Cannabinoid Type 1 Receptor Antagonists Modulate Transport Activity of Multidrug Resistance-Associated Proteins MRP1, MRP2, MRP3, and MRP4


Department of Pharmacology and Toxicology, Radboud University Nijmegen Medical Centre, Nijmegen Centre for Molecular Life Sciences, Nijmegen, The Netherlands (H.G.M.W., J.J.M.W.v.d.H., P.H.H.v.d.B., J.B.K., F.G.M.R.); and Abbott Products GmbH, Hannover, Germany (H.D.-H.)

Received December 15, 2010; accepted April 21, 2011

ABSTRACT:
Cannabinoid type 1 (CB1) receptor antagonists have been developed for the treatment of obesity, but a major disadvantage is that they cause unwanted psychiatric effects. Selective targeting of peripheral CB1 receptors might be an option to circumvent these side effects. Multidrug resistance-associated proteins (MRPs) can influence the pharmacokinetics of drugs and thereby affect their disposition in the body. In this study, we investigated the interaction of the prototypic CB1 receptor antagonist rimonabant and a series of 3,4-diarylpyrazolines CB1 receptor antagonists with MRP1, MRP2, MRP3, and MRP4 in vitro. Their effect on ATP-dependent transport of estradiol 17-β-d-glucuronide (E217βG) was measured in inside-out membrane vesicles isolated from transporter-overexpressing human embryonic kidney 293 cells. Rimonabant inhibited MRP1 transport activity more potently than MRP4 (Kᵢ of 1.4 and 4 μM, respectively), whereas the 3,4-diarylpyrazolines were stronger inhibitors of MRP4- than MRP1-mediated transport. A number of CB1 receptor antagonists, including rimonabant, stimulated MRP2 and MRP3 transport activity at low substrate concentrations but inhibited E217βG transport at high substrate concentrations. The interaction of 3,4-diarylpyrazolines and rimonabant with MRP1–4 indicates their potential for drug-drug interactions. Preliminary in vivo data suggested that for some 3,4-diarylpyrazolines the relatively lower brain efficacy may be related to their inhibitory potency against MRP4 activity. Furthermore, this study shows that the modulatory effects of the 3,4-diarylpyrazolines were influenced by their chemical properties and that small variations in structure can determine the affinity of these compounds for efflux transporters and thereby affect their pharmacokinetic behavior.

Introduction
The cannabinoid type 1 (CB1) receptor is involved in regulation of feeding behavior, metabolism and energy balance (Di Marzo, 2008). Studies in rodents have shown that antagonism of this receptor leads to reduced food intake and weight reduction (Boyd and Fremming, 2005). Several CB1 receptor antagonists were developed for the treatment of obesity, and clinical studies showed a reduction in appetite, weight loss, and improved metabolic risk factors (Boyd and Fremming, 2005; Bifulco et al., 2009). Rimonabant was the first and only selective CB1 receptor antagonist approved for therapeutic use. However, the drug was withdrawn from the market within 2 years of its introduction, because psychiatric adverse effects, in particular depression, were revealed in additional clinical studies (Jones, 2008; Nissen et al., 2008).

The CB1 receptor is expressed in brain and peripheral tissues such as adipose, skeletal muscle, liver, gut, and pancreas (Di Marzo, 2008).

In the brain, activation of the endocannabinoid system appears to be involved in coping with stress and anxiety. Therefore, the psychiatric side effects seen for CB1 receptor antagonists could be due to inhibition of the endocannabinoid system (Bifulco et al., 2009). It is believed that the positive effect of antagonists on metabolic factors could also be mediated via peripheral CB1 receptors (Di Marzo, 2008). Indeed, a recent study with a peripheral CB1 receptor antagonist in obese mice showed that this antagonist could improve the cardiometabolic risk in these mice without inhibition of the central CB1 receptor (Tam et al., 2010). Therefore, peripheral CB1 receptor antagonists might have therapeutic potential for improving metabolic risk in obese patients without causing psychiatric side effects.

