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Multidrug resistance protein 1 protects the choroid plexus epithelium and contributes to the blood-cerebrospinal fluid barrier

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Multidrug resistance protein 1 (MRP1) is a transporter protein that helps to protect normal cells and tumor cells against the influx of certain xenobiots. We previously showed that Mrp1 protects against cytotoxic drugs at the testis-blood barrier, the oral epithelium, and the kidney urinary collecting duct tubules. Here, we generated Mrp1/Mdr1a/Mdr1b triple-knockout (TKO) mice, and used them together with Mdr1a/Mdr1b double-knockout (DKO) mice to study the contribution of Mrp1 to the tissue distribution and pharmacokinetics of etoposide. We observed increased toxicity in the TKO mice, which accumulated etoposide in brown adipose tissue, colon, salivary gland, heart, and the female urogenital system. Immunohistochemical staining revealed the presence of Mrp1 in the oviduct, uterus, salivary gland, and choroid plexus (CP) epithelium. To explore the transport function of Mrp1 in the CP epithelium, we used TKO and DKO mice cannulated for cerebrospinal fluid (CSF). We show here that the lack of Mrp1 protein causes etoposide levels to increase about 10-fold in the CSF after intravenous administration of the drug. Our results indicate that Mrp1 helps to limit tissue distribution of certain drugs and contributes to the blood-CSF drug-permeability barrier.


Introduction

Cancer cells overproducing cellular drug extruders may become resistant to a wide spectrum of drugs with different structures or cellular targets. This phenomenon is called multidrug resistance (MDR) (1). Three ATP-dependent transmembrane drug transporters — the multidrug resistance gene product MDRI P-glycoprotein (Pgp) (1), the breast cancer resistance protein (2–4), and multidrug resistance protein 1 (MRP1) (5–9) — can render cells multidrug resistant in vitro. MRP1 is a so-called glutathione-conjugate pump, or multispecific organic anion transporter (10), and is a versatile pump. It can mediate the extrusion of glutathione-S-conjugates, glucuronide conjugates, and sulfate conjugates of drugs (10–13); it is the major transporter for endogenous LTC₄, an important mediator of the inflammatory response (11, 14); and it can even extrude neutral and basic organic compounds if the cell contains normal levels of glutathione (15–18).

To elucidate the physiological functions of the MDR-conferring transporters, mutant mice have been generated lacking Mdr1a Pgp and Mdr1b Pgp (19, 20), or lacking Mrp1 (14, 21). Mdr1a Pgp plays an important role in the intestinal epithelium, where it actively excretes xenobiots absorbed from the intestinal lumen back into the lumen. It thereby limits the entry of Pgp substrates into the body. In addition, Mdr1a Pgp plays an important role in the blood-brain barrier (19, 20, 22–24). This barrier is primarily formed by the endothelium of the blood capillaries in the brain. The presence of Mdr1a Pgp in the apical (luminal) plasma membranes of these capillary endothelial cells (25) is crucial for the protection of the brain against several xenobiots entering from the blood (19).

Mrp1-deficient mice lack the main high-affinity glutathione conjugate pump activity in erythrocytes, and cells derived from these mice show increased sensitivity to anti-cancer drugs (14). Mrp1 has important protective roles in the epithelium of the tongue and cheek, the urinary collecting duct epithelium, and the epithelial Sertoli cells in the testicular tubules; we have shown that Mrp1 prevents drug-induced oral mucositis, dia-
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Monoclonal antibodies against MRP1 (27, 28) detect this transport protein in several tissues. Its presence has been demonstrated in the basolateral plasma membrane of the Sertoli cells (26), in the basolateral membranes of the lung epithelium (26, 29), in the liver (30), in the rat choroid plexus (CP) epithelium (31), and in transfected kidney cell lines overproducing human MRP1 (32). Here, we show that Mrp1 is also present in the mouse CP epithelium.

The brain is protected against drugs by 2 drug-permeability barriers: the blood-brain barrier and the blood-cerebrospinal fluid (CSF) barrier. The blood-brain barrier is formed by the endothelium of the blood capillaries; diffusion of some hydrophobic drugs through this barrier is counteracted by transporters such as Mdr1a Pgp (19, 33). The blood-CSF barrier (34) is formed by the epithelium of the CP (35). Recently, some drug transporters (e.g., organic anion transporter protein 1, MDR1 Pgp, and MRP1) have been postulated to play a drug-transporting role in the CP (31, 36, 37). The polarized choroidal epithelium uses active transport mechanisms to extract micronutrients from the blood, and produces and secretes CSF (38). The CP also has an important function in the clearance of metabolic waste products and substrates such as LTC4 (39), estradiol 17β-glucuronide (37), prostaglandins (40), iodide (41), benzylpenicillin (42), cephalosporin (39), estradiol 17β-glucuronide (37), prostaglandins (40), iodide (41), benzylpenicillin (42), cephalosporin (39), zidovudine (44–46), and 2,4,5-trichlorophenoxy-acetic acid (47) from the CSF toward the blood.

