Interaction of Macrolide Antibiotics with Intestinally Expressed Human and Rat Organic Anion-Transporting Polypeptides^S

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ABSTRACT:

The macrolide antibiotics azithromycin and clarithromycin are large molecular weight compounds that exhibit moderate to excellent oral bioavailability in preclinical species and humans. Previous concomitant dosing studies in rats using rifamycin SV, a general organic anion-transporting polypeptide (OATP) inhibitor, suggested that the high oral absorption of azithromycin and clarithromycin may be caused by facilitative uptake by intestinal Oatps. In this study, we used OATP/Oatp-expressing cells to investigate the interaction of macrolides with rat Oatp1a5, human OATP1A2, and human/rat OATP2B1/Oatp2b1. These experiments showed that azithromycin and clarithromycin were potent inhibitors of rat Oatp1a5-mediated taurocholate uptake with apparent inhibitor constant (K_i) values of 3.3 and 2.4 μ M, respectively. The macrolides

functioned as noncompetitive inhibitors but were not transport substrates for rat Oatp1a5, as assessed by direct uptake measurements of radiolabeled azithromycin and clarithromycin. *cis*-Inhibition and direct uptake studies further showed that azithromycin and clarithromycin were only very weak inhibitors and not substrates for human OATP1A2 and human/rat OATP2B1/Oatp2b1. In summary, these results indicate that the macrolides azithromycin and clarithromycin potentially inhibit rat Oatp1a5 but do not significantly interact with OATP1A2 and OATP2B1/Oatp2b1. These intestinally expressed OATP/Oatp(s) are not responsible for the postulated facilitative uptake of azithromycin and clarithromycin, and alternative facilitative pathways must exist for their intestinal absorption.

Macrolide antibiotics such as erythromycin, clarithromycin, and azithromycin can alter drug metabolism by several mechanisms that include inhibiting CYP3A4 (Ito et al., 2003; Polasek and Miners, 2006) and P-glycoprotein (Kim et al., 1999; Marzolini et al., 2004) in the intestine and liver. Another potential mechanism is through direct interactions with members of the organic anion-transporting polypeptide (OATP/*SLCO*) family of transporters. The OATPs comprise a superfamily of sodium-independent transporters that facilitate transport of endogenous compounds and structurally diverse xenobiotics (Kim, 2003; Hagenbuch and Meier, 2004). The OATP/*SLCO* family includes 11 human and 15 rodent genes, which are widely expressed in many tissues, including those responsible for mediating the absorption, distribution, metabolism, and excretion properties of drugs such as the liver, kidney, blood-brain barrier, and intestine (Hagenbuch and Gui, 2008). A variety of drugs are transported by members of the

OATP/*SLCO* family, including statins (cerivastatin, fluvastatin, pitavastatin, pravastatin, rosuvastatin), benzylpenicillin, digoxin, fexofenadine, methotrexate, and rifampicin (Hagenbuch and Meier, 2003; König et al., 2006). In addition, certain drugs and nutritional supplements, although not OATP substrates themselves, can act as inhibitors of OATP-mediated transport, thereby increasing the potential for significant drug-drug or drug-nutrient interactions (Fuchikami et al., 2006; König et al., 2006; Poirier et al., 2007). These safety concerns are underscored by the recent identification of common variants of *SLCO1B1* that are strongly associated with an increased risk of statin-induced myopathy (Link et al., 2008).

Previous studies have shown a significant role for the hepatic OATPs, OATP1B1 and OATP1B3, in drug metabolism (Smith et al., 2005; Ho et al., 2006; Ishiguro et al., 2006; Seithel et al., 2007). Competition for OATP-mediated intestinal absorption may influence drug disposition and represents a potential mechanism for significant drug interactions. Among the OATP/*SLCO* family members expressed in small intestine, efforts have concentrated on human OATP1A2 (OATP-A; gene symbol *SLCO1A2*) and OATP2B1 (OATP-B; gene symbol *SLCO2B1*), as well as rat Oatp1a5 (Oatp3; gene symbol *Slco1a5*) (Kobayashi et al., 2003; Kikuchi et al., 2006; Glaeser et al., 2007; Tani et al., 2008). Although first identified in liver, *SLCO1A2* mRNA is expressed at higher levels in brain, kidney,