Multidrug resistance-associated proteins (MRPs) are efflux transporters that can influence drug disposition by transporting a wide variety of substrates out of the cell (Zhou et al., 2008), preventing drugs from entering specific tissues or organs (e.g., intestine and brain), or increasing elimination of compounds, e.g., via liver and kidney (Yu et al., 2007). MRP1, MRP2, MRP3, and MRP4 belong to the ATP-binding cassette (ABC) transporter subfamily C and have
overlapping substrate specificities (Kruh and Belinsky, 2003). MRP1 is present in many tissues, with the highest protein expression in lung, adrenal gland, heart, and skeletal muscle, and lower amounts in brain, choroid plexus, spleen, kidney, intestine, testes, placenta, and liver (Flens et al., 1996; Rao et al., 1999; Nies et al., 2004; Leslie et al., 2005). It is expressed basolaterally in most tissues, but it has an apical localization in brain capillary endothelial cells (Nies et al., 2004; Leslie et al., 2005). MRP2 is highly expressed in liver, and lower expression levels can be found in the apical membranes of kidney tubules, gastrointestinal tract, gallbladder, placenta, and bronchi (van Aubel et al., 2000; Nies and Keppler, 2007). MRP3 is expressed in kidney, colon, small intestine, liver, and gallbladder, where it is found mostly in basolateral membranes (Scheffer et al., 2002). MRP4 is widely distributed in tissues and blood cells and has a dual membrane localization, which is basolateral in prostate tubuloacinar cells, hepatocytes, and choroid plexus, and apical in kidney proximal tubule cells and brain capillary endothelium (Nies et al., 2004; Russel et al., 2008). The expression of MRP1–4 at locations that are involved in drug disposition and penetration suggests that they influence drug concentrations in plasma and different organs, and because of their presence in the blood-brain-barrier and choroid plexus, MRP4 and MRP1 might play a role in restricting CB1 receptor antagonists from the brain.

Interaction of a drug with efflux transporters not only can influence its own pharmacokinetics, but it also can change the disposition of other compounds that are substrates for the same transporter. Studies describing the interaction of CB1 receptor antagonists with MRP1–4 may give information not only on the pharmacokinetics of these antagonists but also on possible drug-drug interactions. Here, we investigated the in vitro effect of a series of 3,4-diarylpyrazoline CB1 receptor antagonists (Fig. 1) (Lange et al., 2005) and the prototypic CB1 receptor antagonist rimonabant on MRP1–4 transport activity. In addition, for some 3,4-diarylpyrazolines, we related their transporter interaction to preliminary in vivo pharmacodynamic effects measured in rats.

Materials and Methods

Materials. [6,7-3H(N)]Estradiol 17-β-D-glucuronide (41.8 Ci/mmol) was purchased from PerkinElmer Life and Analytical Sciences (Groningen, The Netherlands). Bac-to-Bac and Gateway systems, Dulbecco’s modified Eagle’s medium + GlutaMAX-I culture medium, and fetal calf serum were purchased from Invitrogen (Breda, The Netherlands). Triplicate flask (500 cm²) were purchased from Sanbio BV Biological Products (Uden, The Netherlands). Estradiol 17-β-D-glucuronide (E₂17βG), adenosine 5’-triphosphate magnesium salt (from bacterial source), and adenosine 5’-monophosphate monohydrate (from yeast) were purchased from Sigma-Aldrich (Zwijndrecht, The Netherlands). Protein concentrations were determined with a Bio-Rad protein assay kit from Bio-Rad Laboratories (Veenendaal, The Netherlands). Monoclonal mouse-anti-human MRP3 antibody MIII-21 was purchased from Abcam (Cambridge, UK). Monoclonal mouse-anti-human MRP1 (QCRL-1) was kindly provided by Dr. S. P. C. Cole (Queen’s University Cancer Research Institute, Kingston, ON, Canada). 3,4-Diarylpyrazoline CB1 receptor antagonists (Lange et al., 2005) and rimonabant were kindly provided by Abbott Healthcare Products (Hannover, Germany).

Generation of Baculovirus. Full-length human MRP1, MRP2, and MRP3 were cloned separately into the Gateway pDONR221 vector. The sequence of MRP1 was equal to GenBank accession number NM_004996 except for three silent mutations at base pairs 1684, 1704, and 4002, which are known polymorphisms (Conrad et al., 2001). The sequence of MRP2 was equal to...
NM_003932 except for three silent mutations at base pairs 264, 1167, and 3972, of which C3972T is a known polymorphism (Ito et al., 2001), and the sequence of MRP3 was equal to NM_003786. Consequently, constructs were also cloned into a VSV-G improved pFastBacDual vector for mammalian cell transduction using the Gateway system (El-Sheikh et al., 2007). Full-length human MRP4 and enhanced yellow fluorescent protein (eYFP), which was used as a negative control, were cloned previously (El-Sheikh et al., 2007). Baculoviruses were produced as described in the Bac-to-Bac manual (Invitrogen).

