Human Pregnane X Receptor Activation and CYP3A4/CYP2B6 Induction by 2,3-Oxidosqualene:Lanosterol Cyclase Inhibition

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ABSTRACT:

The effects of [4′-(6-allyl-methyl-amino-hexyloxy)-2′-fluoro-phenyl]-[4-(bromophenyl)]-methane fumarate (Ro 48-8071), an inhibitor of 2,3-oxidosqualene lanosterol cyclase (cyclase), were evaluated on CYP3A4 and CYP2B6 mRNA content in primary cultured human hepatocytes. In seven hepatocyte culture preparations, 24-h treatment with 3, 10, or 30 μM Ro 48-8071 produced median increases in CYP3A4 mRNA content that were 2.2-, 7.1-, and 8.5-fold greater than untreated control, respectively, and produced increases in CYP2B6 mRNA content that were 3.0-, 4.6-, and 3.4-fold greater than control, respectively. Increases in CYP3A4 immunoreactive protein content were also measured in Ro 48-8071-treated hepatocytes. To evaluate the effects of cyclase inhibitor treatments further, a pregnane X receptor (PXR)-responsive transactivation assay in HepG2 cells was used. Ro 48-8071, trans-N-[4-chlorobenzoyl]-N-methyl-[4-(dimethylaminoethyl)phenyl]-cyclohexylamine (BIBX 79), and 3β-[2-diethylaminoethoxy]androst-5-en-17-one HCl (U18666A) induced luciferase expression from a PXR-responsive reporter with EC50 of 0.113, 0.916, and 0.294 μM, respectively. Treatment of the HepG2 system with (E)-N-ethyl-N-(6,6-dimethyl-2-hepten-4-ynyl)-3-[3,3′-bithiophen-5-yl](methoxy)benzenemethanamine (NB-598), an inhibitor of squalene monooxygenase, at concentrations sufficient to achieve cholesterol biosynthesis inhibition significantly inhibited cyclase inhibitor-mediated, but not rifampicin-mediated, reporter induction. Direct treatment of the HepG2 system with 1 to 10 μM squalene 2,3,22,23-dioxide, but not squalene 2,3-oxide, significantly activated PXR-responsive reporter expression. Also, squalene 2,3,22,23-dioxide bound to human PXR in vitro with an IC50 of 3.35 μM. These data indicate that cyclase inhibitors are capable of producing CYP3A4 and CYP2B6 induction in primary cultured human hepatocytes, and that an endogenous squalene metabolite is a conserved intracrine activator of PXR.

A primary mode of defense that is used by animals against their chemotherapeutic environment involves recognition by a “xenobiotic-sensing” receptor followed by the induction of phase I and phase II xenobiotic-metabolizing enzymes, as well as “phase III” transporters. As the archetype of this mechanism, many xenobiotics bind to the pregnane X receptor (PXR), owing to the receptor’s unusually accommodating ligand-binding pocket (Watkins et al., 2001, 2003). On ligand binding, PXR, in partnership with the retinoic X receptor, is transformed into an active transcription factor that increases the expression of target genes, which include members of the CYP3A family (e.g., CYP3A23 in rat, CYP3A11 in mouse, and CYP3A4 in human). These CYP3A enzymes catalyze the phase I metabolism of numerous xenobiotic substrates, including a large number of clinically used drugs (Quattrochi and Guzelian, 2001).

In addition to serving as a xenobiotic recognition and metabolizing system, PXR and CYP3A enzymes are increasingly perceived to function in the metabolism of endogenous molecules. For example, the cholestatic secondary bile acid, lithocholate, both activates PXR and is a substrate for CYP3A (Staudinger et al., 2001; Xie et al., 2001). We have used chemical inhibitors of various steps of the cholesterol biosynthetic pathway as an approach for identifying endogenous modulators of hepatic cytochrome P450 expression (Fig. 1). In this regard, we have reported that inhibitors of squalene synthase (e.g., squalestatin 1), the first committed step in cholesterol biosynthesis, selectively induce CYP2B expression in primary cultured rat hepatocytes and rat liver through a mechanism that requires the
variability can be attributed to interspecies differences in the amino acid upstream of cyclase (Fig. 1).

cyclase inhibitor-inducible CYP3A expression was suppressed when cholesterol biosynthetic pathway (Shenoy et al., 2004a). For example, tocytes are cotreated with an inhibitor of an upstream step in the squalene metabolite, most likely squalene 2,3-oxide and/or squalene in cultured hepatocytes prepared from PXR-null mice (Shenoy et al., 2004a). This latter effect is mediated by PXR, as clase; e.g., Ro 48-8071), which catalyzes the second step downstream 2,3-Oxidosqualene:Lanosterol Cyclase