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ABBREVIATIONS: OATP (human) or Oatp (rodent), organic anion-transporting polypeptide; AUC, area under the blood-concentration time curve; MDCK, Madin-Darby canine kidney; BSP, bromosulphophthalein; PBS, phosphate-buffered saline; DMEM, Dulbecco's modified Eagle's medium; CI, confidence interval.

testis, and intestine. Furthermore, OATP1A2 protein is expressed at the apical brush-border membrane of human small intestinal epithelial cells, and compelling evidence supports a role for OATP1A2 in the intestinal absorption of fexofenadine (Dresser et al., 2002; Glaeser et al., 2007) and the quinoline antibiotics (Maeda et al., 2007). *SLCO2B1* mRNA is abundantly expressed in various regions of human small intestine (Nishimura and Naito, 2005; Englund et al., 2006; Seithel et al., 2006; Meier et al., 2007). Immunohistochemical studies localized OATP2B1 protein to the enterocyte apical brush-border membrane in human small intestine, where it may be important for pravastatin absorption (Kobayashi et al., 2003). In the rat, *Slco1a5* mRNA is expressed at low levels down the length of the small intestine, and Oatp1a5 protein was detected on the apical brush-border membrane of jejunal enterocytes (Walters et al., 2000). Rat Oatp1a5 directly transports fexofenadine and the β -adrenergic receptor antagonist talinolol with similar affinities to that observed for rat isolated intestinal tissue (Kikuchi et al., 2006; Shirasaka et al., 2009).

Azithromycin and clarithromycin are commonly used macrolide antibiotics with good oral bioavailability in humans of approximately 37 and 52%, respectively (Foulds et al., 1990; Chu et al., 1992), despite their large molecular weights, high hydrogen-bonding potential, and interactions with P-glycoprotein (azithromycin and clarithromycin) and CYP3A4 (clarithromycin) (Kim et al., 1999; Lipinski et al., 2001; Polasek and Miners, 2006). We previously showed that concomitant dosing of rifamycin SV, a general OATP/Oatp inhibitor (Vavricka et al., 2002), significantly reduced the oral area under the blood-concentration time curve (AUC) for azithromycin and clarithromycin in rats (Garver et al., 2008). Additional in vivo studies suggested that the reduced AUC was not caused by increased blood clearance, and in vitro studies showed an interaction of the macrolides with rat Oatp1a5. The present study was designed to determine whether Oatp1a5 and/or other well characterized intestinally expressed human/rodent OATP/Oatps are potentially involved in the absorption of these macrolide antibiotics.

Materials and Methods

Materials. [^3H]Taurocholic acid (5.0 Ci/mmol) and [^3H]estrone-3-sulfate (57.3 Ci/mmol) were purchased from PerkinElmer Life and Analytical Sciences (Waltham, MA); [^3H]azithromycin (80 Ci/mmol) and [^3H]clarithromycin (80 Ci/mmol) were purchased from American Radiolabeled Chemicals (St. Louis, MO). Madin-Darby canine kidney (MDCK) cells were obtained from the American Type Culture Collection (Manassas, VA) and grown in monolayer at 37°C in an atmosphere of 5% CO_2 . The MDCK-rat Oatp1a5-inducible cell line was generated as described previously (Walters et al., 2000). Oatp1a5 transport activity is undetectable under basal conditions but is dramatically induced by previous incubation with sodium butyrate (Walters et al., 2000). Azithromycin was purchased from Pliva Croatia Ltd. (Zagreb, Croatia), and clarithromycin was purchased from Apin Chemicals, Ltd. (Abingdon, Oxon, UK). Erythromycin, rifamycin SV sodium salt, bromosulfophthalein (BSP), sodium butyrate, and taurocholate were purchased from Sigma-Aldrich (St. Louis, MO). Phosphate-buffered saline (PBS), Dulbecco's modified Eagle's medium (DMEM), 10% (v/v) fetal calf serum, penicillin, streptomycin, and G-418 sulfate were purchased from Invitrogen (Carlsbad, CA).