Cell Culture and Transduction of HEK293 Cells. HEK293 cells were grown in Dulbecco’s modified Eagle’s medium-Glutamax-I supplemented with 10% fetal calf serum at 37°C under 5% CO₂–humidified air. HEK293 cells were cultured in 500 cm² triple flasks until 40% confluent, after which culture medium was removed and 25 ml of medium and 10 ml of eYFP, MRP1, MRP2, MRP3, or MRP4 baculovirus was added. Cells were incubated for 15 min at 37°C, after which a further 40 ml of medium was added, and 5 mM sodium butyrate was added 24 h after transduction. Three days after transduction, cells were harvested by centrifugation at 5000 g for 5 min.

Isolation of Membrane Vesicles and Protein Analysis. Membranes were isolated according to a previously described method with slight modifications (El-Sheikh et al., 2008). In brief, harvested cell pellets were resuspended in ice-cold homogenization buffer (0.5 mM sodium phosphate and 0.1 mM EDTA) supplemented with protease inhibitors (100 µM phenylmethylsulfonyl fluoride, 5 µg/ml aprotinin, 5 µg/ml leupeptin, 1 µg/ml pepstatin, and 1 µM N-(trans-epoxysoyuccinyl)-1-leucine 4-guanidinobutyramide (E-64) and shaken at 4°C for 30 min. Lysed cells were centrifuged at 100,000 g for 30 min at 4°C, and the pellets were homogenized in ice-cold TS buffer (10 mM Tris-HEPES and 250 mM sucrose, pH 7.4) supplemented with protease inhibitors described above, using a tight-fitting Dounce homogenizer for 25 strokes. After centrifugation at 1000g for 20 min at 4°C, the supernatant was centrifuged at 100,000g for 60 min at 4°C. The resulting pellet was resuspended in TS buffer without protease inhibitors and passed through a 27-gauge needle 25 times. Protein concentration was determined by a Bio-Rad protein assay kit. Crude membrane vesicles were dispersed in aliquots, frozen in liquid nitrogen, and stored at −80°C until further use.

Western Blotting. Membrane vesicle preparations were solubilized in SDS-polyacrylamide gel electrophoresis sample buffer and separated on SDS gel containing 7.5% acrylamide according to Laemmli. Then, they were blotted onto nitrocellulose membrane using the BioDoc dry blotting system (Invitrogen). Monoclonal mouse-anti-human MRP1 (QCRL-1, 1:700) and MRP3 (M3H-21, 1:200) antibodies and affinity-purified, polyclonal rabbit-anti-human MRP2 (polyclonal antibody hM2-p2, 1:500) and MRP4 (polyclonal antibody hM4-p4, 1:1000) (van Aubel et al., 2002; Smeets et al., 2004) were used to detect transporters. The secondary antibodies used in 1:10,000 dilution were fluorescent goat-anti-mouse 1Rdye800 (Rockland Immunociences, Gilbertville, PA) and goat-anti-rabbit Alexa Fluor 680 (Invitrogen). Signals were visualized using the Odyssey imaging system (Li-Cor Biosciences, Lincoln, NE).

Vesicular Transport Assays. Uptake of [3H]E217G into membrane vesicles was performed using a rapid filtration technique (van Aubel et al., 1999). The 30-µl reaction mix consisted of TS buffer, 4 mM ATP, 10 mM MgCl₂, E₂₁₇G, and 7.5 µM of membrane vesicles; 0.1 (MRP1), 0.15 (MRP2, MRP4), and 0.2 µCi (MRP3) of [3H]E₂₁₇G was used, supplemented with unlabeled E₂₁₇G to concentrations indicated in legends. The reaction was started when the mixture was incubated at 37°C and then stopped by placing samples on ice and adding 150 µl of ice-cold TS buffer. A MultiScreen_HTS-HV, 0.45-µm, polyvinylidene difluoride 96-well filter plate was prewashed with TS buffer, using a tight-fitting Dounce homogenizer for 25 strokes. After centrifugation at 250 mM sucrose, pH 7.4) supplemented with protease inhibitors described above, and the pellets were homogenized in ice-cold TS buffer (10 mM Tris-HEPES and 250 mM sucrose, pH 7.4) supplemented with protease inhibitors described above, using a tight-fitting Dounce homogenizer for 25 strokes. After centrifugation at 1000g for 20 min at 4°C, the supernatant was centrifuged at 100,000g for 60 min at 4°C. The resulting pellet was resuspended in TS buffer without protease inhibitors and passed through a 27-gauge needle 25 times. Protein concentration was determined by a Bio-Rad protein assay kit. Crude membrane vesicles were dispersed in aliquots, frozen in liquid nitrogen, and stored at −80°C until further use.