Squalene Synthase

Squalene

Squalene Monoxygenase

NB-598

Squalene 2,3-oxide

Squalene 2,3,22,23-dioxide

2,3-Oxidosqualene:Lanosterol Cyclase

Ro 48-8071

BIBX 79

U18666A

24(S),25-Oxidolanosterol

Lanosterol

24(S),25-Epoxycholesterol

Cholesterol

CYP2B

CYP3A

PXRx

Rifampicin

CAR

biosynthesis of one or more endogenous isoprenoids and activation of constitutive androstane receptor (CAR) (Kocarek and Mercer-Haines, 2002). By contrast, treatment of primary cultured rat or mouse hepatocytes with an inhibitor of 2,3-oxidosqualene:lanosterol cyclase (cy- clase; e.g., Ro 48-8071), which catalyzes the second step downstream from squalene synthase, causes the selective induction of CYP3A (Shenoy et al., 2004a). This latter effect is mediated by PXR, as illustrated by the loss of cyclase inhibitor-mediated CYP3A induction in cultured hepatocytes prepared from PXR-null mice (Shenoy et al., 2004a). In addition, cyclase inhibitor-inducible CYP3A expression requires cyclase blockade and the ongoing synthesis of an endogenous squalene metabolite, most likely squalene 2,3-oxide and/or squalene 2,3,22,23-dioxide, as indicated by the loss of induction when hepatocytes are cotreated with an inhibitor of an upstream step in the cholesterol biosynthetic pathway (Shenoy et al., 2004a). For example, cyclase inhibitor-inducible CYP3A expression was suppressed when rat hepatocyte cultures were cotreated with NB-598, a potent inhibitor of squalene monoxygenase, which catalyzes the step immediately upstream of cyclase (Fig. 1).

There are considerable differences among species in the regulation of xenobiotic-metabolizing enzyme expression. A substantial portion of this variability can be attributed to interspecies differences in the amino acid sequences of the ligand-binding domains of PXR, with consequent differences in the dimensions of the large ligand-binding pockets (Jones et al., 2000). As a classic example, the catatotic steroid pregnenolone 16α-carbonitrile is an efficacious activator of rodent PXR and inducer of rodent CYP3A, while having little activity toward the rabbit or human orthologs (Kocarek et al., 1995; Jones et al., 2000). By contrast, the macrocyclic antibiotic rifampicin displays the opposite species dependence for PXR activation and CYP3A induction (Kocarek et al., 1995; Jones et al., 2000). Therefore, it seems possible that interspecies differences apply not only to xenobiotics but also to endogenous molecules. Indeed, this is clearly illustrated by recent findings involving the bile acid precursor sterol 5β-cholestanolic acid-3α,7α,12α-triol. This sterol, which accumulates in the absence of functional CYP27, is an activator of murine PXR and a substrate for CYP3A (Forster and Wikvall, 1999; Honda et al., 2001; Dussault et al., 2003; Goodwin et al., 2003). CYP3A metabolism initiates an alternative pathway of steroid side-chain shortening, permitting the formation of cholic acid in hepatocytes lacking CYP27 activity (Honda et al., 2001; Goodwin et al., 2003). By contrast, bile acid precursor sterols do not activate human PXR, thereby explaining why humans with the genetic disease cerebrotendinous xanthomatosis, attributable to CYP27 deficiency, produce reduced levels of normal bile acids, accumulate sterols in various tissues, and exhibit a host of severe pathologies, whereas mice that have been genetically engineered to lack CYP27 do not (Dussault et al., 2003; Goodwin et al., 2003). This study was undertaken to investigate whether the PXR activation and CYP3A induction that we previously reported to occur in rodent hepatocytes following cyclase inhibition are conserved in human liver cell culture systems.

Materials and Methods

Materials. Ro 48-8071 and U18666A were purchased from BIOMOL Research Laboratories (Plymouth Meeting, PA). BIBX 79 was a gift from Boehringer Ingelheim USA (Ridgefield, CT). NB-598 was a gift from Banyu Pharmaceutical Co., Ltd. (Tokyo, Japan). Rifampicin, cholesterol, squalene, and T0901317 were purchased from Sigma-Aldrich (St. Louis, MO). Squalene 2,3-oxide (2,3-oxidosqualene, racemic) and squalene 2,3,22,23-dioxide (2,3,22,23-dioxide-squalendiol, mixture of diastereomers) were purchased from Echelon Biosciences (Salt Lake City, UT). Cell culture media, fetal bovine serum, and antibiotics were purchased from Invitrogen (Carlsbad, CA). Re- combinant human insulin (Novolin R) was purchased from Novo Nordisk Pharmaceuticals, Inc. (Princeton, NJ). Other materials were obtained from the sources indicated below.

