IDENTIFICATION OF HMG-CoA REDUCTASE INHIBITORS AS ACTIVATORS FOR HUMAN, MOUSE AND RAT CONSTITUTIVE ANDROSTANE RECEPTOR

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ABSTRACT:

Constitutive active (or androstan) receptor (CAR, NR1I3), a member of the nuclear receptor family, is a major regulator for induction of cytochrome P450 2B (CYP2B) genes by phenobarbital. Phenobarbital-like inducer, 1,4-bis[2-(3,5-dichloropyridyloxy)]benzene is a potent mouse CAR ligand that has been used to study CAR target genes in mice but does not activate human CAR (hCAR) or rat CAR (rCAR). Although 6-(4-chlorophenyl) imidazo[2,1-b][1,3]thiazole-5-carbaldehyde O-(3,4-dichlorobenzyl)oxime (CITCO) was reported to be an hCAR agonistic ligand, activation of hCAR by CITCO in cell-based reporter assay was weak. Therefore, we performed a screening of 50 drugs and chemicals using cell-based reporter assays to identify activators of hCAR. Among them, HMG-CoA reductase inhibitors (cerivastatin, simvastatin, fluvastatin, and atorvastatin) enhanced the hCAR-mediated transcriptional activation of phenobarbital-responsive enhancer module reporter gene by up to 3-fold. Similar activation by HMG-CoA reductase inhibitors was also observed with mouse and rat CARs. On the other hand, pravastatin did not activate hCAR at the concentrations tested (up to 30 μM). The extent of activation by the HMG-CoA reductase inhibitors was stronger than that by CITCO. Cerivastatin, simvastatin, fluvastatin, and atorvastatin induced CYP2B6 mRNA in stable hCAR-expressed FLC7 cells but not in original FLC7 cells. Therefore, we concluded that CAR mediates the effects of HMG-CoA reductase inhibitors on the induction of CYP2B genes, although HMG-CoA reductase inhibitors also activate pregnane X receptor. HMG-CoA reductase inhibitors such as cerivastatin would be useful to study for elucidating molecular and cellular mechanisms of hCAR.

Constitutive active (or androstan) receptor (CAR, NR1I3), a member of the nuclear receptor family, is a major regulator of hepatic cytochrome P450 2B1 (CYP2B1) in rats (Muuangmoochai et al., 2001), CYP2B10 in mice (Honkakoski and Negishi, 1997; Kawamoto et al., 1999), and CYP2B6 in humans (Sueyoshi et al., 1999). Treatment of primary hepatocytes with phenobarbital results in the translocation of CAR into the nucleus, where CAR binds to phenobarbital-responsive enhancer module (PBREM) located upstream of the CYP2B gene as a heterodimer with the retinoid X receptor-α (RXRα, NR2B1) and activates transcription of CYP2B genes (Sueyoshi and Negishi, 2001). 1,4-bis[2-(3,5-Dichloropyridyloxy)]benzene (TCPOBOP) is a potent mouse CAR ligand that has been used to study CAR target genes in mice but does not activate human CAR (hCAR) or rat CAR (rCAR). Although 6-(4-chlorophenyl) imidazo[2,1-b][1,3]thiazole-5-carbaldehyde O-(3,4-dichlorobenzyl)oxime (CITCO) and phenytoin have been reported to be hCAR agonist ligands, activation of hCAR by CITCO in cell-based reporter assay was weak. Therefore, we performed a screening of 50 drugs and chemicals using cell-based reporter assays to identify activators of hCAR. Among them, HMG-CoA reductase inhibitors (cerivastatin, simvastatin, fluvastatin, and atorvastatin) enhanced the hCAR-mediated transcriptional activation of phenobarbital-responsive enhancer module reporter gene by up to 3-fold. Similar activation by HMG-CoA reductase inhibitors was also observed with mouse and rat CARs. On the other hand, pravastatin did not activate hCAR at the concentrations tested (up to 30 μM). The extent of activation by the HMG-CoA reductase inhibitors was stronger than that by CITCO. Cerivastatin, simvastatin, fluvastatin, and atorvastatin induced CYP2B6 mRNA in stable hCAR-expressed FLC7 cells but not in original FLC7 cells. Therefore, we concluded that CAR mediates the effects of HMG-CoA reductase inhibitors on the induction of CYP2B genes, although HMG-CoA reductase inhibitors also activate pregnane X receptor. HMG-CoA reductase inhibitors such as cerivastatin would be useful to study for elucidating molecular and cellular mechanisms of hCAR.