Vesicular Interaction Assays. To evaluate the inhibitory effects of 3,4-diarylpyrazolines and rimonabant on [3H]E₂₁₇G uptake in MRP1, 2, 3, and 4 inside-out membrane vesicles, the above-mentioned transport assay was performed in the absence or presence of 10 and 100 µM CB1 receptor antagonists. The concentration-dependent effect of 1 to 100 µM concentrations of compounds 13, 15, and rimonabant was measured at three different E₂₁₇G concentrations: 0.16, 1, and 5 µM for MRP1; 2, 20, and 200 µM for MRP2; 0.08, 1, and 5 µM for MRP3; and 0.1, 0.3, and 1 µM for MRP4. ATP-dependent transport was calculated.

Determination of Actual Concentrations of 3,4-Diarylpyrazolines and Rimonabant with LC-MS/MS. The actual amount of CB1 receptor antagonists dissolved under vesicular transport assay conditions was measured. eYFP vesicles (7.5 µg) were added in each well to mimic the vesicle environment. The reaction mixture without [3H]E₂₁₇G was added on ice and only the AMP condition was measured. The 96-well plate was mixed, and the total reaction mixture from one well was transferred to an Eppendorf tube at room temperature. Sample was spun down at maximal speed (16,000–20,000 g) for 5 min at room temperature and 10 µl of supernatant was reconstituted in 50% acetonitrile-water and 0.1% trifluoroacetic acid (TFA) before LC-MS/MS analysis. Actual concentrations were determined using an Accela ultrahigh-performance liquid chromatograph (Thermo Fisher Scientific, Waltham, MA) coupled to a TSQ Vantage (Thermo Fisher Scientific) triple quadrupole mass spectrometer. The CB1 receptor antagonists were separated on a Zorbax Eclipse Plus column (50 x 2.1 mm, 1.8-µm particle size; Agilent Technologies, Santa Clara, CA). The elution gradient was as follows: 0 min, 50% B; 5 min, 90% B; and 6 min, 50% B. Solvent A consisted of 0.1% TFA in ultrapure water, and solvent B consisted of 0.1% TFA in acetonitrile. The column temperature was set at 40°C, and the flow rate was 200 µl/min. The effluent from the high-performance liquid chromatograph was passed directly into the electrospray ion source. Positive electrospray ionization was achieved using a nitrogen sheath gas with ionization voltage at 4 kV. The capillary temperature was set at 350°C. Detection of each analyte was based on isolation of the protonated molecular ion, [M + H]+, and subsequent MS/MS fragments and selected reaction monitoring were performed. The conditions per compound are summarized in Table 1. CB1 receptor antagonist 4 or 16 was used as an internal standard, and the response ratio of test compound to internal standard was used to determine the concentration. The actual assay concentration of compound was measured in duplicate in at least three independent experiments.

In Vivo Pharmacodynamic Effect of 3,4-Diarylpyrazolines on CP55,940-Induced Hypotension in Rat. The ED₅₀ of 3,4-diarylpyrazolines for attenuation of 5-(1,1-dimethylheptyl)-2-[5-hydroxy-2-(3-hydroxypropyl)cyclohexyl] phenol (CP55,940)-induced hypotension in male, normotensive, anesthetized Wistar rats was determined according to a method described previously using different intravenous doses (n = 2 per dose) of CB1 receptor antagonists 10 min before CP55,940 (0.1 mg/kg i.v.) administration (Lange et al., 2004). Hypotension was achieved within 1 min after administration of the CB1 receptor agonist CP55,940, and the lowest blood pressure was the measure of the hypotensive effect. ED₅₀ was calculated on the linear part of the percentage dose-response curve and is the dose of antagonist that inhibited the hypotensive effect of CP55,940 by 50%. Experiments were performed in 16 animals per group (8 per sex) and the data were analyzed using a two-way ANOVA. The dose-response curve was divided into three dose groups of 0, 0.08, 1, and 5 µM for MRP1; 2, 20, and 200 µM for MRP2; 0.08, 1, and 5 µM for MRP3; and 0.1, 0.3, and 1 µM for MRP4. ATP-dependent transport was calculated.
were approved by the local ethics committee on animal experimentation at Solvay Pharmaceuticals (Weesp, The Netherlands).

