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Title page

Regulation of Breast Cancer Resistant Protein (BCRP) by Peroxisome Proliferator-Activated
Receptor Alpha (PPAR α) in Human Brain Microvessel Endothelial Cells

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Running title page

Running title: PPAR α Regulates BCRP at the Human Brain Endothelium

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List of non-standard abbreviations

ABC, ATP-Binding Cassette

BCRP/ABCG2, breast cancer resistance protein

P-gp, p-glycoprotein

BBB, blood-brain barrier

CNS, central nervous system

PPAR α , peroxisome proliferator-activated receptor alpha

PPAR γ , peroxisome proliferator-activated receptor gamma

hCMEC/D3, human cerebral microvessel endothelial cells

BBB-ECs, human brain-derived microvascular endothelial cells

MX100, BCRP overexpressing human breast adenocarcinoma cell line (MCF-7) cells

HepG2, hepatocellular carcinoma cells

GW7647, 2-methyl-2-[[4-[2-[[[(cyclohexylamino)carbonyl](4-cyclohexylbutyl)amino]-ethyl]phenyl]thio]-propanoic acid

GW6471, [(2S)-2-[[[(1Z)-1-methyl-3-oxo-3-[4-(trifluoromethyl)phenyl]-1-propenyl]amino]-3-[4-[2-(5-methyl-2-phenyl-4-oxazolyl)ethoxy]phenyl]propyl]-carbamic acid ethyl ester

MK886, 1-[(4-chlorophenyl)methyl]-3-[(1,1-dimethylethyl)thio]- α,α -dimethyl-5-(1-methylethyl)-

1H-indole-2-propanoic acid, sodium salt

MTT, (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide

siRNA, small interfering RNA

qPCR, quantitative real-time PCR

ChIP, chromatin immunoprecipitation

Abstract

Breast cancer resistance protein (BCRP/ABCG2), an ATP-Binding Cassette (ABC) membrane-associated drug efflux transporter, is known to localize at the blood-brain barrier (BBB) and can significantly restrict xenobiotic permeability in the brain. The objective of this study is to investigate the regulation of BCRP functional expression by peroxisome proliferator-activated receptor alpha (PPAR α), a ligand-activated transcription factor primarily involved in lipid metabolism, in a cerebral microvascular endothelial cell culture system (hCMEC/D3), representative of human BBB. We demonstrate that PPAR α selective ligands (i.e., clofibrate, GW7647) significantly induce BCRP mRNA and protein expression in a time and concentration-dependent manner, while pharmacological inhibitors (i.e., MK886; GW6471) prevent this induction. Using [3 H]-mitoxantrone, an established BCRP substrate, we observe a significant reduction in its cellular accumulation by monolayer cells treated with clofibrate suggesting increased BCRP efflux activity. Furthermore, we show a significant decrease in BCRP protein expression and function when PPAR α is downregulated by small interfering RNA. Applying chromatin-immunoprecipitation and quantitative real-time PCR, we observe that clofibrate treatment increases PPAR α binding to the peroxisome proliferator response element within ABCG2 gene promoter. This study provides the first evidence of direct BCRP regulation by PPAR α in a human *in vitro* BBB model and suggests new targeting strategies for either improving drug brain bioavailability or increasing neuroprotection.

Introduction

The blood-brain barrier (BBB) localized at the interface of the systemic circulation and brain parenchyma can significantly restrict the permeability of xenobiotics including several pharmacological agents in the central nervous system (CNS) (Pardridge, 2010). In addition to the physical barrier formed by the microvessel endothelial cells, drug penetration into the brain is highly regulated by a biochemical barrier mainly constituted of metabolic enzymes and influx/efflux transport proteins (Abbott et al., 2010). In particular, the membrane-associated efflux drug transporters, breast cancer resistance protein (BCRP) and P-glycoprotein (P-gp), expressed in brain microvessel endothelial cells, have long been recognized to play a significant role in preventing the permeability of several drugs across the BBB presenting a great challenge to the treatment of CNS disorders (Bendayan et al., 2002; Bendayan et al., 2006; Lee et al., 2007; Ronaldson et al., 2008; Vlaming et al., 2009; Miller, 2010)

BCRP/ABCG2 belongs to the G subfamily of the ATP binding cassette (ABC) transporter superfamily. The human ABCG2 gene is located on chromosome 4, band 4q21-4q22, and encodes a 70 kDa, 655 amino acid protein (Polgar et al., 2008). It is known as a half-transporter which upon homodimerization exerts its functional activity. In addition to its localization at the BBB, BCRP is expressed in a wide-range of tissues, including: intestine, liver, kidney, testis, placenta and mammary gland. BCRP is known to be involved in the elimination of many drugs including chemotherapeutic agents such as, mitoxantrone, methotrexate and irinotecan (Doyle et al., 1998; Maliepaard et al., 2001; Ishikawa, 2009).

Early studies have examined the effect of Bcrp on cerebral drug accumulation in animal models, using established substrates, such as dantrolene or the phytoestrogens: daidzein, genistein, and coumestrol. In *Abcg2* knockout mice, brain accumulation of these compounds

were remarkably higher (over 10-fold) compared to the wild-type animals (Enokizono et al., 2007;Enokizono et al., 2008).

Despite the apparent role of BCRP in protecting the brain from xenobiotic exposure, factors that regulate the expression and function of BCRP at both the gene and protein level are poorly defined and not well understood. Recent investigation from our laboratory as well as other groups has implicated nuclear hormone receptors such as: pregnane X receptor (PXR), constitutively active receptor (CAR), aryl hydrocarbon receptor (AhR) and estrogen receptor (ER) in the regulation of drug transporters expression and function in both human and rodent BBB models (Bauer et al., 2004;Bauer et al., 2006;Hartz et al., 2010;Wang et al., 2010;Wang et al., 2011;Chan et al., 2011).

The peroxisome proliferator activated receptor-alpha (PPAR α) belongs to the steroid hormone receptor superfamily (Robyr et al., 2000). At present, three subtypes of PPAR (alpha, beta/delta and gamma) have been identified in many species including humans (Kersten et al., 2000). Like other steroid hormone receptors, upon ligand activation, PPARs heterodimerize with the retinoid-X-receptor (RXR), bind to the specific promoter sequence called the peroxisome proliferator response element (PPRE) and as a result trigger the expression of the target genes. PPRE is composed of two direct repetitions (DR1) of the consensus sequence AGGTCA with a single nucleotide spacing between the two repeats (Schachtrup et al., 2004).

PPAR α is a ligand-activated transcription factor that primarily controls lipid homeostasis by regulating the expression of fatty acid metabolic enzymes (CYP4A isoforms) (Muerhoff et al., 1992). In addition, recent evidence suggests that PPAR α could also serve as a species-specific xenosensor and regulate the expression of membrane drug efflux transporters in the liver and intestine. For example, the prototypic PPAR α synthetic agonists, Wy14643, GW7647 and

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clofibrate, have been shown to induce the expression of Bcrp and multidrug resistant proteins 3 and 4 (Mrp3 and Mrp4) in mouse liver and intestine (Hirai et al., 2007;Moffit et al., 2006). However, direct molecular interaction between PPAR alpha and Bcrp was not demonstrated.

PPAR α is expressed in different compartments of rodent brain including olfactory bulbs, hippocampus, cerebellum, cerebellar granule neurons (Cullingford et al., 1998) as well as in astrocytes (Benani et al., 2003) and microglia (Bright et al., 2008). Also, this nuclear receptor has been reported to be expressed in human brain microvessel endothelial cells (Huang et al., 2008). However, the transcriptional activity of PPAR α in the regulation of drug efflux transporters at the human BBB is currently unknown. In this study, we investigate regulation of BCRP expression and function at the BBB, using a human cerebral microvessel endothelial cell culture system (hCMEC/D3) well characterized to retain several morphological and biochemical features of the human BBB (Weksler et al., 2005). Our results demonstrate that PPAR α is actively involved in the regulation of BCRP in this system. Selective modulation of BCRP expression at the BBB by PPAR α can potentially lead to the development of novel therapeutic strategies for overcoming restricted drug delivery to the brain or to enhance neuroprotection.

Materials and Methods

Materials

Type I collagen was purchased from Becton-Dickinson (Franklin Lakes, NJ, USA). Dimethyl sulfoxide (DMSO) and acrylamide solution were obtained from Bioshop Canada Inc. (Burlington, ON, Canada). Clofibrate; GW7647, 2-methyl-2-[[4-[2-[[[(cyclohexylamino)carbonyl](4-cyclohexylbutyl)amino]-ethyl]phenyl]thio]-propanoic acid); GW6471, [(2S)-2-[[[(1Z)-1-Methyl-3-oxo-3-[4-(trifluoromethyl)phenyl]-1-propenyl]amino]-3-[4-[2-(5-methyl-2-phenyl-4-oxazolyl)ethoxy]phenyl]propyl]-carbamic acid ethyl ester; MK 886, 1-[4-(chlorophenyl)methyl]-3-[(1,1-dimethylethyl)thio]- α,α -dimethyl-5-(1-methylethyl)-1H-indole-2-propanoic acid, sodium salt; (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT); chloroform; paraformaldehyde (37%); phenylmethanesulfonylfluoride (PMSF); Ko143; cold mitoxantrone; anti-Actin (AC40, mouse monoclonal) antibody and protease inhibitor cocktail were all purchased from Sigma-Aldrich Canada (Oakville, ON, Canada). Western blot stripping solution and enhanced chemiluminescent reagents were ordered from Pierce Thermo Fisher Scientific Inc. (Waltham, MA, USA). Hybond-P PVDF membrane and microscope cover glass slide (22x 22 mm, thickness #1) were supplied from GE Healthcare Life Sciences (Piscataway, NJ, USA) and Fisher Scientific (Pittsburgh, PA, USA), respectively. [³H]-mitoxantrone (12.7 Ci/mmol) was ordered from Moravek Biochemicals Inc. (Brea, California, USA). ABI high capacity reverse transcriptase cDNA kit and anti-P-gp antibody (C219) were obtained from Applied Biosystems (Foster City, California, USA) and I.D. Labs Inc. (London, ON, Canada), respectively. PerfeCTa SYBR green Fastmix was purchased from Quanta Biosciences Inc. (Gaithersburg, Maryland, USA). Anti-BCRP (BXP-53, rat monoclonal) and anti-Lamin-A (ab8980, mouse monoclonal) antibodies were purchased from Abcam Inc.