Using wild-type and Mrp1-deficient mice on an Mdr1a Pgp/Mdr1b Pgp-null background (Mrp1+/+Mdr1a+/+Mdr1b+/+ and Mrp1−/−Mdr1a+/+Mdr1b−/−; referred to as DKO and TKO for double knockout and triple knockout, respectively) we demonstrate here that Mrp1 helps to limit the accumulation of etoposide in brown adipose tissue, colon, salivary gland, heart, and the female urogenital tract. Most importantly, we show that Mrp1 in the CP protects against high etoposide levels in the CSF, indicating that Mrp1 is a critical component of the blood-CSF drug-permeability barrier. This implies that specific inhibitors of MRPI and MDR1 Pgp may be used to increase the permeability of the blood-CSF and blood-brain barriers for anti-cancer or other drugs.

**Methods**

**Animals.** The animals used were Mdr1a- and Mdr1b-deficient (Mdr1a+/−/Mdr1b−/−) DKO mice and Mrp1-deficient (Mrp1−/−) mice, generated by gene targeting in embryonic stem cells as described by Schinkel et al. (19) and Wijnholds et al. (14). Using these mice, Mdr1a+/−/Mdr1b−/−/Mrp1−/− triple-knockout (TKO) mice were obtained by crossing. All mice used were on a 50% 129/Ola, 50% FVB genetic background. All animals were housed in constant-temperature rooms with a 12-hour-light/12-hour-dark cycle, and had access to a pelleted chow diet (Hope Farms BV, Woerden, The Netherlands) and acidified water ad libitum. Mouse handling and experimental procedures were conducted in accordance with the Netherlands Cancer Institute guidelines for animal care and use.

**Figure 1**

Loss of body weight in mice lacking Mrp1 on a genetic background lacking Mdr1a Pgp and Mdr1b Pgp (TKO mice). DKO mice, TKO mice, and Mrp1−/− mice received a single intravenous dose of 60 mg/kg Etopophos®, and the loss of body weight (%) was measured over 7 days. *P < 0.001.
Table 1
Etopophos\(^{\circledR}\) toxicity in male wild-type, Mrp1–/–, DKO, and TKO mice

<table>
<thead>
<tr>
<th>Etopophos(^{\circledR}) dose (mg/kg)</th>
<th>Wild type</th>
<th>Mrp1–/–</th>
<th>DKO</th>
<th>TKO</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
<td>3/3</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>-</td>
<td>-</td>
<td>3/3</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>-</td>
<td>3/3(a)</td>
<td>-</td>
<td>1/3</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0/4</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
<td>3/3(b), 5/5(b)</td>
<td>4/5(b)</td>
<td>0/3(b)</td>
</tr>
<tr>
<td>100</td>
<td>-</td>
<td>-</td>
<td>3/3</td>
<td>-</td>
</tr>
<tr>
<td>120</td>
<td>5/5(b)</td>
<td>-</td>
<td>0/2</td>
<td>-</td>
</tr>
</tbody>
</table>

The number of surviving animals per group at each intravenous Etopophos\(^{\circledR}\) dose is shown. The data are from 2 independent experiments (\(a\) and \(b\)), using mice 11–16 weeks old. For additional toxicity experiments using wild-type and Mrp1–/– mice, see ref. 26. TKO mice show increased sensitivity to Etopophos\(^{\circledR}\) (\(P < 0.01\)).

