Statins Activate Human PPARα Promoter and Increase PPARα mRNA Expression and Activation in HepG2 Cells

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Statins increase peroxisome proliferator-activated receptor α (PPARα) mRNA expression, but the mechanism of this increased PPARα production remains elusive. To examine the regulation of PPARα production, we examined the effect of 7 statins (atorvastatin, cerivastatin, fluvastatin, pitavastatin, pravastatin, rosuvastatin, and simvastatin) on human PPARα promoter activity, mRNA expression, nuclear protein levels, and transcriptional activity. The main results are as follows. (1) Majority of statins enhanced PPARα promoter activity in a dose-dependent manner in HepG2 cells transfected with the human PPARα promoter. This enhancement may be mediated by statin-induced HNF-4α. (2) PPARα mRNA expression was increased by statin treatment. (3) The PPARα levels in nuclear fractions were increased by statin treatment. (4) Simvastatin, pravastatin, and cerivastatin markedly enhanced transcriptional activity in 293T cells cotransfected with acyl-coenzyme A oxidase promoter and PPARα/RXRα expression vectors. In summary, these data demonstrate that PPARα production and activation are upregulated through the PPARα promoter activity by statin treatment.

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1. INTRODUCTION

Statins, 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase inhibitors, are the most widely used drugs to lower low-density lipoprotein (LDL) cholesterol. These mechanisms have been reported that treatment with statins results in lowering intracellular cholesterol concentration, and then increasing a proteolytic activation of sterol responsive element-binding proteins (SREBPs) [1]. These transcription factors increase the cholesterol homeostasis controlling genes, such as LDL receptor, lipoprotein lipase, and cholesterol 7α-hydroxylase [2, 3].

Currently, statins are the first choice of therapeutic agent for the treatment of hyperlipidemia. Several mega trials and large cohort studies using statins have shown that statins prevent coronary heart disease and decrease the incidence of cardiovascular events [4–6]. The reasons why cardiovascular events were decreased with statins are reported to be due to many pleiotropic effects, for example, inhibition of the proliferation and migration of endothelial cells, smooth muscle cells, and macrophages [7, 8]. Moreover, statins up-regulate the expression of endothelial nitric oxide synthesis [9] and suppress oxidative stress, as seen in the reduced formation of reactive oxygen species and p22phox expression [10, 11].

The peroxisome proliferator-activated receptors (PPARs) belong to the nuclear receptor superfamily and play an important role in the regulation of lipid and glucose metabolism and adipocyte differentiation [12, 13]. PPARα is expressed in the liver, kidney, heart, and muscle where it regulates energy homeostasis. PPARα forms a heterodimer with retinoid X receptor α (RXR α), which enhances its binding to peroxisome proliferator response elements (PPREs) and activates target genes. PPARα activates the uptake and catabolism of fatty acids that result in a decrease of triglyceride (TG), stimulate gluconeogenesis, and enhance high-density lipoprotein synthesis [14, 15]. Fibrates, which are a ligand for PPARα, have been reported to lower the
serum TG levels [16]. Some statins were also reported to decrease the serum TG levels to same extent [17–19]. Although it is reported that several statins increase PPARα [20, 21], it is not clear how statins regulate nuclear transcription, and PPARα mRNA expression and activity. Previously, simvastatin activated mouse PPARα promoter and induced the transcription of PPARα gene [22], but there is no report that statins activate the human PPARα promoter and transcription of this gene.

In the present study, we investigated the effect of 7 statins (atorvastatin, cerivastatin, fluvastatin, pitavastatin, pravastatin, rosuvastatin, simvastatin) on the regulation of PPARα mRNA expression and PPARα protein levels in nuclear fraction of the human hepatoblastoma cell line (HepG2 cells). We also investigated the effect of statin treatment on the promoter activity of the human PPARα gene. In addition, we investigated whether statin treatment could induce transcriptional activity of PPARα.