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(Boston, Massachusetts, USA). The rabbit polyclonal anti- Na^+/K^+ -ATPase- $\alpha 1$ (H-300) antibody was purchased from Santa Cruz Biotechnology (Santa Cruz, California, USA). Anti-P-glycoprotein antibody (C219, mouse monoclonal) was supplied from ID Labs (London, ON, Canada). The mouse monoclonal anti-PPAR α (H0723) and rabbit polyclonal anti-PPAR α (H-98) antibodies were obtained from Perseus Proteomics Inc. (Tokyo, Japan) and Santa Cruz Biotechnology, Inc. (Santa Cruz, CA, USA), respectively. The goat anti-mouse, anti-rat and anti-rabbit horseradish peroxidase-conjugated secondary antibodies were ordered from Jackson ImmunoResearch Inc. (West Grove, Pennsylvania, USA). Alexafluor-488 and Alexafluor-594-conjugated secondary antibodies, Trypsin (0.25%) and the TRIzol reagent were supplied from Invitrogen Inc. (Carlsbad, California, USA). Vectorshield mounting media containing 4',6-diamidino-2-phenylindole (DAPI) was ordered from Vector Labs Inc. (Burlingame, California, USA). Small interfering RNA (siRNA) against PPAR α (HSS108289) and non-silencing negative control siRNA (cat# AM4611) were purchased from Invitrogen (Carlsbad, California, USA) and Ambion (Carlsbad, CA, USA), respectively.

Methods

Cell Culture Systems. The immortalized human brain microvessel endothelial cell line, hCMEC/D3, was kindly provided by Dr. P.O. Couraud (Institut Cochin, Departement Biologie Cellulaire and INSERM, Paris, France). This cell line has been widely utilized as a potential *in vitro* model of human BBB and is known to display many morphological and biochemical properties of human brain microvascular endothelium *in vivo*, such as functional expression of tight junction proteins, endothelial cell markers and drug efflux transporters. Cells were used at passages 28-39 for all the experiments and were maintained at 37 °C, 5 % CO_2 , and 95 %

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humidified air in endothelial cell growth medium (Lonza, Walkersville, MD, USA) supplemented with vascular endothelial growth factor, insulin-like growth factor 1, epidermal growth factor, fibroblast growth factors, hydrocortisone, ascorbate, gentamycin (Lonza, Walkersville, MD, USA), and 2.5 % fetal bovine serum. Cells were grown on rat tail collagen type I coated 75 cm flasks, 150 cm dishes or 6 well plates as previously described (Weksler et al., 2005;Zastre et al., 2009;Chan et al., 2011). Whole cell pellets of primary cultures of human brain-derived microvascular endothelial cells (BBB-ECs) were generously provided by Dr. Alexandre Prat (Neuroimmunology Research Laboratory, Center of Excellence in Neuromics, Faculty of Medicine, Centre Hospitalier de l'Université de Montréal, Montréal, Québec, Canada). These cells were isolated from brain tissue samples obtained from young adults undergoing surgery for the treatment of intractable epilepsy and constitute an additional in vitro model of human brain microvascular endothelium. Informed consent and ethical approval were obtained from the patients prior to the surgery. Human fetal brain tissue samples were collected from consenting patients undergoing elective pregnancy termination (10-14 weeks of gestation age). Ethics approval was obtained from the University Health Network (Toronto, ON, Canada). The BCRP overexpressing human breast cancer cell line, MCF7-MX100, was a generous gift from Dr. Susan Bates (Bethesda, Maryland, USA). The cells were cultured and maintained in RPMI 1640 media supplemented with fetal bovine serum (10%), L-glutamine (1%), penicillin (100 U/ml), streptomycin (100 µg/ml) and mitoxantrone (100 nM). The HepG2 cells were cultured in alpha-minimum essential medium supplemented with 10% FBS and 1% penicillin/streptomycin.

Cell viability assay. Cell viability in the presence of the various ligands was assessed using an MTT assay in which cells were incubated for 2 h at 37 °C with a 2.5 mg/mL MTT

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solution in PBS. The formazan content, dissolved in DMSO, from each well was determined by UV analysis at 580 nm using a SpectraMax 384 microplate reader (Molecular Devices, Sunnyvale, CA). Cell viability was expressed as the ratio between the absorbance of treated cells and the absorbance of non-treated (control) cells.

Cell treatment. hCMEC/D3 monolayers grown on collagen coated six well plates, 75/175 cm flasks (approximately 80-90% confluence) were treated with PPAR α ligands (clofibrate or GW7647) or PPAR α antagonist (MK886/GW6471) or in combination with ligands and antagonists at specific time points (3 h - 72 h) and concentrations (1.25 nM – 125 μ M). At the beginning of each experiment, culture medium was aspirated and fresh medium containing ligands dissolved in ethanol or DMSO was added. Control cells were exposed to 0.1% (v/v) ethanol or DMSO (vehicle) in the absence of ligands. To ensure cells remain viable during treatment, all ligand concentrations used were tested applying the MTT assay as described above.

Total RNA extraction, cDNA synthesis and quantitative real-time polymerase chain reaction (qPCR). Total RNA was extracted from hCMEC/D3 cells using TRIzol reagent (Invitrogen) according to manufacturer's instructions. The concentration (absorbance at 260 nm) and purity (absorbance 260 nm / absorbance 280 nm ratio) of RNA samples were assessed using Beckman Coulter DU Series 700 UV/Vis Scanning Spectrophotometer (Mississauga, Ontario, Canada). Isolated total RNA was subjected to DNase I digestion (0.1 U/ml) according to manufacturer's instructions to remove genomic DNA. Reverse transcription was then performed with DNase-treated total RNA (2 μ g) in a final reaction volume of 40 μ l using an ABI high

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capacity reverse transcription cDNA kit according to manufacturer's instructions. All sample reactions were carried at 25 °C for 10 minutes, followed by 37 °C for 120 minutes and then 85 °C for 5 minutes using Mastercycler EP Realplex 2S thermal cycler (Eppendorf Canada, Mississauga, Ontario, Canada). ABCG2 and peptidylprolyl isomerase B (cyclophilin B) genes were quantified by qPCR on Mastercycler EP Realplex 2S thermal cycler using SYBR green fluorescence detection. The 10 µl final reaction mixtures contained 1.25 µl of diluted cDNA, 5 µl of PerfeCTa SYBR green Fastmix, 0.6 µl of 1.25 µM of each primer and 2.55 µl of nuclease-free water. Specific primers were designed using Primer Express 3 (Applied Biosystems, Foster City, California, USA) and were on exon-exon junctions to avoid any potential amplification of genomic DNA. The specificity of each reaction was assessed by melting curve analysis to ensure the presence of only a single amplification product. Validated primer sequences are shown in Table 1. CT values for ABCG2 mRNA are normalized to the housekeeping gene cyclophilin B. Results are expressed as percent fold change \pm standard error, using comparative CT method ($\Delta\Delta$ CT). Changes in ABCG2 mRNA expression were calibrated to vehicle-treated cells.

siRNA downregulation studies. Cells were plated in a 6-well plate with a density of 0.4×10^6 cells / well. After 24 h, cell monolayers at approx. 80% confluence were subjected to siRNA transfection. Transfection mix was prepared in Opti-MEM GlutaMax (Invitrogen) medium with siRNA and lipofectamine 2000 (Invitrogen) according to manufacturer's protocol. The final concentration of siRNA and lipofectamine added to the cells were 100 nM and 2 µl/ml, respectively. Cells were cultured in the presence of transfection mixture for 24 h, as described previously (Huang et al., 2009). The following day, transfection mixture was replaced by fresh pre-warm hCMEC/D3 medium and cell culture was pursued for an additional 48 h. After 72 h of

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siRNA transfection, cells were either harvested to analyze BCRP and PPAR α protein expression by immunoblotting or used for transport assays to determine mitoxantrone accumulation.

Chromatin immunoprecipitation (ChIP). Chromatin immunoprecipitation was carried out using a ChIP assay kit and protocol provided by Affymetrix (Affymetrix, Inc.). Briefly, hCMEC/D3 cells cultured on a 15 cm dish were treated with Clofibrate (100 μ M) or GW7647 (20 nM) for 3 h and subsequently cross-linked in 1% formaldehyde for 10 min at room temperature. Cross-linking was stopped by addition of glycine to a final concentration of 125 mM for 5 minutes at room temperature, and followed by washing the cells twice in ice-cold PBS. After scrapping and centrifugation, cells pellets were suspended in 1.0 ml lysis buffer containing protease inhibitor (Affymetrix). The chromatin was sheared to 200 – 1000 bp by sonication. The sonicated chromatin was diluted 2-fold in lysis buffer (Affymetrix); 600 μ l of diluted sample per immunoprecipitation was used. After 1-hour pre-clearing with protein A agarose beads (50 μ l/IP), 10 μ g of specific anti-PPAR α (H-98) antibody (Santa Cruz Biotechnology Inc.), previously validated in ChIP assays (Nagasawa et al., 2009), was added for overnight incubation. In parallel, a no antibody sample was run as control. Protein A agarose (50 μ l/IP) was used to recover the immune complexes (2 hours at 4°C). Washes and elutions were performed in accordance with the ChIP assay kit. Eluted (225 μ l) and input (40 μ l) DNA were reverse cross-linked overnight at 65 °C in presence of 0.2 M NaCl, and purified using a spin column to a final volume of 40 μ l. qPCR was performed using 2 μ l of template DNA per 25 μ l PCR amplification scale. Quantification of PPAR α occupancy to the peroxisome proliferator response elements within the ABCG2 gene promoter (-3946/-3796) by SYBR green real-time PCR was carried out using the following primer set: forward, 5'-AGG-GCA-GAG-GGC-AAT-GG-3' and reverse, 5'-

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AGG-AGA-CTG-ATT-TGC-ACA-AGG-TT-3' which amplifies a product of 150 bp (-3946/-3796). The detection of another region (-1527/-1268) of the same ABCG2 gene promoter, which serves as negative control, was included in similar PCR reactions using the following primer set: forward, 5'-CTC-CTC-CTG-TAG-TGC-CTT-CAG-ATC-TTG-CT-3' and reverse, 5'-TTG-CAA-ATG-ACC-CGA-GAT-CCC-ACC-A-3' which amplifies a product of 259 bp (-1527/-1268). Quantification was performed by QPCR (standard curve method) using serial dilutions of the input as standards. All measurements were done in triplicate, and results were verified in at least three independent chromatin preparations.