anesthetized mouse was fixed in a stereotactic apparatus. The skin covering the skull was shaved and disinfected with 70% ethanol, and then cut crosswise and folded aside. The exposed tissue was locally anesthetized using lidocaine (1% in 0.9% NaCl) and was removed by scraping to expose the skull. The skull was thoroughly cleaned. Two holes were drilled 1.1 mm apart (laterally) at 0.6 mm rostral to bregma. A homemade double cannula made of 19-gauge and 23-gauge needles with 4-mm extending tips of fused silica (outer diameter 0.29 mm, inner diameter 0.10 mm; Composite Metal Services Ltd., Worcester, UK) was fixed in a micromanipulator on the stereotactic apparatus. This double cannula was subsequently lowered through the brain tissue into the lateral ventricles to a ventral coordinate at 2.5 mm to bregma, and fixed first with Cyanolit glue and then with dental cement. The micromanipulator was carefully removed. The mouse was put on a heating pad at 37–39°C and was not allowed to awaken. A solution of 145 mM NaCl, 0.6 mM KCl, 1.0 mM MgCl\(_2\), 1.2 mM CaCl\(_2\), and 0.2 mM ascorbic acid in 2 mM phosphate buffer (pH 7.4) was perfused into the right lateral ventricle at a flow rate of 0.1 \(\mu\)L/min at a constant rate with a syringe pump. One of the intracerebroventricular cannula lanes was used for infusing the perfusion solution (Baby Bee Hive pump; Bioanalytical Systems Inc., West Lafayette, Indiana, USA), while the other was used to withdraw CSF at the same flow rate into the outlet tubing (home-adjusted Harvard `33' pump; Harvard Apparatus Inc., Holliston, Massachusetts, USA). Once the perfusion and collection had been running constantly for 10 minutes, Etopophos\(^{\circledR}\) (60 mg/kg) was infused through a tail cannula with the aid of a syringe pump (100 \(\mu\)L in 2 minutes). During the 1 hour after the start of Etopophos\(^{\circledR}\) administration, CSF was collected through the outlet tubing. The mouse was decapitated and blood and brain were collected. Blood was centrifuged for 10 minutes at 2,000 \(\times\) g to obtain plasma. CSF, brain tissue, and plasma were stored at −30°C pending analysis.

Analysis of etoposide in plasma, CSF, and brain tissue. After gently thawing, the CSF sample was introduced into an HPLC system that consisted of a Spherisorb C18 column (100 mm × 0.8 mm inner diameter, 5 \(\mu\)m particle diameter; Capital HPLC Ltd., Broxburn, UK) using a solvent system of 50 mM sodium acetate buffer with 50 \(\mu\)M EDTA (pH 3.8) and acetonitril (3.8:1 vol/vol) at a flow rate of 40 \(\mu\)L/min (48).

Plasma was diluted with phosphate buffer (50 mM at pH 6.0), and brain tissue was homogenized with a Polytron (0.2 g tissue/mL phosphate buffer). Etoposide in diluted plasma and homogenized brain tissue was extracted with diethyl ether and dichloromethane (2:1, vol/vol), and then separated on an Econosil C18 column (250 mm × 4.6 mm inner diameter, 10 \(\mu\)m particle diameter; Alltech Associates Inc., Deerfield, Illinois, USA) using a solvent system of 50 mM sodium acetate with 50 \(\mu\)M EDTA (pH 3.8) and acetonitril (2.1, vol/vol) at a flow rate of 1.1 mL/min (49). Detection was performed electrochemically (\(\Delta V = 900\) mV) using a glassy carbon working electrode (Decade; Antec Leyden BV, Zoeterwoude, The Netherlands). The system was set at 40°C.

Statistical evaluation. The results are presented as mean ± SE. The difference between groups was evaluated with the unpaired, 2-tailed Student’s \(t\) test.

Results

Altered drug sensitivity in mice lacking Mrp1 on an Mdr1a/Mdr1b–null genetic background. We have previously shown that Mrp1 deficiency renders mice hypersensitive to etoposide or its water-soluble derivative, etoposide phosphate (Etopophos\(^{\circledR}\)) (14, 26). Because etoposide is also transported by Mdr1-type Pgps, we crossed Mrp1–/– mice with DKO Mdr1a–/–/Mdr1b–/– mice to obtain TKO Mrp1–/–/Mdr1a–/–/Mdr1b–/– mice. No differences in health, life span, or fertility were observed among TKO, DKO, Mrp1–/–, or wild-type mice in our animal facility. The TKO mice are more sensitive to etoposide than are DKO and Mrp1–/– mice; all 3 of those groups are more sensitive than are wild-type mice (Tables 1 and 2). Seven days after a single intravenous 60 mg/kg dose of Etopophos\(^{\circledR}\), female Mrp1–/– mice (\(n = 5\)) retained 92.3 ± 3.8% of their body weight (24.7 ± 1.1 g at day 0) and DKO mice (\(n = 5\)) retained 99.5 ± 1.1% of their body weight (27.8 ± 0.9 g at day 0), whereas female
TKO mice \((n = 5)\) retained \(74.1 \pm 2.6\% \) \((P < 0.01)\) of their body weight \((26.5 \pm 0.7\ \text{g at day 0})\) (Figure 1).

