western blot analysis. Mouse intestinal mucosa (pool of two mouse intestines) was scrapped, and rIL2 was added to the samples at 0 (controls), 30, 300, and 3,000, and
30,000 ng/ml in buffer before homogenization. Crude membranes were prepared as described above. Pgp expression of the five samples was measured by Western blot.

**Semi-quantitative Determination of mdr1a mRNA.** After laparotomy, intestines of mice were removed and washed with sterile ice-cold isotonic saline. Mucosae were scraped with a slide glass, on ice, in sterile conditions. Total RNA was extracted from mucosa using Trizol (Sigma-Aldrich).

RT of 2.5 μg of total RNA using 0.25 μg of Oligo(dT)12-18 primer was performed for 50 min at 42°C using Superscript RTase H-Reverse transcriptase (Invitrogen, Carlsbad, CA). The technique of Murphy was applied to quantify the expression of specific mRNAs in each sample (Murphy et al., 1990). The polymerase chain reaction (PCR) was found to be both sensitive and quantitative during the exponential range of the reaction. To reach these experimental conditions, serial dilutions of the RNA RT products (0.702–62.5 ng) were amplified by PCR during 35 cycles. Finally, 7.8 ng of the RNA RT products of each sample was amplified by semi-quantitative PCR. PCR amplification using specific primers for mdr1a (forward-5’ AGCATCTTGGACACACAT3’; reverse-5’ GTTGTCTTCTACCCGCTTG3’) and for β-actin (used as housekeeping gene) as described previously (Damon et al., 1996) was performed in the presence of TaqDNA polymerase (Roche Applied Science). For mdr1a and β-actin amplifications, a 5-min incubation at 94°C was followed by 35 cycles of denaturation at 94°C for 30 s, annealing at 53°C for 30 s, and extension at 72°C for 60 s. The final extension was at 72°C for 7 min. PCR products were separated on a 1.2% agarose gel stained with 2 μg/ml ethidium bromide, to visualize the DNA bands.

**In Vivo Digoxin Pharmacokinetic Studies.** Mice received digoxin (5 μg/ml 0.1 ml Digoxin Nativelle solution diluted up to 1 μg/ml with distilled water) by gavage (33.3 μg/kg of body weight). Mice were killed by decapitation at 0.25, 0.5, 1, 2, 3, 4, 6, 8, and 24 h after digoxin administration. Six animals per each time point were used for both control and rIL2-pretreated groups.

Blood was collected on heparinized polypropylene tubes and centrifuged at 4000 g for 20 min at 4°C. Plasma was stored at −20°C until digoxin analysis. Plasma digoxin concentration was measured using an automated microparticle enzyme immunoassay (Abbott, Saint-Remy-sur-Avre, France).

**In Vivo Saquinavir Pharmacokinetic Studies.** For oral administration, the content of Invirase capsules was mixed with 0.2% (carboxymethyl)cellulose to obtain a saquinavir suspension of 8 mg/ml. Saquinavir was administered at 100 μg/kg of body weight by gavage. Mice were killed by decapitation at 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, and 180 min after saquinavir administration. For intravenous administration, saquinavir was dissolved in a 7.5% ethanol/7.5% Cremophor EL saline solution to obtain a concentration of 1.5 g/l. Saquinavir was administered at 7.5 mg/kg of body weight by injection in the tail vein. Mice were killed by decapitation at 2, 6, 10, 20, 30, 45, 60, 90, 120, 150, and 180 min after saquinavir administration. Six animals per each time point were used in both control and rIL2-pretreated groups.

Blood was collected on heparinized polypropylene tubes and centrifuged at 4000 g for 20 min at 4°C. Plasma was stored at −20°C until saquinavir analysis. Plasma saquinavir was quantified by a reversed phase high-performance liquid chromatography method with a spectrophotometric detection at 240 nm. Separation was made on a C18 column (4.6 × 250 mm, 5-μm Hypersil; Hypersil, Les Ulis, France). Mobile phase was a mixture of 0.4% trifluoroacetic acid/distilled water/acetonitrile/diethylamine (10:35:55:0.1, v/v/v/v). pH was adjusted at 6.5 with acetic acid. The flow rate was 1 ml/min.

