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Effect of oxidative stress on expression and function of human and rat organic anion transporting polypeptides in the liver

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Abstract

Reactive oxygen species (ROS) have physiological function and involve alteration of physical state. However, it is not clear effect of oxidative stress on pharmacokinetics. Organic anion transporting polypeptides (human: OATPs, rodent: Oatps) are important for uptake of endogenous and exogenous compounds into hepatocytes. Thus, alteration of OATPs/Oatps expression level may affect pharmacokinetics of various drugs. In this study, we investigated the alteration of OATPs/Oatps expression levels and function by oxidative stress, and the effect of alteration of those on pharmacokinetics of a typical OATPs/Oatps substrate pravastatin. OATPs/Oatps expression levels and function were altered by H$_2$O$_2$-induced oxidative stress in \textit{in vitro} experiments. The alteration of Oatps expression by oxidative stress also occurred in \textit{in vivo} experiments. Oatp1a1, Oatp1a4 and Oatp1b2 expression in the liver were decreased in rats fed powdery diet containing 2\% inosine, which induces oxidative stress through activation of xanthine oxidase, for 1 day. The decrease in Oatps expression levels by oxidative stress caused the suppression of pravastatin uptake to the liver, and resulted in high plasma concentration of pravastatin and low biliary excretion. In conclusion, oxidative stress induces alteration of OATPs/Oatps expression and function in hepatocytes, resulting in alteration of pharmacokinetics of their substrates.
Chemical compounds studied in this article

Hydrogen Peroxide (PubChem CID: 784); Inosine (PubChem CID: 6021); Pravastatin (PubChem CID: 16759173)

Keywords: organic anion transporting polypeptide, hydrogen peroxide, oxidative stress, pharmacokinetics
1. Introduction

Oxidative stress is involved several types of cancer, diabetes mellitus, ischemic diseases, hepatitis and other diseases (Afanas'ev, 2011; Wu et al., 2004; Itagaki et al., 2010; Loguercio and Federico, 2003). It is well known that reactive oxygen species (ROS) cause oxidative stress. In the body, O$_2$ produces energy required for multiple cellular functions. ROS including hydroxyl radicals (•OH), superoxide anion (O$_2^-$) and hydrogen peroxide (H$_2$O$_2$) accumulate as by-products of the energy production process (Rojkind et al., 2002). H$_2$O$_2$ is more stable than other ROS, less reactive and acts as a second intracellular messenger that plays roles in the regulation of immunostimulation, cell growth and apoptosis (Murray and Cohn, 1980; Varela et al., 2004). On the other hand, excessive ROS cause cell death by induction of lipid peroxidation and alteration of protein conformation after oxidation of cysteine and methionine residues (Rojkind et al., 2002). In addition, severe oxidative stress causes several diseases as described above, and various drugs are used to treat oxidative stress-induced diseases. Therefore, it is important to clarify the effect of oxidative stress on pharmacokinetics.

Organic anion transporting polypeptides (humans: OATPs, rodents: Oatps) transport of a wide range of organic compounds such as bile acids, thyroid hormones, conjugated steroids and drugs (Takikawa et al., 2002; Fujiwara et al., 2001; Kanai et al., 1996). Moreover, there are some subtypes that recognize not only organic anion compounds but also organic cation compounds.
OATPs/Oatps are expressed at high levels in the liver and transport endogenous and exogenous compounds into hepatocytes (Kullak-Ublick et al., 2001; Kalliokoski and Niemi, 2009). The relationship between pharmacokinetics of statins and transport activity of OATPs/Oatps has been studied extensively. It has been shown that SLCO1B1 (coding for OATP1B1) polymorphism affects the pharmacokinetics of pravastatin and pitavastatin (Niemi et al., 2006; Wen and Xiong, 2010). In Oatp1b2 knockout mice, liver-to-plasma concentration ratios of lovastatin and cerivastatin were shown to be lower than those in wild-type mice (Chen et al., 2008). Moreover, it is well known that various drugs such as angiotensin-converting enzyme (ACE) inhibitors and angiotensin receptor blockers (ARBs) (Kalliokoski and Niemi, 2009) are substrates of OATPs/Oatps. These findings indicate that elucidation of the expression levels and function of OATPs/Oatps are important for understanding of pharmacokinetics of various drugs such as statins.