Kinetic Analysis. All data are expressed as means ± S.E.M. Curve-fitting of the resulting concentration-dependent transport curves and determination of IC50 values for the CB1 receptor antagonists was performed by nonlinear regression analysis using GraphPad Prism software (version 5.02; GraphPad Software Inc., San Diego, CA). The following equation was fitted to the data: \( y = \text{bottom} + \left( \frac{\text{top} - \text{bottom}}{1 + 10^{(\log IC50 - x)} / \text{Hill slope}} \right) \), in which \( x \) is the log inhibitor concentration and \( y \) is expressed as uptake versus control (percentage). A Michaelis-Menten fit was used for MRP1, MRP3, and MRP4 E17βG curves, and an allosteric sigmoidal fit was used for MRP2. Log (inhibitor or stimulator) versus response with variable slope was used to plot the inhibition and stimulation curves with 13, 15, or rimonabant. Results of the inhibition assay for interaction of MRP1/4 with 13 and rimonabant were analyzed using Dixon’s method combined with linear regression analysis to estimate the inhibitory constant (Kᵢ). Statistical differences were determined using one-way analysis of variance with Dunnett’s multiple comparison test in GraphPad Prism. Differences were considered to be significant at \( p < 0.05 \).

Results
Expression of MRP1, MRP2, MRP3, and MRP4 in Isolated Membrane Vesicles. Immunoblot analysis performed on membrane vesicles from HEK293 cells overexpressing MRP1, MRP2, MRP3, and MRP4 demonstrated that all four transporters were successfully expressed (data not shown). MRP1 seemed to be less glycosylated as indicated by a band at \( \approx 160 \) kDa, but this had no influence on its transport activity (Fig. 2A). The negative control, consisting of membrane vesicles from eYFP-overexpressing HEK293 cells, showed no expression of MRP1–4.

Concentration-Dependent Transport of E17βG into MRP1-, MRP2-, MRP3-, and MRP4-Overexpressing Membrane Vesicles. Concentration-dependent uptake of E17βG into membrane vesicles was measured after 5 min for all transporters, and typical curves are shown in Fig. 2. A to D. ATP-dependent E17βG transport reached maximal activities (Vmax) of 31 ± 1, 2220 ± 100, and 94 ± 5 pmol·mg⁻¹·min⁻¹ for MRP1, MRP3, and MRP4, respectively. The affinity of E17βG (Km) for MRP1, MRP3, and MRP4 was 7.5 ± 0.1, 56 ± 6, and 15 ± 3 μM, respectively. Repetition of the experiment for each transporter gave comparable kinetic parameters; only the Vmax of MRP3 varied between different batches of membrane vesicles, because of different expression levels of the transporter. Transport activity of MRP2 followed a sigmoidal relationship with increased E17βG concentration (Fig. 2B). A Hill slope of 1.6 ± 0.03 was calculated for MRP2 activity, which is indicative of positive cooperativity.

Effects of 3,4-Diarylpyrazolines and Rimonabant on MRP1-, MRP2-, MRP3-, and MRP4-Mediated E17βG Transport. Based on the kinetics of E17βG uptake by MRP1–4, the following E17βG concentrations, well below the Kᵢ, were chosen for interaction studies with 3,4-diarylpyrazolines and rimonabant (Fig. 1): 0.16 μM for MRP1, 20 μM for MRP2, 0.08 μM for MRP3, and 0.12 μM for MRP4. In the case of MRP2, 20 μM substrate was used to measure both stimulation and inhibition.