A volume of 100 μl of borate buffer (0.1 M, pH 9.5) was added to 100 μl of plasma and vortexed during 20 s. Then, a volume of 300 μl of methanol was added and vortexed during 20 s. After centrifugation (10 min at 12,000g), an aliquot of 350 μl of supernatant was evaporated to dryness under air. Samples were reconstituted in 100 μl of mobile phase. For the analysis, 20 μl was injected in the chromatographic system.

The interday coefficients of variation in the studied concentration range (0.09–9 mg/l) were below 10%. The limit of quantification was 0.045 mg/l.

**Data Analysis.** The results are expressed as mean ± S.E.M. Statistical comparisons between control group and rIL2-pretreated group were made using a Student’s t test. Statistical significance was accepted as p < 0.05.

Compartmental methods were used to calculate digoxin and saquinavir pharmacokinetic parameters. The MicroPharm software was used. The area under the plasma drug concentration-time curve (AUC) was calculated by the linear trapezoidal method from 0 to 24 h for digoxin and from 0 to 180 min for saquinavir.

**Results**

**Transport of Rhodamine 123 in Mouse Everted Gut Sac.** The transport of rhodamine 123 from the serosal to the mucosal side of the gut was investigated during 180 min. The transport was linear between 20 and 100 min. The curve was no more linear over 100 min, suggesting a decrease in the viability of the everted gut sac. The rate of transport was measured between 20 and 80 min.

The rate of transport was measured in the absence and in the presence of several competitors to test the specificity of rhodamine 123 secretion in this model (see Materials and Methods). The transport of rhodamine 123 was significantly decreased by 73% in the presence of 25 μM verapamil and by 76% in the presence of 250 μM verapamil (Fig. 1A). Therefore, the inhibition of rhodamine transport was already maximal with 25 μM verapamil. This verapamil concentration will be used in the next experiments. The transport of rhodamine 123 was significantly decreased by 75% in the presence of 10 μM cyclosporin A and by 79% in the presence of 50 μM cyclosporin A (Fig. 1B). Therefore, the inhibition of rhodamine 123 transport was already maximal with 10 μM cyclosporin A.

The transport was not affected by 25 μM probenecid or by 100 μM probenecid (Fig. 1C). The transport of rhodamine 123 that can be inhibited by Pgp blockers was considered as the difference between the basal transport (without inhibitor) and the residual transport (in the presence of Pgp inhibitors). This Pgp-mediated transport of rhodamine 123 was 0.55 ± 0.04 and 0.52 ± 0.05%/min, respectively, in the presence of 25 μM verapamil and 10 μM cyclosporin A (Fig. 1, A and B). The transport of rhodamine 123 was not affected in the presence of 1 μM rIL2 (Fig. 1D).

**Influence of rIL2 Treatment on Rhodamine 123 Transport in Mouse Everted Gut Sac.** For everted sacs prepared with intestine from control and rIL2-pretreated mice, rhodamine 123 transport was measured in the absence and in the presence of 25 μM verapamil. The basal transport of rhodamine 123 across mouse intestine was significantly decreased by 32% in rIL2-pretreated group compared with control group (Fig. 2A). In the presence of verapamil, the transport of rhodamine 123 was significantly decreased by 65 and 59% in control and rIL2-pretreated groups, respectively (Fig. 2A). The Pgp-mediated transport of rhodamine 123 was significantly decreased by 37% in rIL2-pretreated group compared with control group (Fig. 2B).

**Western Blot Analysis.** The monoclonal antibody C219 used for Western blot analyses revealed a double band of 165 and 112 kDa. The intensity was very weak in intestinal crude membranes of rIL2-pretreated mice compared with controls.
Another band of 80 kDa also revealed by C219 was similar between both groups. Densitometric analysis of the whole showed a significant decrease of 57% in Pgp protein expression of rIL2-pretreated mice compared with control group (Fig. 3B).

Pgp expression was not modified by the addition of rIL2 in the homogenization buffer for crude membranes preparation (Fig. 4). These results rule out an experimental artifact. The weaker intensity of the bands revealed by Western blot in intestines of mice pretreated with rIL2 really corresponds to a decrease in Pgp protein expression.