Rodent and Human Transporter Expression Plasmids. The rat Oatp2b1 expression plasmid was constructed as follows. A pair of oligonucleotide primers, 5'-GGAAGATCTCACCTGAGGCAAGTGTGTGAC-3' and 5'-CAAAGGCTCAGAAGATGCATGGCTGTG-3', corresponding to rat *Slco2b1* nucleotides 24 to 53 and 2223 to 2197, respectively, were used to polymerase chain reaction-amplify the rat *Slco2b1* from Sprague-Dawley rat liver cDNA using previously described conditions (Walters et al., 2000). The 2200-base pair product was subcloned into a pGEM-T-Easy vector (Promega, Madison, WI) and then transferred to the pcDNA3 expression vector (Invitrogen) for transfection experiments. The human OATP1A2 (variant 1; accession number NM_134431.1) and OATP2B1 expression plasmids were obtained from Ori-

gene (Rockville, MD). The mouse Oatp2b1 plasmid (I.M.A.G.E. cDNA clone 5101188) was obtained from Open Biosystems (Huntsville, AL); the mouse Oatp2b1 expression plasmid includes 101 nucleotides of 5' untranslated region, the full-length 2052 nucleotide coding region, and 183 nucleotides of 3' untranslated region. The cDNA inserts for all the transporter expression plasmids were verified by DNA sequencing.

Transport Assays in Stably Transfected MDCK Cells and Transiently Transfected COS Cells. MDCK and MDCK-rat Oatp1a5 cells were maintained in DMEM containing 1000 mg/l D-glucose, 10% (v/v) fetal calf serum, 100 U/ml penicillin, and 100 $\mu\text{g}/\text{ml}$ streptomycin (Medium B) or Medium B containing 350 $\mu\text{g}/\text{ml}$ G-418, respectively. For determination of the EC_{50} and K_i values, MDCK or MDCK-rat Oatp1a5 cells were seeded onto 24-well plates at 1.3×10^5 and 6.5×10^4 cells/well, respectively. On day 2, the cells were refed the same media (MDCK) or the media containing 10 mM sodium butyrate to induce expression of Oatp1a5 (MDCK-rat Oatp1a5). On day 3, the cells were washed with prewarmed PBS and incubated at 37°C in triplicate with DMEM (without antibiotics and calf serum) containing the indicated concentration of [^3H]taurocholate plus vehicle or competitor. After 10 min at 37°C, the cell monolayers were washed three times with ice-cold PBS and processed to determine cell-associated protein and radioactivity as described previously (Walters et al., 2000; Garver et al., 2008). Uptake values were corrected for background at each concentration of solute or competitor by subtracting the uptake values from parallel plates of parental MDCK cells. The K_i was estimated by measuring the uptake at several fixed concentrations of [^3H]taurocholate and competitors (Dixon, 1953).

COS-1 cells were maintained in DMEM plus 4500 mg/l glucose, 10% (v/v) fetal calf serum, 100 U/ml penicillin, and 100 $\mu\text{g}/\text{ml}$ streptomycin (Medium A). On day 0, cells were seeded onto 100-mm dishes at 2×10^6 cells/100-mm dish. On day 1, the cells were transfected with 24 μg of Oatp/OATP expression plasmid or 24 μg of a mixture of control plasmids that included 10 μg of pEYFP-C1 (Clontech, Mountain View, CA) and 14 μg of pcDNA3.1/Hygro(+) plasmid (Invitrogen) using Lipofectamine Transfection Reagent (Invitrogen). On day 2, transfected cells were trypsinized and reseeded onto 24-well plates at 2×10^5 cells/well. On day 4, cells were washed and preincubated for 30 min at 37°C in uptake buffer that included 125 mM NaCl, 48 mM KCl, 5.6 mM D-glucose, 1.2 mM CaCl_2 , 1.2 mM KH_2PO_4 , 12 mM MgSO_4 , and 25 mM MES, pH 6.0 buffer, or 25 mM HEPES, pH 7.4 buffer (Kobayashi et al., 2003). The cells were then washed and incubated at 37°C with the indicated radiolabeled solute in the presence of vehicle or unlabeled competitor. After 10 min at 37°C, the cell monolayers were washed three times with ice-cold PBS and processed to determine cell-associated protein and radioactivity (Walters et al., 2000; Garver et al., 2008). Uptake was linear over this period, and the values were corrected for the background at each concentration of solute or competitor by subtracting the uptake values from parallel plates of control plasmid-transfected COS cells.