Western blot analysis. Western blot analysis was performed as described previously (Zastre et al., 2009; Ronaldson et al., 2010) with minor modifications. Briefly, the hCMEC/D3 monolayers, the primary cultures of human microvessel endothelial cells (BBB-ECs) and the human fetal brain tissue (hFBT) were washed with ice-cold PBS and collected by scraping in ice-cold PBS. Following centrifugation, whole cell lysates were prepared by lysing cell pellets in lysis buffer [(1% (v/v) NP-40, 20 mM Tris, 150 mM NaCl, 5 mM EDTA at pH 7.5 containing 1 mM PMSF and 0.1 % (v/v) protease inhibitor cocktail)] for 20 min at 4 °C. Cell lysates were sonicated for 5 seconds and centrifuged at 14,000 rpm for 10 min at 4 °C to remove cell debris. The whole cell lysates were then mixed in Laemmli sample buffer and resolved on 10 % SDS polyacrylamide gel. After electrophoresis, the gels were washed in transfer buffer (25 mM Tris-HCl, pH 8, 200 mM glycine) containing 20% (v/v) methanol and then electrotransferred onto polyvinylidene difluoride (PVDF) membranes. The membranes were blocked in TBST-T buffer containing 5% (m/v) skim milk followed by incubation with primary antibody overnight at 4 °C. The membranes were then washed in TBS-T and incubated with anti-mouse, anti-rat or anti-

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rabbit horseradish peroxidase-conjugated secondary antibodies (all at 1:10,000 dilution) for 1.5 h. The BCRP protein expression was detected using a rat monoclonal anti-BCRP (BXP53, 1:200 dilution) antibody, which recognizes an epitope corresponding to amino acids 221-394 of mouse Bcrp. MCF7 MX100 overexpressing BCRP was used as a positive control. The P-gp protein expression was detected using a mouse monoclonal anti-P-gp (C219, 1:500 dilution) antibody raised against an internal epitope of human P-gp. MDA435/LCC6-MDR1 cell lysates was used as a positive control for P-gp. PPAR α expression was detected using rabbit polyclonal (H-98, 1:500 dilution) or mouse monoclonal (H0723, 1:500 dilution) anti-PPAR α antibodies, which recognize the epitopes corresponding to 4-96 amino acids and 1-98 amino acids of human PPAR α protein, respectively. HepG2 cell lysates were used as positive control for PPAR α expression. Actin expression was used as loading control and was detected using mouse monoclonal AC40 antibody (1:2000 dilution). Protein bands were visualized by enhanced chemiluminescence, and protein expression was determined by densitometric analysis using Alpha DigiDoc RT2 imaging software (Alpha Innotech, San Leandro, CA, USA).

Immunofluorescence studies. The subcellular localization of BCRP and PPAR α proteins were examined by confocal microscopy in untreated hCMEC/D3 cells, as well as in cells treated with vehicle (EtOH or DMSO) or PPAR α ligands, clofibrate (100 μ M) or GW7647 (20 nM) for 20 h. Cell monolayers grown on glass coverslips were fixed with 100% methanol on ice for 20 min. After fixation, cells were washed in PBS and permeabilized with 0.1 % Triton X-100 for 5 min at room temperature as described previously (Hoque and Ishikawa, 2001). Fixed cells were blocked with 0.1 % (m/v) bovine serum albumin and 0.1 % (m/v) skim milk in PBS for 1 h prior to primary antibody incubation for 1.5 h at room temperature or overnight at 4 °C.

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The rat monoclonal (BXP53, 1:20 dilution) and rabbit polyclonal (H-98, 1:200 dilution) antibodies were used to detect BCRP and PPAR α subcellular localization, respectively. The mouse monoclonal (ab8980) antibody was used to visualize Lamin A expression, a marker for nuclear envelope. Following primary antibody incubation, cells were washed with PBS by gentle agitation and followed by incubation with anti-mouse Alexa Fluor® 594 or anti-rabbit Alexa Fluor® 488 conjugated secondary antibody (both in 1:500 dilution) (Invitrogen) for 1.5 h at room temperature. Staining in the absence of primary antibodies was used as a negative control. Following secondary antibody incubation, cells were washed again with PBS and mounted on a 76 x 26 mm microscope slide (VWR, West Chester, PA, USA) using vectashield mounting solution containing DAPI. Cells were then visualized using a Plan C-Apochromat-63x/1.4 oil differential interference contrast objective and Zeiss LSM 510 META NLO two-photon confocal laser-scanning microscope (Carl-Zeiss AG, Oberkochen, Germany) equipped with argon (458 nm, 476 nm, 488 nm, 513 nm wavelengths), helium-neon (533 nm wavelength) and a tunable Chameleon (720 – 930 nm wavelengths) laser lines. Measurement of nuclear fluorescence intensity was determined using ImageJ software (ver. 1.38; <http://rsb.info.nih.gov/ij>). The average fluorescence intensity for each treatment group was the mean of all measurements taken from at least 100 cells.

Functional studies. BCRP activity was measured with the use of mitoxantrone, an established substrate. Mitoxantrone accumulation by hCMEC/D3 cells was performed in Hanks' Balanced Salt Solution (HBSS), containing 1.3 mM KCl, 0.44 mM KH₂PO₄, 138 mM NaCl, 0.34 mM Na₂PO₄ and 5.6 mM D-glucose, supplemented with 0.01% bovine serum albumin and 25 mM HEPES, pH 7.4. Throughout the manuscript, supplemented HBSS buffer is referred to as

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transport buffer. Cells were plated at a cell density of 40,000 cells / cm² and accumulation experiments were performed at 100% cell monolayer confluence.

Cellular accumulation of [³H]-mitoxantrone, a known substrate of BCRP, was determined applying a radioactive transport assay as described previously (Lee et al., 2007) with slight modification. Briefly, hCMEC/D3 cells were incubated with transport buffer containing 20 μM mitoxantrone (³H-mitoxantrone - 0.1 μCi /ml) in the absence or presence of the BCRP selective inhibitor K0143 (5 μM). After 2 h, mitoxantrone containing medium was aspirated and cells were washed twice with ice-cold PBS and solubilized in 1% Triton X-100 at 37 °C for 30 min. The content of each well was collected, mixed with 3 ml of PicoFluor 40 scintillation fluid (PerkinElmer Life and Analytical Sciences, Waltham Massachusetts, USA), and the total radioactivity was measured using a Beckman Coulter LS5600 liquid scintillation counter (Fullerton, California, USA). Background accumulation was estimated by determining the retention of radiolabeled compounds by the cells after zero time exposure, by removing the radiolabeled solution immediately after its addition into each well, followed by two subsequent washes with ice-cold PBS and quantified using liquid scintillation counting. Total radioactive cellular accumulation was normalized to the total cellular protein content as determined by Bio-Rad DC Protein Assay, using bovine serum albumin as the standard. For all the accumulation assays, data are reported as accumulation of the substrate at steady-state in the absence or presence of inhibitor.

Statistical analysis. All experiments were repeated at least three times in cells pertaining to different passages. Results are reported as a mean ± S.D. or as mean ± S.E. as appropriate. Comparisons between groups were performed using either two-tailed Student's *t* test or One-

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Way Analyses of Variance (ANOVA) with Bonferroni multiple comparison post-hoc test. Data were analyzed by Graphpad InStat 3.0 software (Graphpad Software Inc., San Diego, California, USA), and a value of $p < 0.05$ was considered to be statistically significant.

Results

Expression of BCRP and PPAR α proteins in hCMEC/D3 cells, human BBB-ECs and human fetal brain tissues. In order to document the expression of BCRP and PPAR α in immortalized human cerebral microvessel endothelial cells (hCMEC/D3), primary cultures of human brain microvessel endothelial cells (BBB-ECs) and human fetal brain tissues, we performed immunoblotting analysis using whole cell/tissue lysates with specific antibodies known to recognize BCRP and PPAR α proteins, respectively. We detected BCRP and PPAR α at approximately 70 and 52 kDa bands in all cell/tissue lysates examined, respectively (Fig. 1A; Fig. 2A, 2B). These are molecular weights previously reported for the two proteins (Szatmari et al., 2006;Huang et al., 2009). We observed some inter-individual differences in BCRP and to a lesser extent PPAR α expression in BBB-ECs (Fig. 2A). We further investigated the cellular localization of BCRP and PPAR α by confocal microscopy. Anti-Na⁺/K⁺-ATPase α 1 antibody was used as a marker of the plasma membrane. BCRP protein appeared to be primarily localized at the cell plasma membrane while PPAR α was found in both the nucleus and cytoplasm (Fig. 1B).

Ligand-mediated nuclear accumulation of PPAR α in hCMEC/D3 cells. PPAR α is a ligand activated transcription factor known to translocate into the nucleus from the cytoplasm upon ligand binding (Xu et al., 2002). We therefore performed immunofluorescence experiments to investigate PPAR α nuclear accumulation in hCMEC/D3 upon activation with PPAR α specific ligands, cofibrate and GW7647. We observed approximately 34.8% and 31.67% increase in PPAR α nuclear fluorescence intensity in cells treated with clofibrate (100 μ M) or GW7647 (20 nM) compared to control (Fig. 3A, 3B, 3C). These results suggest that the increase in PPAR α

nuclear accumulation could be mediated by an interaction with clofibrate or GW7647, two established PPAR α ligands.