2. MATERIALS AND METHODS

2.1. Reagents and cell culture

Seven statins were kindly provided as follows; atorvastatin (Warner-Lambert Co., Ltd.), cerivastatin (Bayel Co., Ltd.), fluvastatin (Novartis Co., Ltd.), pitavastatin (Kowa Co., Ltd.), pravastatin (Sankyo Co., Ltd.), and rosuvastatin (AstraZeneca Ltd.). Simvastatin was purchased from Wako Pure Chemical Industries, Ltd. (Tokyo, Japan). Fenofibric acid (FA) was kindly provided by Kaken Pharmaceutical Co., Ltd. Atorvastatin, cerivastatin, fluvastatin, pitavastatin, rosuvastatin, and FA were dissolved in dimethyl sulfoxide (DMSO); simvastatin was dissolved in ethanol, and pravastatin was dissolved in distilled water. In all assays, the final concentrations of DMSO and ethanol were less than 0.5%. HepG2 cells were purchased from JCRB (cell number: JCRB1054) and human kidney 293T cells (293T cells) from Dainippon Pharmaceutical Co., Ltd. They were cultured in Dulbecco’s modified Eagle’s medium (DMEM) (Invitrogen) containing 10% heat-inactivated fetal bovine serum (FBS) (JRH Biosciences) and PNS antibiotic mixture (Invitrogen) at 37°C in 5% CO2.

2.2. Cloning of the PPARα promoter and plasmid constructions

To generate human PPARα promoter-reporter plasmid, we referred to the genomic sequence that has been reported previously [23]. Human PPARα promoter containing −1553 bp to +88 bp was obtained by polymerase chain reaction (PCR) with human genomic DNA (Clontech) using a forward primer 5′-CATAAGCTTACCCACGAGATGTCAGGAT-3′ (including a Hind III site, underlined) and a reverse primer 5′-CGTAAGCTTCGCAAGAGTCTCCTGTTGT-3′ (including a Hind III site, underlined). This promoter was cloned into the Hind III site of a pGL3-Basic vector (Promega). Plasmid DNA used for transfection was prepared using the Wizard Plus Minipreps DNA Purification System (Promega). Nucleotide sequences of this plasmid were confirmed by sequencing using ABI PRISM 310 Genetic Analyzer (Applied Biosystems).

2.3. Luciferase assay of PPARα promoter activity

HepG2 cells were transfected using Lipofectamine 2000 (Invitrogen) according to the manufacturer’s protocols. The cells (1 × 10^5 cells/well) were seeded in 24-well plates (Falcon) and incubated for 18 hours before transfection. The cells were transfected with the use of Lipofectamine 2000 with 1 μg of human PPARα promoter-reporter plasmid and 0.1 μg of pRL-TK (Promega), a renilla luciferase reporter vector as internal control for transfection efficiency. After 3 hours, the transfection medium was replaced by 10% FBS-DMEM plus the various amounts of statin (0, 1, 10, 25, and 50 μM) or vehicle (DMSO, ethanol, or distilled water) and the cells were incubated for 24 hours. Luciferase activities were quantified using a Dual-Luciferase Reporter Assay System (Promega) according to the manufacturer’s protocols.

2.4. Real-time reverse transcription (RT)-PCR analysis

HepG2 cells (2 × 10^5 cells/dish) were incubated with various amounts of statin (0, 5, 10, and 20 μM, pravastatin was 50, 100, and 250 μM) at 37°C for 24 hours. After treatment with statins, cells were homogenized in 1 mL of ISOGEN (Nippogen), and then total RNA was extracted with chloroform and precipitated with ethanol. First-strand cDNA was generated from total RNA with random hexamers and MuLV transcriptase (Applied Biosystems) according to the manufacturer’s protocols. PCR reactions were performed with TaqMan Universal PCR Master Mix and TaqMan Gene Expression Assays (Applied Biosystems). Identification numbers of the assay mixture of target gene-specific primers and probes were as follows: human PPARα, Hs00231882_m1; 18S ribosomal RNA (house-keeping gene), Hs99999901_s1.
Figure 2: Continued.
Figure 2: PPARα mRNA expression in HepG2 cells after treatment with atorvastatin (Ator), cerivastatin (Ceri), fluvastatin (Flu), pitavastatin (Pita), pravastatin (Pra), rosuvastatin (Rosu), and simvastatin (Sim) for 24 hours. (a) Each statin was used at concentrations of 5, 10, and 20 μM. Nontreated cells (statin concentration 0 μM) were the control. (b) Pravastatin was used at higher concentrations of 20, 50, 100, and 250 μM. Nontreated cells (pravastatin concentration 0 μM) were the control. The data are expressed as % of controls. Values are presented as the mean ± SEM of three separate experiments, significantly different from control at *P < .05, **P < .01.