It has been shown that expression levels of ATP-binding cassette (ABC) transporters, such as P-glycoprotein (P-gp) and multidrug resistance-associated protein 2 (MRP2), are altered by oxidative stress (Zieman et al., 1999; Payen et al., 2001). Although alteration in the expression of OATPs/Oatps in oxidative stress-related diseases has been demonstrated (Tanaka et al., 2006; Obaidat et al., 2012), the direct effect of ROS on the expression of OATPs/Oatps has not been fully revealed. In this study, we investigated alterations of the expression and function of
OATPs/Oatps caused by oxidative stress directly and the effect of those alterations on pharmacokinetics of a typical substrate of OATPs/Oatps, pravastatin. We found that oxidative stress affects the expression levels of OATPs/Oatps and the pharmacokinetics of pravastatin.
2. Materials and methods

2.1. Chemicals

Hydrogen peroxide (H$_2$O$_2$) and inosine were purchased from Wako Pure Chemical Industries (Osaka, Japan). $[^{14}]$C Cholic acid (CA) (specific activity: 48.6 mCi/mmol), $[^{3}]$H Taurocholic acid (TCA) (specific activity: 5.0 Ci/mmol) and $[^{3}]$H Estrone-3-sulfate (E3S) (specific activity: 57.3 Ci/mmol) were purchased from Perkin Elmer (Boston, MA). Pravastatin sodium was kindly donated by Daiichi Sankyo (Tokyo, Japan). All other reagents were of the highest grade available and used without further purification.

2.2. Cell culture

Human hepatocellular carcinoma cells (HLE cells) obtained from JCRB Cell Bank (Osaka, Japan) were maintained in plastic culture flasks (Corning Costar Corp., Cambridge, MA). The cells were kept in Dulbecco’s modified Eagle’s medium (Sigma Aldrich Japan, Tokyo, Japan) supplemented by 10% fetal bovine serum (Thermo Fisher Scientific K.K., Yokohama, Japan) and 100 IU/mL penicillin-100 μg/mL streptomycin (Sigma Aldrich Japan) at 37°C under 5% CO$_2$-95% air. Rat primary hepatocytes were isolated by the collagenase perfusion technique as described previously with some modifications (Miyazaki et al., 1998). Collagen-coated 6-well and 24-well plates (Corning Costar Corp.) were prepared by using 1.4 mL/well and 0.7 mL/well
of 50 μg/mL collagen solution, respectively. The plates were allowed to dry in a laminar flow cabinet for 16 h. Isolated primary hepatocytes were plated onto the collagen-coated plates in William's E medium (Invitrogen, Grand Island, NY) supplemented with 10% fetal bovine serum (Thermo Fisher Scientific K.K.) and 100 IU/mL penicillin-100 μg/mL streptomycin (Sigma Aldrich Japan) and left to attach for 6 h in an incubator at 37°C under 5% CO2-95% air.

2.3. Treatment of HLE cells and rat primary hepatocytes with H2O2

HLE cells were seeded (5.0×10^5 cells/mL) and cultured for 24 h, and rat primary hepatocytes were seeded (1.0×10^6 cells/mL) and cultured for 6 h. Following cell attachment, 1 mM H2O2 was added for 6 h or 48 h in HLE cells and 12 h or 48 h in rat primary hepatocytes.

2.4. Animals

Male Wistar rats, aged 6 weeks, were obtained from Jla (Tokyo, Japan). The rats were housed for at least 1 day (190-350 g in body weight). The housing conditions were the same as those described previously (Ogura et al., 2012). During the period of acclimatization, the rats were allowed free access to food and water. The experimental protocols were reviewed and approved by the Hokkaido University Animal Care Committee in accordance with the “Guide for Care and Use of Laboratory Animals”.

