Molecular Pharmacology Fast Forward. Published on November 5, 2010 as doi:10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

MOL #67256

Itraconazole-induced cholestasis: involvement of the inhibition of bile canalicular phospholipid translocator MDR3/ABCB4

Takashi Yoshikado, Tappei Takada, Takehito Yamamoto, Hiroko Yamaji, Kousei Ito, Tomofumi Santa, Hiromitsu Yokota, Yutaka Yatomi, Haruhiko Yoshida, Jun Goto, Shoji Tsuji and Hiroshi Suzuki

Department of Pharmacy, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan (T.Yoshikado, T.T., T.Yamamoto, H.Y., K.I., H.S.)

Laboratory of Biomedical and Pharmaceutical Analysis, Graduate School of Pharmaceutical Sciences, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan (T.Yoshikado, T.S.)

Department of Clinical Laboratory, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan (H.Yokota, Y.Y.)

Department of Gastroenterology, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan (H.Yoshida)

Department of Neurology, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan (J.G., S.T.)

Department of Clinical Genomics, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan (J.G., S.T.)

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Running Title: Inhibition of MDR3/ABCB4 by itraconazole

Corresponding author: Tappei Takada, Ph.D., Assistant Professor

Address: Department of Pharmacy, the University of Tokyo Hospital, Faculty of Medicine, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan.

Phone: +81-3-3815-5411 (ext. 35297) Fax: +81-3-3816-6159

E-mail: tappei-tky@umin.ac.jp

Text pages: 39

Table: 1, Supplemental Tables: 2

Figures: 4, Supplemental Figures: 2

References: 37

Words in Abstract: 187

Words in Introduction: 503

Words in Discussion: 1350

Abbreviations:

ABC, ATP-binding cassette; ALP, alkaline phosphatase; ALT, alanine aminotransferase; AST, aspartate aminotransferase; BSEP, bile salt export pump; DILI, drug-induced liver injury; EGFP, enhanced green fluorescent protein; γ-GTP, γ-glutamyl transpeptidase; ITZ, itraconazole; LFTs, liver function tests; LLC-BSEP/NTCP, BSEP- and NTCP-expressing LLC-PK1 cell; LLC-EGFP, EGFP-expressing LLC-PK1 cell; LLC-EGFP/NTCP, EGFP- and NTCP-expressing LLC-PK1 cell; LLC-MDR3, MDR3-expressing LLC-PK1 cell; MDR, multidrug resistance; MOI, multiplicity of infection; NTCP, Na^+/taurocholate cotransporting polypeptide; PC, phosphatidylcholine; PFIC, progressive familial intrahepatic cholestasis; TLC, thin-layer chromatography

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Abstract

Biliary secretion of bile acids and phospholipids, both of which are essential components of biliary micelles, are mediated by the bile salt export pump (BSEP/ABCB11) and multidrug resistance 3 P-glycoprotein (MDR3/ABCB4), respectively, and their genetic dysfunction leads to the acquisition of severe cholestatic diseases. In the present study, we found two patients suffering from itraconazole (ITZ)-induced cholestatic liver injury with markedly high serum ITZ concentrations. To characterize the effect of ITZ on bile formation *in vivo*, biliary bile acids and phospholipids were analyzed in ITZ-treated rats and it was revealed that biliary phospholipids, rather than bile acids, were drastically reduced in the presence of clinically relevant concentrations of ITZ. Moreover, by using MDR3-expressing LLC-PK1 cells, we found that MDR3-mediated efflux of [^{14}C]phosphatidylcholine was significantly reduced by ITZ. In contrast, BSEP-mediated transport of [^{3}H]taurocholate was not significantly affected by ITZ, which is consistent with our *in vivo* observations. In conclusion, this study suggests the involvement of the inhibition of MDR3-mediated biliary phospholipids secretion in ITZ-induced cholestasis. Our approach may be useful for analyzing mechanisms of drug-induced cholestasis and evaluating the cholestatic potential of clinically-used drugs and drug candidates.

Introduction

Bile formation is one of the most essential functions of the liver and several ATP-binding cassette (ABC) transporters are known to be involved in the biliary secretion of biliary lipids, organic solutes and xenobiotics (Oude Elferink and Paulusma, 2007). Among them, the bile salt export pump (BSEP/ABCB11) and multidrug resistance 3 P-glycoprotein (MDR3/ABCB4) have been recognized to play particularly crucial roles in the physiological formation of bile, since genetic dysfunction of each of these two transporters causes a severe hereditary disorder, progressive familial intrahepatic cholestasis (PFIC). BSEP is expressed on the bile canalicular membrane of hepatocytes and functions as an exporter of bile acids into bile (Gerloff et al., 1998; Noe et al., 2002) and its dysfunction leads to the intrahepatic accumulation of bile acids resulting in the acquisition of the severe liver damage. MDR3 mediates the translocation of phospholipids from the inner to outer leaflet of bile canalicular membranes (Smit et al., 1993; van Helvoort et al., 1996), and the translocated phospholipids are necessary to form biliary micelles with bile acids. Without secretion of phospolipids, hepatocytes and cells lining the biliary tract suffer from the detergent effect of bile acids in bile.

Considering the physiological significance of BSEP and MDR3, drug-mediated functional disruption of these transporters may result in drug-induced cholestasis, which is one form of drug-induced liver injury (DILI) and is characterized by elevations of

alkaline phosphatase (ALP), serum γ-glutamyl transpeptidase (γ-GTP) and total bilirubin. Indeed, several cholestatic drugs are known to inhibit BSEP-mediated transport of bile acids *in vitro* (Horikawa et al., 2003; Stieger et al., 2000; Wang et al., 2001), although their inhibitory effects have been usually observed at much higher concentrations than those seen in clinical situations. In addition, serum γ-GTP levels generally remain normal in BSEP-related genetic cholestasis (PFIC2), whereas serum levels of this enzyme are markedly elevated in MDR3-related genetic cholestasis (PFIC3). These pieces of information suggest that drug-induced cholestasis may occur by the inhibition of MDR3 rather than BSEP.

Concerning the clinically observed drug-induced cholestasis, an antifungal agent itraconazole (ITZ) has been reported to cause cholestatic liver injuries (Gallardo-Quesada et al., 1995; Hann et al., 1993; Lavrijsen et al., 1992; Srebrnik et al., 2005). In addition, the US Food and Drug Administration has received reports of at least 24 cases of DILI including 11 deaths associated with the use of ITZ (Song and Deresinski, 2005). In the present study, we also observed marked elevations of serum ALP, γ-GTP and total bilirubin levels in two patients who received the administration of ITZ. Since serum concentrations of ITZ in these patients were remarkably higher than the concentrations reported in a population pharmacokinetics study of Japanese patients (Yamaguchi et al., 2006), we suspected that the high concentrations of ITZ in the liver might inhibit bile formation and increase risk of cholestasis. In order to verify this

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

hypothesis, we analyzed the biliary secretion of bile acids and phospholipids in ITZ-administered rats, in combination with *in vitro* experiments for the inhibitory effect of ITZ on human MDR3- and BSEP-mediated transport.

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Materials and Methods

Materials. ITZ solution (Itrizole® Injection 1%) was purchased from Janssen Pharmaceutical K.K. (Tokyo, Japan). [^{14}C]choline (55 mCi/mmol) was purchased from American Radiolabeled Chemicals Inc. (St. Louis, MO) and [^{3}H]taurocholate (4.6 Ci/mmol) was purchased from PerkinElmer Life Sciences (Boston, MA). LLC-PK1 cells were purchased from American Type Culture Collection (Manassas, VA) and cultured in Medium 199 (Sigma-Aldrich, St. Louis, MO) with 10% fetal bovine serum (GIBCO, Tokyo, Japan) and 1% penicillin/streptomycin (Nacalai Tesque, Kyoto, Japan) at 37°C in an atmosphere supplemented with 5% CO_2. All other chemicals used were commercially available and of reagent grade.