ABBREVIATIONS: CAR, constitutive active (or androstan) receptor; P450, cytochrome P450; PBREM, phenobarbital-responsive enhancer module; hCAR, human CAR; mCAR, mouse CAR; prPXRE, proximal PXR response element; PXR, pregnane X receptor; rCAR, rat CAR; XREM, xenobiotic-responsive enhancer module; RXRα, retinoid X receptor-α; TCPOBOP, 1,4-bis[2-(3,5-dichloropyridyloxy)]benzene; PB, phenobarbital; CITCO, 6-(4-chlorophenyl) imidazo[2,1-b][1,3]thiazole-5-carbaldehyde O-(3,4-dichlorobenzyl)oxime; PCR, polymerase chain reaction; DMSO, dimethyl sulfoxide; PXR, human PXR; SR12813, (2-(3,5-di-tert-butyl-4-hydroxy-phenyl)-1-(diethoxy-phosphoryl)-vinyl)-l-phosphonic acid diethyl ester; OATP-C, organic anion-transporting peptide-C.
inducers, including drugs, steroids, and environmental chemicals, in cell-based reporter assays (Jones et al., 2000; Moore et al., 2000). Thus, selective chemical tools (e.g., rifampicin) are available to study the function of PXR in humans.

Previous studies have demonstrated that 3-hydroxy-3-methylglutaryl-CoA (HMG-CoA) reductase inhibitors, which are in widespread clinical use for the treatment of hypercholesterolemia, increase the expression of P450s. Kocarek and Reddy (1996) demonstrated that treatment of primary cultures of rat hepatocytes with lovastatin, simvastatin, or fluvastatin increased the levels of CYP2B and CYP3A mRNA and immunoreactive protein. In contrast, pravastatin had little or no effect on the amount of any of the P450s examined in rat hepatocyte cultures. In addition, fluvastatin activated luciferase expression in primary cultures of rat hepatocytes that were transfected with the CYP2B1 reporter plasmid in the presence of cotransfected plasmid expressing mCAR or rCAR (Kocarek and Mercer-Haines, 2002). After the discovery that PXR mediates the effects of many CYP3A-inducing agents, El-Sankary et al. (2001) demonstrated that simvastatin or lovastatin, but not pravastatin, activated transcription from a CYP3A4 reporter plasmid in transiently transfected HepG2 cells. Furthermore, treatment of primary cultures of human hepatocytes with simvastatin, lovastatin, or atorvastatin increased the levels of CYP3A4 and CYP2B6 mRNA and immunoreactive active protein, but treatment with pravastatin did not (Kocarek et al., 2002). Although some HMG-CoA reductase inhibitors could activate human PXR and increase the amounts of CYP3A4 mRNA and immunoreactive protein as described above, it is not known whether activation of hCAR is involved in the induction of transcription of the CYP2B6 gene by treatment with HMG-CoA reductase inhibitors.

Therefore, we performed a screening of 50 drugs, including HMG-CoA reductase inhibitors, by using cell-based reporter assays to identify hCAR activators. Among them, HMG-CoA reductase inhibitors (cerivastatin, simvastatin, fluvastatin, and atorvastatin) enhanced the hCAR-mediated transcriptional activation of the PBREM-reporter gene. They also enhanced mCAR- and rCAR-mediated activation.