Primary Cultured Human Hepatocytes. Plated primary cultures of human hepatocytes were obtained through the Liver Tissue and Cell Distribution System (N01-DK-7-0004; University of Minnesota, Minneapolis, MN). Following hepatocyte preparation and overnight culture at the University of Pittsburgh, the hepatocytes, in T25 flasks, were express-shipped to Wayne State University and maintained as described previously (Duniec-Dmuchowski et al., 2007). The day following Matrigel treatment, the hepatocytes were incubated with fresh medium alone (untreated) or containing 3 to 30 μM Ro 48-8071, 0.1% dimethyl sulfoxide (DMSO), or 50 μM rifampicin (in DMSO). The cultures were either harvested after 24-h incubation or retreated at 24 h and harvested after a total of 48 h of incubation.

TaQMan Real-Time Reverse Transcription-Polymerase Chain Reaction Analysis. Total RNA was prepared from individual T25 flasks of human hepatocytes, and levels of CYP3A4 and CYP2B6 mRNA were measured using TaqMan Gene Expression Assays Hs00430021_m1 and Hs00167937_g1, re- spectively (Applied Biosystems, Foster City, CA), as described previously (Duniec-Dmuchowski et al., 2007). Normalized mRNA contents were expressed relative to the untreated or DMSO-treated control group. The Wilcoxon sign-rank test was used to compare median -fold changes against the hypothetical value of 1 (GraphPad Prism, version 5.0; GraphPad Software Inc., San Diego, CA). This test requires a sample size of at least six and therefore was applied only to the data shown in Fig. 2.

Western Blot Analysis. Microsomes were isolated from primary cultures of human hepatocytes (two pooled T25 flasks of hepatocytes per treatment group) as described previously (Kocarek and Reddy, 1996; Kocarek et al., 2002). Protein concentrations were determined by the bicinchoninic acid assay (Smith et al., 1985) using bovine serum albumin as standard. One microgram of microsomal protein of each sample was resolved by SDS-polyacrylamide gel electrophoresis on a Criterion prestained 10% acrylamide Tris-HCl gel (Bio-Rad, Hercules, CA) and electrophoretically transferred to a polyvinylidene difluo- ride membrane (Bio-Rad). Blots were blocked overnight in 5% nonfat dry milk in Tris-buffered saline/Tween 20 (TBST) in a cold room. After brief washing in TBST, blots were incubated with a 1:20,000 dilution of monoclonal anti- body WB-MAB-3A (reported to detect CYP3A4 and CYP3A5; BD Gentest, Woburn, MA) in blocking buffer overnight in a cold room. After extensive
washing in TBST, blots were incubated with horseradish peroxidase-conjugated goat anti-mouse antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, CA) diluted 1:20,000 in blocking buffer for 1 h at room temperature. Immunoreactive bands were visualized using ECL Plus Western Blotting Detection Reagents (GE Healthcare) according to the manufacturer’s instructions.

Transient Transfection Analysis. HepG2 cells were cultured and transfected with the PXR-responsive reporter plasmid XREM-CYP3A4-Luc (provided by Dr. Bryan Goodwin, GlaxoSmithKline, Research Triangle Park, NC), the human PXR expression plasmid pSG5-hPXR1 (provided by Dr. Steven Kliewer, University of Texas Southwestern, Dallas, TX), and pRL-CMV (Promega, Madison, WI) as described previously (Duniec-Dmuchowski et al., 2007). The following day, the cells were treated as described in the legends to Figs. 4, 5, and 7. Twenty-four hours later, the cells were harvested for measurement of firefly and Renilla luciferase activities using the Dual-Luciferase Reporter Assay System (Promega). Luciferase data were analyzed by one-way analysis of variance followed by the Newman-Keuls or Dunnett’s multiple comparison test and by fitting of concentration-response relationships with sigmoidal curves (variable slopes) using Prism version 5.0 (GraphPad Software Inc.).