Patient information. The protocol of the present clinical study was approved by the Institutional Ethics Committee of the University of Tokyo and conducted in accordance with the ethical guidelines of the Declaration of Helsinki. Twenty-four inpatients in the University of Tokyo Hospital, whose written informed consent was obtained from October, 2007 to December, 2008, were diagnosed as to suffering from DILI; for these patients, possibilities of other common causes of hepatic injury (such as liver carcinoma, viral hepatitis, gallstone and primary biliary cirrhosis) were excluded. Among them, a 67-year-old female (Patient 1), a 43-year-old male (Patient 2) and a 36-year-old female (Patient 3) exhibited elevations in liver function tests (LFTs) during the administration

of ITZ (once-daily dosing of 200 mg as oral solution) and after discontinuing the administration, LFTs returned to normal. In the present study, serum ITZ concentrations in these patients were determined using the serum specimens remained after routine laboratory analyses for clinical purposes. DNA microarray analyses using the patients' genomic specimens were performed with DMET Plus Premier Pack (Affymetrix, Santa Clara, CA) according to the manufacturer's protocol.

Determination of serum ITZ concentration. To measure the serum concentrations of ITZ, serum specimens were mixed with 5 volumes of methanol and centrifuged at 20,000-g for 15 min. Supernatants were used for the analysis using an ACQUITY UPLC-Quattro Premier XE (Waters Corporation, Milford, MA), an ultra-performance liquid chromatography coupled with an electrospray ionization tandem mass spectrometry system (UPLC-MS/MS). The column used was a Waters UPLC BEH C18 Shield (3 μm; 2 · 100 mm) and UPLC was performed under gradient mobile phase conditions using a mixture of 0.1% formic acid in water and 0.1% formic acid in acetonitrile as solvents (0.3 mL/min; 0-1.0 min 95:5 v/v, 1.0-7.0 min 95:5 v/v to 5:95 v/v, 7.0-9.0 min 5:95 v/v to 95:5 v/v, 9.0-10.0 min 95:5 v/v). The UPLC eluent was introduced into a mass spectrometer via positive electrospray ionization mode (ESI+). Quantification of ITZ was performed in multiple reactions monitoring (MRM) mode (705.14 > 392.30; Cone 60 V, Collision 36 eV) using lovastatin as the internal standard

(405.25 > 173.10, Cone 20 V, Collision 22 eV).

***In vivo* experiments.** Animal studies were performed according to the method approved by the Institutional Animal Care Committee of the University of Tokyo. All animals received human care according to the criteria outlined in the "Guide for the Care and Use of Laboratory animals" prepared by the National Academy of Sciences and published by the National Institute of Health (NIH publication 86-23 revised 1985).

Male Sprague-Dawley rats (Japan SLC, Shizuoka, Japan) weighting 210-250 g were fed standard rat chow and water. Before operation, rats were anesthetized with an intraperitoneal injection of 1.25 g/kg urethane (Sigma Aldrich). The femoral artery and vein were cannulated with SP-31 (0.5 mm) polyethylene tube (Natsume, Tokyo, Japan) and bile duct with SP-8 (0.2 mm) polyethylene tube (Natsume). Then, rats received 10 mg/mL ITZ solution intravenously (containing 0.40 g/mL hydroxypropyl-β-cyclodextrin (HP-β-CD) and 25 μL/mL propylene glycol) as a bolus dose of 43 mg/kg, and then infused with 3.3 mg/mL ITZ solution (containing 0.13 g/mL HP-β-CD and 8.3 μL/mL propylene glycol) for 2 hr at a rate of 7.3 mg/kg/hr (0.5 mL/hr). Bile and blood specimens were taken every 30 min, and liver samples were collected after euthanasia. Plasma specimens were obtained by centrifuging blood specimens at 1,000-g for 15 min. Control rats underwent the same protocol with the control solution containing the same concentration of HP-β-CD and propylene glycol.

Analytical methods for *in vivo* experiments. Plasma and liver concentrations of ITZ in rats were determined using UPLC-MS/MS system described above. Liver tissue samples were homogenized with phosphate buffered saline (PBS) to prepare 20% tissue homogenates and subjected to the same procedure as plasma specimens. Concentrations of biliary lipids were measured by enzymatic methods using Total Bile Acids-Test, Phospholipids C-Test and Total Cholesterol-Test (Wako Pure Chemical, Osaka, Japan). Bile specimens were weighted and the biliary volume was determined assuming a specific gravity of 1.0 g/mL (Fouassier et al., 2002). LFTs (AST, ALT, ALP, γ-GTP and total bilirubin) in rats were performed by outsourcing service (SRL, Tokyo, Japan) using plasma specimens collected after 2-hr infusion of ITZ. Liver adenosine triphosphate (ATP) levels after 2-hr infusion of ITZ were analyzed according to a conventional method (Tissue ATP Assay Kit, TOYO INK, Tokyo, Japan). Plasma bile acid levels were determined by the similar method as biliary bile acids.

Construction of recombinant adenoviruses. Complementary DNA cloning of human MDR3 was performed as described in our previous report (Ikebuchi et al., 2009). For human BSEP, three fragments of the coding region (1-151 nt, 152-2,151 nt and 2,152-3,969 nt) were amplified from total RNA of HepG2 cells and were ligated by overlapping PCR method to obtain the full-length of BSEP, which was then cloned into

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Hind III / Kpn I sites of pEGFP-N1 vector (Clontech/Takara-Bio, Mountain View, CA). Human Na^+/taurocholate cotransporting polypeptide (NTCP/SLC10A1) was amplified from total RNA of HepG2 cells and was cloned into Kpn I / Xba I sites of pcDNA3.1/mycHis vector (Invitrogen, Carlsbad, CA).

These cDNAs were then cloned into pTRE-Shuttle2 vectors (MDR3 into Nhe I / EcoRV sites, BSEP-EGFP into Nhe I / Not I sites and NTCP-mycHis into Sac II / Nhe I sites) of Adeno-X Tet-Off Expression System 1 Kit (Clontech/Takara-Bio) and recombinant adenoviruses were constructed according to the manufacturer's protocol (Ad-MDR3, Ad-BSEP-EGFP and Ad-NTCP-mycHis). For mock infections, recombinant adenoviruses containing enhanced green fluorescence protein (EGFP) were similarly constructed (Ad-EGFP). Tet-regulatory adenoviruses (Ad-Tet) required for the expression of target proteins were included in the kit. Those recombinant adenoviruses were amplified in HEK293 cells and purified by the cesium chloride (CsCl) gradient ultracentrifugation method. The viral titers were determined using an Adeno-X Rapid Titer Kit (Clontech/Takara-Bio) and subsequent experiments with adenoviruses were performed after the optimization of multiplicity of infection (MOI) to cells.

MDR3-mediated efflux of PC. LLC-PK1 cells were seeded on 12-well plates (BD FALCON, Bedford, MA) at a density of 1.6×10^5 cells/well and, 48 hr later, the cells

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

were infected with 5 MOI Ad-MDR3 and 10 MOI Ad-Tet (LLC-MDR3). For control experiments, Ad-MDR3 was replaced by Ad-EGFP (LLC-EGFP). Twenty four hours after infection, each well was washed with Krebs-Henseleit buffer (118 mM NaCl, 23.8 mM $NaHCO_3$, 4.83 mM KCl, 0.96 mM KH_2PO_4, 1.20 mM $MgSO_4$, 12.5 mM HEPES, 5.0 mM glucose, 1.53 mM $CaCl_2$, pH 7.4) and then preincubated with the buffer containing [^{14}C]choline and drugs (ITZ or verapamil) for 3 hr at 37°C, under an atmosphere of 5% CO_2. After being washed twice with Krebs-Henseleit buffer, the cells were incubated with the buffer containing 3 mM taurocholate and each drug for additional 3 hr. Incubated buffer was collected from each well, lyophilized using a vacuum freeze drier and diluted in chloroform (medium specimens). The remained cells were washed twice with ice-cold Krebs-Henseleit buffer, lysed with 0.1 M NaOH plus 0.l% SDS and then neutralized with 0.1 M HCl. Then, cell lysate was collected from each well, lyophilized and diluted in chloroform (cell lysate specimens).

The medium and cell lysate specimens were subjected to the thin-layer chromatography (TLC) on Silica 60 plate (Merck KGaA, Darmstadt, Germany) using a development solvent containing chloroform : methanol : 30% ammonia solution = 65 : 35 : 8. To detect phosphatidylcholine (PC) on the plate, non-radioactive PC was subjected to the plate and visualized using a Dragendorff's reagent which specifically reacts with choline lipids (Wagner et al., 1961). Radioactive PC spots on the TLC plates were detected with a Cyclone Phosphor Imager (PerlinElmer, Waltham, MA) and

the cellular efflux activities of PC were evaluated using the following equation: efflux PC / (cellular PC + efflux PC) x 100 (%).