Ligand-mediated upregulation of ABCG2 mRNA in hCMEC/D3 cells. We examined the mRNA expression of ABCG2 in hCMEC/D3 cells treated with PPAR α ligands, clofibrate or GW7647, for 24 h. Both ligands significantly induced ABCG2 mRNA expression by approximately 71% and 49%, respectively when compared to vehicle treated control cells (Fig. 4A, 4B). Our observations in hCMEC/D3 cells corroborate with previous findings where PPAR α agonists i.e., Wy14643, GW7647 and clofibrate are reported to induce the mRNA expression of several drug transporters including Abcg2 in mouse liver and intestine (Hirai et al., 2007; Moffit et al., 2006). In order to evaluate whether the observed ABCG2 induction is mediated by PPAR α , hCMEC/D3 cells were exposed to selective PPAR α antagonists, MK886 (5 μ M) or GW6471 (5 μ M), in conjunction with the ligands for 24 h. MK886 and GW6471 are known to attenuate ligand mediated activation of PPAR α in other *in vitro* cell culture systems (Kehrer et al., 2001; Goto et al., 2011). As expected, addition of MK886 or GW6471 abolished ABCG2 mRNA induction mediated by clofibrate and GW7647 (Fig. 4A and 4B).

Ligand-mediated upregulation of BCRP protein expression in hCMEC/D3 cells. To determine whether the increase in ABCG2 mRNA expression resulted in changes in BCRP protein expression, hCMEC/D3 cells were cultured with increasing concentrations of clofibrate or GW7647 for 72 h. We observed a significant concentration dependent upregulation of BCRP protein in the presence ligands (Fig. 5, panel-A and panel-C). The highest induction of BCRP protein approximately 175% and 125% was observed when cells were incubated with 125 μ M

clofibrate or 20 nM GW7646, respectively. To assess the kinetics of BCRP protein expression induction, hCMEC/D3 cells were incubated with either clofibrate (100 μ M) or GW7647 (20 nM) at several time points (6 h - 72 h). As shown in Fig. 5, panel-B and panel-D, significant induction of BCRP protein expression was observed as early as 24 h and 48 h treatment with clofibrate and GW7647, respectively. The highest BCRP protein induction by both ligands (approximately 200%) was observed at 72 h (Fig. 5, panel-B and panel-D). Interestingly, we could not detect any significant increase in P-glycoprotein expression, another major ABC drug efflux transporter known to be expressed at the BBB, by PPAR α ligands in the cell culture system (data not shown).

Effect of PPAR α inhibitors on ligand-mediated BCRP protein induction. We further tested whether the observed BCRP protein induction is primarily mediated by PPAR α in hCMEC/D3 cells exposed to varying concentrations of PPAR α specific antagonists (MK886 or GW6471) in conjunction with the ligands, clofibrate or GW7647 for 48 h. As expected, addition of MK886 (5 μ M) with clofibrate (100 μ M) or GW7647 (20 nM) decreased BCRP protein induction to nearly 0% (Fig. 6A, 6B). Similar data were observed when another PPAR α selective antagonist, GW6471 was used in a similar set of experiments (data not shown).

Effect of clofibrate treatment on BCRP function in hCMEC/D3 cells. To investigate whether the increase in protein expression resulted in a greater BCRP functional activity, we measured the accumulation of mitoxantrone, a chemotherapeutic agent and BCRP substrate in hCMEC/D3 cells treated with clofibrate for 72 h. 3 H-Mitoxantrone accumulation was significantly reduced in cells treated with clofibrate when compared to vehicle treated control

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(5483 ± 435 pmol/mg protein versus 6270 ± 345 pmol/mg protein; $p < 0.05$). These data suggest that the higher level of BCRP expression in clofibrate treated cells is most likely associated with greater drug efflux activity resulting in lower levels of mitoxantrone accumulation by these cells. This effect was reversed in the presence of an established BCRP inhibitor, Ko143, in both vehicle and clofibrate treated cells further confirming a BCRP-mediated efflux of mitoxantrone (Fig. 7).

Downregulation of BCRP expression and function by PPAR α siRNA in hCMEC/D3 cells. PPAR α targeting siRNA was used to further examine the direct involvement of PPAR α in the regulation of BCRP in hCMEC/D3 cells. In PPAR α siRNA transfected cells, PPAR α protein expression was downregulated by approximately 60% while BCRP expression was reduced by nearly 23% as reflected by immunoblotting (Fig. 8A, 8B) when compared to cells treated with control scrambled siRNA. To investigate if the decreased BCRP expression in PPAR α siRNA treated cells was associated with a lesser BCRP activity, we measured the accumulation of mitoxantrone in siRNA transfected cells. Mitoxantrone accumulation was significantly higher in PPAR α siRNA treated cells when compared to control siRNA treated cells (8442 ± 610 pmol/mg protein versus 7752 ± 686 pmol/mg protein; $p < 0.05$) suggesting a lower BCRP function (Fig. 8C).

Involvement of PPAR α in the transcriptional regulation of ABCG2 gene in hCMEC/D3 cells. Bioinformatics analyses of 5'-flanking region of human ABCG2 promoter have identified a well conserved 150-bp region (-3946/-3796) containing three putative peroxisome proliferator response elements (Szatmari et al., 2006). We therefore hypothesized

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that PPAR α binds to this region to mediate the induction of ABCG2. To test this hypothesis, we examined PPAR α recruitment to this region in the native chromatin context by ChIP using specific anti-PPAR α (H-98) antibody previously validated in ChIP assays (Nagasawa et al., 2009). As shown in Fig. 9, an increased PPAR α occupancy to the (-3946/-3796) region of ABCG2 promoter was evident in hCMEC/D3 cells exposed to clofibrate for 3 h. PPAR α occupancy was not increased in another region (-1527/-1268) of the same ABCG2 promoter suggesting the affinity of PPAR α to the peroxisome proliferator response elements located at the -3946/-3796 region of ABCG2 gene promoter. Similar observations were made with another PPAR α ligand (GW7647) (data not shown).

Discussion

In addition to the well-established role of PPAR α in lipid metabolism, recent studies have suggested that PPAR α could regulate the expression of transport proteins in the liver and intestine (Hirai et al., 2007; Moffit et al., 2006). However, at the BBB, the involvement of PPAR α in the regulation of drug transporters is currently unknown. The objective of this study was to investigate the role of PPAR α in the regulation of the drug efflux transporter, BCRP, expression and function at the human BBB. Due to the challenge in obtaining healthy human brain samples and sufficient tissue, we utilized the hMEC/D3 cell culture system, an *in vitro* representative model of the human BBB (Weksler et al., 2005). When possible, human brain tissues and primary cultures of human brain microvessel endothelial cells were also used.

In this study, we detected PPAR α protein expression and localization by western blotting and immunofluorescence experiments in hCMEC/D3 cells (Fig. 1A, 1B). An earlier report also documented PPAR α expression in hMCEC/D3 cells by immunoblotting (Huang et al., 2009). In addition, we observed PPAR α protein expression in primary cultures of human BBB-ECs and human fetal brain tissues (Fig. 2A, 2B). These findings provide evidence that PPAR α is expressed in human brain tissue and brain microvessel endothelial cells, and can serve as a potential site for drug-receptor interactions and regulation of drug transporters and metabolic enzymes. PPAR α has been reported to translocate into the cell nucleus upon ligand (fenofibrate) activation in human umbilical vein ECs (HUVECs) (Xu et al., 2002). Our results corroborate these data in hCMEC/D3 cells showing increased PPAR α nuclear accumulation upon treatment with two different PPAR α ligands, clofibrate and GW7647 further confirming the proposed mechanism of PPARs activation. Together, these observations provide the first evidence that PPAR α is likely to be functional at the human BBB.

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Previous studies have shown that PPAR α ligands can induce Bcrp expression at the mRNA level in mouse intestine and liver (Hirai et al., 2007; Moffit et al., 2006). In the current study, we demonstrated that the earliest induction (approximately 49% - 72%) of ABCG2 mRNA took place at 24 h in post treatment of hCMEC/D3 cells by two different PPAR α ligands. Furthermore, the PPAR α antagonists, MK886 and GW6471, were able to attenuate the ligand mediated ABCG2 mRNA induction. In addition to the induction of ABCG2 mRNA expression, PPAR α ligands could also induce BCRP protein expression in a time and concentration-dependent manner (approximately 100% - 200%), and these effects were attenuated by the PPAR α selective antagonists. Taken together, these observations strongly suggest for the first time that PPAR α is involved in the regulation of BCRP at both the mRNA and protein level in human brain microvessel endothelial cells.

In our transport experiments, we demonstrated significantly higher BCRP function in hCMEC/D3 cells treated with clofibrate compared to control. Similar trend was also observed in GW7647 treated cells. We further characterized the involvement of PPAR α in the regulation of BCRP expression and function by using siRNA and observed reduced BCRP protein expression (over 20%) in hCMEC/D3 cells transfected with PPAR α siRNA when compared to control. Furthermore, significant higher mitoxantrone accumulation in PPAR α siRNA treated cells was observed suggesting reduced BCRP function in the brain microvessel endothelial cells.

Applying the ChIP assay, we observed an enhanced PPAR α binding to the -3946/-3796 region of the human *ABCG2* gene promoter in clofibrate treated hCMEC/D3 cells. Similar enhancement is not seen in other regions (-1527/-1268) of the same *ABCG2* gene promoter reported to have no PPRE consensus (Szatmari et al., 2006). These data provide first evidence that PPAR α can directly bind to the -3946/-3796 region of *ABCG2* gene promoter in hCMEC/D3

cells. A previous report identified three peroxisome proliferator response elements located at the -3946/-3796 region of the human ABCG2 gene promoter for PPAR γ , another PPAR isoform, binding in human dendritic cells (Szatmari et al., 2006). These findings further support the fact that PPAR receptors recognize a similar PPRE consensus for their binding to the target gene promoter.

The expression of BCRP is believed to be associated with the regulation of xenobiotic bioavailability, distribution and toxicity in many tissues including the brain. Hence, the wide substrate specificity and tissue distribution of this transporter may play a major role in pharmacotherapy. Both endogenous (fatty acids, eicosanoids) and synthetic (lipid lowering agents, insulin sensitizers) PPAR α ligands are known to modulate PPAR α activity. Drug efflux transporters such as BCRP and P-gp, can serve as a major pathway for CNS drug clearance at the BBB and brain parenchyma where drug metabolizing enzymes appear to be expressed at very low levels (Dauchy et al., 2008) (Woodland et al., 2008). We propose that inhibiting PPAR α activity can reduce BCRP functional expression rendering the BBB more permeable and potentially increasing the delivery of CNS drugs that are known BCRP substrates. On the other hand, activating PPAR α can induce BCRP expression resulting in a less permeable barrier with increased protection against neurotoxins. Our data provide first evidence that the activity of PPAR α in a human BBB model can be pharmacologically modulated by selective ligands (clofibrate, GW7647) or inhibitors (MK886, GW6471). This in turn, could result in induction or downregulation of BCRP expression and function in the brain.