Thin-Layer Chromatographic Detection of Metabolically Labeled Lipids. Metabolic labeling and detection of nonsaponifiable lipids was performed by modification of methods described by Pill et al. (1987) and Boogaard et al. (1987). In brief, 1.5 million HepG2 cells were plated into 60-mm dishes in Dulbecco’s modified Eagle’s medium supplemented with nonessential amino acids, 10% fetal bovine serum, 100 U/ml penicillin, and 100 µg/ml streptomycin and incubated for 48 h. The cells were then treated with 0.1% DMSO, rifampicin, NB-598, and/or Ro 48-8071, as described in the legend to Fig. 6. One hour later, 2 µCi RS-[2,3-14C]mevalonate (MVA) (specific activity 55 mCi/mmol; GE Healthcare) was added to the culture medium. After 24 h, cells were washed with and scraped into cold phosphate-buffered saline and pelleted. The cell pellets were saponified in 15% potassium hydroxide in ethanol for 1 h at 80°C. Nonsaponifiable lipids were extracted twice with n-hexane, and extracts were combined and evaporated under nitrogen. The residues were dissolved in 60 µl of hexane-chloroform (70:30, v/v) and spotted onto reverse-phase thin-layer chromatography plates (KC18; Whatman, Clifton, NJ), which were then developed twice with acetoni trile-chloroform (2:1, v/v). Authentic samples of cholesterol, squalene, squalene 2,3-oxide, and squalene 2,3,22,23-diole were served as markers. These standards were spotted onto separate lanes and detected by spraying with 10% sulfuric acid in ethanol and heating. Radiolabeled lipids were then detected by exposing the plate to Eastman Kodak (Rochester, NY) BioMax XAR film for 3 days at room temperature.

PXR in Vitro Binding Assay. The LanthanaScreen time-resolved fluorescence energy transfer (TR-FRET) PXR [steroid and xenobiotic receptor (SXR)] competitive binding assay (Invitrogen) was performed essentially according to the manufacturer’s instructions except that the assay volume was reduced to 20 µl. All of the steps were carried out at room temperature. A serial dilution series of each test compound (squalene 2,3-oxide, squalene 2,3,22,23-diole, and T901317) was prepared in the appropriate solvent (ethanol for the squalene metabolites, DMSO for T901317). The test compounds were then diluted to 2 times their final concentrations in TR-FRET PXR (SXR) assay buffer, and 10 µl of each dilution was aliquoted in triplicate into the wells of a black 384-well assay plate (MatriCal Bioscience, Spokane, WA). Then, 5 µl of 4× Fluromone PXR (SXR) Green (fluorescent PXR ligand) was added to each well, followed by addition of 5 µl of 4× PXR-ligand-binding domain (glutathione-δ-transferase fusion/dithiothreitol/terbi um-labeled anti-glutathione-δ-transferase fusion) solution in assay buffer. The plate was protected from light and incubated with shaking for 1 h, after which TR-FRET was measured using a Victor3 multilabel reader (PerkinElmer Life and Analytical Sciences, Waltham, MA) at the following settings: excitation wavelength 340 nm, emission wavelengths 520 and 490 nm, delay time 100 µs, and integration time 200 µs. The TR-FRET ratio for each sample was calculated by dividing the emission signal at 520 nm by the emission signal at 490 nm. Binding curves with IC50 values were generated by fitting emission ratio versus log molar ligand concentration data with sigmoid curves [log(inhibitor) versus response — variable slope] using Prism version 5.0 (GraphPad Software Inc.).
Results

Hepatocytes isolated from seven human livers were incubated for 24 h with the prototypical PXR ligand, rifampicin (at 50 µM), or with the cyclase inhibitor, Ro 48-8071, at concentrations of 3, 10, and 30 µM, and effects on CYP3A4 and CYP2B6 mRNA levels were measured (Fig. 2). Figure 2A shows the data plotted as -fold increases over control (i.e., Ro 48-8071 relative to untreated and rifampicin relative to DMSO-treated) in box and whisker format. Ro 48-8071 concentrations of 3, 10, and 30 µM produced significant median increases in CYP3A4 mRNA levels of 2.2-, 7.1-, and 8.5-fold, respectively, and increased CYP2B6 mRNA levels by 3.0-, 4.6-, and 3.4-fold, respectively (although only the effect at 10 µM was significant). For comparison, rifampicin treatment increased CYP3A4 and CYP2B6 mRNA levels by 59- and 8.7-fold in these hepatocyte preparations. There was considerable variability in the effects of Ro 48-8071 among hepatocyte preparations, as indicated both by the box and whisker plots (Fig. 2A) and the individual concentration-response plots shown in Fig. 2B. In most of the preparations, the Ro 48-8071-mediated increase in CYP3A4 mRNA content was maximal or near-maximal at 10 µM, although in two of the preparations the increase was at least 30% greater at 30 µM than it was at 10 µM. For CYP2B6, the Ro 48-8071-mediated increase in mRNA content was greatest at 10 µM in all but one preparation.