BSEP-mediated transport of taurocholate. LLC-PK1 cells were seeded on Transwell membrane inserts (pore size of 3 μm; BD FALCON) in 24-well plates at a density of 1.4 x 10^5 cells/insert. Twenty four hours later, the cells were infected with 10 MOI Ad-BSEP-EGFP, 10 MOI Ad-NTCP-mycHis and 20 MOI Ad-Tet (LLC-BSEP/NTCP). For control experiments, Ad-BSEP-EGFP was replaced by Ad-EGFP (LLC-EGFP/NTCP). Forty eight hours after infection, both apical and basal compartments of each well were washed with Krebs-Henseleit buffer and preincubated with ITZ for 3 hr at 37°C, in an atmosphere of 5% CO_2. Subsequently, the basal compartment buffer was substituted with Krebs-Henseleit buffer containing [^{3}H]taurocholate and ITZ. Buffer was collected from each apical compartment at 3 hr after incubation and radioactivity was measured using a Tri-Carb Liquid Scintillation Counter (PerkinElmer). At the end of the experiment, the cells were washed twice with Krebs-Henseleit buffer and lysed with 0.1 M NaOH plus 0.l% SDS and then neutralized with 0.1 M HCl. Intracellular radioactivity was similarly measured and the protein concentration was determined by the method of Lowry (Lowry et al., 1951).

The kinetic parameters of the transcellular transport experiments were calculated according to the method described previously (Mita et al., 2005). For this analysis, the

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

appearance rate of taurocholate in the apical compartment (V_{apical}, pmol/hr/mg protein) was determined experimentally. Then, the permeability-surface area product (PS) for the basal-to-apical transport of taurocholate (PS_{b-a}, μL/hr/mg protein) was calculated by dividing V_{apical} by the taurocholate concentration in the basal medium (C_{med}, pmol/μL). In addition, the PS product for the efflux of taurocholate across the apical membrane (PS_{apical}, μL/hr/mg protein) was calculated by dividing V_{apical} by the taurocholate concentration in cells (C_{cell}, pmol/μL). C_{cell} was calculated assuming that the cellular volume per milligram of cellular protein is 4 μL (Mita et al., 2006).

Western blot analyses. LLC-PK1 cells were seeded on 60-mm dishes (BD FALCON) at a density of 1.0 x 10^6 cells/dish and infected with the adenoviruses at the MOI described in the transport experiments. Crude membrane fractions were prepared and protein concentrations were determined by the method of Lowry (Lowry et al., 1951). Proteins (15 μg / lane) were size-fractionated on 7% (for MDR3 and BSEP-EGFP) or 10% (for NTCP-mycHis) of SDS-polyacrylamide gels and transferred onto Immobilon (Millipore, Billerica, MA). Molecular weights of proteins were examined using a PageRuler Prestained Protein Ladder (Fermentas, Burlington, Canada). After blocking with 3% bovine serum albumin, membranes were immunoblotted with primary antibodies; mouse P3II26 antibodies (MONOSAN, Uden, the Netherlands) for MDR3, mouse anti-GFP antibodies (Sigma-Aldrich) for

BSEP-EGFP and mouse anti-c-myc antibodies (Roche Diagnostics, Indianapolis, IN) for NTCP-mycHis. As the secondary antibody, anti-mouse IgG antibody labeled with horseradish peroxidase (GE Healthcare, Piscataway, NJ) was used. These immunoblotted membranes were treated with an ECL Plus (GE Healthcare) and analyzed using a Chemidoc XRS (Bio-Rad Laboratories, Richmond, CA).

Immunostaining of transporters. LLC-PK1 cells were seeded on 35-mm glass dishes (IWAKI, Chiba, Japan) at a density of 4.0×10^5 cells/dish and infected with the adenoviruses at the MOI described in the transport experiments. LLC-MDR3 cells were fixed with 100% methanol and immunostained with anti-MDR3 antibody as the primary antibody and anti-mouse IgG antibody labeled with Alexa Fluor 488 (Invitrogen) as the secondary antibody. LLC-BSEP/NTCP cells were similarly fixed and immunostained with anti-c-myc antibody followed by anti-mouse IgG antibody labeled with Alexa Fluor 543 (Invitrogen). In each specimen, nuclei were visualized with TO-PRO-3 (Invitrogen). Observations of samples were performed using a FV1000 Confocal Laser Microscope (Olympus, Tokyo, Japan).

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Results

Abnormalities in LFTs were associated with the elevated plasma ITZ concentration in DILI patients. In Patients 1, 2 and 3, ITZ may be the cause of liver injury, since (1) elevations in LFTs were observed during the administration of ITZ and LFTs returned to normal after discontinuing ITZ, and (2) possibilities of other common causes of hepatic injury were excluded. Furthermore, in Patients 1 and 2, serum ITZ concentrations were significantly high, which should increase the risk of hepatotoxicity. Patients 1, 2 and 3 suffered from ITZ-induced liver injury 62, 20 and 2 days after starting ITZ-administration, respectively (Table 1), which is consistent with the previous report that the time period to exhibit elevations in LFTs after starting ITZ-administration varied from several days to several weeks in ITZ-induced liver injury (Gallardo-Quesada et al., 1995; Hann et al., 1993; Lavrijsen et al., 1992; Srebrnik et al., 2005). In the present study, Day 0 was defined as the day on which ITZ-administration was started for Patients 1 and 2. For Patient 3, Day 0 was defined as the day from which the serum specimens were obtained, and ITZ-administration was started on Day 23. In addition, the list of simultaneously administered drugs is shown in Table 1.

Patient 1 experienced elevations in LFTs with ALT 81 IU/L, AST 70 IU/L, ALP 312 IU/L, γ-GTP 80 IU/L and total bilirubin 0.8 mg/dL on Day 70 (Fig. 1A-C). On Day 72, administration of ITZ and other drugs (furosemide, spironolactone and

demethylchlortetracycline) were discontinued and LFTs gradually returned to normal. Due to the therapeutic requirements, the patient received further ITZ from Day 86 and elevations in LFTs were observed again. We found that the trough concentration of serum ITZ reached 1.7 μM (1,238 ng/mL) on Day 61 (Fig. 1D), which was 2.5-fold higher than the mean trough concentration in a Japanese population receiving the same dose of ITZ (Yamaguchi et al., 2006). Since the peaks of serum ITZ and elevated LFTs were observed at almost the same time on Day 70, we have to consider both possibilities that the increase in ITZ concentration caused liver damage and that liver damage caused the increase in ITZ concentration. After re-administration from Day 86, the serum ITZ concentration increased again and reached 3.0 μM (2,131 ng/mL) on Day 110. It was found that, although serum concentration of ITZ in Patient 1 is higher on Day 110 than that on Day 100, elevated LFTs were more remarkable on Day 105 than those on Day 110. This discrepancy may be accounted for by a hypothesis that the peak concentration of ITZ may have been observed between Day 100 and Day 110, although it is difficult to certify this point because of the absence of serum specimens. Another possibility is that cumulative damage of the liver might cause the decreased metabolism of ITZ and resulted in the increase in its serum concentration.

In Patient 2, elevations in LFTs were observed 3 weeks after starting ITZ and famotidine. Although administration of these two drugs was discontinued on Day 25, LFTs were still elevated with ALT 874 IU/L, AST 432 IU/L, ALP 539 IU/L, γ-GTP 356

IU/L and total bilirubin 1.4 mg/dL on Day 34 and then gradually returned to normal (Fig. 1E-G). The serum ITZ concentrations were clearly increased before elevations in LFTs were observed (Fig. 1E-G); the trough concentration of serum ITZ reached 2.0 μM (1,365 ng/mL) on Day 20 (Fig. 1H), which was 2.7-fold higher than the mean trough concentration in a Japanese population (Yamaguchi et al., 2006). These results suggest that the increase in ITZ concentration may have caused liver damage in Patient 2. In contrast, the serum concentration of famotidine on Day 25 was in a normal range of its clinical use (< 10 ng/mL as the trough concentration).