2.5. Western blot analysis

HepG2 cells (2 × 10⁵ cells/dish) were seeded in 60 mm dishes (Falcon) and incubated for 18 hours. Then, the cells were incubated with 10 and 25 μM statin at 37°C for 24 hours. After treatment with statins, cells were washed with ice-cold phosphate buffered saline and collected. After centrifugation (15,000×g), the cytoplasmic and nuclear proteins of the cells were extracted with NE-PER Nuclear and Cytoplasmic Extraction Reagents (PIERCE) according to the manufacturer’s protocols and the proteins concentration was determined with a BCA Protein Assay kit (PIERCE). Aliquots (15 μg) of cytoplasmic or nuclear proteins were electrophoresed on 9% sodium dodecyl sulfate-polyacrylamide gels and transferred to polyvinylidene difluoride membranes (Millipore). The membranes were blocked with BlockingOne (Nacalai Tesque, Inc.), and incubated overnight with goat anti-PPARα IgG antibody (sc-1985, Santa Cruz) (diluted 1:1000 with BlockingOne) or mouse anti-hepatocyte nuclear factor-4α (HNF-4α) IgG antibody (Clone no.: H1415, Perseus Proteomics Co., Ltd.). After washing four times with Tris-buffered saline-containing 0.5% Tween 20, signals from Western blots were obtained using horseradish peroxidase-conjugated secondary anti-goat antibody (diluted 1:2000 with BlockingOne) and visualized with the ECL detection system (Amersham Biosciences). The PPARα protein levels were quantified with an imaging analyzer (Densitograph, ATTO). The data are expressed as % of control.

2.6. Luciferase assay of PPRE activity

Constructions of pCI-PPARα and pCI-RXRα expression plasmids were described previously [24]. Briefly, the full-length human PPARα (GenBank accession no. L02932) and human RXRα (GenBank accession no. X52773) were prepared by PCR. The specific DNA fragment of human PPARα was cloned into the Sall-NotI sites of the pCI-neo mammalian expression vector (Promega). The human RXRα was also cloned into the Xhol-NotI sites of the pCI-neo. The human acyl-coenzyme A oxidase (AOX) promoter (GenBank accession no. NT_010641) construct containing the PPREs was previously cloned into the KpnI-Ncol sites of pGL3-Basic vector [25].

To measure the transcriptional activation of PPRE, 293T cells (0.5 × 10⁵ cells/well) were seeded in collagen type I-coated 24-well plate (Iwaki) and incubated for 18 hours before transfection. The cells were transfected using Lipofectamine 2000 with 0.5 μg of human AOX promoter-reporter plasmid, 0.1 μg of pRL-TK as internal control for transfection efficiency and either 0.25 μg of pCI-PPARα and pCI-RXRα expression vectors or 0.5 μg of pCI-neo vector. After 3 hours, the transfection medium was replaced by 10% FBS-DMEM plus the various amounts of statin (0, 1, 10, 25, and 50 μM), fenofibric acid (0, 1, 10, 50, 100 μM), or vehicle (DMSO, ethanol, or distilled water) and the cells were incubated for 24 hours. Luciferase activities were quantified using a Dual-Luciferase Reporter Assay System (Promega) according to the manufacturer’s protocols.
Figure 3: PPARα promoter activity in HepG2 cells transfected with human PPARα promoter-reporter plasmid after treatment with atorvastatin (Ator), cerivastatin (Ceri), fluvasatin (Flu), pitavastatin (Pita), pravastatin (Pra), rosuvastatin (Rosu), and simvastatin (Sim) for 24 hours. Each statin was used at doses of 1, 10, 25, and 50 μM. Nontreated cells (statin concentration 0 μM) were the control. The data are expressed as % of controls. Values are presented as the mean ± SEM of three separate experiments, significantly different from control at *P < .05, **P < .01.
2.7. Statistical analysis

All data are presented as the means ± SEM. Statistical analysis was performed using ANOVA followed by the Dunnett test or Scheffe test (StatView software). Statistical significance was considered as $P < .05$.

3. RESULTS

3.1. Statins increased PPARα mRNA expression in HepG2 cells

We first examined the effect of simvastatin on the PPARα mRNA expression in HepG2 cells. The time-course study for the PPARα mRNA expression in HepG2 cells treated with 10 μM simvastatin is shown in Figure 1. Simvastatin significantly increased PPARα mRNA expression by 2.0-fold (versus the control) at 12 and 24 hours.

We next examined the effect of atorvastatin, cerivastatin, fluvastatin, pitavastatin, pravastatin, rosuvastatin, and simvastatin for 24 hours on PPARα mRNA expression in HepG2 cells. PPARα mRNA expression following treatment of HepG2 cells with various amounts of statin is shown in Figure 2. In Figure 2(a), atorvastatin (20 μM), cerivastatin (5, 10, and 20 μM), fluvastatin (5, 10, and 20 μM), pitavastatin (20 μM), rosuvastatin (10 μM), and simvastatin (10 μM) significantly increased PPARα mRNA expression by more than 1.5-fold (versus the control). Pravastatin did not increase PPARα mRNA expression at these concentrations, but the higher concentrations of pravastatin-treatment (100 and 250 μM) significantly increased PPARα mRNA expression (Figure 2(b)).