In four additional human hepatocyte preparations, 48-h treatment with Ro 48-8071 increased CYP3A4 mRNA content 3.4- to 4.8-fold and increased CYP2B6 mRNA content 1.7- to 2.4-fold at 3 and 10 µM, respectively (Fig. 3A). Although the sample size was insufficient to show statistical significance, in two of these hepatocyte preparations, microsomal CYP3A4 immunoreactive protein levels were also evaluated and found to be increased in Ro 48-8071-treated hepatocytes relative to untreated controls (Fig. 3B).

The above-described experiments showed that treatment of primary cultured human hepatocytes with a cyclase inhibitor, Ro 48-8071, was capable of increasing CYP3A4 and CYP2B6 expression. To investigate the underlying mechanism, we used a HepG2-based platform, in which the cells were transiently cotransfected with a plasmid expressing human PXR and a PXR-responsive reporter plasmid (Dmuchowski et al., 2007). When the transfected HepG2 cells were treated with Ro 48-8071, luciferase expression increased with an EC$_{50}$ of 0.113 µM (Fig. 4A). Ro 48-8071-mediated induction was maximal at 1 µM and maintained at 10 µM but was completely attenuated at 30 µM (Fig. 4A). Treatment with either of two additional cyclase inhibitors, BIBX-79 or U18666A, also potently increased luciferase expression (EC$_{90}$ of 0.916 and 0.294 µM, respectively) (Fig. 4B). In these experiments, Ro 48-8071, BIBX-79, and U18666A all produced maximal increases over control of ~7- to 8-fold (Fig. 4, A and B) by comparison with rifampicin, which increased reporter activity ~12-fold (data not shown).

To determine whether cyclase inhibitor treatments activated human PXR as a consequence of cyclase inhibition, rather than by functioning as direct PXR ligands, experiments were performed in which the step in the cholesterol biosynthetic pathway immediately preceding cyclase-catalyzed conversion of 2,3-oxidosqualene to lanosterol was inhibited (Fig. 1). Thus, NB-598 was used to inhibit squalene monooxygenase, which catalyzes the conversion of squalene to 2,3-oxidosqualene. In our previous study, NB-598 treatment inhibited Ro 48-8071-inducible CYP3A expression in primary cultured rat hepatocytes, but the inhibitory effect was critically dependent on the NB-598 concentration (Shenoy et al., 2004a). Therefore, transfected HepG2 cells were treated with a range of NB-598 concentrations, alone or in combination with a cyclase inhibitor (Fig. 5, A–C) or rifampicin, as a direct PXR ligand control (Fig. 5D). Treatment with NB-598 alone at concentrations of 0.1 or 0.3 µM had no significant effect on luciferase expression (Fig. 5, A–D) but markedly inhibited cholesterol biosynthesis as indicated by reduction of [14C]MVA incorporation into cholesterol with corresponding accumulation of
and (A) or with medium containing 0.1% DMSO or 10 µM NB-598. As described above, treatment with Ro 48-8071 increased PXR-responsive reporter expression (~2.5-fold increase at 10 µM), treatment with squalene 2,3:22,23-dioxide produced a marked concentration-dependent increase in reporter expression (~18.4-fold increase at 10 µM) (Fig. 7A, top). As expected, rifampicin treatment had no effect on luciferase activity at any concentration tested (Fig. 5D). Rather, cotreatment with NB-598 did not suppress rifampicin-inducible luciferase activity at any concentration tested (Fig. 5D). Therefore, cotreatment with NB-598 concentrations of 1 µM or greater significantly enhanced the reporter induction that was produced by rifampicin treatment (Fig. 5D).

The abilities of squalene 2,3-oxide and squalene 2,3:22,23-dioxide to activate human PXR directly were evaluated next. Transfected HepG2 cells were treated with 0.3 to 10 µM squalene 2,3-oxide or squalene 2,3:22,23-dioxide, either alone (Fig. 7A, top) or in combination with Ro 48-8071 and NB-598, to prevent both endogenous formation and cyclase-mediated conversion of the squalene metabolites (Fig. 7A, bottom). Whereas treatment with squalene 2,3-oxide alone did not significantly increase PXR-responsive reporter expression (~1.5-fold increase at 10 µM), treatment with squalene 2,3:22,23-dioxide produced a marked concentration-dependent increase in reporter expression (~5-fold increase at 10 µM) (Fig. 7A, top). As expected, rifampicin treatment had no effect on luciferase activity at any concentration tested (Fig. 5D). Rather, cotreatment with NB-598 concentrations of 1 µM or greater significantly enhanced the reporter induction that was produced by rifampicin treatment (Fig. 5D).