Figure 3 shows the effect of 10 and 100 μM concentrations of the CB1 receptor antagonists on E17βG transport by MRP1–4. Because of poor solubility, the actual concentrations of the 3,4-diarylpyrazolines and rimonabant were 3- to 100-fold lower than the predicted concentrations (see legend to Fig. 3). The highest concentration of the series of 3,4-diarylpyrazolines inhibited MRP4 transport activity (Fig. 3D) more potently than MRP1 activity (Fig. 3A). Of the 3,4-diarylpyrazolines, compounds 4 and 12 to 14 significantly inhibited MRP1- and MRP4-mediated E17βG transport. Compound 13 had the highest inhibitory effect on both transporters, with −34 ± 13 and −72 ± 8% for MRP1 and MRP4, respectively. Transport of E17βG by MRP1 and MRP4 was not inhibited by compounds 15 to 17 and 23, whereas compound 11 did inhibit MRP4, but not MRP1. Rimonabant inhibited MRP1 more potently than MRP4, viz. −84 ± 4 versus −58 ± 3% (Fig. 3, A and D). In contrast to MRP1 and MRP4, MRP2 transport activity was stimulated by most compounds at both concentrations tested (Fig. 3B). At the lower concentration, compounds 15 to 17 significantly increased uptake of E17βG into MRP2 vesicles (256–305%). Stimulation of MRP2 was strongest at the high concentration of compounds 4 to 14 (543–734%) and less by compounds 15 to 17 (349–412%) and rimonabant (513%).
Compound 23 did not significantly increase transport. Figure 3C shows that, although E17βG itself inhibited transport, MRP3-mediated E17βG transport was significantly stimulated by rimonabant and most 3,4-diarylpyrazolines, of which compounds 11 and 13 had the highest stimulatory effect (155%).

Mechanism of Modulation of MRP1–4 Transport by Compounds 13, 15, and Rimonabant. To get a better understanding of the mechanism of interaction, we measured concentration-dependent effects of certain CB1 receptor antagonists on MRP1–4 transport at three different E17βG concentrations for each transporter (Fig. 4). 3,4-Diarylpyrazoline derivatives 13 and 15 and rimonabant were selected for further investigation because the magnitude of their effects on the transport activity were different.

Increasing E17βG concentrations did not decrease the potency of 3,4-diarylpyrazolines 13 and 15 and rimonabant for inhibiting MRP1 and MRP4 (Fig. 4, A–C and J–L); the percentage of inhibition and the IC50 values of 13 and rimonabant for MRP4 and MRP1 were similar at different E17βG concentrations. Dixon plots for 13- and rimonabant-mediated inhibition of MRP4 and MRP1 show that the lines intersected virtually at the x-axis for both compounds, which is indicative of noncompetitive inhibition (Fig. 5, A–C). The intersections corresponded to a KI of ~1.4 μM rimonabant for MRP1, ~4
Rimonabant for MRP4, and compound 13 for MRP4. 3,4-Diarylpyrazoline 15 did not inhibit MRP1 transport activity at any of the concentrations tested and only moderately inhibited MRP4 (Fig. 4, A–C and J–L).

MRP2-mediated transport was stimulated by compounds 13, 15, and rimonabant at the lowest E$_217$G concentration of 2 $\mu$M (Fig. 4D). Stimulation was decreased at 20 $\mu$M E$_217$G, and transport was inhibited at 200 $\mu$M E$_217$G (Fig. 4, D–F). Rimonabant and compound 15 appeared to have the same stimulatory and inhibitory potency on MRP2-mediated transport.

MRP3-mediated E$_217$G transport was stimulated at a low substrate concentration, which gradually disappeared at higher substrate concentrations (Fig. 4, G–I). At a concentration of 15 $\mu$M E$_217$G, high concentrations of compounds 13 and 15 and rimonabant inhibited E$_217$G transport via MRP3 (data not shown).

In Vivo Pharmacodynamic Effect of 3,4-Diarylpyrazolines on CP55,940-Induced Hypotension in Rat. To get an impression of the relative brain penetration of the 3,4-diarylpyrazolines, the CB1 receptor-mediated blood pressure effect of compounds 4, 11, 14, and 15 was compared with their in vitro CB1 receptor binding affinity. For this purpose, in rats, we measured the initial rapid effect of CB1 receptor antagonists on CP55,940-induced hypotension, which is considered to originate primarily from a central sympathetic response (Vollmer et al., 1974). Table 2 describes the effective intravenous dose (ED$_{50}$) that was needed for 50% inhibition of the hypotensive effect of CP55,940 and the binding affinity (expressed as $K_i$) of these compounds for the CB1 receptor, as determined previously (Lange et al., 2005). The in vivo data show that CB1 receptor antagonist 15 had the lowest ED$_{50}$ value. If the ED$_{50}$ of 15 relative to its binding affinity is extrapolated to compounds 4, 11, and 14 on basis of their $K_i$ values for