Data Analysis. All the data with the exception of the EC_{50} values are expressed as mean $\pm$ S.E.M. The EC_{50} values, the concentration of competitor required to inhibit 50% of specific solute uptake, were calculated by fitting the data to a sigmoidal dose-response curve using GraphPad Prism (GraphPad Software Inc., San Diego, CA) and are expressed as the mean and 95% confidence intervals (CIs). Statistical analysis was performed using the Student's paired t test with $P < 0.05$ as the criterion for significance.

Results

Inhibition of Taurocholate Uptake by Macrolides in Rat Oatp1a5-Expressing MDCK Cells. Previous studies showed that azithromycin and clarithromycin inhibited [^3H]taurocholate uptake by MDCK-rat Oatp1a5-expressing cells (Garver et al., 2008). To further quantify macrolide interactions with Oatp1a5, additional dose-response inhibition studies were performed. As shown in Fig. 1, after addition of increasing concentrations up to 100 μM , azithromycin, clarithromycin, and erythromycin all showed a clear dose-dependent inhibition of rat Oatp1a5-mediated taurocholate uptake. The macrolides were similarly effective, with calculated mean EC_{50} values of 2.0 μM (1.4–2.7), 2.9 μM (2.3–3.6), and 5.3 μM (3.6–7.8) (95% CI) for azithromycin, clarithromycin, and erythromycin, respectively.

FIG. 1. Inhibition of taurocholate uptake by macrolides in MDCK-rat Oatp1a5 cells. The inhibitory effect of azithromycin (A), clarithromycin (B), and erythromycin (C) on rat Oatp1a5-mediated $[^3\text{H}]$ taurocholate ($5 \mu\text{M}$) uptake was measured. The Oatp1a5-specific uptake of taurocholate was determined by subtracting the $[^3\text{H}]$ taurocholate uptake by parental MDCK cells incubated under parallel conditions as the MDCK-rat Oatp1a5 cells. Each data point represents the mean $\pm$ S.E.M. of triplicate determinations. Taurocholate uptake in the absence of azithromycin ($48.2 \pm 11.4 \text{ pmol} \cdot \text{mg cell protein}^{-1} \cdot 10 \text{ min}^{-1}$), clarithromycin ($52.1 \pm 9.4 \text{ pmol} \cdot \text{mg cell protein}^{-1} \cdot 10 \text{ min}^{-1}$), or erythromycin ($41.4 \pm 11.7 \text{ pmol} \cdot \text{mg cell protein}^{-1} \cdot 10 \text{ min}^{-1}$) was set at 100%. The EC_{50} values, the concentration of macrolide required to inhibit 50% of specific $[^3\text{H}]$ taurocholate uptake, were calculated by fitting the data to a sigmoidal dose-response curve using GraphPad Prism (GraphPad Software Inc.).

To gain insight into the mechanism underlying the inhibition of rat Oatp1a5 by macrolides, the transport activity of MDCK-rat Oatp1a5 cells was analyzed at several concentrations of $[^3\text{H}]$ taurocholate and unlabeled azithromycin or clarithromycin. The results were then subjected to Dixon plot analysis to derive an apparent inhibition constant (K_i) and to determine the apparent mode of inhibition. Analysis of the fitted data (Fig. 2) revealed potent inhibition of rat Oatp1a5-mediated taurocholate uptake, with apparent K_i values of approximately $3.3 \pm$

0.4 and $2.4 \pm 0.3 \mu\text{M}$ for azithromycin and clarithromycin, respectively. The analysis was consistent with a noncompetitive mode of inhibition for each macrolide.