**Semiquantitative Determination of mdr1a mRNA.** The expression of mdr1a and /H9252-actin mRNA showed no difference between control and rIL2-pretreated mice (Fig. 5).

**Pharmacokinetics of Digoxin after an Oral Dose, with and without Pretreatment of Mice by rIL2.** Plasma levels of digoxin were significantly increased at all time points in mice pretreated with rIL2 compared with controls (Fig. 6). Pharmacokinetic profile of digoxin versus time course fitted in a monocompartmental model. Digoxin AUC was significantly increased by 2.8-fold in rIL2-pretreated mice compared with controls. CL/F and Vd/F were significantly decreased by 60 and 50% in rIL2-pretreated mice compared with controls, respectively. MRT and t\textsubscript{1/2} were significantly increased by 38 and 30% in rIL2-pretreated mice compared with controls, respectively (Table 1).

**Pharmacokinetics of Saquinavir with and without Pretreatment of Mice by rIL2.** After oral administration, plasma levels of saquinavir were significantly increased at 30, 45, and 75 min, respectively, by 220, 90, and 160% in rIL2-pretreated mice compared with controls (Fig. 7A). After intravenous administration, plasma levels of saquinavir
were not different between both groups (Fig. 7B). Pharmacokinetic profile of intravenous administered saquinavir fitted in a bicompartmental model. After oral administration, pharmacokinetic profile of saquinavir fitted in a monocompartmental model. rIL2 pretreatment increased the AUC of orally administered saquinavir by 80% and decreased CL/F by 45% (Table 2). For i.v. administration, rIL2 pretreatment did not modify saquinavir AUC, CL, Vd, and MRT (Table 2). Elimination half-life was not affected by rIL2 pretreatment in both oral and intravenous studies (Table 2). The bioavailability of saquinavir was increased by rIL2 pretreatment from 2.5 to 4.5%.

**Discussion**

Our study demonstrated that rIL2, administered at 9 MIU/kg twice a day intraperitoneally for 4 days in mice, induces a 2-fold decrease in the protein expression of intes-
**Fig. 5.** Expression of mdr1a and β-actin mRNA in intestine by semiquantitative RT-PCR. Mice were treated with 9 MIU/kg of rIL2 or with 5% glucose i.p. twice daily for 4 days and were sacrificed on day 5. Total RNA was extracted from intestinal mucosa using TRizol. PCR products were separated on a 1.2% agarose gel stained with 2 μg/ml ethidium bromide, to visualize the DNA bands. Sd, PCR standard marker. A, expression of mdr1a mRNA. B, expression of β-actin mRNA.

**Fig. 6.** Digoxin plasma concentration versus time curves after oral administration (33.3 μg/kg). Mice were treated with 9 MIU/kg of rIL2 (solid line; squares) or with 5% glucose (dashed line; circles) i.p. twice daily for 4 days, and pharmacokinetic studies were performed on day 5. Data are expressed as mean ± S.E.M (n = 6).

The Pgp-mediated transport of rhodamine 123 was significantly lower across intestine of mice pretreated with rIL2 compared with control mice. Rhodamine 123 transport (across intestine of control mice) was not affected by the addition of 1 μM rIL2 to the experimental medium. This is in agreement with the study of Drach reporting that rhodamine 123 transport (0.5 μM) is nearly unaffected by the addition of IL2 (20 nM), in human colon carcinoma cells (Drach et al., 1996). Then, the decrease in vitro Pgp-mediated transport of rhodamine 123 across everted gut sacs of rIL2-pretreated mice can be attributed to the lower Pgp protein expression and not to a direct interaction between rIL2 and rhodamine 123. The decrease in intestinal Pgp protein expression, measured with the specific monoclonal antibody C219 on Western blot, was in agreement with the lower Pgp-mediated transport of rhodamine 123. In contrast, mRNA of mdr1a, the gene encoding for Pgp in mouse intestine, was not modified by rIL2 pretreatment. Hypothesis of an experimental artifact masking adequate revelation of Pgp protein in Western blot analysis was ruled out. So, the discrepancy between the Western blot data and the mRNA levels suggests a post-transcriptional modification of the protein by the cytokine. Such a post-transcriptional modification of Pgp level by IL2 is also observed in the study reported by Stein et al. (1996) in human colon carcinoma cells. Therefore, these in vitro results agree with our present in vivo results. Possible post-transcriptional mechanisms have not been investigated in most of the studies reporting modifications of Pgp protein expression. According to our knowledge, an alteration in Pgp translation step has never been demonstrated. According to the literature, only two kinds of modifications could explain a post-transcriptional decrease in Pgp protein expression: one