In summary, in this work, we demonstrate the expression of PPAR α in two *in vitro* representative systems of the human BBB, human cerebral microvessel endothelial cell culture system (hCMEC/D3) and primary cultures of human brain-derived microvascular endothelial

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cells (BBB-ECs) as well as in human fetal brain tissue samples. We also provide first evidence that pharmacological activation of PPAR α can increase BCRP gene and protein expression as well as function in hCMEC/D3 cells and that this effect can be attenuated by specific PPAR α inhibitors. Furthermore, we show that BCRP expression and function can be downregulated by targeting PPAR α using siRNA and demonstrate the ligand-induced PPAR α binding to the peroxisome proliferator response elements (PPRE) in BCRP promoter region suggesting the direct involvement of PPAR α in the regulation of this transport protein. As more xenobiotics are identified as ligands of PPAR α , the selective tightening of the human BBB could be modulated by a careful design of drug regimens which could improve CNS drug delivery or enhance neuroprotection.

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Authorship Contributions

Participated in research design:	MTH, RB
Conducted research experiments:	MTH, KRR
Contributed to Reagents or analytical tools:	RB
Performed data analysis:	MTH, KRR, RB
Contributed to the writing of the manuscript:	MTH, RB

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References

Abbott NJ, Patabendige A A, Dolman D E, Yusof S R and Begley D J (2010) Structure and Function of the Blood-Brain Barrier. *Neurobiol Dis* **37**:13-25.

Bauer B, Hartz A M, Fricker G and Miller D S (2004) Pregnane X Receptor Up-Regulation of P-Glycoprotein Expression and Transport Function at the Blood-Brain Barrier. *Mol Pharmacol* **66**:413-419.

Bauer B, Yang X, Hartz A M, Olson E R, Zhao R, Kalvass J C, Pollack G M and Miller D S (2006) In Vivo Activation of Human Pregnane X Receptor Tightens the Blood-Brain Barrier to Methadone Through P-Glycoprotein Up-Regulation. *Mol Pharmacol* **70**:1212-1219.

Benani A, Kremarik-Bouillaud P, Bianchi A, Netter P, Minn A and Dauca M (2003) Evidence for the Presence of Both Peroxisome Proliferator-Activated Receptors Alpha and Beta in the Rat Spinal Cord. *J Chem Neuroanat* **25**:29-38.

Bendayan R, Lee G and Bendayan M (2002) Functional Expression and Localization of P-Glycoprotein at the Blood Brain Barrier. *Microsc Res Tech* **57**:365-380.

Bendayan R, Ronaldson P T, Gingras D and Bendayan M (2006) In Situ Localization of P-Glycoprotein (ABCB1) in Human and Rat Brain. *J Histochem Cytochem* **54**:1159-1167.

Bright JJ, Kanakasabai S, Chearwae W and Chakraborty S (2008) PPAR Regulation of Inflammatory Signaling in CNS Diseases. *PPAR Res* **2008**:658520.

Chan GN, Hoque M T, Cummins C L and Bendayan R (2011) Regulation of P-Glycoprotein by Orphan Nuclear Receptors in Human Brain Microvessel Endothelial Cells. *J Neurochem* **118**:163-175.

Cullingford TE, Bhakoo K, Peuchen S, Dolphin C T, Patel R and Clark J B (1998) Distribution of MRNAs Encoding the Peroxisome Proliferator-Activated Receptor Alpha, Beta, and Gamma and the Retinoid X Receptor Alpha, Beta, and Gamma in Rat Central Nervous System. *J Neurochem* **70**:1366-1375.

Dauchy S, Dutheil F, Weaver R J, Chassoux F, umas-Duport C, Couraud P O, Scherrmann J M, De W, I and Declèves X (2008) ABC Transporters, Cytochromes P450 and Their Main

Transcription Factors: Expression at the Human Blood-Brain Barrier. *J Neurochem* **107**:1518-1528.

Doyle LA, Yang W, Abruzzo L V, Krogmann T, Gao Y, Rishi A K and Ross D D (1998) A Multidrug Resistance Transporter From Human MCF-7 Breast Cancer Cells. *Proc Natl Acad Sci U S A* **95**:15665-15670.

Enokizono J, Kusuhara H, Ose A, Schinkel A H and Sugiyama Y (2008) Quantitative Investigation of the Role of Breast Cancer Resistance Protein (Bcrp/Abcg2) in Limiting Brain and Testis Penetration of Xenobiotic Compounds. *Drug Metab Dispos* **36**:995-1002.

Enokizono J, Kusuhara H and Sugiyama Y (2007) Effect of Breast Cancer Resistance Protein (Bcrp/Abcg2) on the Disposition of Phytoestrogens. *Mol Pharmacol* **72**:967-975.

Goto T, Lee J Y, Teraminami A, Kim Y I, Hirai S, Uemura T, Inoue H, Takahashi N and Kawada T (2011) Activation of Peroxisome Proliferator-Activated Receptor-Alpha Stimulates Both Differentiation and Fatty Acid Oxidation in Adipocytes. *J Lipid Res* **52**:873-884.

Hartz AM, Mahringer A, Miller D S and Bauer B (2010) 17-Beta-Estradiol: a Powerful Modulator of Blood-Brain Barrier BCRP Activity. *J Cereb Blood Flow Metab* **30**:1742-1755.

Hirai T, Fukui Y and Motojima K (2007) PPARalpha Agonists Positively and Negatively Regulate the Expression of Several Nutrient/Drug Transporters in Mouse Small Intestine. *Biol Pharm Bull* **30**:2185-2190.

Hoque MT and Ishikawa F (2001) Human Chromatid Cohesin Component HRad21 Is Phosphorylated in M Phase and Associated With Metaphase Centromeres. *J Biol Chem* **276**:5059-5067.

Huang W, Eum S Y, Andras I E, Hennig B and Toborek M (2009) PPARalpha and PPARgamma Attenuate HIV-Induced Dysregulation of Tight Junction Proteins by Modulations of Matrix Metalloproteinase and Proteasome Activities. *FASEB J* **23**:1596-1606.

Huang W, Rha G B, Han M J, Eum S Y, Andras I E, Zhong Y, Hennig B and Toborek M (2008) PPARalpha and PPARgamma Effectively Protect Against HIV-Induced Inflammatory Responses in Brain Endothelial Cells. *J Neurochem* **107**:497-509.

Ishikawa T (2009) The Role of Human ABC Transporter ABCG2 (BCRP) in Pharmacotherapy. *Adv Drug Deliv Rev* **61**:1-2.

Kehrer JP, Biswal S S, La E, Thuillier P, Datta K, Fischer S M and Vanden Heuvel J P (2001) Inhibition of Peroxisome-Proliferator-Activated Receptor (PPAR)Alpha by MK886. *Biochem J* **356**:899-906.

Kersten S, Desvergne B and Wahli W (2000) Roles of PPARs in Health and Disease. *Nature* **405**:421-424.

Lee G, Babakhanian K, Ramaswamy M, Prat A, Wosik K and Bendayan R (2007) Expression of the ATP-Binding Cassette Membrane Transporter, ABCG2, in Human and Rodent Brain Microvessel Endothelial and Glial Cell Culture Systems. *Pharm Res* **24**:1262-1274.

Maliepaard M, Scheffer G L, Faneyte I F, van Gastelen M A, Pijnenborg A C, Schinkel A H, van De Vijver M J, Scheper R J and Schellens J H (2001) Subcellular Localization and Distribution of the Breast Cancer Resistance Protein Transporter in Normal Human Tissues. *Cancer Res* **61**:3458-3464.

Miller DS (2010) Regulation of P-Glycoprotein and Other ABC Drug Transporters at the Blood-Brain Barrier. *Trends Pharmacol Sci* **31**:246-254.

Moffit JS, Aleksunes L M, Maher J M, Scheffer G L, Klaassen C D and Manautou J E (2006) Induction of Hepatic Transporters Multidrug Resistance-Associated Proteins (Mrp) 3 and 4 by Clofibrate Is Regulated by Peroxisome Proliferator-Activated Receptor Alpha. *J Pharmacol Exp Ther* **317**:537-545.

Muerhoff AS, Griffin K J and Johnson E F (1992) The Peroxisome Proliferator-Activated Receptor Mediates the Induction of CYP4A6, a Cytochrome P450 Fatty Acid Omega-Hydroxylase, by Clofibric Acid. *J Biol Chem* **267**:19051-19053.

Nagasawa M, Hara T, Kashino A, Akasaka Y, Ide T and Murakami K (2009) Identification of a Functional Peroxisome Proliferator-Activated Receptor (PPAR) Response Element (PPRE) in the Human Apolipoprotein A-IV Gene. *Biochem Pharmacol* **78**:523-530.

Pardridge WM (2010) Biopharmaceutical Drug Targeting to the Brain. *J Drug Target* **18**:157-167.

Polgar O, Robey R W and Bates S E (2008) ABCG2: Structure, Function and Role in Drug Response. *Expert Opin Drug Metab Toxicol* **4**:1-15.

MOL #76745

Robyr D, Wolffe A P and Wahli W (2000) Nuclear Hormone Receptor Coregulators in Action: Diversity for Shared Tasks. *Mol Endocrinol* **14**:329-347.

Ronaldson PT, Ashraf T and Bendayan R (2010) Regulation of Multidrug Resistance Protein 1 by Tumor Necrosis Factor Alpha in Cultured Glial Cells: Involvement of Nuclear Factor-KappaB and C-Jun N-Terminal Kinase Signaling Pathways. *Mol Pharmacol* **77**:644-659.

Ronaldson PT, Persidsky Y and Bendayan R (2008) Regulation of ABC Membrane Transporters in Glial Cells: Relevance to the Pharmacotherapy of Brain HIV-1 Infection. *Glia* **56**:1711-1735.

Schachtrup C, Emmler T, Bleck B, Sandqvist A and Spener F (2004) Functional Analysis of Peroxisome-Proliferator-Responsive Element Motifs in Genes of Fatty Acid-Binding Proteins. *Biochem J* **382**:239-245.