Macrolide Interaction with Human OATP1A2 Expressed in Transfected COS Cells. To begin identifying human intestinally expressed OATPs that interact with the macrolides, *cis*-inhibition studies were performed using human OATP1A2-transfected COS cells. As one of the goals of these studies was to examine the interaction of macrolides with OATPs under conditions that mimic the surface microclimate of the small intestine (Lucas, 1983), pilot studies were performed to examine the effect of pH on OATP1A2-mediated transport in transfected COS cells. Similar to previous studies that showed a pH dependence for methotrexate transport by human OATP1A2-expressing *Xenopus laevis* oocytes (Badagnani et al., 2006), OATP1A2-mediated $[^3\text{H}]$ taurocholate or $[^3\text{H}]$ estrone-3-sulfate uptake in transfected COS cells was increased at pH 6.0 versus pH 7.4 (Supplemental Data Fig. 7). Similar increases in radiolabeled taurocholate or estrone-3-sulfate uptake were observed for rat Oatp1a5 and human OATP2B1 (Supplemental Data Fig. 7). Based on previous reports showing increased transport at acidic pH by the intestinally expressed OATPs/Oatps, including OATP1A2, OATP2B1, and Oatp1a5 (Kobayashi et al., 2003; Nozawa et al., 2004; Badagnani et al., 2006; Tani et al., 2008), and our pilot data (Supplemental Data Fig. 7), subsequent uptake studies were carried out under the pH 6.0 conditions.

As shown in Fig. 3A, uptake of $5 \mu\text{M}$ $[^3\text{H}]$ estrone-3-sulfate in the presence of the indicated competitor at $250 \mu\text{M}$ was analyzed using human OATP1A2-transfected COS cells. Whereas BSP and rifamycin SV strongly inhibited estrone-3-sulfate uptake by approximately 90 and 80%, respectively, the macrolides showed only weak inhibition. To further quantify the macrolide interactions with OATP1A2, additional dose-response inhibition studies were performed using azithromycin, clarithromycin, erythromycin, and BSP. After addition of increasing concentrations up to $500 \mu\text{M}$, azithromycin, clarithromycin, and erythromycin showed little inhibition of $1 \mu\text{M}$ $[^3\text{H}]$ estrone-3-sulfate uptake by human OATP1A2 (Fig. 3, B–D). In contrast, BSP showed a clear dose-dependent inhibition of human OATP1A2-mediated estrone-3-sulfate uptake by the transfected COS cells (Fig. 3E) with a calculated EC_{50} value of approximately $3.8 \mu\text{M}$ (2.6 – 5.0 ; 95% CI).

Direct Uptake Studies of Azithromycin and Clarithromycin Using Rat Oatp1a5 and Human OATP1A2-Transfected Cells. The *cis*-inhibition studies showed that the macrolides are potent inhibitors of rat Oatp1a5 but not human OATP1A2-mediated transport. To clarify whether the macrolides are also substrates for rat Oatp1a5 and to further explore their interaction with OATP1A2, direct uptake experiments were performed using $[^3\text{H}]$ azithromycin and $[^3\text{H}]$ clarithromycin. Pilot studies were initially performed using the MDCK-rat Oatp1a5 cells. As shown in Supplemental Data Fig. 8, rat Oatp1a5 exhibited significant $[^3\text{H}]$ taurocholate uptake that was approximately 20-fold over background and only an extremely low level of $[^3\text{H}]$ azithromycin uptake that was approximately 30% over background. Attempts to examine the uptake of $[^3\text{H}]$ clarithromycin using the MDCK-rat Oatp1a5 cells were unsuccessful because of a very high background level of clarithromycin binding/uptake for the Oatp1a5-expressing and Oatp1a5-negative MDCK cells (Supplemental Data Fig. 8C). However, evaluation of other cell expression systems indicated that transfected COS cells exhibited an acceptable background for radiolabeled macrolide uptake. In transfected COS cells, rat Oatp1a5 exhibited significant uptake of $5 \mu\text{M}$ $[^3\text{H}]$ estrone-3-sulfate, a prototypical low-affinity Oatp1a5 substrate (Yarim et al., 2005), that was approximately 9-fold over background. However, there was no