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2.5. Rats receiving powdery diet containing 2% inosine

Rodent labo diet 5L37 was ground into powder. Inosine at 2% was mixed with the powdery diet (Stirpe and Dellacorte, 1965). Rats were fed powdery diet containing 2% inosine for 1 day, 2 days or 5 days.

2.6. Quantitative real-time PCR

Real-time PCR was performed as described previously (Ogura et al., 2008). Total RNA was prepared from HLE cells, rat primary hepatocytes and rat liver using an ISOGEN (Nippon Gene, Tokyo, Japan) and an RNase-Free DNase Set (QIAGEN, Tokyo, Japan). Single-stranded cDNA was made from 1 μg total RNA by reverse transcription (RT) using a ReverTraAce (TOYOBO, Osaka, Japan). Gene-specific primers for hOATP1A2, hOATP1B1, hOATP1B3, hOATP2B1, hGAPDH, rOatp1a1, rOatp1a4, rOatp1b2, rOatp2b1 and rGapdh are shown in Table 1. Quantitative real-time PCR was performed using an Mx3000™ Real-time PCR System (STRATAGENE, Tokyo, Japan) with GoTaq® qPCR Master Mix (Promega, Tokyo, Japan) following the manufacturer’s protocol and through 40 cycles of 95°C for 15 sec, 58°C (for OATP1A2, OATP1B1, OATP1B3 and OATP2B1), 56°C (for Oatp1b2) or 50°C (Oatp1a1, Oatp1a4 and Oatp2b1) for 30 sec and 72°C for 30 sec. The PCR products were normalized to
amplified GAPDH, which was the internal reference.

2.7. Protein extraction from HLE cells and rat primary cells

All steps were performed on ice or at 4°C. The growth medium was removed and cells were washed twice with ice-cold phosphate buffered saline (PBS). The cells were suspended in lysis buffer containing 1.0% Triton-X100, 0.1% sodium dodecyl sulphate (SDS) and 4.5 M urea. The suspension was left to stand for 5 min and sonicated for 15 min at 4°C. Then it was centrifuged at 12,000×g for 15 min at 4°C.

2.8. Protein extraction from rat liver

All steps were performed on ice or at 4°C. The liver was washed with ice-cold saline and cut. The pieces were homogenized in lysis buffer. The homogenate was left to stand for 5 min and sonicated for 15 min at 4°C. Then it was centrifuged at 12,000×g for 15 min at 4°C.

2.9. Western blot analysis

The samples for Western blot analysis were protein extracts from HLE cells, rat primary hepatocytes and rat liver. Protein concentration in the clear supernatant was determined by the method of Lowry et al. (1951). The samples were denatured at 100°C for 3 min in a loading
buffer containing 50 mM Tris (hydroxymethyl)-aminomethane (Tris)-HCl, 2% SDS, 5%
2-mercaptoethanol, 10% glycerol, 0.002% bromophenol blue (BPB) and 3.6 M urea and
separated on 4.5% stacking and 10% SDS polyacrylamide gels. Proteins were transferred
electrophoretically onto nitrocellulose membranes (for OATP1A2, OATP1B3, Oatp1a4 and actin)
or polyvinylidene difluoride membranes (for OATP1B1, OATP2B1, Oatp1a1, Oatp1b2 and
Oatp2b1) at 15 V for 90 min. The membranes were blocked with PBS containing 0.05% Tween
20 (PBS/T) and 10% or 1% non-fat dry milk for 1 h at room temperature. After being washed
with PBS/T, the membranes were incubated with rabbit anti-OATP1 polyclonal antibody (H-55)
(Santa Cruz Biotechnology, Santa Cruz, CA) (diluted 1:250), goat anti-OATP-C polyclonal
antibody (N-16) (Santa Cruz Biotechnology) (diluted 1:250), rabbit anti-OATP8 polyclonal
antibody (H-52) (Santa Cruz Biotechnology) (diluted 1:250), rabbit anti-OATP-B polyclonal
antibody (M-153) (Santa Cruz Biotechnology) (diluted 1:250), rabbit anti-OATP1 affinity
purified polyclonal antibody (Millipore, Bedford, MA) (diluted 1:500), rabbit anti-OATP2
polyclonal antibody (M-50) (Santa Cruz Biotechnology) (diluted 1:500), goat anti-OATP4
polyclonal antibody (N-17) (Santa Cruz Biotechnology) (diluted 1:250) or mouse anti-actin
monoclonal antibody (Millipore) (diluted 1:500) overnight at room temperature and washed three
times with PBS/T for 10 min each time. The membranes were subsequently incubated for 1 h at
room temperature with horseradish peroxidase-conjugated goat anti-rabbit secondary antibody
(Santa Cruz Biotechnology), horseradish peroxidase-conjugated donkey anti-goat secondary antibody (Santa Cruz Biotechnology) or horseradish peroxidase-conjugated goat anti-mouse secondary antibody (Santa Cruz Biotechnology) at a dilution of 1:2,000 or 1:4,000 and washed three times with PBS/T for 10 min each time. The bands were visualized by enhanced chemiluminescence according to the instructions of the manufacturer (Amersham Bioscience Corp., Piscataway, NJ).