Materials and Methods

Chemicals. 5α-Androstan-3α-ol (3α-androstanol) was obtained from Steraloids (Newport, RI). Atorvastatin, cerivastatin, fluvastatin, pravastatin, and simvastatin were kindly provided by Sankyo Co. Ltd. (Tokyo, Japan). TCPOBOP was synthesized as described by Kende et al. (1985). Crito was obtained from BIORAD Research Laboratories (Plymouth Meeting, PA).

Plasmids. The open reading frame of hCAR was amplified from a liver 5′-stretch plus cdna library (BD Biosciences Clontech, Palo Alto, CA) using specific primers (5′-TGACGCATGGCGCAGTTAGGAGAATG-3′ and 5′-GAGCATGCCCTGCTGCAGATCTCC-3′). The PCR fragment was cloned into pEG-T Easy vector (Promega, Madison, WI). After EcoRI digestion, the fragment was ligated into the EcoRI site of pTARGET vector (Promega), resulting in pTARGET-hCAR. Correct insert orientation was confirmed by DNA sequence analysis. An mCAR expression plasmid was generated by PCR amplification of C57BL/6Cr mouse hepatic cdna using specific primers (5′-AGGAGAACCATTGACAGCAGTGATCTGTTAAAAC-3′ and 5′-GGTCTGGGAGAGATGGCACGTCG-3′) and insertion into the EcoRI site of pTARGET vector, resulting in pTARGET-mCAR. A human PXR expression vector was generated as described previously (Kobayashi et al., 2004). An rCAR expression vector (pCR3-rCAR) was constructed as described previously (Yoshinami et al., 2001). A chimeric CYP2B6 luciferase reporter plasmid was prepared as follows. A CYP2B6 5′-flanking fragment (~1789 to ~1667) containing the PBREM was generated by PCR from human genomic DNA as a template and was cloned into pG3-L-promoter vector (Promega) digested with NheI and BglII to generate a PBREM-luciferase plasmid (pG3-PBREM). A chimeric CYP3A4 luciferase reporter plasmid containing XREM and pPXRE (pG3-XREM/pPXRE) was generated as described previously (Kobayashi et al., 2004).

Cell Culture and Transfection Assay. FLC7, a human hepatocellular carcinoma cell line, was kindly provided by Dr. S. Nagamori (Kyorin University, Tokyo, Japan). FLC7 cells (Kawada et al., 1998) were cultured in Dulbecco’s modified Eagle’s medium:F-12 supplemented with 10% fetal bovine serum. Cells (1.8×104/well) were plated in 24-well plates 1 day before transfection. Plasmid pG3-L-PBREM (200 ng/well) was cotransfected with pTARGET-hCAR (20 ng/well) and phRL-TK vector (Promega; 4 ng/well) into FLC7 cells by LipofectAMINE reagent and PLUS reagent (Invitrogen, Carlsbad, CA). At 4 h after transfection, the cells were treated with chemicals at the indicated concentrations. Stock solutions of the chemicals were prepared in dimethyl sulfoxide (DMSO), and the final concentration of the solvent was 0.1% (v/v). Control cultures received vehicle (0.1% DMSO) alone. Luciferase reporter activities after 24 h were measured using a Dual-Luciferase reporter assay system (Promega and Tuner Designs Luminiometer TD-20/20 (Tuner Designs, Sunnyvale, CA) according to the manufacturer’s instructions. The Renilla luciferase activity of the control plasmid phRL-TK was used to normalize the results of the firefly luciferase activity of the plasmid pG3-L-PBREM.