Szatmari I, Vamosi G, Brazda P, Balint B L, Benko S, Szeles L, Jeney V, Ozvegy-Laczka C, Szanto A, Barta E, Balla J, Sarkadi B and Nagy L (2006) Peroxisome Proliferator-Activated Receptor Gamma-Regulated ABCG2 Expression Confers Cytoprotection to Human Dendritic Cells. *J Biol Chem* **281**:23812-23823.

Vlaming ML, Lagas J S and Schinkel A H (2009) Physiological and Pharmacological Roles of ABCG2 (BCRP): Recent Findings in Abcg2 Knockout Mice. *Adv Drug Deliv Rev* **61**:14-25.

Wang X, Hawkins B T and Miller D S (2011) Aryl Hydrocarbon Receptor-Mediated Up-Regulation of ATP-Driven Xenobiotic Efflux Transporters at the Blood-Brain Barrier. *FASEB J* **25**:644-652.

Wang X, Sykes D B and Miller D S (2010) Constitutive Androstane Receptor-Mediated Up-Regulation of ATP-Driven Xenobiotic Efflux Transporters at the Blood-Brain Barrier. *Mol Pharmacol* **78**:376-383.

Weksler BB, Subileau E A, Perriere N, Charneau P, Holloway K, Leveque M, Tricoire-Leignel H, Nicotra A, Bourdoulous S, Turowski P, Male D K, Roux F, Greenwood J, Romero I A and Couraud P O (2005) Blood-Brain Barrier-Specific Properties of a Human Adult Brain Endothelial Cell Line. *FASEB J* **19**:1872-1874.

Woodland C, Huang T T, Gryz E, Bendayan R and Fawcett J P (2008) Expression, Activity and Regulation of CYP3A in Human and Rodent Brain. *Drug Metab Rev* **40**:149-168.

MOL #76745

Xu X, Otsuki M, Sumitani S, Saito H, Kouhara H and Kasayama S (2002) RU486 Antagonizes the Inhibitory Effect of Peroxisome Proliferator-Activated Receptor Alpha on Interleukin-6 Production in Vascular Endothelial Cells. *J Steroid Biochem Mol Biol* **81**:141-146.

Zastre JA, Chan G N, Ronaldson P T, Ramaswamy M, Couraud P O, Romero I A, Weksler B, Bendayan M and Bendayan R (2009) Up-Regulation of P-Glycoprotein by HIV Protease Inhibitors in a Human Brain Microvessel Endothelial Cell Line. *J Neurosci Res* **87**:1023-1036.

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- (c) Request for reprints should be addressed to Dr. Reina Bendayan, Department of Pharmaceutical Sciences, Leslie Dan Faculty of Pharmacy, University of Toronto, 144 College Street, Toronto, ON, M5S 3M2, Canada - email: r.bendayan@utoronto.ca

Figure Legends

Fig. 1. Immunoblot analysis and immunocytochemical localization of BCRP and PPAR α in human cerebral microvessel endothelial cells (hCMEC/D3). *A)* Whole cell lysates prepared from BCRP overexpressing MCF7 MX100 (BCRP control, 5 μ g), HepG2 cells (PPAR α control, 50 μ g) and hCMEC/D3 cells (5, 20 or 50 μ g/lane) were separated on 10% SDS-PAGE gel and subsequently transferred to PVDF membrane. The membranes were then blotted with anti-BCRP (BXP53, rat monoclonal, upper panel), anti-PPAR α (mouse monoclonal, middle panel) or anti-Actin (AC40, mouse monoclonal, lower panel) antibodies followed by incubation with respective horse radish peroxidase conjugated anti-rat or anti-mouse secondary antibodies. *B)* hCMEC/D3 cells cultured on collagen-coated coverslips were fixed with ice-cold methanol and permeabilized with 0.1 % Triton X-100. Cellular localization of BCRP, Na⁺/K⁺-ATPase α 1 and PPAR α proteins were detected by mouse monoclonal anti-BCRP (BXP53, 1:20 dilution), rabbit polyclonal anti-Na⁺/K⁺-ATPase α 1 (H-300, 1:100 dilution) and rabbit polyclonal anti-PPAR α (H-98, 1:200 dilution) followed by incubation with anti-rat Alexa-594 and anti-rabbit Alexa-488 conjugated secondary antibodies (1:500 dilution/each). DNA was stained with DAPI. For negative controls, only the Alexa-conjugated secondary antibodies were used.

Fig. 2. Immunoblot analysis of BCRP and PPAR α in primary cultures of human brain-derived microvascular endothelial cells (BBB-ECs) and human fetal brain tissues (hFBT). *A)* Whole cell lysates prepared from human BBB-ECs pellet obtained from four individuals (S1-S4) (50 μ g/each) and *B)* human fetal brain tissues obtained from two individuals (1-2) were resolved on a 10% SDS-PAGE gel and transferred to a PVDF membrane. HepG2 (50 μ g) and MCF7 MX100

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cells (5 μ g) were used as positive controls for PPAR α and BCRP proteins, respectively. BCRP and PPAR α proteins were detected using rat (BXP53) and mouse monoclonal antibodies, respectively. Actin was detected using mouse monoclonal (AC40) antibody (Fig. 2A, 2B). Data generated from densitometric analysis is presented as ratio of BCRP and PPAR α expression normalized to Actin (loading control).

Fig. 3. Ligand-induced nuclear accumulation of PPAR α in hCMEC/D3 cells. hCMEC/D3 cells grown on collagen-coated cover slips were induced with PPAR α agonists, A) clofibrate or B) GW7647 or vehicle control (ethanol/DMSO), dissolved in hCMEC/D3 culture medium without serum for 24 h. Cells were then fixed with ice-cold methanol and permeabilized with Triton X-100 (0.1%). Cellular localization of PPAR α protein was detected by rabbit polyclonal anti-PPAR α antibody (H-98, 1:200 dilution) followed by incubation with anti-rabbit Alexa-488 conjugated secondary antibody (1:500). Nuclear envelope was visualized with mouse monoclonal anti-Lamin-A (ab8980) antibody (1:500 dilution). C) Average PPAR α nuclear fluorescence normalized to vehicle control were obtained from three independent experiments performed in cells pertaining to different passages (>100 cells/ treatment group). * Statistically significant differences in nuclear fluorescence compared to control as determined by one way ANOVA with Bonferroni post-hoc test ($p < 0.05$).

Fig. 4. Induction of ABCG2 mRNA expression by PPAR α ligands in hCMEC/D3 cells. Monolayers of hCMEC/D3 cells were exposed to PPAR α selective agonists, A) 100 μ M clofibrate or B) 20 nM GW7647 or in conjunction with antagonist: MK886 or GW6471 (5 μ M) for 24 h. ABCG2 mRNA expression was measured by qPCR. All treatment and vehicle groups

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were performed in triplicate in three independent experiments pertaining to different cell passages. Ct values for ABCG2 mRNA were normalized with the housekeeping gene cyclophilin B mRNA. Results are expressed as percentage fold change \pm SEM, using comparative CT method ($\Delta\Delta$ CT). * Statistically significant differences in ABCG2 mRNA expression compared to control as determined by one way ANOVA with Bonferroni post-hoc test ($p < 0.05$).

Fig. 5. Time and concentration-dependent induction of BCRP by PPAR α ligands in hCMEC/D3 cells. BCRP protein expression was measured in hCMEC/D3 cells treated with different concentrations of clofibrate (0.2 - 125 μ M) or GW7647 (1.25 - 20 nM) or respective vehicle controls (ethanol/DMSO) for 72 h. *Panel-A, panel-B*) Representative Immunoblots (top panels) and densitometric analyses (bottom panels) demonstrating the clofibrate and GW7647 concentration-dependent increase of BCRP protein expression. Quantitative densitometry analysis of three independent experiments is also shown. *Panel-C, panel-D*) Representative immunoblots (top panels) and densitometric analyses (bottom panels) demonstrating the clofibrate and GW7647 time-dependent increase of BCRP protein expression. The relative levels of BCRP expression were determined by densitometric analysis. Results are expressed as percentage fold change normalized to vehicle treated control (control) and reported as mean \pm SD obtained from three independent experiments performed in cells pertaining to different passages. * Statistically significant differences between treatment group as determined by one way ANOVA with Bonferroni post-hoc tests at a significant level of $p < 0.05$.

Fig. 6. Inhibition of BCRP protein induction by PPAR α antagonists in hCMEC/D3 cells. BCRP protein expression was determined in hCMEC/D3 cells treated with PPAR α ligands alone,

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clofibrate (100 μ M)/ GW7647 (20 nM) or in conjunction with clofibrate or GW7644 in the presence of different concentrations of PPAR α antagonist, MK886 (1, 5 and 10 μ M). *A*) Representative immunoblot (top) and densitometric analysis (bottom) of BCRP expression in hCMEC/D3 cells exposed to vehicle, 100 μ M clofibrate alone or 100 μ M clofibrate in conjunction with 1, 5 or 10 μ M MK886. *B*) Representative immunoblot (top) and densitometric analysis (bottom) of BCRP expression in hCMEC/D3 cells exposed to vehicle, 20 nM GW7647 alone or 20 nM GW7647 in conjunction with 1, 5 or 10 μ M MK886. Whole cell lysates from hCMEC/D3 cells (50 μ g/each) were resolved on a 10% SDS-PAGE gel and probed with anti-BCRP or anti-Actin antibodies, respectively. The relative levels of BCRP expression were determined by densitometric analysis. Results are expressed as percentage fold change normalized to vehicle treated control (control) and reported as mean \pm SD obtained from three independent experiments performed in cells pertaining to different passages. * Statistically significant differences between treatment groups as determined by one way ANOVA with Bonferroni post-hoc tests at a significant level of $p < 0.05$.

Fig. 7. Effect of clofibrate treatment on 3 H-Mitoxantrone accumulation by hCMEC/D3 monolayer cells. Accumulation of 20 μ M 3 H-Mitoxantrone (2 h) was measured in the absence or presence of selective BCRP inhibitor Ko143, by hCMEC/D3 cells treated with either ethanol (vehicle) or clofibrate (100 μ M) for 72 h. Results are expressed as mean % control \pm SEM of three separate experiments with each data point in an individual experiment representing triplicate measurements. Asterisks represent data points that are significantly different from control (* $p < 0.05$).