In Patient 3, although ITZ was suspected to be the cause of liver injury since elevations in LFTs were observed during ITZ-administration and LFTs returned to normal after discontinuing the drug, its serum concentration was rather lower compared with the therapeutic serum concentrations. Simultaneously administered drugs may not be related to the cause of liver injury, since these other drugs were administered continuously during the period. Before ITZ-administration, this patient had experienced brotizolam-induced liver injury and the peak of elevated LFTs were observed on Day 7 as ALT 269 IU/L, AST 153 IU/L, ALP 178 IU/L, γ-GTP 126 IU/L and total bilirubin 4.3 mg/dL, which was 2 days after starting brotizolam-administration (Figure 1I-K). On Day 9, brotizolam-administration was discontinued and, consequently, on Day 17, LFTs returned to normal. On Day 23, ITZ-administration was started for the patient, and LFTs were elevated again with ALT 172 IU/L, AST 135

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

IU/L, ALP 343 IU/L, γ-GTP 524 IU/L and total bilirubin 8.6 mg/dL on Day 35. The maximum trough concentration of serum ITZ was 0.069 μM (48.9 ng/mL) (Fig. 1L), which was much lower than those in Patients 1 and 2, and it is possible that brotizolam-induced liver injury that occurred before ITZ-administration might have increased the sensitivity to the cholestatic effect of ITZ.

Effect of ITZ on the bile flow rate and biliary secretion of bile acids and phospholipids. ITZ has been reported to cause cholestatic liver injuries (Gallardo-Quesada et al., 1995; Hann et al., 1993; Lavrijsen et al., 1992; Srebrnik et al., 2005) and our clinical data also suggested a cholestatic effect of ITZ with elevations of ALP, γ-GTP and direct bilirubin (Fig. 1). In order to characterize the effect of ITZ in *in vivo* experiments, we analyzed the secretions of biliary lipids in rats whose plasma concentration of ITZ was set at around 11 μM, which was confirmed by UPLC-MS/MS. This concentration should correspond to the peak plasma concentration of ITZ in Patients 1 and 2; since the peak concentration (C_{max}) is estimated to be 3 to 4-fold higher than the trough concentration after once-daily dosing (Yamaguchi et al., 2006), the C_{max} values of ITZ in the two patients are expected to be as high as 11 μM.

Our *in vivo* experiments indicated that the bile flow rate was significantly decreased at 30 min after starting ITZ-administration (ITZ-treated vs. control rats = 55.1 ± 7.4% vs. 81.2 ± 5.4% of the initial bile flow rate) and this effect continued during the

2-hr infusion (Fig. 2A). Although the output of bile acids was decreased in the ITZ-administered rats (ITZ-treated vs. control rats = 60.6 ± 14.8% vs. 85.5 ± 10.0% of the initial secretion) at 30 min, effects were more significant in the phospholipids output (ITZ-treated vs. control rats = 49.9 ± 8.3% vs. 102.8 ± 3.2% of the initial secretion) and cholesterol output (ITZ-treated vs. control rats = 44.8 ± 8.2% vs. 96.8 ± 5.4% of the initial secretion) (Fig. 2B-D). In order to exclude the possibility that the acute hepatotoxicity of ITZ secondarily caused the changes in biliary components, LFTs (AST, ALT, ALP, γ-GTP and total bilirubin) and liver ATP levels were analyzed in ITZ-administered rats. It was indicated that no significant changes were observed by the administration of ITZ (Supplemental Table 1 and Supplemental Figure 1). On the other hand, plasma bile acids were slightly increased in ITZ-administered rats (Supplemental Figure 2), which may be accounted for by considering the secondary effect caused by the reduction in the biliary secretion of bile acids (Fig. 2B).

Since the secretions of biliary lipids are known to be mediated by ABC transporters expressed on the bile canalicular membrane, our *in vivo* data suggest that ITZ has some inhibitory effects on these transporters.

Effect of ITZ on MDR3-mediated efflux of PC *in vitro*. Some of the drug-induced cholestasis may result from the inhibition of MDR3 and/or BSEP, since the genetic disruption of these transporters causes PFIC diseases. In order to examine the effect of

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

ITZ on MDR3-mediated transport, we investigated the efflux of PC, a major component of phospholipids in bile (Oude Elferink and Paulusma, 2007), from LLC-MDR3 cells in the presence of ITZ. Results of the Western blot analysis suggested that MDR3 was predominantly expressed as an approximately 140 kDa protein, which may represent the mature, and fully-glycosylated form (Fig. 3A) (Morita et al., 2007). In addition, results of immunostaining showed the localization of MDR3 protein on the apical membrane of LLC-PK1 cells (Fig. 3B), which mimic its physiological localization. Since MDR3 is known to mediate the efflux of PC in the presence of lipid acceptors *in vitro* (Morita et al., 2007; Smith et al., 1994; van Helvoort et al., 1996), we performed PC-efflux assay using taurocholate as an acceptor for PC. As shown in Fig. 3C, LLC-MDR3 cells exported twice as much PC as control LLC-EGFP cells and the MDR3-mediated transport was completely abolished in the presence of 5 μM verapamil, a well-established inhibitor of MDR3 (Morita et al., 2007; van Helvoort et al., 1996). Moreover, incubation with 0.04, 0.2, 1 and 5 μM of ITZ caused a concentration-dependent increase in the cellular concentration of ITZ confirmed by UPLC-MS/MS (data not shown). In addition, 0.2, 1 and 5 μM ITZ inhibited the function of MDR3 in a concentration-dependent manner (Fig. 3C). This concentration range of ITZ, which exhibited the inhibitory effects on MDR3, should correspond to the *in vivo* experiments using rats (Fig. 2), since the unbound concentration of ITZ in rat liver was calculated to be 0.29 μM; this value was calculated by multiplying the ITZ

concentration in rat liver in the present analysis (119 ± 14 μM) by the unbound fraction of ITZ in rat liver (0.0024) reported by Yamano et al. (Yamano et al., 1999). Collectively, the inhibition of MDR3 function *in vitro* and the disturbance of biliary phospholipids secretion *in vivo* were observed over a similar range of ITZ concentrations, suggesting that ITZ may be involved in the cholestatic liver injury via the inhibition of MDR3-mediated biliary secretion of phospholipids.

Effect of ITZ on BSEP-mediated efflux of taurocholate *in vitro*. Furthermore, we examined the effect of ITZ on BSEP function using LLC-BSEP/NTCP cells. The expressions of BSEP fused with EGFP (approximately 180 kDa protein) and NTCP (approximately 50 kDa protein), which is an uptake transporter of bile acids (Boyer et al., 1994), were confirmed by the Western blot analyses (Fig. 4A). In addition, the results of immunostaining studies indicated that BSEP and NTCP are expressed on the apical and basal membranes of LLC-BSEP/NTCP cells, respectively, which correspond to the expression under physiological conditions (Fig. 4B). The effect of ITZ on the transcellular transport of taurocholate was examined in LLC-BSEP/NTCP cells, after confirming that the cellular concentrations of ITZ were almost the same as those in LLC-MDR3 cells. It was found that the basal-to-apical transport of taurocholate ($PS_{b\text{-}a}$) across LLC-BSEP/NTCP was not significantly affected by ITZ (Fig. 4C). Considering that the cellular concentration (C_{cell}) and apical membrane-mediated

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

transport of taurocholate (PS_{apical}) were not significantly affected by 0.04-5 μM ITZ (Fig. 4D-E), the effect of ITZ on both BSEP-mediated excretion and NTCP-mediated uptake of bile acids appeared to be minor, if any.

Collectively, these *in vitro* results indicated that ITZ inhibits MDR3 funcion at much lower concentrations (Fig. 3C) compared with those required to inhibit BSEP function (Fig. 4E), which may explain the *in vivo* observations that ITZ had more significant influence on the biliary secretion of phospholipids than that of bile acids in rats.

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Discussion

In the present study, we found two patients suffering from ITZ-induced cholestatic liver injury whose serum ITZ concentrations were increased 3 to 4-fold compared with the normal range in clinical situations (Fig. 1D and 1H, Patient 1 and Patient 2) (Yamaguchi et al., 2006). Based on these results, we conducted *in vivo* and *in vitro* studies to examine the effect of ITZ on biliary secretion. It was found that the biliay secretion of phospholipids, rather than bile acids, was markedly reduced in ITZ-administered rats (Fig. 2), and ITZ was shown to inhibit MDR3-mediated efflux of PC in the *in vitro* assays (Fig. 3) without significantly affecting BSEP-mediated apical transport of taurocholate (Fig. 4).