---

**FIG. 4.** Effect of CB1 receptor antagonists 13 (○), 15 (▲), -- -- --, and rimonabant (●) on MRP-mediated E$_217$G transport at different substrate concentrations. E$_217$G concentrations were 0.16 (A), 1 (B), and 5 $\mu$M (C) for MRP1; 2 (D), 20 (E), and 200 $\mu$M (F) for MRP2; 0.08 (G), 1 (H), and 5 $\mu$M (I) for MRP3, and 0.1 (J), 0.3 (K), and 1 $\mu$M (L) for MRP4. ATP-dependent transport was determined after 5 min for MRP1, MRP2, and MRP4 and after 2 min for MRP3. Transport rates are expressed as a percentage of uptake measured in the absence of the CB1 receptor antagonist tested against the log drug concentration. Two to three independent experiments were performed in duplicate. The mean ± S.E.M. of $n$ = 3 to 6 is shown.
in the literature (Loe et al., 1996; Zeng et al., 2000; Chen et al., 2001).

MRP1 and 0.1 represent the mean 1/V regression analysis was used for plotting lines and determination of efflux transporters MRP1, MRP2, MRP3, and MRP4. E217 higher than expected, indicating a lower brain permeability compared to compounds 4, 11, and 14 (Table 2) were respectively, would have been expected. However, the actual ED50 values of compounds 4, 11, and 14 (Table 2) were 2, ~10, and ~4.7 times higher than expected, indicating a lower brain permeability compared with that for compound 15.

Discussion

This study shows that CB1 receptor antagonists interacted with the efflux transporters MRP1, MRP2, MRP3, and MRP4. E217βG was used as a model substrate to investigate the effect of CB1 receptor antagonists on transport activity of these transporters. The kinetic parameters for E217βG found in this study were comparable to those in the literature (Loe et al., 1996; Zeng et al., 2000; Chen et al., 2001). Unlike MRP1, MRP3, and MRP4, MRP2 transported E217βG in a positive cooperative manner, which was previously demonstrated by others (Bodo et al., 2003a; Zelcer et al., 2003).

Actual tested concentrations of the very lipophilic CB1 receptor antagonists in the experimental assays were determined by LC-MS/MS and were 3- to 100-fold lower than expected. This result may be due to incomplete dissolution or nonspecific binding. In our study, compounds 15 to 17 stimulated MRP2 better than compounds 4 to 14 at low concentrations. In contrast, the opposite was found at higher concentrations, at which the actual concentrations of compounds 15 to 17 were lower (1–3 μM) than those of 4 to 14 (7–33 μM) (Fig. 3). This result indicates that compounds 15 to 17, which contain N-substituents that make them more lipophilic, have a higher potency in affecting MRP2 but have a limited effect because of their low solubility. The same was found for MRP3, and the lack of effect of compounds 15 to 23 on MRP1 and MRP4 might also be explained by their low actual concentrations.

Although we used E217βG as a substrate for all transporters, the effect of the CB1 receptor antagonists on transport of this substrate via MRP1–4 was different. MRP1- and MRP4-mediated transport was inhibited by several CB1 receptor antagonists. The inhibitory affinity of rimonabant was somewhat higher for MRP1-mediated E217βG transport than for MRP4-mediated transport, with a KI of ~1.4 μM versus ~4 μM. The maximal plasma concentration found in male human subjects treated with a therapeutic dose of rimonabant is 0.4 μM (Turpault et al., 2006). Rimonabant and 3,4-diarylpyrazoline 13 appeared to inhibit MRP1 and MRP4 in a noncompetitive manner (Fig. 5, A–C). In addition, MRP1 and MRP4 were stimulated at low substrate and rimonabant concentrations, indicating that rimonabant probably does not compete for the E217βG binding site of either transporter (Fig. 4, A and J). Whether rimonabant and the 3,4-diarylpyrazolines are only inhibitors or are also substrates of MRP1 or MRP4 cannot be concluded from this study.

In contrast to MRP1 and MRP4, MRP2-mediated transport was stimulated by all CB1 receptor antagonists, except for compound 23. The results presented in this study suggest that 3,4-diarylpyrazolines and rimonabant stimulate MRP2 allosterically at low E217βG concentrations and compete for the E17βG binding site at high concentrations. This type of interaction is supported by other studies (Bakos et al., 2000; Evers et al., 2000; Zelcer et al., 2003). The study of Zelcer et al. (2003) showed that several aromatic compounds, most of them containing sulfone or tosyl groups, stimulate MRP2-mediated transport of E217βG into membrane vesicles. Compounds that normalized the stimulated transport rates at increasing concentrations, such as sulfinpyrazone and indomethacin, also appeared to be substrates for MRP2 (Evers et al., 2000; Zelcer et al., 2003). 3,4-Diarylpyrazolines chemically resemble sulfinpyrazone, which, together with the fact that compounds 13 and 15 and rimonabant might compete with E217βG at higher substrate concentrations, could indicate that they are substrates for MRP2.