2.10. Uptake study in HLE cells and rat primary hepatocytes

The concentrations of substrates were 1 μM for [14C]CA, 50 nM for [3H]TCA and 5 nM for [3H]E3S (Uptake times were 10 sec/2 min for [14C]CA, 30 sec/3 min for [3H]TCA and 1/3 min for [3H]E3S in HLE cells/rat primary hepatocytes, respectively.). The incubation medium used for the uptake study was Hanks’ Balanced Salt Solution (HBSS) buffer (pH 7.4) (25 mM D-glucose, 137 mM NaCl, 5.37 mM KCl, 0.3 mM Na2HPO4, 0.44 mM KH2PO4, 1.26 mM CaCl2, 0.8 mM MgCl2 and 10 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES)). After removal of the growth medium, cells were preincubated at 37°C for 10 min with 0.5 mL HBSS buffer (pH 7.4). After removal of the incubation medium, 0.5 mL of incubation medium containing radiolabeled compounds was added. The cells were incubated for the indicated time at 37°C. The cells were washed rapidly twice with ice-cold incubation medium at the end of the
incubation period. To quantify the radioactivity of radiolabeled compounds, the cells were
solubilized in 1% SDS/0.2 N NaOH. The remainder of the sample was mixed with 3 mL of
scintillation cocktail (Perkin Elmer) to measure the radioactivity. All of the uptake values were
corrected against the protein content. The protein content was determined by the method of BCA
protein assay.

2.11. Evaluation of oxidative stress

Evaluation of oxidative stress through determination of malondialdehyde (MDA) levels
was performed as described previously (Ogura et al., 2011). Thiobarbituric acid (TBA) solution
consisted of 2.6 mM TBA, 918 mM trichloroacetic acid, 0.3 mM HCl and 1.8 mM 2, 6-di-tert-butyl-4-methylphenol in 22% ethanol. The reaction mixture contained 0.2 mL of rat liver
homogenate, 0.2 mL of 8.1% SDS, 1.5 mL of 20% acetic acid buffer (pH 3.5), and 1.5 mL of
TBA solution. After vortexing, the mixture was heated at 95°C for 1 h. Subsequently, the mixture
was cooled in iced water for 3 min. After the cooling process, 1 mL of distilled water and 5 mL
of n-butanol were added, and the mixture was individually mixed by vortexing. Finally, the
mixture was centrifuged at 330×g for 5 min at 4°C. The colored upper layer was placed in a glass
cell for spectrophotometer reading at 535 nm with 1, 1, 3, 3-tetraethoxypropane (TEP) as a
standard. The amount of MDA was corrected by protein content. The protein content was
determined by the method of BCA protein assay.