According to the previous reports, ITZ-induced liver injury was associated with significant elevations of ALP, γ-GTP and total bilirubin, which suggest the cholestatic effect of ITZ (Gallardo-Quesada et al., 1995; Hann et al., 1993; Lavrijsen et al., 1992; Srebrnik et al., 2005). In addition, the liver biopsy specimens from patients with ITZ-induced liver injury showed histological patterns of cholestasis (Adriaenssens et al., 2001). In the present study, in Patients 1, 2 and 3, ALP, γ-GTP and total bilirubin were increased during ITZ-administration (Fig. 1), suggesting that cholestasis might be involved in the acquisition and aggravation of those liver injuries. However, ALT and AST levels, which are regarded as the markers of hepatocellular damage, were also elevated, particularly in Patient 2. These results suggest the possibility that ITZ causes

liver injuries not only by the cholestatic mechanisms but also by direct damage to hepatocytes.

It was found that the serum ITZ concentrations in Patients 1 and 2 were much higher than the mean concentrations in Japanese patients (Yamaguchi et al., 2006). The reasons for such increase in ITZ concentrations are unclear; drug-drug interactions between ITZ and the co-administered drugs via its metabolic pathway are not reported, since ITZ is supposed to be predominantly metabolized by CYP3A4 (Nivoix et al., 2008) and none of the co-administered drugs are reported to inhibit this enzyme. In addition, drug-drug interactions via the inhibition of efflux transporters may be unlikely, since ITZ is predominantly eliminated from the body by metabolic conversion. Therefore, we could not attribute the increases in serum ITZ concentrations in Patients 1 and 2 to some drug-drug interactions.

To examine the possibility that Patients 1, 2 and 3 had some genetic factors in *MDR3* gene to increase the risk of ITZ-induced cholestasis, SNPs in the gene were analyzed by DMET Plus DNA microarray using the patients' genomic specimens. According to the analyses, some alleles that are minor in Asian population were found in *MDR3* genes of Patients 1 and 2 (rs2109505, rs2302387, rs4148808 and rs4148805) (Supplemental Table 2). Among them, two SNPs are silent mutations in the coding region (rs2109505 and rs2302387) and the others are in the upstream region (rs4148808 and rs4148805). Although there has been no report analyzing the effects of these

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

SNPs, it is still possible that they may affect the expression level of MDR3 protein. In addition, SNPs in *CYP3A4* gene which might affect the metabolism of ITZ were analyzed; all patients carried *CYP3A4*1/*1* (wild-type) alleles.

In order to examine the effect of ITZ under *in vivo* conditions, rats were administered with ITZ and exhibited a significant reduction in the secretion of phospholipids, rather than bile acids (Fig. 2). Since these *in vivo* experiments were performed in the range of ITZ concentration similar to those in Patients 1 and 2 (Fig. 1), the inhibition of the secretion of biliary phospholipids may also occur under clinical situations. Elevations in LFTs (AST, ALT, ALP, γ-GTP and total bilirubin) were not observed after the 2-hr infusion of ITZ into rats (Supplemental Table 1), suggesting that the acute liver damage might not take place in the *in vivo* experiments. In the same manner, Somchit et al. reported that elevations in LFTs and histological changes (hepatocellular necrosis, degeneration of periacinar and mizonal hepatocytes, bile duct hyperplasia and biliary cirrhosis and giant cell granuloma) were observed in rats with a subchronic administration of ITZ, but not with a single administration of ITZ (Somchit et al., 2004). It is possible that subchronic inhibition of MDR3-mediated biliary secretion of phospholipids by ITZ may result in the acquisition of liver injury.

To reveal the inhibitory effect of ITZ on MDR3-mediated transport, *in vitro* studies were performed using MDR3-expressing LLC-PK1 cells (Fig. 3C). ITZ significantly inhibited the MDR3-mediated efflux of PC at 0.2 μM, which was similar

to the intrahepatic unbound concentration in our *in vivo* experiments (0.29 μM, see Results). In contrast, the inhibitory effect of ITZ on the BSEP-mediated apical transport of taurocholate appeared to be weak (Fig. 4E). Collectively, our *in vitro* data suggest that ITZ is involved in the acquisition of cholestasis via the inhibition of MDR3 rather than BSEP.

Considering the results of our *in vivo* data in humans and rats and the *in vitro* data, it is possible that the inhibitory effect of ITZ on MDR3-mediated biliary phospholipids secretion contributes to the development of cholestasis. Although delayed elevations in LFTs in Patients 1 and 2 were observed several weeks after starting ITZ-administration, such delays may be explained by hypothesizing that the damage to the bile canalicular membrane via the inhibition of MDR3 acts as one of the factors for the progression of liver injury, which is gradually reflected to abnormal LFTs. Additionally, other mechanisms, such as cellular stress and activation of immune system (Gunawan and Kaplowitz, 2007), are also supposed to play a role in clinical situations.

Since both MDR3 and BSEP play essential roles in the process of bile formation, inhibition of their functions may be related to cholestasis induced by not only ITZ, but also other clinically-used drugs. At the present moment, little is known on the inhibition of MDR3 by cholestatic drugs, although several drugs have been reported to inhibit BSEP function. For example, troglitazone, which was withdrawn from the market due to its hepatotoxicity, and its sulfate metabolite were shown to inhibit rat

Bsep *in vitro* at concentrations similar to the intrahepatic concentration in a troglitazone-induced cholestatic rat model (Funk et al., 2001). Additionally, some other cholestatic drugs such as cyclosporine A, rifampicin, glibenclamide and chlorpromazine are reported to have inhibitory effects on BSEP *in vitro* (Byrne et al., 2002; Horikawa et al., 2003; Stieger et al., 2000; Wang et al., 2003), although their Ki or IC_{50} values are much higher than those observed under *in vivo* conditions. Taking into consideration the fact that γ-GTP, a cholestatic marker, is elevated in MDR3-deficient type PFIC (PFIC3), but not in BSEP-deficient type (PFIC2) in general (Oude Elferink et al., 2006), it is possible that these drugs may inhibit MDR3 at clinically-relevant Ki or IC_{50} values, which is lower than for BSEP inhibition.

Although little information is available for drugs causing MDR3 inhibition, there are some candidate drugs. Since MDR3/ABCB4 has the closest similarity to MDR1/ABCB1 among genes in the ABC transporter family and is known to have some overlapping substrate specificities with MDR1, such as digoxin, paclitaxel, and vinblastine (Smith et al., 2000), cholestatic drugs which can act as MDR1 inhibitors may also inhibit MDR3-mediated biliary secretion of phospholipids. In fact, ITZ is a potential inhibitor of MDR1 (Gupta et al., 1991; Iida et al., 2001; Takara et al., 1999) as well as MDR3. Furthermore, tacrine, which often increases LFTs, may also have an inhibitory effect on MDR3; its risk of hepatotoxicity was particularly high in humans carrying some variants of the *MDR3* gene (Alfirevic et al., 2007). The *in vitro*

experimental system used in the present study may be useful in determining the inhibitory effect of various compounds on MDR3 function.

In conclusion, the results of the present study suggest that the inhibition of MDR3-mediated biliary secretion of phospholipids by ITZ may contribute to its cholestatic effect. The possibility of MDR3 inhibition, in addition to BSEP inhibition, should be taken into account for a better understanding of the mechanism of drug-induced cholestasis. The *in vitro* cell systems constructed in the present study should be useful for evaluating cholestatic potential of clinically-used drugs and drug candidates under development.

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Authorship contributions

Participated in research design: Yoshikado, Takada, Yamamoto, Ito, Yokota, Yatomi, Yoshida, Goto, Tsuji, and Suzuki.

Conducted experiments: Yoshikado, and Yamamoto.

Contributed new reagents or analytic tools: Yamaji, and Ito.

Performed data analysis: Yoshikado, Takada, Yamamoto, Santa, and Suzuki.

Wrote or contributed to the writing of the manuscript: Yoshikado, Takada, and Suzuki.

References

Adriaenssens B, Roskams T, Steger P and Van Steenbergen W (2001) Hepatotoxicity related to itraconazole: report of three cases. *Acta Clin Belg* **56**(6):364-369.

Alfirevic A, Mills T, Carr D, Barratt BJ, Jawaid A, Sherwood J, Smith JC, Tugwood J, Hartkoorn R, Owen A, Park KB and Pirmohamed M (2007) Tacrine-induced liver damage: an analysis of 19 candidate genes. *Pharmacogenet Genomics* **17**(12):1091-1100.