### TABLE 1

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<th>AUC (mg min l⁻¹)</th>
<th>CL/F (10⁻³ l min⁻¹ kg⁻¹)</th>
<th>MRT (min)</th>
<th>Vd/F (l kg⁻¹)</th>
<th>t₁/₂ (min)</th>
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<td>Controls</td>
<td>3.5 ± 0.5</td>
<td>9.6 ± 0.5</td>
<td>3.4 ± 0.3</td>
<td>202 ± 17</td>
<td>168 ± 15</td>
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<tr>
<td>rIL2</td>
<td>9.7 ± 1.5**</td>
<td>3.8 ± 0.5**</td>
<td>4.7 ± 0.3</td>
<td>283 ± 19**</td>
<td>218 ± 9*</td>
</tr>
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*Vd/F = volume of distribution / body weight

**t₁/₂**, elimination half-life.

**Significantly different from controls (**p < 0.05, ***p < 0.01, ****p < 0.001).
at the level of Pgp glycosylation and the other at the level of Pgp trafficking. First, after synthesis, Pgp needs to be glycosylated to reach the plasma membrane. An alteration in glycosylation involves an increase in the degradation of the native protein, leading to a decrease in its expression (Kramer et al., 1995; Loo and Clarke, 1999; Gribar et al., 2000). Second, a reduction of Pgp movement from a cytoplasmic pool to the cell surface could also explain a down-regulation of Pgp protein expression. This kind of regulation has been reported about Pgp protein overexpression induced by an enhancement of the trafficking of functional Pgp to the plasma membrane (Maitra et al., 2001).

rIL2 pretreatment modified pharmacokinetics of orally administered digoxin as shown by the 2.8-fold increase in plasma AUC in mice pretreated with rIL2 compared with the controls. In mice, the absorption of digoxin as well as the direct intestinal secretion have been shown to be dependent on intestinal Pgp using mdr1a knockout mice (Mayer et al., 1996). Digoxin is selectively transported by Pgp across intestine (Stephens et al., 2001). Fifty percent of the initial dose of digoxin is eliminated by the kidney. Kawahara et al. (1999) showed that Pgp contributes to digoxin renal clearance. In the present work, elimination half-life of digoxin was greater in mice pretreated with rIL2 compared with control mice. Renal Pgp protein expression was not affected by rIL2 pretreatment (data not shown). Therefore, the large increase in digoxin AUC can be imputed to the decrease in intestinal Pgp activity induced by rIL2 pretreatment.

rIL2 pretreatment increased plasma AUC of orally administered saquinavir by 80% but did not modify plasma levels of saquinavir administered intravenously. Therefore, bioavailability of saquinavir was increased by 80% (from 2.5 to 4.5%) in mice pretreated with rIL2 compared with control mice. This 1.8-fold increase in saquinavir bioavailability is an important increase considering the relative value but quite small considering the absolute value. Then, absolute bioavailability remains in the lower range (4.5%) after rIL2 pretreatment. Bioavailability of saquinavir is limited by both intestinal and hepatic first-pass metabolism and also by a Pgp-mediated intestinal efflux. The protease inhibitor is mainly eliminated by metabolism via CYP3A. In our study, the total clearance of saquinavir was not affected by rIL2 pretreatment, showing that P450-mediated metabolism of the protease inhibitor was similar between rIL2-pretreated mice and controls. The same range of rIL2 dosage has been reported to reduce total hepatic P450 activity by 20% in mice, and more specifically the isoforms 1A1 and 2B1/2 activities (Cantoni et al., 1995). However, the activity of CYP3A was not specifically measured by Cantoni et al. (1995). According to our i.v. study, activity of CYP3A-mediated metabolism of saquinavir is unaffected by rIL2 pretreatment. These data suggest that rIL2 pretreatment did not affect hepatic first-pass metabolism of orally administered saquinavir. The decrease in intestinal Pgp activity by rIL2 pretreatment did not affect the plasma pharmacokinetic profile of saquinavir after

| TABLE 2 |

Saquinavir pharmacokinetic parameters after oral (100 mg/kg) and i.v. (7.5 mg/kg) administrations

Data are expressed as mean ± S.E.M. (n = 6).