Finally, a TR-FRET-based in vitro competitive binding assay was used to assess the abilities of squalene 2,3-oxide and squalene 2,3:22,23-dioxide to bind directly to human PXR. T0901317 was used as a positive control PXR ligand in this assay, as we and others have recently reported that this compound is a potent activator of human PXR (Duniec-Dmuchowski et al., 2007; Mitro et al., 2007; Xue et al., 2007). T0901317 bound to PXR with an IC50 of 44.1 nM (Fig. 7B), consistent with the published PXR-activating and binding affinity of this compound (Duniec-Dmuchowski et al., 2007; Mitro et al., 2007; Xue et al., 2007). The competition curve for squalene 2,3:22,23-dioxide resembled that for T0901317, both in terms of slope and maximal displacement of the fluorescent PXR ligand (Fig. 7B, left). Squalene 2,3:22,23-dioxide bound to PXR with an IC50 of 3.35 µM (Fig. 7B, left), which was in accord with the concentration range that produced effective PXR transactivation in the HepG2 system. By contrast, although squalene 2,3-oxide bound to PXR with a calculated IC50 of 0.183 µM, the competition curve for this squalene metabolite was shallow and showed less maximal fluorescent ligand displacement relative to those for T0901317 and squalene 2,3:22,23-dioxide (Fig. 7B, left). For comparison, Ro 48-8071 showed little evidence of PXR binding at concentrations up to 10 µM. Higher concentrations caused fluorescent ligand displacement with a steep slope that permitted only estimation of an IC50 value (24.1 µM) without confidence intervals (Fig. 7B, right).

Discussion

Treatment of primary cultures of human hepatocytes with the cyclase inhibitor Ro 48-8071 increased the expression of CYP3A4, as well as expression of CYP2B6, which like CYP3A4 is a target gene for both PXR and CAR (Goodwin et al., 2001). Although there was considerable variability in the magnitude of Ro 48-8071-mediated CYP3A4/CYP2B6 induction among hepatocyte culture preparations, this variability was consistent with that observed with other inducers. For example, when 23 preparations of primary cultured human hepatocytes were treated with rifampicin, we observed CYP3A4 mRNA levels to increase from 1.6- to 436-fold (Fang et al., 2007). In most preparations, the magnitude of CYP3A4 mRNA induction that was
produced by Ro 48-8071 treatment was lower than that produced by rifampicin treatment. For example, after 24-h treatment with 10 μM Ro 48-8071, the median increase in CYP3A4 mRNA content was 7.1-fold, whereas the median increase produced by rifampicin treatment was 59-fold.

The Ro 48-8071 concentrations required to produce effective CYP3A4 induction in primary cultured human hepatocytes were in the low micromolar range (3–30 μM), whereas PXR-responsive reporter activation in transfected HepG2 cells was maximal at 1 μM Ro 48-8071. Thus, the Ro 48-8071 concentrations that produced CYP3A4 induction in primary cultured human hepatocytes were comparable with those we previously reported to cause CYP3A induction in primary cultured rat hepatocytes (Shenoy et al., 2004a) but were higher than those required to produce PXR activation in HepG2 cells. We speculate that these differences in Ro 48-8071 concentration-mediated effects between the primary hepatocyte and HepG2 systems are probably attributable to differences in the xenobiotic metabolism/transport capabilities of the cells.