Boyer JL, Ng OC, Ananthanarayanan M, Hofmann AF, Schteingart CD, Hagenbuch B, Stieger B and Meier PJ (1994) Expression and characterization of a functional rat liver Na+ bile acid cotransport system in COS-7 cells. *Am J Physiol* **266**(3 Pt 1):G382-387.

Byrne JA, Strautnieks SS, Mieli-Vergani G, Higgins CF, Linton KJ and Thompson RJ (2002) The human bile salt export pump: characterization of substrate specificity and identification of inhibitors. *Gastroenterology* **123**(5):1649-1658.

Fouassier L, Kinnman N, Lefevre G, Lasnier E, Rey C, Poupon R, Elferink RP and Housset C (2002) Contribution of mrp2 in alterations of canalicular bile formation by the endothelin antagonist bosentan. *J Hepatol* **37**(2):184-191.

Funk C, Ponelle C, Scheuermann G and Pantze M (2001) Cholestatic potential of troglitazone as a possible factor contributing to troglitazone-induced hepatotoxicity: in vivo and in vitro interaction at the canalicular bile salt export

pump (Bsep) in the rat. *Mol Pharmacol* **59**(3):627-635.

Gallardo-Quesada S, Luelmo-Aguilar J and Guanyabens-Calvet C (1995) Hepatotoxicity associated with itraconazole. *Int J Dermatol* **34**(8):589.

Gerloff T, Stieger B, Hagenbuch B, Madon J, Landmann L, Roth J, Hofmann AF and Meier PJ (1998) The sister of P-glycoprotein represents the canalicular bile salt export pump of mammalian liver. *J Biol Chem* **273**(16):10046-10050.

Gunawan BK and Kaplowitz N (2007) Mechanisms of drug-induced liver disease. *Clin Liver Dis* **11**(3):459-475, v.

Gupta S, Kim J and Gollapudi S (1991) Reversal of daunorubicin resistance in P388/ADR cells by itraconazole. *J Clin Invest* **87**(4):1467-1469.

Hann SK, Kim JB, Im S, Han KH and Park YK (1993) Itraconazole-induced acute hepatitis. *Br J Dermatol* **129**(4):500-501.

Horikawa M, Kato Y, Tyson CA and Sugiyama Y (2003) Potential cholestatic activity of various therapeutic agents assessed by bile canalicular membrane vesicles isolated from rats and humans. *Drug Metab Pharmacokinet* **18**(1):16-22.

Iida N, Takara K, Ohmoto N, Nakamura T, Kimura T, Wada A, Hirai M, Sakaeda T and Okumura K (2001) Reversal effects of antifungal drugs on multidrug resistance in MDR1-overexpressing HeLa cells. *Biol Pharm Bull* **24**(9):1032-1036.

Ikebuchi Y, Takada T, Ito K, Yoshikado T, Anzai N, Kanai Y and Suzuki H (2009) Receptor for activated C-kinase 1 regulates the cellular localization and function

of ABCB4. *Hepatol Res* **39**(11):1091-1107.

Lavrijsen AP, Balmus KJ, Nugteren-Huying WM, Roldaan AC, van't Wout JW and Stricker BH (1992) Hepatic injury associated with itraconazole. *Lancet* **340**(8813):251-252.

Lowry OH, Rosebrough NJ, Farr AL and Randall RJ (1951) Protein measurement with the Folin phenol reagent. *J Biol Chem* **193**(1):265-275.

Mita S, Suzuki H, Akita H, Hayashi H, Onuki R, Hofmann AF and Sugiyama Y (2006) Inhibition of bile acid transport across Na+/taurocholate cotransporting polypeptide (SLC10A1) and bile salt export pump (ABCB 11)-coexpressing LLC-PK1 cells by cholestasis-inducing drugs. *Drug Metab Dispos* **34**(9):1575-1581.

Mita S, Suzuki H, Akita H, Stieger B, Meier PJ, Hofmann AF and Sugiyama Y (2005) Vectorial transport of bile salts across MDCK cells expressing both rat Na+-taurocholate cotransporting polypeptide and rat bile salt export pump. *Am J Physiol Gastrointest Liver Physiol* **288**(1):G159-167.

Morita SY, Kobayashi A, Takanezawa Y, Kioka N, Handa T, Arai H, Matsuo M and Ueda K (2007) Bile salt-dependent efflux of cellular phospholipids mediated by ATP binding cassette protein B4. *Hepatology* **46**(1):188-199.

Nivoix Y, Leveque D, Herbrecht R, Koffel JC, Beretz L and Ubeaud-Sequier G (2008) The enzymatic basis of drug-drug interactions with systemic triazole antifungals.

Clin Pharmacokinet **47**(12):779-792.

Noe J, Stieger B and Meier PJ (2002) Functional expression of the canalicular bile salt export pump of human liver. *Gastroenterology* **123**(5):1659-1666.

Oude Elferink RP and Paulusma CC (2007) Function and pathophysiological importance of ABCB4 (MDR3 P-glycoprotein). *Pflugers Arch* **453**(5):601-610.

Oude Elferink RP, Paulusma CC and Groen AK (2006) Hepatocanalicular transport defects: pathophysiologic mechanisms of rare diseases. *Gastroenterology* **130**(3):908-925.

Smit JJ, Schinkel AH, Oude Elferink RP, Groen AK, Wagenaar E, van Deemter L, Mol CA, Ottenhoff R, van der Lugt NM, van Roon MA and et al. (1993) Homozygous disruption of the murine mdr2 P-glycoprotein gene leads to a complete absence of phospholipid from bile and to liver disease. *Cell* **75**(3):451-462.

Smith AJ, Timmermans-Hereijgers JL, Roelofsen B, Wirtz KW, van Blitterswijk WJ, Smit JJ, Schinkel AH and Borst P (1994) The human MDR3 P-glycoprotein promotes translocation of phosphatidylcholine through the plasma membrane of fibroblasts from transgenic mice. *FEBS Lett* **354**(3):263-266.

Smith AJ, van Helvoort A, van Meer G, Szabo K, Welker E, Szakacs G, Varadi A, Sarkadi B and Borst P (2000) MDR3 P-glycoprotein, a phosphatidylcholine translocase, transports several cytotoxic drugs and directly interacts with drugs

as judged by interference with nucleotide trapping. *J Biol Chem* **275**(31):23530-23539.

Somchit N, Norshahida AR, Hasiah AH, Zuraini A, Sulaiman MR and Noordin MM (2004) Hepatotoxicity induced by antifungal drugs itraconazole and fluconazole in rats: a comparative in vivo study. *Hum Exp Toxicol* **23**(11):519-525.

Song JC and Deresinski S (2005) Hepatotoxicity of antifungal agents. *Curr Opin Investig Drugs* **6**(2):170-177.

Srebrnik A, Levtov S, Ben-Ami R and Brenner S (2005) Liver failure and transplantation after itraconazole treatment for toenail onychomycosis. *J Eur Acad Dermatol Venereol* **19**(2):205-207.

Stieger B, Fattinger K, Madon J, Kullak-Ublick GA and Meier PJ (2000) Drug- and estrogen-induced cholestasis through inhibition of the hepatocellular bile salt export pump (Bsep) of rat liver. *Gastroenterology* **118**(2):422-430.

Takara K, Tanigawara Y, Komada F, Nishiguchi K, Sakaeda T and Okumura K (1999) Cellular pharmacokinetic aspects of reversal effect of itraconazole on P-glycoprotein-mediated resistance of anticancer drugs. *Biol Pharm Bull* **22**(12):1355-1359.

van Helvoort A, Smith AJ, Sprong H, Fritzsche I, Schinkel AH, Borst P and van Meer G (1996) MDR1 P-glycoprotein is a lipid translocase of broad specificity, while MDR3 P-glycoprotein specifically translocates phosphatidylcholine. *Cell*

87(3):507-517.

Wagner H, Hoerhammer L and Wolff P (1961) [Thin layer chromatography of phosphatides and glycolipids.]. *Biochem Z* **334**:175-184.

Wang EJ, Casciano CN, Clement RP and Johnson WW (2003) Fluorescent substrates of sister-P-glycoprotein (BSEP) evaluated as markers of active transport and inhibition: evidence for contingent unequal binding sites. *Pharm Res* **20**(4):537-544.