FIG. 2. Analysis of the inhibition of taurocholate uptake by macrolides in MDCK-rat Oatp1a5 cells. A and B, the uptake of [3 H]taurocholate at the fixed concentrations of 5, 10, and 25 μ M was measured in the absence or presence of the indicated concentrations of azithromycin (A) or clarithromycin (B). C and D, Dixon plot analysis of taurocholate uptake data in the presence of azithromycin (C) or clarithromycin (D). Each point represents the mean $\pm$ S.E.M. of triplicate determinations. The apparent K_i value, the concentration of macrolide required to double the slope of the $1/\text{velocity}$ versus $1/\text{substrate}$ concentration plot, was calculated from the fitted lines using GraphPad Prism (GraphPad Software Inc.). The K_i values for azithromycin and clarithromycin inhibition of Oatp1a5-mediated taurocholate uptake were 3.3 ± 0.2 and 2.4 ± 0.1 μ M, respectively (mean $\pm$ S.E.M.).

appreciable uptake of 10 μ M [3 H]azithromycin or [3 H]clarithromycin over background (Fig. 4A). In addition, studies using increasing concentrations of [3 H]clarithromycin up to 200 μ M showed only background levels of uptake by the rat Oatp1a5-transfected COS cells (data not shown). In studies using OATP1A2-transfected COS cells, there was also significant uptake of [3 H]estrone-3-sulfate that was approximately 2-fold over background, but no uptake of 10 μ M [3 H]azithromycin or [3 H]clarithromycin over background (Fig. 4B).

Interaction of Azithromycin and Clarithromycin with Human OATP2B1 and Rat Oatp2b1 Expressed in Transfected COS Cells. To identify other intestinally expressed OATPs/Oatps that interact with the macrolides, additional *cis*-inhibition studies were performed using human and rodent OATP2B1/Oatp2b1-transfected cells. The uptake of 5 μ M [3 H]estrone-3-sulfate in the presence of the indicated competitor at 250 μ M was analyzed using human/rat OATP2B1/Oatp2b1-transfected COS cells. Whereas BSP and rifamycin SV strongly inhibited OATP2B1-mediated estrone-3-sulfate uptake by approximately 90 and 85%, respectively, the macrolides showed only weak inhibition (Fig. 5A). Rat Oatp2b1-mediated estrone-3-sulfate uptake was strongly inhibited by BSP, weakly inhibited by rifamycin SV, and unaffected by azithromycin or clarithromycin (Fig. 5B). A similar lack of interaction with the macrolides was observed for mouse Oatp2b1-transfected COS cells (Supplemental Data Fig. 9). The weak potential interaction of the macrolides with human OATP2B1 was further examined in dose-response inhibition studies.

After addition of increasing concentrations up to 500 μ M, azithromycin, clarithromycin, and erythromycin showed little inhibition of 1 μ M [3 H]estrone-3-sulfate uptake by human OATP2B1 (Fig. 6, A–C). In contrast, BSP showed a clear dose-dependent inhibition of human OATP2B1-mediated estrone-3-sulfate uptake by the transfected COS cells (Fig. 6D) with a calculated EC_{50} value of approximately 1.7 μ M (1.1–2.3; 95% CI).

Although the *cis*-inhibition studies suggested that the macrolides are poor inhibitors of human/rat OATP2B1/Oatp2b1-mediated transport, additional direct uptake studies were also performed to further explore these potential interactions. In transfected COS cells, human OATP2B1 and rat Oatp2b1 exhibited significant uptake of 5 μ M [3 H]estrone-3-sulfate that was approximately 8- and 1.7-fold over background, respectively. In contrast to the estrone-3-sulfate, there was no appreciable uptake of [3 H]azithromycin or [3 H]clarithromycin over background (Supplemental Data Fig. 10).