3.2. Statins increased human PPARα promoter activity

To investigate the mechanism by which statins increase PPARα mRNA expression, we cloned the human PPARα promoter region (−1553 to +88 bp) and examined promoter activity in HepG2 cells transfected with the human PPARα promoter-reporter plasmid. Figure 3 shows the PPARα promoter activity following treatment of HepG2 cells with various amounts of statin for 24 hours. Except for pravastatin, 6 statins significantly increased PPARα promoter activity in a dose-dependent manner. Atorvastatin, cerivastatin, fluvastatin, rosuvastatin, and simvastatin increased PPARα promoter activity by more than 1.5-fold (versus the control). However, pravastatin only slightly increased PPARα promoter activity that was significant only at 10 μM.
FA conc. (μM)

Luciferase activity (AOX promoter/pRL-TK)

(a) Ator (μM)

Luciferase activity (AOX promoter/pRL-TK)

(b) Pra (μM)

Luciferase activity (AOX promoter/pRL-TK)

(c) Ceri (μM)

Luciferase activity (AOX promoter/pRL-TK)

(d) Rosu (μM)

Luciferase activity (AOX promoter/pRL-TK)

(e) Flu (μM)

Luciferase activity (AOX promoter/pRL-TK)

(f) Sim (μM)

** Figure 5: Continued.**
3.3. Statins increased PPARα levels in nuclear fraction

We next examined the increasing effect of statins on PPARα protein levels in nuclear fraction of HepG2 cells. Results are shown in Figure 4. In a nuclear fraction of HepG2 cells treated with 10 μM statin, PPARα protein levels were significantly increased by treatment with rosuvastatin (Figure 4(a)). Moreover, PPARα protein levels were significantly increased by treatment with 25 μM of pitavastatin, simvastatin, and atorvastatin, and the other statins slightly increased PPARα protein levels (Figure 4(b)). However, in a cytoplasmic fraction, PPARα protein levels were not changed by the treatment with 10 and 25 μM statins.

3.4. Statins increased PPARα activity

We next examined the effect of statins on the transcriptional activity of PPARα in 293T cells transfected with human AOX promoter-reporter plasmid containing PPREs region, human PPARα, and RXRa expression plasmids. In Figure 5(a), fenofibric acid that was used as a positive control increased PPARα activity in a dose-dependent manner. In Figure 5(b), the treatment with cerivastatin (10 μM) and simvastatin (50 μM) significantly increased transcriptional activity of PPARα by more than 1.5-fold (versus the control). Fluvastatin, pitavastatin, pravastatin, and rosuvastatin tended to increase transcriptional activity of PPARα by 1.2- to 1.4-fold (versus the control). However, atorvastatin did not increase the transcriptional activity of PPARα.

3.5. Statins increased HNF-4α levels in nuclear fraction

Next, to elucidate the downstream effects of statins on transcriptional activation by PPARα, we detected HNF-4α levels in nuclear fraction of HepG2 cells treated with statins by the use of Western blot analysis. Results are shown in Figure 6. At 10 μM statin treatment, fluvastatin, pravastatin, and rosuvastatin significantly increased HNF-4α levels in nuclear fraction (Figure 6(a)). Moreover, at 25 μM statin treatment, except for cerivastatin, 6 statins significantly increased HNF-4α levels in nuclear fraction (Figure 6(b)).

4. DISCUSSION

The main findings of the present study were (1) most statins increased PPARα mRNA expression, which might be caused via PPARα promoter activation, (2) atorvastatin, pitavastatin, and simvastatin significantly increased PPARα protein levels in nuclear fraction, (3) some, not but all, statins interacted with AOX promoter containing PPRE and increased PPARα activity, and (4) the PPARα promoter activity could be regulated by the increase of statin-induced HNF-4α.

Statin therapy has been reported to reduce the incidence of cardiovascular disease risk in patients with the metabolic syndrome and hyperlipidemia [26], and these benefits have been regarded to mainly derive from their lipid-lowering effect. However, recent studies have suggested that there are additional, beneficial anti-inflammatory effects of stains, which are independent of their cholesterol-lowering effect [27, 28]. There are many reports that the anti-inflammatory effects of statins are induced via PPARs signaling-pathway [11, 29].