Except for their weight loss, the drug-treated TKO mice showed no clear gross abnormalities. Microscopic analysis at day 7 of TKO, DKO, and Mrp1–/– tissues from mice treated with 60 mg/kg Etopophos showed a disruption of the epithelial layer of the tongue and cheek only in the TKO mouse tissue (all TKO mice were thus affected). Inflammation of the tongue epithelium was detected in 4 out of 5 TKO animals (results not shown). The defects were similar to those observed in Mrp1-deficient mice after higher drug doses (26). Analysis of the colon of mice treated with 50–60 mg/kg Etopophos showed crypt degeneration (9 of 12 TKO mice; 3 of 11 DKO mice) and colitis (5 of 12 TKO mice; 1 of 11 DKO mice) (data not shown). The increase in gut damage to TKO mice suggests that Mrp1 contributes to the protection of the colon. Except for sporadic signs of inflammation in the stomach (in 3 of 5 mice), and a degeneration of the oocytes in the ovary (in 2 of 5 mice), an extensive histopathological examination revealed no further abnormalities in other tissues (data not shown) of the TKO mice.

We previously found that Mrp1-deficient mice, when treated with a dose of 100 mg Etopophos per kg body weight, developed diabetes insipidus, demonstrated by the overproduction of dilute urine (26). At close to the maximal drug dose tolerated by the TKO mice in metabolic cages (50 mg/kg), water intake, urine production (DKO, 1.7 ± 0.5 mL per 48 hours; TKO, 1.3 ± 0.3 mL per 48 hours), food consumption, and feces production did not differ between DKO and TKO mice. No differences were detected 7 days after drug administration in plasma sodium, urea, creatinine, or protein levels. The number of leukocytes was reduced in TKO mice (DKO, \([13.6 \pm 1.5] \times 10^9/L\); TKO, \([3.0 \pm 1.2] \times 10^9/L\); \(P < 0.01\)), whereas hemoglobin, hematocrit, and the number of thrombocytes did not differ between DKO mice and TKO mice (data not shown).

Altered drug tissue distribution in mice lacking Mrp1. Although Mrp1 is a ubiquitous protein present in several epithelia (26, 27, 29, 31), our previous etoposide tissue distribution experiments did not show a significant increase in the accumulation of etoposide in Mrp1-deficient tissues (14). This negative result could be explained by redundancy of etoposide transporters; obvious candidates for the redundant transporters are the Mdr1-type Pgps. To test whether Mrp1 can contribute to etoposide cellular clearing in vivo, we administered 1 mg/kg of radiolabeled etoposide intravenously to DKO mice and TKO mice, and determined the tissue distribution of total radioactivity 4 hours after injection. Table 3 shows that the etoposide plasma levels of DKO and TKO mice were comparable, indicating that Mrp1 does not significantly contribute to the renal, liver, or intestinal clearance of etoposide as was observed for Mdr1-type Pgps (19, 20). In the TKO mice, however, we observed increased etoposide accumulation in brown adipose (2.7-fold), colon (2.3-fold), urogenital tract (1.5-fold), salivary gland (1.4-fold), and heart (1.3-fold) tissues \((P < 0.05)\); no significant accumulation was detected in brain, liver, kidney, or...
other tissues. The observed altered distribution of etoposide in some tissues (with no differences in plasma levels) indicates that Mrp1 contributes to the protection against drugs of a limited set of tissues or cells. The absence of Mrp1 in the basolateral epithelia lining the lumina of some of these tissues (e.g., salivary gland, oviduct, or uterus) could lead to reduced active clearance of drugs from such epithelia to the interstitial fluid and toward the blood as proposed previously (26).

Mrp1 in salivary gland, uterus, oviduct, and CP. To correlate the altered drug distribution with Mrp1 protein location, we stained tissue sections from wild-type mice with the monoclonal antibody MRPr1 (27). As controls, we used mice lacking Mrp1, and isotype-matched control antibodies. We found Mrp1 in the intercalated ducts of the salivary gland, and in the oviduct and uterus (Figure 2, c, e, and g). Sections through the brain showed no staining for Mrp1 in the endothelium of the blood capillaries, but immunostaining was abundant in the epithelium of the CP (Figure 2a). In rat CP epithelium, staining for Mrp1 protein (31, 37) has been reported as well. Mrp1 protein levels were below the detection level in brown adipose tissue, colon, and heart (data not shown). The unexpected lack of immunostaining for Mrp1 in these tissues may be due to the homogeneous distribution of low levels of Mrp1. In previous experiments we showed that Mrp1 is present in heart (14) using Western blots. Using the MRPr1 monoclonal antibody, Peng et al. detected mouse Mrp1 in all colon cells lining the crypt-villus axis, mainly in their basolateral membranes (50). Immunostaining has shown MRPr1 to be present in the myocardium of the human heart as well as in the epithelium of the human colon (27).