mRNA Levels. A stable hCAR-transfected FLC7 cell line (FLC7-hCAR) was cotransfected with pTARGET-hCAR expression vector and selected by neomycin resistance. To measure the CYP2B6 mRNA level, cdna, prepared from total RNA of FLC7-hCAR cells and FLC7 cells treated with a 30 μM concentration of each HMG-CoA reductase inhibitor, was subjected to quantitative real-time PCR with an ABI Prism 7000 Sequence Detection System (Applied Biosystems, Foster City, CA). The mRNA levels of CYP2B6 were determined by using Human Assays-On-Demand (Applied Biosystems), a gene expression product for CYP2B6. The mRNA levels were normalized against 18S rRNA determined by Predesveloped TaqMan Assay Reagents for 18S rRNA (Applied Biosystems). To measure CYP2B6 mRNA levels in HepG2 cells and FLC7 cells, total RNA was prepared from nontreated cells using TRIzol reagent (Invitrogen). Each cdna (0.5 μl in 25 μl of reaction mixture) synthesized from 2 μg of RNA was subjected to 40-cycle amplification of CYP2B6 mRNA. The primers (5′-CACTATGCAGCTTGGGATG-3′ and 5′-GGCTGAGGGTGGGATGCGG-3′) were designed from the reported sequences (GenBank accession number NM_000767) across intron 3. PCRs were performed using AmpliTaq Gold (Applied Biosystems) at 95°C for 1 min, 60°C for 30 s, and 72°C for 30 s. The amplified DNA (151 base pairs) was separated on a 3% agarose gel and visualized with staining by ethidium bromide. Glyceraldehyde-3-phosphate dehydrogenase mRNA was amplified as an internal control.

Statistics. Results are expressed as mean ± S.D. Differences between two groups were analyzed using a two-sample t test.

Results

Identification of hCAR Activators in a Cell-Based Reporter Gene Assay Screening. Fifty drugs, including five HMG-CoA reductase inhibitors, were screened in cell-based reporter gene assays using hCAR and PBREM-reporter gene construct. These drugs consisted of antiinflammatories, antidepressants, antithrombotic drugs, NSAIDs, etc., in addition to HMG-CoA reductase inhibitors, which are hydrophobic and mainly metabolized via P450. Therefore, we considered that these drugs penetrated the cell membrane and were screened in cell-based reporter gene assay. As shown in Fig. 1A, compounds that increased hCAR-mediated transcriptional activity at the concentration of 10 μM were cerivastatin (2.8-fold), simvastatin (1.9-fold), atorvastatin (1.8-fold), and fluvastatin (1.7-fold). Temazepam and thiourida decreased hCAR-mediated transcriptional activity by >50%. The effects of the other 44 chemicals on the hCAR-mediated transcriptional activity were weak or negligible (<1.5-fold).

hCAR-Mediated Transcriptional Activation by HMG-CoA Reductase Inhibitors. Since four HMG-CoA reductase inhibitors showed activation of the reporter gene (Fig. 1A), five HMG-CoA reductase inhibitors, including pravastatin, were selected for further analysis. As shown in Fig. 1B, cerivastatin significantly increased hCAR-mediated transcriptional activity at the concentration of 1 μM.
Simvastatin, fluvastatin, and atorvastatin also showed significant activation of the reporter gene at the concentration of 30 μM. The manner of activation of hCAR-mediated transcription by the four HMG-CoA reductase inhibitors was dose-dependent. Maximum induction of hCAR-mediated transcriptional activity by the four HMG-CoA reductase inhibitors at the concentrations tested was 2- to 4-fold. On the other hand, pravastatin did not show dose-dependent activation of hCAR at the concentrations tested (up to 30 μM). In addition, we tried treating the cells with HMG-CoA reductase inhibitors in the presence of exogenous mevalonate, whereas the results were essentially the same as those obtained under standard treatment conditions (data not shown).