The CB1 receptor antagonists had comparable effects on MRP3 transport activity, but their effects were less pronounced than those for MRP2 (Fig. 4, G–I). Other studies reported that MRP3-mediated E217βG transport activity can be inhibited as well as stimulated by different compounds, e.g., 6-hydroxy-5,7-dimethyl-2-methylamino-4-(3-pyridylmethyl) benzothiazole (E3040) sulfate, indomethacin, and benzbromaron (Akita et al., 2002; Bodó et al., 2003a,b). This result indicates that the 3,4-diarylpyrazolines and rimonabant would interact with the CB1 receptor, ED50 values of 0.14, 0.02, and 0.15 mg/kg, respectively, would have been expected. However, the actual ED50 values of compounds 4, 11, and 14 (Table 2) were 2, ~10, and ~4.7 times higher than expected, indicating a lower brain permeability compared with that for compound 15.

**TABLE 2**

<table>
<thead>
<tr>
<th>Compound</th>
<th>CB1α (K0.5)</th>
<th>ED50</th>
<th>mg/kg i.v.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>223 ± 103</td>
<td>&gt;0.3</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>30 ± 14</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>231 ± 66</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>155 ± 69</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

a CB1α, displacement of specific CP55,940 binding in CHO cells stably transfected with human CB1 receptor, expressed as K0.5 ± S.E.M. Data were adapted from Lange et al. (2005).

b Dose of CB1 receptor antagonist that attenuates CP55,940-induced hypotension in rats (n = 2/dose) by 50%.
with a modulating site and the substrate site of MRP3, causing stimulation of E217βG transport at low substrate concentrations and inhibition at higher substrate concentrations because of competition for the substrate site.

Our results show that rimonabant and 3,4-diarylpyrazolines can modulate MRP1–4 transport activity, which implies the possibility of drug-drug interactions. Because of the brief clinical use of rimonabant, few data are available on its in vivo interaction potential with drug transporters. Rimonabant was found to moderately affect the pharmacokinetics of the P-glycoprotein (ABCB1) substrate cyclosporine, but not of tacrolimus and digoxin (Kanamaduru et al., 2005; Amundsen et al., 2009).

The pharmacokinetic data available for rimonabant do not suggest an important role for the MRPs in determining its disposition. Rimonabant is shown to accumulate in fat tissue, spleen, thyroid, thymus, liver, plasma, and brain and is reported to cross the placental barrier (Barna et al., 2009) (European Medicines Agency-European Public Assessment Reports scientific discussion about rimonabant, http://www.ema.europa.eu/docs/en_GB/document_library/EPAR_-_Scientific_Discussion/human/000666/WC500021284.pdf). Although rimonabant showed a strong interaction with MRP1, its accumulation in the brain and passage across the placental barrier indicates that it is either a poor substrate of this transporter, or MRP1 is not efficacious enough as a barrier for rimonabant.

MRP1 and MRP4 are expressed at the blood-brain-barrier and the choroid plexus, where these transporters could be involved in limiting the brain penetration of the 3,4-diarylpyrazoline CB1 receptor antagonists. Because there are only minor differences in the structures of the 3,4-diarylpyrazolines, the rate and extent of passive diffusion of these compounds into the brain and other tissues is expected to be similar, which should reflect in a similar relationship between ED50 values. The rate and extent of passive diffusion of the lipophilic 3,4-diarylpyrazolines, in vivo studies should be performed to determine the affinity for the efflux transporters and thereby possibly affect their pharmacokinetic behavior.

Acknowledgments

We thank Tiny J. P. Adolfs from Abbott Healthcare Products B.V. (formerly Solvay Pharmaceuticals) for providing the in vivo pharmacology data. We also thank Dr. Kevin Weigl (Abbott Products GmbH) for critical reading of the manuscript.

Authorship Contributions

Participated in research design: Wittgen, Dinter-Heidorn, Koenderink, and Russel.

Conducted experiments: Wittgen and van den Heuvel.

Contributed new reagents or analytic tools: van den Broek and Dinter-Heidorn.

Performed data analysis: Wittgen and van den Heuvel.

Wrote or contributed to the writing of the manuscript: Wittgen, Koenderink, and Russel.

References


Wittgen ET Al.