Our present results show that most statins increased PPARα mRNA expression in HepG2 cells after 24 hours treatment, especially atorvastatin, cerivastatin, fluvastatin, pitavastatin, rosuvastatin, and simvastatin (more than 1.5-fold versus control). Statins are classified into hydrophilic compounds and lipophilic compounds. In this study, the
majority of the statins are lipophilic compounds, but pravastatin and rosuvastatin are hydrophilic compounds. Our results of PPARα mRNA expression in HepG2 cells treated with statins show that higher concentrations of pravastatin (100 and 250 μM) significantly increased PPARα mRNA expression. Therefore, in hydrophilic statin (pravastatin), the higher concentrations compared with other statins would be required for increase PPARα mRNA expression.

There are many reports that statins increase PPARα mRNA expression [11, 21]; however, there are no reports about the effect of statins on human PPARα promoter activity. We, therefore, cloned the human PPARα promoter region (−1553 bp to +88 bp) and measured the promoter activity in HepG2 cells treated with statins. Our present results show that 6 statins (except for pravastatin) significantly increased PPARα promoter activity in a dose-dependent manner. Although the effect of statins on mouse PPARα promoter activity has been reported previously [22], our present study is the first to report the effect of statins on human PPARα promoter activity.

PPARα promoter region includes many transcription factor binding domains, such as HNF-4α, PPRE, E-Box, early growth response factor (Egr-1), and transcription factor Sp1. HNF-4α is a nuclear receptor that plays a key role in liver-specific gene expression. Previously, it was reported that human PPARα promoter region contains HNF-4α response element (−1,492 bp to −1,483 bp), and HNF-4α induces human PPARα promoter activity [23]. Therefore, we detected HNF-4α levels in nuclear fraction of statin-treated HepG2 cells. In our present studies, all statins (25 μM) significantly increased HNF-4α in nuclear fractions. This result shows that statins may regulate PPARα gene transcription mediated by downstream transcriptional factors (e.g., HNF-4α). Further studies will be necessary to elucidate molecular mechanisms of statins to regulate the other transcriptional factors related to PPARα gene transcription.

Previously, we reported that cerivastatin, fluvastatin, and simvastatin increased nuclear translocation of PPARα protein [11]. Our present results show that the 7 statins utilized in the present studies increased nuclear translocation of PPARα protein in HepG2 cells compared with nontreated control cells. We next examined the effect of statins on transcriptional analysis of human AOX promoter in 293T cells cotransfected with human PPARα and RXRα expression vector. 293T cells were used for these studies expressed very low levels of endogenous PPARα production when treated with statins (data not shown). Our present results show that simvastatin increased human AOX promoter-transcriptional activity via PPARα/RXRα heterodimer. In fact, we identified the upregulation of human AOX mRNA on HepG2 cells and 293T cells treated with statins (data not shown). PPARα is a ligand-activated transcription factor and is activated by fatty acid, arachidonic acid [30], and several fibric acids.
PPARα-dependent transcriptional activation of many genes is well documented, and direct, ligand-enhanced interactions between PPARα and the coactivators, p300/cAMP-response element-binding protein (CREB) binding protein (p300/CBP), steroid receptor coactivator-1 (SRC-1), PPAR-binding protein (PPB), and PPARy coactivator-1 (PGC-1) are thought to play a role in PPARα activation [32–34]. The recruitment of specific coactivators and the release of corepressors (e.g., nuclear receptor corepressor, NCoR) that associate with the liganded PPARα/RXRα heterodimer allow further fine control of gene transcription. PPARα/RXRα heterodimer can also bind to PPRE in the unliganded state [35]. The molecular structures of the PPARα/RXRα heterodimeric complex and coactivators remain to be elucidated. Further studies will be necessary to be undertaken of the molecular mechanisms of statin regulation of the gene transcription by binding to PPREs in the promoter region of target genes.

In conclusion, statins activate PPARα promoter and then up-regulate PPARα mRNA expression in HepG2 cells. The effect on PPARα transcription is likely regulated by various downstream transcriptional factors (e.g., HNF-4α). Statins increase PPARα protein levels in nuclear fraction, and moreover, some statins, such as cerivastatin, fluvastatin, and simvastatin, significantly activate the transcription of the PPARα target genes.

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REFERENCES


[19] M. S. Kostapanos, H. J. Milionis, K. G. Lagos, C. B. Rizos, A. D. Tslepis, and M. S. Eliaf, “Baseline triglyceride levels and insulin sensitivity are major determinants of the increase of LDL particle size and buoyancy induced by rosuvastatin...