Repressive Effects of Androstanol on HMG-CoA Reductase Inhibitor-Induced hCAR-, mCAR- and rCAR-Mediated Transactivation. In agreement with previous reports (Sueyoshi et al., 1999), expression of the transfected PBREM-reporter gene was activated by cotransfection of the hCAR expression vector in FLC7 cells (Fig. 2A). 3α-Androstanol repressed this hCAR-mediated activation by 45%. 3α-Androstanol also repressed the increase in PBREM-luciferase activity induced by HMG-CoA reductase inhibitors (30 μM). When not only hCAR but also mCAR or rCAR was cotransfected, increase in PBREM-luciferase activity induced by HMG-CoA reductase inhibitors and repression by 3α-androstanol were observed (Fig. 2, B and C). On the other hand, distinct activation profiles by the potent PB-type inducer TCPOBOP were observed when the hCAR, mCAR, or rCAR expression vector was cotransfected with a PBREM-luciferase reporter. TCPOBOP elicited a significant induction of the reporter in the presence of mCAR, but induction by TCPOBOP at an equivalent concentration was not evident when hCAR or rCAR was cotransfected.

Potency of Cerivastatin for CAR Activation Compared with That of CITCO. As shown in Fig. 3, hCAR has been shown to transactivate the PBREM-reporter gene in the absence of any exogenous ligands. In addition, CITCO, a hCAR-specific ligand, enhanced the hCAR-mediated transcriptional activation of PBREM-reporter (by ~1.3-fold) at a concentration of 10 μM, as reported by Jinno et al. (2004). On the other hand, the effect of an HMG-CoA reductase inhibitor, cerivastatin, at the concentration of 10 μM on hCAR-mediated transcriptional activity was much greater than that of CITCO.

hCAR-Mediated Induction of CYP2B6 mRNA in Human Hepatoma Cell Line. To assess the hCAR-mediated induction of CYP2B6 mRNA by HMG-CoA reductase inhibitors, HMG-CoA reductase inhibitors were treated with hCAR-expressing cells derived from FLC7 cells (FLC7-hCAR). Unlike HepG2 cells, FLC7 cells constitutively express CYP2B6 mRNA (Fig. 4A). However, no inductive effect of HMG-CoA reductase inhibitors on CYP2B6 mRNA levels was observed in FLC7 cells. In contrast, CYP2B6 mRNA levels in FLC7-hCAR were increased by cerivastatin, simvastatin, fluvastatin, and atorvastatin but not by pravastatin (Fig. 4B).

Effects of HMG-CoA Reductase Inhibitors on hPXR-Mediated Transcriptional Activities. To compare the effects of HMG-CoA reductase inhibitors on transactivation of hCAR with those of human PXR, a human PXR expression vector was cotransfected with the PBREM-reporter gene, and a reporter gene assay was performed. Except for atorvastatin and pravastatin, the HMG-CoA reductase inhibitors significantly enhanced the expression of the PBREM-reporter gene (Fig. 5A). The extent of the activation at the concentration of 30 μM was about 3-fold. On the other hand, when XREM/prPXRE-reporter gene construct was used, atorvastatin (12.2-fold), in addition to cerivastatin (29.4-fold), simvastatin (26.6-fold), and fluvastatin (39.8-fold) also enhanced the expression of the XREM/prPXRE-reporter gene (Fig. 5B).

Discussion

The present study showed that HMG-CoA reductase inhibitors, cerivastatin, simvastatin, fluvastatin, and atorvastatin, were effective in activating hCAR in a cell-based reporter gene assay using human hepatocellular carcinoma FLC7 cells. In addition, the increase in the level of CYP2B6 mRNA induced by these HMG-CoA reductase inhibitors was shown to be regulated by hCAR. These findings were
supported by the following results. Since the expression of CAR and PXR in FLC7 cells is negligible (data not shown), no effect of treatment with HMG-CoA reductase inhibitors on CYP2B6 mRNA level was observed in FLC7 cells. In contrast, significant induction of CYP2B6 mRNA by treatment with HMG-CoA reductase inhibitors was detected in stable hCAR-expressing FLC7 cells (termed FLC7-hCAR; Fig. 4B). CITCO has been reported to be a selective hCAR activator.
It is well known that CAR is translocated from the cytoplasm to the nucleus after treatment with phenobarbital (Kawamoto et al., 1999). Although it has not been determined whether HMG-CoA reductase inhibitors directly bind to CAR, HMG-CoA reductase inhibitors could activate hCAR, rCAR, and mCAR at least in cell-based reporter gene assay (Fig. 2). The availability of activators for hCAR, rCAR, and mCAR will enable direct comparison of their similarities and differences in the transactivation mechanism.