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Fig. 8. Effect of PPAR α downregulation on BCRP protein expression and function in hCMEC/D3 cells. *A*) Equal protein loading (50 μ g/each) of homogenates derived from either control siRNA treated hCMEC/D3 cells or cells treated with siRNA directed against PPAR α were subjected to immunoblotting with anti-PPAR α antibody (top panel). The blots were subsequently stripped and probed with anti-BCRP (middle panel) or anti-Actin antibody as loading control (lower panel). *B*) Relative levels of PPAR α and BCRP expression were determined by densitometric analyses. Results are expressed as percentage fold change normalized to control siRNA and reported as mean \pm SD obtained from three independent experiments performed in cells pertaining to different passages. * Statistically significant differences in BCRP and PPAR α expression compared to control (control siRNA) were determined by two-tailed Student's *t*-test with $p < 0.05$. *C*) Accumulation of 20 μ M 3 H-Mitoxantrone (2 h) in hCMEC/D3 cells treated with either control siRNA or siRNA directed against PPAR α . Results are expressed as mean % control \pm SEM of three separate experiments with each data point in an individual experiment representing triplicate measurements. Asterisks represent data points that are significantly different from control (* $p < 0.05$).

Fig. 9. Involvement of PPAR α in the transcriptional regulation of *ABCG2* gene. Chromatin immunoprecipitation (ChIP) was performed with anti-PPAR α antibody (rabbit polyclonal) from hCMEC/D3 cells treated with clofibrate for 3 h. The precipitated DNA content was analyzed by qPCR using primers designed to amplify the PPRE containing region of the *ABCG2* gene promoter (-3946/-3796) or a non-specific region of the same gene promoter (-1527/-1268). Results are shown as percentage of input DNA. As a negative control no-antibody control (No

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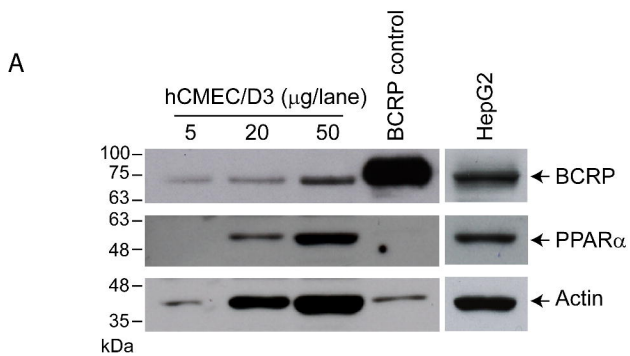
Ab) was used. All measurements were done in triplicate. Data are the average of three independent experiments.

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Table 1. Specific qPCR forward and reverse primers

Genes		Primer Sequence (5'- 3')	Accession
ABCG2	Forward	GGC-CTT-GGG-ATA-CTT-TGA-ATC	NM_004827
	Reverse	GAA-TCT-CCA-TTA-ATG-ATG-TCC-A	
Cyclophilin B	Forward	GGA-GAT-GGC-ACA-GGA-GGA-A	NM000942
	Reverse	GCC-CGT-AGT-GCT-TCA-GTT-T	
ABCG2 promoter (-3946/-3796)	Forward	AGG-GCA-GAG-GGC-AAT-GG	NM_001878
	Reverse	AGG-AGA-CTG-ATT-TGC-ACA-AGG-TT	
ABCG2 promoter (-1527/-1268)	Forward	CTC-CTC-CTG-TAG-TGC-CTT-CAG-ATC-TTG-CT	NM_001878
	Reverse	TTG-CAA-ATG-ACC-CGA-GAT-CCC-ACC-A	

Figure 1



B

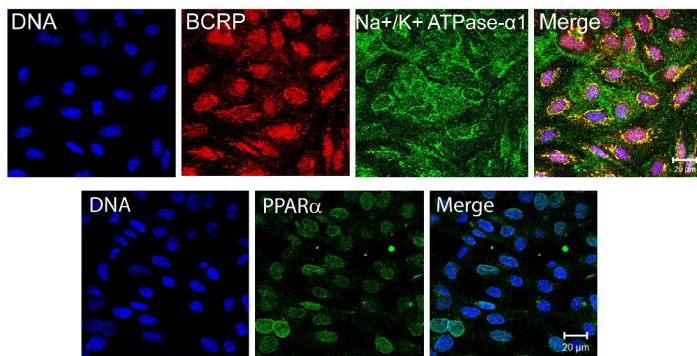


Figure 2

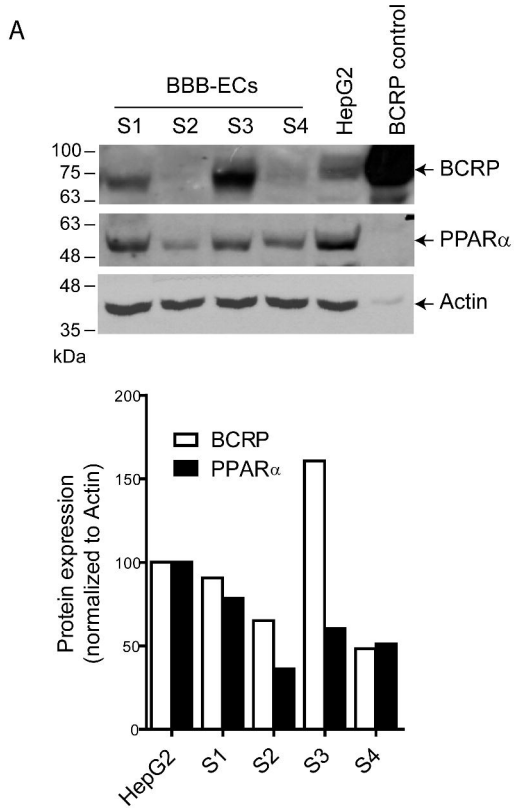


Figure 2

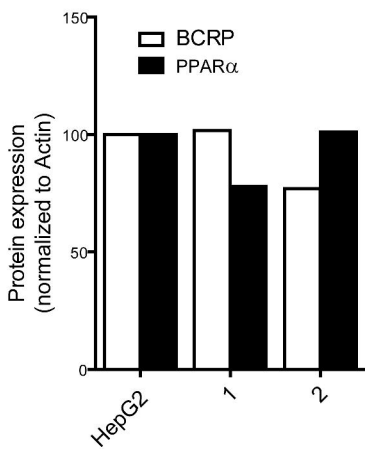
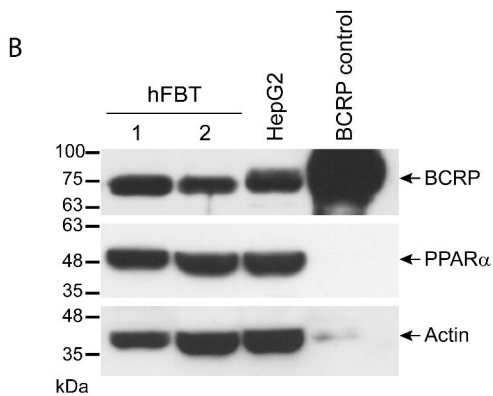


Figure 3

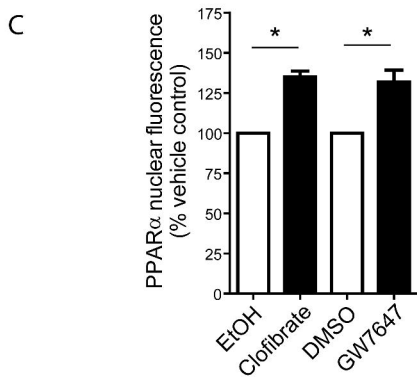
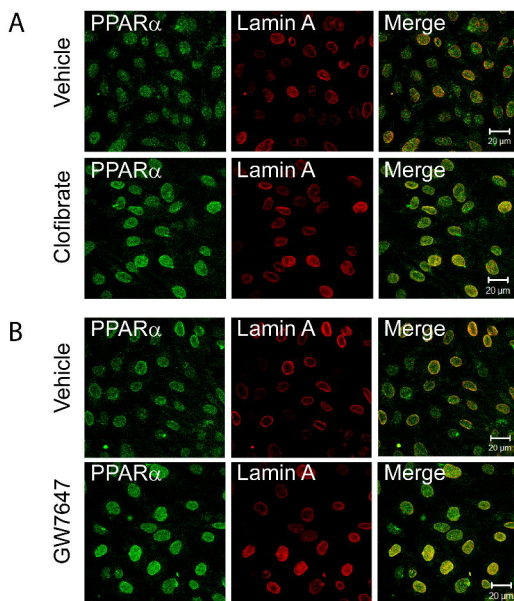
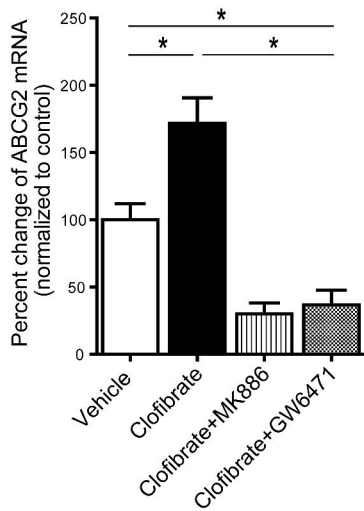