Wang R, Salem M, Yousef IM, Tuchweber B, Lam P, Childs SJ, Helgason CD, Ackerley C, Phillips MJ and Ling V (2001) Targeted inactivation of sister of P-glycoprotein gene (spgp) in mice results in nonprogressive but persistent intrahepatic cholestasis. *Proc Natl Acad Sci U S A* **98**(4):2011-2016.

Yamaguchi H, Enomoto S, Kaku M, Sakamaki H, Tanaka K and Yoshida M (2006) An open randomized parallel-comparison study of itraconazole oral solution versus itraconazole capsules in treatment of patients with oropharyngeal candidiasis. *Jpn J Chemother* **54**(S-1):18-31.

Yamano K, Yamamoto K, Kotaki H, Sawada Y and Iga T (1999) Quantitative prediction of metabolic inhibition of midazolam by itraconazole and ketoconazole in rats: implication of concentrative uptake of inhibitors into liver. *Drug Metab Dispos* **27**(3):395-402.

Footnotes

This work was financially supported by the research grant, Research on Human Genome Tailor Made, from the Ministry of Health, Labor and Welfare [H19-Genome-Ippan-004].

Legends for Figures

Figure 1 ----- Profiles of liver function tests (LFTs) and serum ITZ concentrations in DILI patients. Patient 1 (A-D), Patient 2 (E-H) and Patient 3 (I-L) received ITZ-administration and exhibited elevations in LFTs. (A), (E) and (I), serum levels of ALT and AST. (B), (F) and (J), serum levels of ALP and γ-GTP. (C), (G) and (K), serum levels of total bilirubin (T.B.), indirect bilirubin (I.B.) and direct bilirubin (D.B.). (D), (H) and (L), circles represent the serum ITZ concentrations, whereas the dotted lines show the daily dose of ITZ. The arrows in I-L indicate the period of brotizolam-administration.

Figure 2 ----- Effect of ITZ on the bile formation and biliary secretion of phospholipids and bile acids in rats. ITZ (closed symbols) or control solution (open symbols) was administered to rats and the bile secretion was analyzed. The initial value of each panel is defined as 100%. (A) Bile flow rate. The initial value was 2.45 ± 0.52 mL/hr/kg. (B) Biliary secretion of bile acids. The initial value was 0.62 ± 0.27 μmol/min/kg. (C) Biliary secretion of phospholipids. The initial value was 140 ± 52 nmol/min/kg. (D) Biliary secretion of cholesterol. The initial value was 12.6 ± 3.9 nmol/min/kg. Data are shown as the mean ± S.D. of 4 independent experiments. $^{**}p < 0.01$ and $^{*}p < 0.05$, significantly different from control by Student's t-test.

Figure 3 ----- Effect of ITZ on MDR3-mediated efflux of PC. The expression of MDR3 was determined in LLC-MDR3 cells and the effect of ITZ on MDR3-mediated efflux of PC was examined. (A) Western blot analysis was performed to examine the expression of MDR3 protein in LLC-PK1 cells. (B) Subcellular localization of MDR3 protein was examined by immunofluorescence. The Z-section images are shown. Green and blue fluorescence represent MDR3 and nuclei, respectively. Bar = 10 μm. (C) Efflux of [^{14}C]PC by MDR3-expressing cells was examined at 37°C for 3 hr. Cells were incubated with ITZ or verapamil at indicated concentrations. The data are presented as mean ± S.E. (n = 6). **$p < 0.01$, significantly different from non-treated MDR3-expressing cells by ANOVA followed by Dunnett's test. *$p < 0.05$, significantly different from MDR3-expressing cells treated with 0.2 μM ITZ by ANOVA followed by SNK test.

Figure 4 ----- Effect of ITZ on BSEP/NTCP-mediated transcellular transport of taurocholate. The expression of BSEP/NTCP was determined in the LLC-BSEP/NTCP cells and the effect of ITZ on BSEP/NTCP-mediated transport of tauchocholate was examined. (A) Western blot analysis was performed to examine the expression of BSEP and NTCP protein in LLC-PK1 cells. (B) Subcellular localization of BSEP and NTCP protein was examined by immunofluorescence. The Z-section

images are shown. Green, red and blue fluorescence represent BSEP, NTCP and nuclei, respectively. Bars = 10 μm. (C)-(E) Transport of [^{3}H]taurocholate by NTCP- and BSEP/NTCP-expressing cells was examined at 37°C for 3 hr. Cells were incubated with ITZ at indicated concentrations. PS_{b-a} of [^{3}H]taurocholate (Panel C), C_{cell}, of [^{3}H]taurocholate (Panel D) and PS_{apical} of [^{3}H]taurocholate (Panel E) are shown. The data are presented as mean ± S.E. (n = 7). **$p < 0.01$ and *$p < 0.05$, significantly different from non-treated BSEP/NTCP-expressing cells by ANOVA followed by Dunnett's test.

Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Table 1. Profiles of drug administration to the patients.

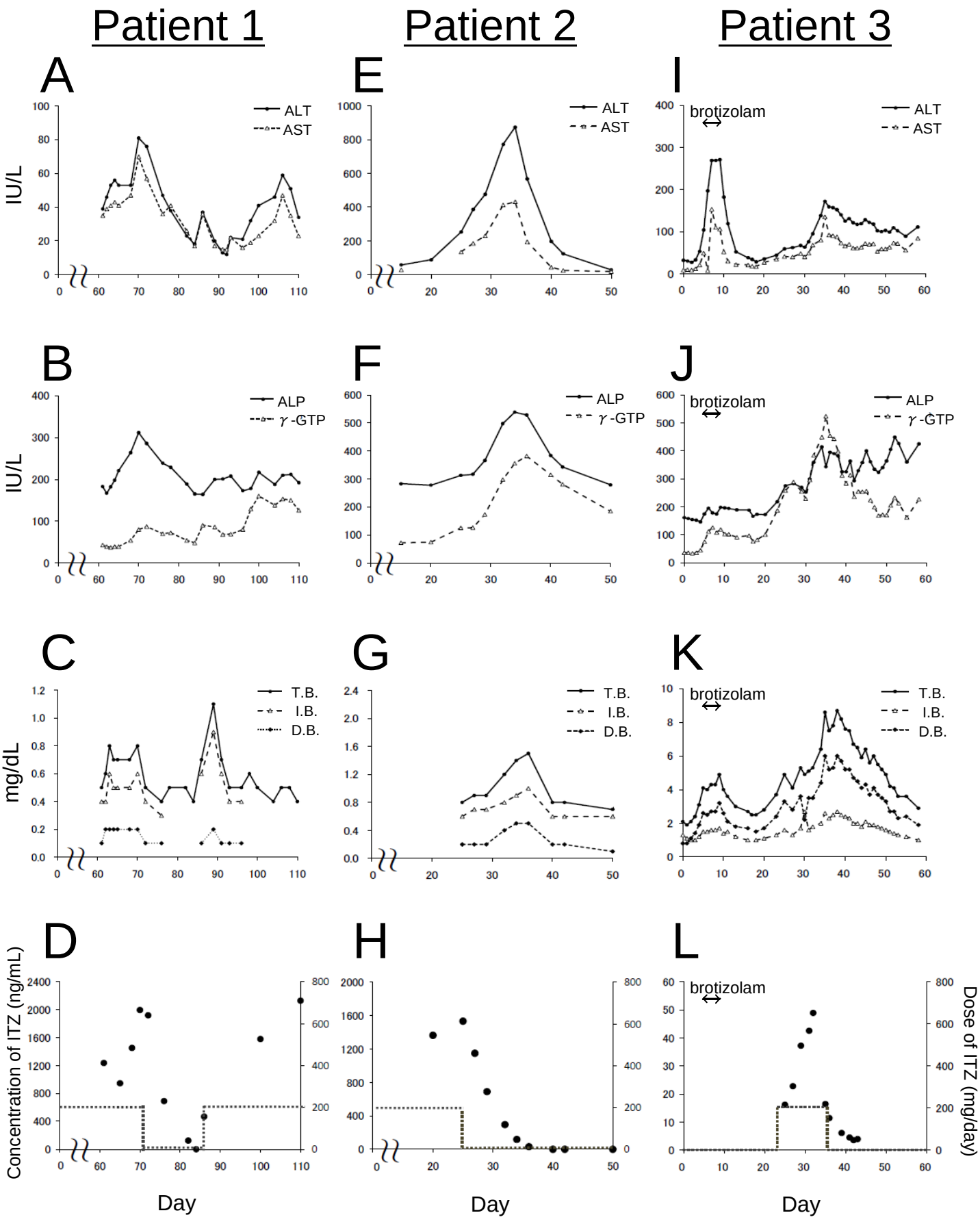
Patient No.	Age/sex	* Period of ITZ administration	* Time to elevated LFTs from starting ITZ	Other medication
1	67/F	Day 0-71, Day 86-110	62 days	furosemide, spironolactone, demethylchlortetracycline
2	43/M	Day 0-24	20 days	famotidine
3	36/F	** Day 23-36	** 2 days	cyclosporin A, omeprazole, zolpidem, sulfamethoxazole/tripethoprim, cefepime, vancomycin, ganciclovir, methylprednisolone

* Also see Figure 1.