Discussion

The macrolide antibiotics azithromycin and clarithromycin exhibit undesirable physicochemical (e.g., large molecular weight and extensive potential for hydrogen bonding) and biopharmaceutical (e.g., substrates for efflux transporter P-glycoprotein) properties but show moderate to excellent oral bioavailability in preclinical species and humans. Among the potential explanations for this paradox is that intestinal transporters facilitate macrolide absorption. Previous studies

FIG. 3. Inhibition of estrone-3-sulfate uptake by macrolides in human OATP1A2-transfected COS cells. COS cells were transiently transfected with human OATP1A2 plasmid or a mixture of control expression plasmids. The OATP1A2-specific uptake was determined by subtracting the [³H]estrone-3-sulfate uptake for control plasmid-transfected COS cells incubated under parallel conditions. A, the transfected COS cells were incubated for 10 min at 37°C in pH 6.0 buffer containing 5 μ M [³H]estrone-3-sulfate plus the indicated competitor at 250 μ M, BSP, rifamycin SV (Rif), azithromycin (Azi), clarithromycin (Clari), or erythromycin (Ery). Estrone-3-sulfate uptake in the absence of competitor, 28.7 ± 2.1 pmol $\cdot$ mg cell protein⁻¹ $\cdot$ 10 min⁻¹, was set at 100%. B–E, the inhibitory effect of azithromycin (B), clarithromycin (C), erythromycin (D), and BSP (E) on human OATP1A2-mediated [³H]estrone-3-sulfate (1 μ M) uptake. Estrone-3-sulfate uptake in the absence of azithromycin (4.4 ± 0.1 pmol $\cdot$ mg cell protein⁻¹ $\cdot$ 10 min⁻¹), clarithromycin (2.7 ± 0.1 pmol $\cdot$ mg cell protein⁻¹ $\cdot$ 10 min⁻¹), erythromycin (9.3 ± 0.2 pmol $\cdot$ mg cell protein⁻¹ $\cdot$ 10 min⁻¹), or BSP (3.8 ± 0.2 pmol $\cdot$ mg cell protein⁻¹ $\cdot$ 10 min⁻¹) was set at 100%. Each bar or point represents the mean $\pm$ S.E.M. of triplicate determinations. *, $P < 0.05$; **, $P < 0.005$ versus uptake in the absence of competitor (control).

in rats suggested that oral absorption of azithromycin and clarithromycin is mediated by an Oatp and/or other rifamycin SV-sensitive intestinal transporter (Garver et al., 2008). The present study was designed to identify candidate OATP/Oatps that mediate the oral

absorption of macrolide antibiotics. The major findings of this study are that the macrolide antibiotics are potent inhibitors but not substrates of rat Oatp1a5, and that the macrolides interact only weakly with human OATP1A2 and human/rat OATP2B1/Oatp2b1, other well

FIG. 4. Uptake of radiolabeled solutes by rat Oatp1a5 and human OATP1A2. COS cells were transiently transfected with rat Oatp1a5 (A) or human OATP1A2 (B) and a mixture of control expression plasmids. The transfected COS cells were incubated for 10 min at 37°C in pH 6.0 buffer with the indicated concentrations of [³H]azithromycin, [³H]clarithromycin, or [³H]estrone-3-sulfate and then processed to determine cell-associated protein and radioactivity. Each bar represents the mean $\pm$ S.E.M. ($n = 6$). **, $P < 0.005$ versus control plasmid-transfected cells (YFP).

characterized members of the OATP/Oatp family that are expressed in small intestine.

Although interaction of macrolide and ketolide antibiotics with human OATP1B1 and OATP1B3 has been studied (Seithel et al., 2007), the interaction of macrolides with intestinally expressed OATP/Oatps has not been fully investigated. Direct uptake and *cis*-inhibition experiments were performed using rat Oatp1a5 expressed in stably transfected MDCK cells and transiently transfected COS cells. As previously suggested (Garver et al., 2008), we found a strong dose-dependent inhibition of Oatp1a5-mediated transport by the macrolides. To further understand the mechanism of Oatp1a5 inhibition, transport was examined using various concentrations of [³H]taurocholate and unlabeled macrolide. The study revealed that azithromycin and clarithromycin potently inhibited Oatp1a5-mediated [³H]taurocholate uptake in a noncompetitive fashion with apparent K_i values of 3.3 ± 0.4 and 2.4 ± 0.3 μM, respectively. The finding that the macrolides were not competitive-type inhibitors was further supported by direct uptake experiments using radiolabeled substrates. Whereas rat Oatp1a5 exhibited robust [³H]taurocholate and [³H]estrone-3-