One facet of cyclase inhibitor pharmacology that has been repeatedly observed is the ability of concentrations that produce submaximal inhibition of cyclase activity to cause accumulation of 24(S),25-epoxycholesterol, a potent endogenous LXR agonist, whereas maximally effective concentrations of cyclase inhibitors prevent 24(S),25-epoxycholesterol production (Mark et al., 1996; Morand et al., 1997; Janowski et al., 1999). We and others have reported that 24(S),25-epoxycholesterol is an effective activator of rodent PXR (Shenoy et al., 2004b; Gnerre et al., 2005). Therefore, in determining the mechanism by which cyclase inhibitor treatment causes PXR activation, it is necessary to consider whether effects are caused by 1) direct actions of the drugs as PXR ligand agonists, 2) effects of endogenous oxysterols that are formed downstream of cyclase, such as 24(S),25-epoxycholesterol, or 3) effects of endogenous metabolites produced by Ro 48-8071 treatment at ASPET Journals on June 2, 2017 dmd.aspetjournals.org Downloaded from
that accumulate upstream of cyclase blockade. In this regard, we
previously reported, through the use of various upstream pathway
inhibitors and estimation of cellular squalene/sterol metabolite con-
tents, that cyclase inhibition activated rodent PXR through accumu-
lation of one or both of the squalene metabolites, squalene 2,3-oxide
and squalene 2,3:22,23-dioxide (Shenoy et al., 2004a). The concen-
tration-dependent effects of cyclase inhibitor treatments on squalene/
sterol metabolite production in HepG2 cells have been investigated
previously. Ro 48-8071 concentrations of 3 to 10 nM caused accumu-
lution of 24(S),25-epoxycholesterol, whereas 100 nM Ro 48-8071
produced almost complete blockade of cholesterol biosynthesis, pre-
vented 24(S),25-epoxycholesterol accumulation, and promoted accumu-
lation of squalene 2,3-oxide and squalene 2,3:22,23-dioxide (Mor-
ard et al., 1997). BBIX 79 and U18666A produced their greatest
effects on PXR-responsive reporter expression at concentrations of 10
and 1 µM, respectively. Short-term incubation of HepG2 cells with
BBIX 79 was reported to inhibit cholesterol biosynthesis by greater
than 98% at 1 µM, a concentration that completely blocked 24(S),25-
epoxycholesterol formation but caused substantial accumulation of
squalene 2,3-oxide and squalene 2,3:22,23-dioxide (Mark et al.,
1996). In the same study, incubation with 0.1 µM U18666A effect-
ively inhibited cholesterol biosynthesis, although 24(S),25-epoxycho-
lesterol continued to accumulate at this concentration (Mark et al.,
1996). At 1 µM U18666A, biosynthesis of cholesterol and 24(S),25-
epoxycholesterol was abolished, whereas squalene 2,3-oxide and
squalene 2,3:22,23-dioxide accumulated substantially (Mark et al.,
1996). Therefore, the concentrations of the various cyclase inhibitors
that caused PXR activation in HepG2 cells were those that promote
the accumulation of squalene 2,3-oxide and squalene 2,3:22,23-diox-
ide, but not 24(S),25-epoxycholesterol. Consistent with these findings,
we have observed that direct incubation of human PXR/reporter-
transfected HepG2 cells with 24(S),25-epoxycholesterol does not
cause reporter induction (Duniec-Dmuchowski et al., 2007). These
findings suggest that 24(S),25-epoxycholesterol, like the bile acid
precursor sterol, 5β-cholestanolic acid-3α,7α,12α-triol, activates ro-
dent but not human PXR.

Our findings using the squalene monoxygenase inhibitor NB-598
in combination with the various cyclase inhibitors strongly implicate
either or both of the squalene metabolites, squalene 2,3-oxide and
squalene 2,3:22,23-dioxide, as endogenous activators of human PXR.
NB-598 concentrations of 0.1 to 0.3 µM are sufficient to produce
effective inhibition of cholesterol biosynthesis in HepG2 cells (Horie
et al., 1990) (Fig. 6A). These NB-598 concentrations caused signifi-
cant inhibition of the PXR-responsive reporter induction that was
produced by all the cyclase inhibitors, while having no inhibitory
effect on rifampicin-mediated induction. Higher concentrations of
NB-598 produced concentration-dependent increases in PXR-respon-
sive reporter expression, either when used alone or in combination
with a cyclase inhibitor, an effect we speculate is attributable to direct
PXR ligand activity. However, coincubation with NB-598, at concen-
trations of 1 µM and higher, also produced significant increases in
reporter induction above that produced by a maximally effective
concentration of the direct-acting PXR ligand rifampicin. The mech-
anism underlying this drug interaction is under investigation.

Direct treatments of PXR/reporter-transfected HepG2 cells with
squalene 2,3-oxide or squalene 2,3:22,23-dioxide revealed that the
latter compound was capable of producing marked PXR activation.
This effect was observed either when squalene 2,3:22,23-dioxide was
applied as the only treatment or when the squalene 2,3:22,23-dioxide
was used together with NB-598 and Ro 48-8071, the combination of
which served both to prevent the endogenous formation of squalene
oxide metabolites and their further conversion to lanosterol or
24(S),25-oxidolanosterol and downstream sterols. Use of an in vitro
TR-FRET-based assay confirmed the ability of squalene 2,3:22,23-
dioxide to bind directly to human PXR with an affinity that was
consistent with the ability of this metabolite to transactivate PXR in
the HepG2 system. These results indicate that squalene 2,3:22,23-
dioxide is capable of activating human PXR and therefore may
mediate the PXR activation that occurs following treatment with a
cyclase inhibitor. Although the HepG2 transfection data do not sup-
port a role for squalene 2,3-oxide in PXR activation, it is not possible
to conclude definitively that squalene 2,3-oxide is inactive in this
regard because the degree of cellular uptake of this metabolite fol-
lowing exogenous treatment is unknown. Squalene 2,3-oxide did
show some ability to bind to human PXR in vitro, although the
binding curve did not reveal the same efficacy of fluorescent ligand
placement that was seen for squalene 2,3:22,23-dioxide. It is also
important to emphasize that the squalene oxide compounds that were
used for these studies were mixtures of optical isomers rather than the
pure enantiomers that are formed by endogenous metabolism. As a
final point, although NB-598 treatment significantly inhibited cyclase-
mediated PXR activation, the PXR activity was not reduced to the
control level occurring in untreated HepG2 cells. This residual PXR
activation is probably attributable to some ability of the cyclase
inhibitors to function as direct PXR ligands. In this regard, Ro