** Before starting the administration of ITZ, Patient 3 received the administration of brotizolam on Day 5-8 and experienced brotizolam-induced liver injury.

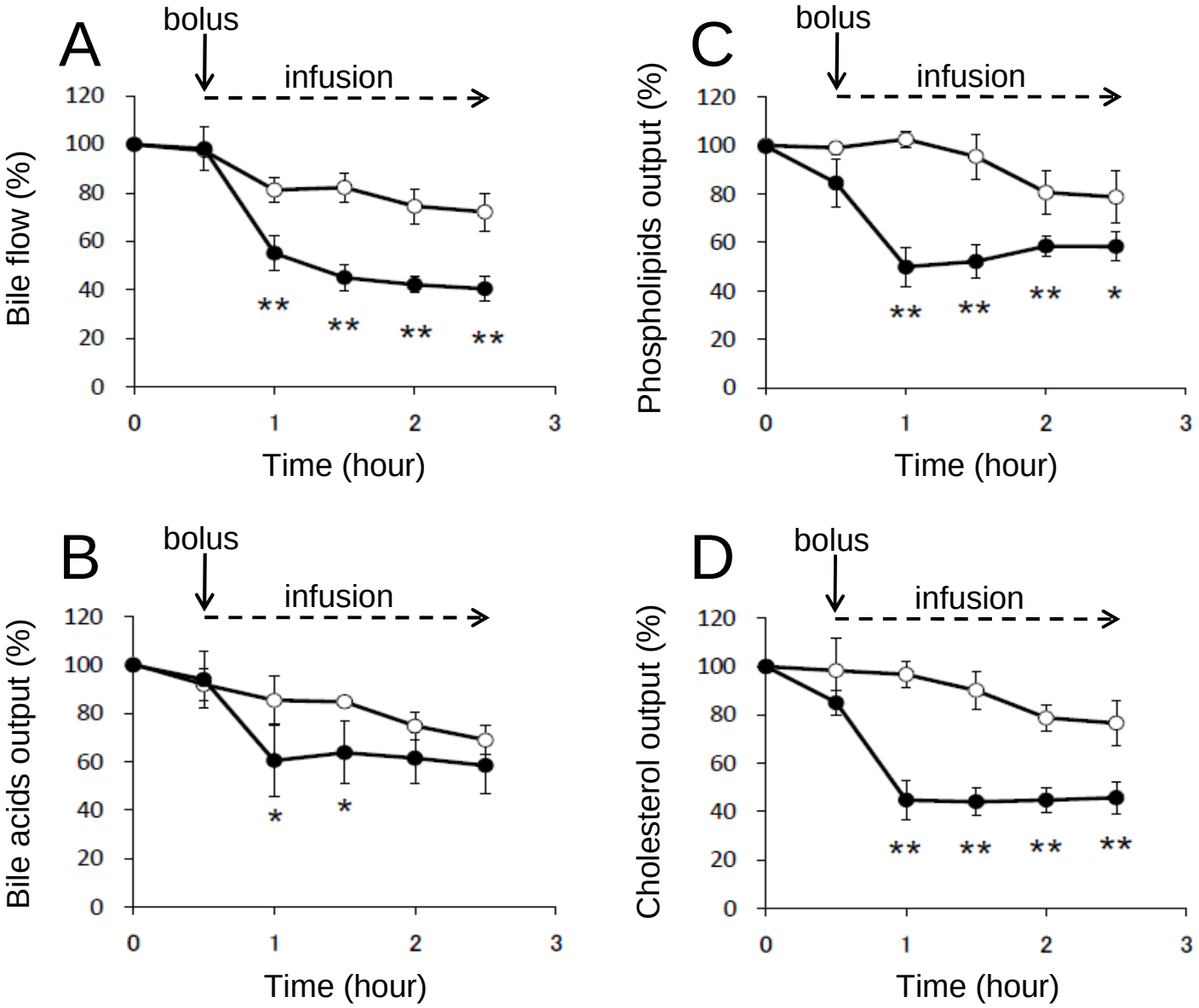
Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Figure 1



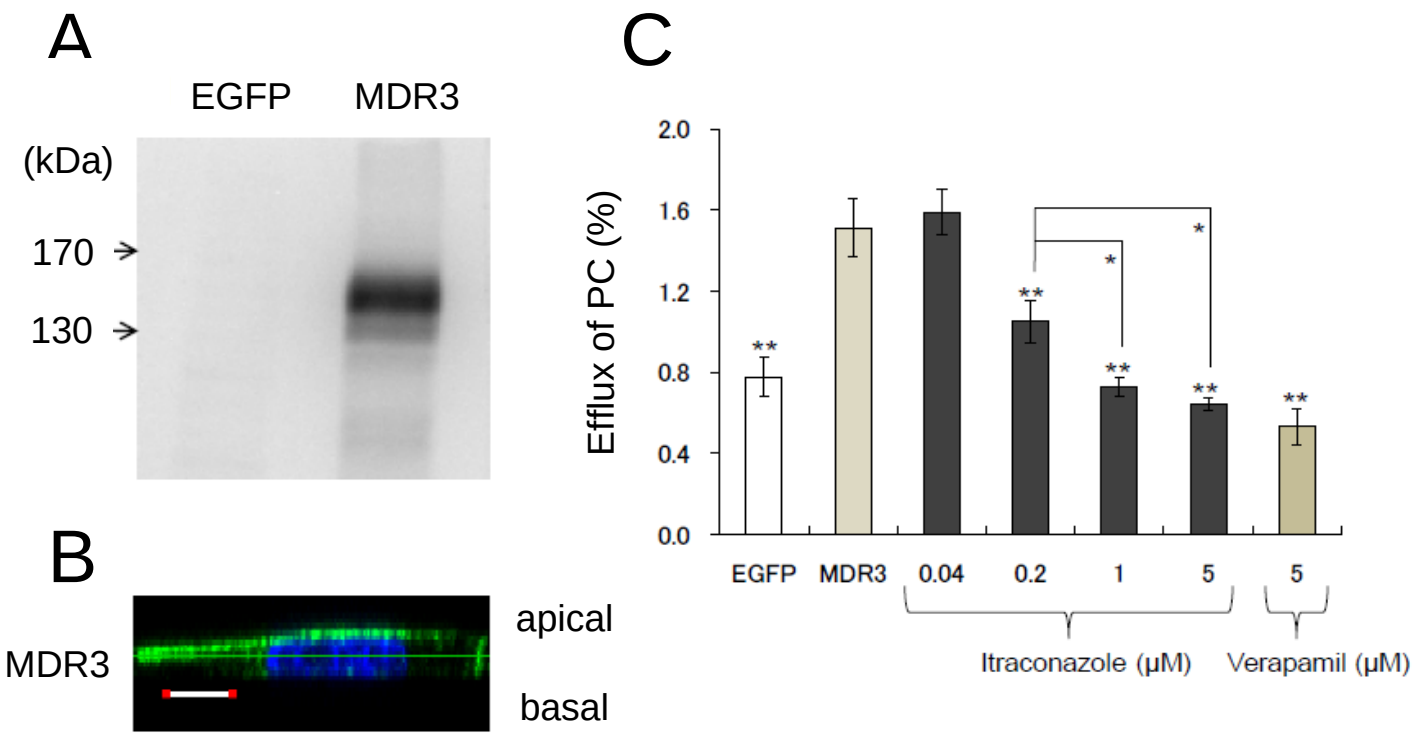
Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Figure 2



Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Figure 3



Molecular Pharmacology Fast Forward. Published on November 5, 2010 as DOI: 10.1124/mol.110.067256
This article has not been copyedited and formatted. The final version may differ from this version.

Figure 4