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<tr>
<th>AUC</th>
<th>CL</th>
<th>CL/F</th>
<th>MRT</th>
<th>Vd</th>
<th>Vd/F</th>
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<td>mg min l⁻²</td>
<td>l min⁻² kg⁻¹</td>
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<td>min</td>
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| Controls | 7.5 mg/kg i.v. | 152 ± 11 | 0.051 ± 0.004 | 25 ± 1 | 5.1 ± 0.2 | 71 ± 6 |
| 100 mg/kg p.o. | 55 ± 8 | 2.2 ± 0.3 | 74 ± 4 | 209 ± 81 | 64 ± 16 |
| rIL2 | 7.5 mg/kg i.v. | 154 ± 8 | 0.050 ± 0.003 | 26 ± 2 | 5.1 ± 0.3 | 73 ± 5 |
| 100 mg/kg p.o. | 98 ± 14* | 1.2 ± 0.2* | 71 ± 4 | 92 ± 25 | 51 ± 9 |

*Significantly different from controls (*p < 0.05, **p < 0.01, ***p < 0.001).
intravenous administration. This result is in agreement with previous studies in mice depleted in Pgp. After intravenous administration, no difference was observed in saquinavir plasma levels between mdrla (−/−) and mdrla (+/+) mice (Kim et al., 1998; Washington et al., 2000; Huisman et al., 2001). Thus, in our study, the increased bioavailability of saquinavir by rIL2 pretreatment can be explained by an effect on the absorption process, and more specifically by a decrease of the intestinal Pgp-mediated efflux of saquinavir as a consequence of a lower Pgp protein expression. Therefore, a 2-fold decrease in Pgp protein expression led to a small increase in saquinavir bioavailability (Pgp substrate strongly metabolized), showing that in this case, CYP3A-mediated metabolism is the major factor limiting bioavailability.

Furthermore, hypothesis of a direct interaction between rIL2 and saquinavir can be excluded because we studied the direct effect of rIL2 on saquinavir bioavailability in mice. A simultaneous administration of rIL2 (18 MIU/kg i.p.) and saquinavir (100 mg/kg p.o.) did not affect pharmacokinetic profile of the protease inhibitor (data not shown). Therefore, the increase in saquinavir bioavailability can really be attributed to the lower Pgp function induced by the decrease in Pgp protein expression and not to an interaction between rIL2 and saquinavir.

In conclusion, rIL2 treatment led to a decrease in intestinal Pgp protein expression in mice, by a post-transcriptional mechanism. Moreover, rIL2 treatment induced a decrease in Pgp-mediated transport of rhodamine 123 in everted gut sacs. This in vitro model is adequate to measure specifically Pgp activity, especially without interference with MRP-mediated transport. Saquinavir bioavailability was 1.8-fold enhanced after rIL2 treatment. The still low bioavailability of saquinavir despite of the net decrease in Pgp activity outlines the moderate influence of intestinal Pgp on the oral bioavailability of Pgp substrates as strongly metabolized as saquinavir. However, the 2-fold decrease in Pgp protein expression induced a large increase in AUC of orally administered digoxin. These results outline the influence of the decrease in Pgp protein expression on the oral bioavailability of Pgp substrates poorly metabolized. Moreover, this could have clinical relevance for other weakly metabolized Pgp substrates used in association with rIL2 as anticancer chemotherapy or anti-HIV therapy.

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References
vander Sandt ICI, Bloem-Rossemalen MCM, de Beer AG, and Breimer DD (2000)


Address correspondence to: Prof. R. Farinotti, Unité Propre de Recherche de l’Enseignement Supérieur 2706, Faculté de Pharmacie, 5 rue J. B. Clément, 92296 Châtenay-Malabry cedex, France. E-mail: robert.farinotti@cep.u-psud.fr