FIG. 5. Inhibition of estrone-3-sulfate uptake by macrolides in rat Oatp2b1 and human OATP2B1-transfected COS cells. COS cells were transiently transfected with rat Oatp2b1 (A), human OATP2B1 (B), or a mixture of control expression plasmids. The transfected COS cells were incubated for 10 min in pH 6.0 buffer at 37°C with 5 μM [³H]estrone-3-sulfate plus the indicated competitor at 250 μM. The Oatp2b1/OATP2B1-specific uptake was determined by subtracting the [³H]estrone-3-sulfate uptake for control expression plasmid-transfected COS cells incubated under parallel conditions. Estrone-3-sulfate uptake in the absence of competitor, 5.8 ± 0.1 and 45.8 ± 0.6 pmol · mg cell protein⁻¹ · 10 min⁻¹ for rat Oatp2b1 and human OATP2B1, respectively, was set at 100%. Each bar represents the mean $\pm$ S.E.M. of triplicate determinations. **, $P < 0.005$ versus uptake in the absence of competitor (control).

sulfate uptake, there was no significant [³H]azithromycin and [³H]clarithromycin uptake over background.

Another major intestinally expressed OATP/*SLCO* family member is human OATP1A2. In contrast to their potent interaction with rat Oatp1a5, the macrolides did not inhibit human OATP1A2-mediated transport. The identification of a compound selective for rat Oatp1a5 versus OATP1A2 is not without precedence. OATP1A2 and Oatp1a5 share 72% amino acid identity and transport many common substrates such as taurocholate, estrone-3-sulfate, fexofenadine, and BSP (Hagenbuch and Meier, 2003). However, there are examples of compounds such as methotrexate, which are not shared substrates and selectively interact with one but not the other carrier (Cattori et al., 2001; Ohtsuki et al., 2003; Badagnani et al., 2006). In addition to OATP1A2, OATP2B1 is expressed on the apical brush-border membrane of the human intestine and is believed to have a role in drug absorption (Kobayashi et al., 2003; Nozawa et al., 2004). As was found for

FIG. 6. Inhibition of estrone-3-sulfate uptake by macrolides in human OATP2B1-transfected COS cells. The inhibitory effect of azithromycin (A), clarithromycin (B), erythromycin (C), and BSP (D) on human OATP2B1-mediated uptake of 1 μM [^3H]estrone-3-sulfate. Estrone-3-sulfate uptake in the absence of azithromycin (15.0 ± 0.3 pmol $\cdot$ mg cell protein $^{-1} \cdot 10$ min $^{-1}$), clarithromycin (15.3 ± 0.6 pmol $\cdot$ mg cell protein $^{-1} \cdot 10$ min $^{-1}$), erythromycin (27.3 ± 0.7 pmol $\cdot$ mg cell protein $^{-1} \cdot 10$ min $^{-1}$), or BSP (15.1 ± 0.2 pmol $\cdot$ mg cell protein $^{-1} \cdot 10$ min $^{-1}$) was set at 100%. Each point represents the mean $\pm$ S.E.M. of triplicate determinations.

OATP1A2, azithromycin and clarithromycin did not significantly inhibit OATP2B1-mediated uptake of estrone-3-sulfate, a prototypical substrate. The rat and mouse Oatp2b1, which share $\sim 77\%$ amino acid identity with human OATP2B1, showed a similar lack of interaction with azithromycin and clarithromycin. In addition, no significant transport of azithromycin or clarithromycin was observed in direct uptake studies using COS cells transfected with OATP1A2 or human/rat OATP2B1/Oatp2b1.

In conclusion, these studies show that azithromycin and clarithromycin are not efficiently transported by the major characterized intestinally expressed OATP/Oatps, including Oatp1a5, OATP1A2, and OATP2B1/Oatp2b1. Because the inhibition of OATP/Oatp-mediated transport by rifamycin SV is well documented, it is possible that the decreased oral exposure of the macrolides following coadministration of rifamycin SV is caused by inhibition of other members of the OATP/Oatp family, such as OATP3A1 and OATP4A1, which may be expressed in the small intestine. In addition, because it is unlikely that rifamycin SV inhibits only OATP/Oatp transporters, it is possible that other non-Oatp uptake transporters are involved in the intestinal absorption of the macrolides.

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