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**Fig. 6. Effects of NB-598 and Ro 48-8071 treatments on sterol biosynthesis in HepG2 cells. A and B, HepG2 cells were incubated for 24 h with medium containing 0.1% DMSO, 30 µM rifampicin (Rif), or 0.1 to 10 µM NB-598 (A) or with 0.1% DMSO (0, 0), 10 µM Ro 48-8071, 0.1 µM NB-598, or Ro 48-8071 and NB-598 in combination (B).**

**Methods**

with 0.1% DMSO (0, 0), 10 µM [14C]MVA, cells were harvested for evaluation of nonsaponifiable lipid contents by thin-layer chromatography and autoradiography as described under Materials and Methods.
48-8071 did exhibit ability to bind to human PXR in vitro at high concentrations.

In summary, our results indicate that cyclase inhibitors are capable of producing CYP3A4 and CYP2B6 induction in primary cultures of human hepatocytes and of activating human PXR. As in rodent systems, these effects are mediated through the actions of endogenous squalene metabolites, the likeliest candidate being squalene 2,3:22,23-dioxide. Unlike the endogenous sterols that have been found capable of activating rodent but not human PXR, the PXR-activating abilities of the squalene metabolites are conserved from rodent to human. Of the other known endogenous inducers of CYP3A4, vitamin D3 exerts its effect through the vitamin D receptor (Schmiedlin-Ren et al., 2001). In addition, although the primary bile acid chenodeoxycholic acid has been reported to be capable of activating PXR (Xie et al.,...

**FIG. 7.** Concentration-dependent abilities of squalene 2,3-oxide and squalene 2,3:22,23-dioxide treatments to activate PXR-responsive reporter expression in HepG2 cells and to bind to PXR in vitro. A, HepG2 cells were transiently transfected with pSG5-hPXR1, XREM-CYP3A4-Luc, and pRL-CMV and then incubated for 24 h with (top) medium alone (UT) or containing 0.1% DMSO (DM), 0.1% methanol (MeOH), 0.3 to 10 µM squalene 2,3-oxide (SO), or 0.3 to 10 µM squalene 2,3:22,23-dioxide (SDO) or (bottom) 10 µM Ro 48-8071 (Ro), 0.1 µM NB-598 (NB), Ro and DM, or Ro and NB alone (UT) or in combination with MeOH, SO, or SDO. After treatment, cells were harvested for measurement of firefly and Renilla luciferase activities. Normalized (firefly/Renilla) values are expressed as mean ± S.D. (n = 3 wells/treatment group). Groups not sharing a letter are significantly different from each other, p < 0.05. B, the Lanthascreen TR-FRET PXR (SXR) competitive binding assay was used to evaluate the abilities of SO and SDO (left) and Ro 48-8071 (right) to interact with PXR in vitro. T0901317 was included as a positive control PXR ligand (the same binding data for T0901317 are replicated in each panel). IC_{50} values and 95% confidence intervals (CIs) are shown. For the Ro 48-8071 data, the IC_{50} value is an estimate, and CI could not be calculated.
2001), recent findings indicate that primary bile acids can also induce CYP3A4 as a consequence of farnesoid X receptor activation, both directly through the transactivation of CYP3A4 as a farnesoid X receptor target gene (Gnerre et al., 2004) and indirectly through the transcriptional up-regulation of PXR (Jung et al., 2006). Certain secondary bile acids, such as lithocholic acid and Ursodeoxycholic acid, are known to activate murine and human PXR, consistent with a conserved role for PXR in protection from cholestasis (Uppal et al., 2007). Our results show that squilene metabolites are conserved intracrine activators of PXR and that cyclase may be considered to be a “receptor” that regulates the expression of CYP3A4 and other PXR target genes.

References


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