Currently available information on the role of hCAR in the regulation of human CYP2B6 gene expression is limited. Accumulated evidence suggests that the human CYP2B6 gene is also regulated in a PXR-dependent manner. The majority of known PXR activators are capable of potently inducing CYP2B6 in primary human hepatocyte cultures, including those that activate hPXR only (rifampin, hyperforin, SR12813), those that activate both hPXR and hCAR (phenobarbital), or those that selectively activate hCAR (phenytoin). The present study showed that cerivastatin, simvastatin, fluvastatin, and atorvastatin enhanced the PBREM-reporter gene mediated by hCAR (Fig. 1B) and the XREM/prPXRE-reporter gene mediated by hPXR (Fig. 5B). Furthermore, Kocarek et al. (2002) reported that simvastatin, fluvastatin, and atorvastatin increased the amount of CYP2B6 and CYP3A mRNA in primary human hepatocytes. Therefore, it was thought that cerivastatin, simvastatin, fluvastatin, and atorvastatin are capable of activating both hCAR and hPXR and of inducing CYP2B6 in primary human hepatocyte cultures.

Among the HMG-CoA reductase inhibitors studied, only pravastatin did not enhance the hCAR-mediated expression of the PBREM-reporter gene (Fig. 1B). Due to the hydrophilic nature of pravastatin, the amount of cellular uptake by diffusion is small. In human hepatocytes, organic anion-transporting peptide-C (OATP-C) plays a predominant role in the uptake of some HMG-CoA reductase inhibitors such as pravastatin (Nakai et al., 2001). However, HepG2 cells, a frequently used cell model of human hepatocytes, have been immuno-histochemically demonstrated to express no OATP-C (Nakai et al., 2001). Therefore, an OATP-C expression vector was cotransfected in FLC7 cells with hCAR and a reporter vector as a preliminary study. However, hCAR-mediated transcriptional activity was not induced by pravastatin, even in the presence of OATP-C (data not shown). Kocarek et al. (2002) reported that treatment with pravastatin had no effect on the mRNA level of either CYP2B6 or CYP3A4 in human primary hepatocytes, although pravastatin treatment did produce the expected increase in HMG-CoA reductase mRNA level. Therefore, it appears that pravastatin was not an activator of hCAR in either human primary hepatocytes or human hepatoma cells.

The present screening in cell-based reporter gene assays using hCAR and PBREM-reporter gene construct indicated that temazepam and thyroid hormone decreased hCAR-mediated transcriptional activity (Fig. 1A). 3a-Androstanol and antimyocytic clomifimazole have been reported to deactivate hCAR through direct interactions with the ligand-binding domain of hCAR (Moore et al., 2000). Although further studies to clarify dose-responsibility and direct interaction with hCAR of temazepam and thyroid hormone are needed, these drugs may also be deactivators or antagonists of hCAR.

In conclusion, cerivastatin, simvastatin, fluvastatin, and atorvastatin enhanced hCAR-mediated transcriptional activity in FLC7 cells and induced the expression of CYP2B6 mRNA in hCAR-expressing FLC7 cells. The activation of hCAR by these HMG-CoA reductase inhibitors in a cell-based reporter gene assay is more effective than that by a specific hCAR ligand, CICICO, although these HMG-CoA reductase inhibitors also activated hPXR. Therefore, HMG-CoA reductase inhibitors are thought to be useful tools to study the function of hCAR in a cell-based reporter gene assay using FLC7 cells.
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References


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