Figure 4

A



B

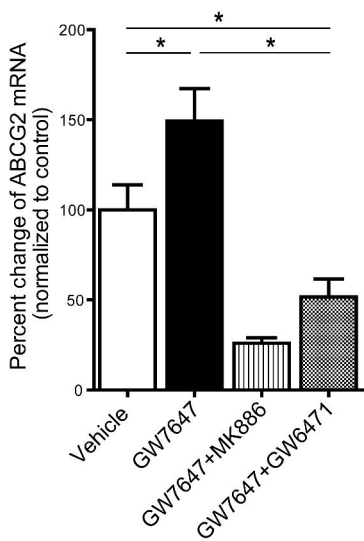


Figure 5

panel-A

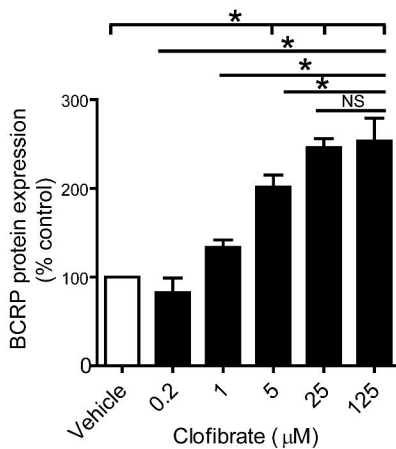
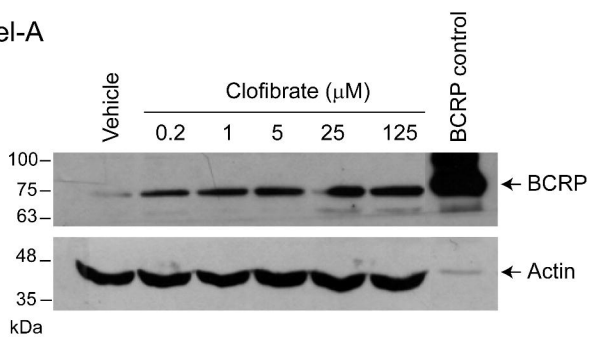


Figure 5

panel-B

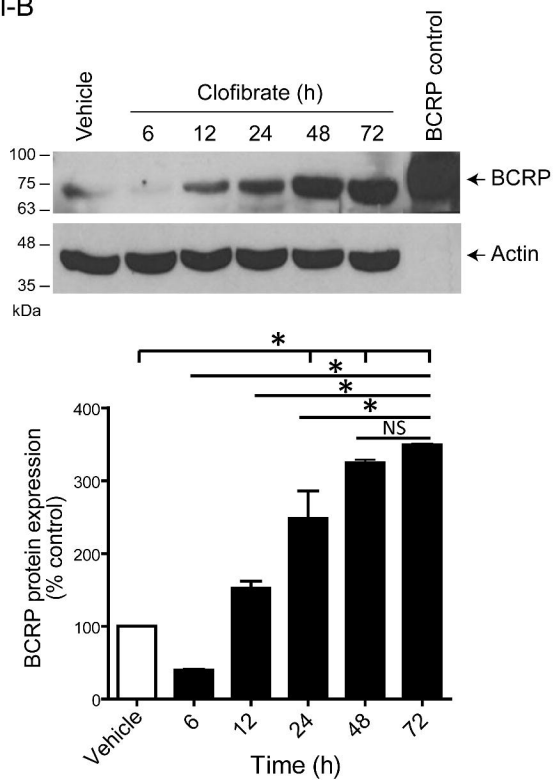


Figure 5

panel-C

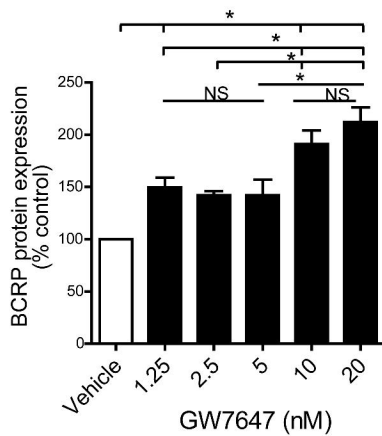
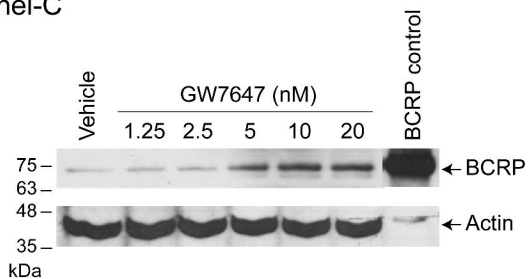


Figure 5

panel-D

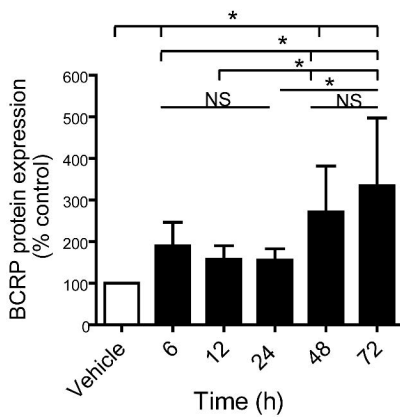
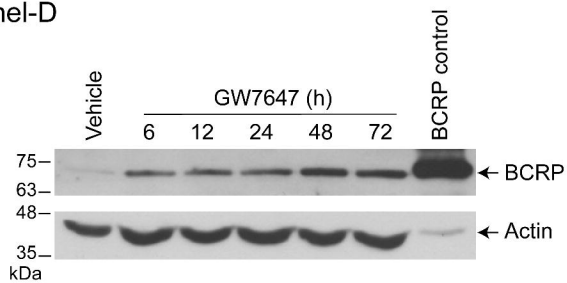


Figure 6

A

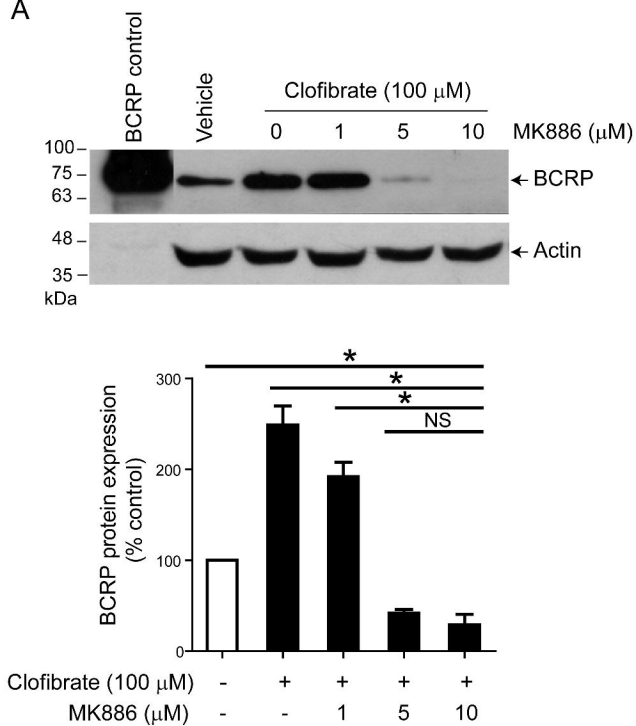


Figure 6

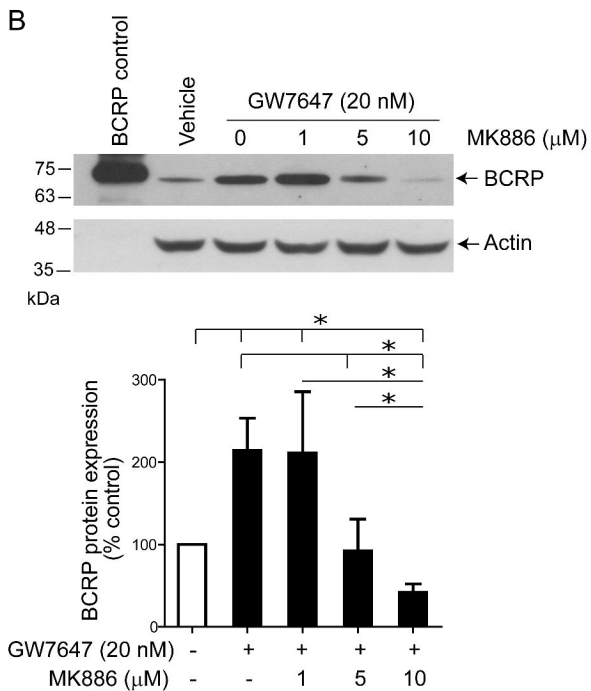


Figure 7

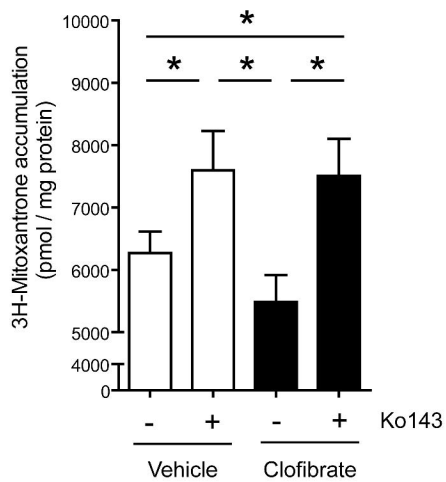


Figure 8

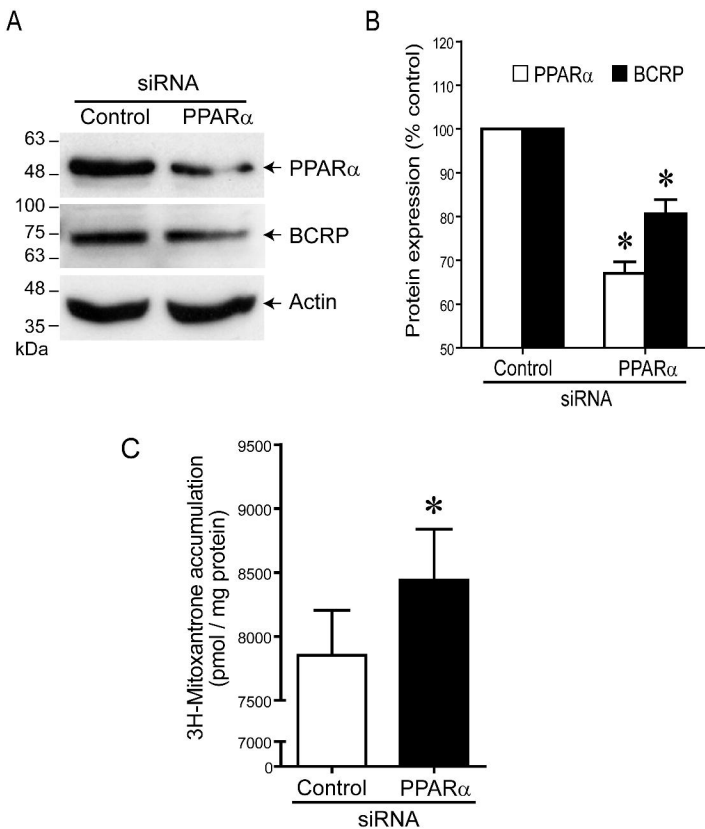


Figure 9