Mrp1 in the CP limits the entry of drugs into the CSF. The presence of Mrp1 in the CP prompted us to test the possibility that Mrp1 contributes to the transport of drugs at the blood-CSF barrier. Mrp1 is known to route to the basolateral membranes in all epithelia analyzed (26, 32), including the rat CP epithelium (31). If Mrp1 contributes to the drug-permeability barrier between blood and CSF, we would anticipate that Mrp1 transports drugs specifically from the CP toward the blood. To test this hypothesis, we compared the accumulation of etoposide in the CSF of DKO mice and TKO mice. This allowed us to avoid the complicating contribution of Mdr1a Pgp, which is present in the brain capillaries (20) and is reported to be present in the apical membrane of the CP epithelium (31). We chose etoposide as a model substrate because it is clinically relevant and is the best (anti-cancer) drug substrate reported for Mrp1. We preferred to use etoposide as the substrate because the best substrates reported — e.g., the physiological substrate LTC4 and the test substance S-(2,4-dinitrophenyl)-glutathione — are hydrophilic and are unlikely to enter the CP epithelium. Cannulas were inserted into the left and right lateral brain ventricles adjacent to the CP, and artificial CSF was slowly perfused at a rate of 0.1 μL/min through the brain lateral ventricles. Etopophos® (60 mg/kg) was administered into a tail artery, and CSF was collected for a period of 1 hour. We found that the TKO mice accumulated 10-fold more etoposide in the CSF than did the DKO mice (P < 0.001), whereas levels in total brain and plasma did not differ 1 hour after drug administration (Figure 3, a and b). These results show the potential importance of Mrp1 at the blood-CSF barrier in determining drug levels in the CSF.

Discussion
Our results indicate that Mrp1 helps to prevent the accumulation of etoposide in vivo, especially in epithelial tissues lining lumina. For some tissues, this protection by Mrp1 is considerable — for example in the CP, as we show in this report. This is also the case in the oral epithelium, the Sertoli cells in the testicular tubules, the urinary collecting duct cells, and white blood cells, as shown previously (26). The protection is significant but small in brown adipose tissue, colon,
salivary gland, heart, and urogenital tract, as demonstrated by the lack of an observed altered drug distribution in the presence of Mdr1-type Pgps (14).

Most importantly, our experiments provide new information on the physiological function of Mrp1 in the CP. Rao et al. (31) recently showed that enriched membrane fractions of human, rat, and mouse CP contain Mrp1, and that the Mrp1 band on Western blots is missing in CP from Mrp1<sup>−/−</sup> mice. Staining with the anti-Mrp1 antibody was confined to epithelial cells, and mainly the basolateral part of the cells was stained. In cultured rat CP epithelial cells, most of the Mrp1 was present in a vesicular compartment (31). Inhibition of Mrp1 with the LTD<sub>4</sub>-receptor antagonist and the Mrp1 inhibitor MK-571 increased accumulation of Tc-sestamibi (an Mrp1 substrate) by 2-fold in these cells, but did not inhibit transport of Tc-sestamibi through the cell monolayer. Our experiments on the accumulation of etoposide in CSF of DKO mice and TKO mice show that mouse Mrp1 is present in the CP, and that the CP epithelium containing Mrp1 is a barrier for certain drugs coming from the blood into the CSF. These results provide new information on Mrp1 function, and demonstrate its potential as a target for drug development.

The increased accumulation of etoposide in brown adipose tissue of drug-treated TKO mice indicates a protective function for Mrp1. However, we could not detect Mrp1 protein in brown adipose tissue. The increased accumulation of etoposide after its intravenous administration may be caused by the drug-clearing activity of Mrp1 present at low levels. Tissue-level concentrations of drugs taken up by passive diffusion are determined by the partition ratio and the perfusion rate, however, and these may differ between TKO and DKO mice. Damage or disturbance of the normal function of brown adipose cells may disturb body temperature regulation and contribute to weight loss. The increased accumulation of etoposide in the female urogenital system may lead to a degeneration of oocytes, as was observed for some of the drug-treated TKO animals. The increased accumulation of etoposide in the salivary glands may result in abnormal function of this epithelium, such as an overproduction of mucus as has been reported (14).

In conclusion, these results indicate that at least 2 drug-transporter proteins (MDR1 Pgp and MRPI in humans) may affect the tissue distribution and pharmacokinetics of an anti-cancer drug such as etoposide.

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