2.12. Pharmacokinetic study

A pharmacokinetic study was carried out in male Wistar rats (7 weeks old) fed powdery diet containing 2% inosine for 1 day or 5 days. The common bile duct of each rat was cannulated with a polyethylene tube (SP10, NATSUME, Tokyo, Japan) to collect bile specimens. Pravastatin sodium dissolved in saline (10 mg/mL) was administered as an intravenous injection at a dose of 10 mg/kg. Blood samples (each 0.4 mL) were collected from the jugular vein at designated time points (1, 3, 5, 15, 30, 45 and 60 min after injection) into eppendorf tubes containing trace heparin. Plasma was prepared by centrifugation (850xg for 5 min at 4°C) of blood samples. Bile samples were collected from the bile duct at designated time points (0-15, 15-30, 30-45 and 45-60 min after injection). Liver samples were harvested at 60 min after injection and homogenized in distilled water. All samples were stored at −30°C until analysis.

2.13. Sample preparation

To 100 μL of a plasma sample, 0.5 mL of methanol was added for de-proteination and mixed by vortexing. After vortexing, the sample was centrifuged at 12,000xg for 5 min at room temperature. The supernatant was filtrated using a Cosmonice filter W (pore size of 0.45 μm,
Nacalai Tesque, Kyoto, Japan). Bile samples were prepared by liquid–liquid extraction. To 100 μL of a bile sample, 1 mL of ethyl acetate was added and mixed by vortexing. After vortexing, the sample was centrifuged at 12,000×g for 5 min at room temperature. After centrifugation, the upper layer was evaporated to dryness at 40°C using a gentle stream of air. The residue was reconstituted in 500 μL of distilled water. Liver samples were prepared by liquid–liquid extraction and solid-phase extraction. Three milliliters of a sample was centrifuged at 12,000×g for 5 min at room temperature. To 1.5 mL of the supernatant, 5 mL of ethyl acetate was added and mixed by vortexing. After vortexing, the sample was centrifuged at 12,000×g for 5 min at room temperature. After centrifugation, the upper layer was evaporated to dryness at 40°C using a gentle stream of air. The residue was reconstituted in 150 μL of methanol and 150 μL of distilled water. After reconstitution, the sample was purified by solid-phase extraction using Bond-Elute C18 solid phase extraction cartridges (Agilent Technologies, Tokyo, Japan). The cartridges were conditioned with 1 mL of methanol and 1 mL of distilled water before applying the liver samples. The samples were transferred to solid-phase extraction cartridges and centrifuged at 1,300×g for 5 min at room temperature to obtain a flow through the cartridges. After centrifugation, the cartridges were eluted twice with 1 mL of methanol. The eluting solvent was evaporated to dryness at 40°C using a gentle stream of air. The residue was reconstituted in 200 μL of distilled water.
2.14. Analytical procedures

Pravastatin concentration was determined using an HPLC system equipped with a RHEODYNE 7125 valve, Hitachi L-7110 pump, Hitachi L-7450 UV detector, Hitachi D-2500 chromato-integrator and Hitachi L-7300 column oven. The column was a Mightysil RP-8 GP (250 mm×4.6 mm in i.d., KANTO CHEMICAL, Tokyo, Japan) with a guard column of a Mightysil RP-18 GP Aqua (5 mm×4.6 mm in i.d., KANTO CHEMICAL). A mobile phase consisting of water and acetonitrile mixture (63:17 (v/v), containing CH₃COONH₃ at a final conc. of 1.25 mM) was used. Column temperature and flow rate were 40 °C and 1.5 mL/min, respectively. The wavelength of the detector was 238 nm. The samples were diluted appropriately, and 50 μL of each sample was injected onto the HPLC column. The standard solution was diluted with blood, bile and liver homogenate mixture to prepare calibration curves. The calibration curves were constructed at 4-6 concentration levels for standard solutions of each analyte.

Statistical significance was evaluated by Student’s t-test, and a value of p<0.05 was considered significant.
3. Results

3.1. Effects of H2O2 on mRNA, protein expression levels and function of OATPs in HLE cells

Firstly, we examined alterations of mRNA and protein expression levels of OATPs induced by H2O2 in HLE cells (Fig. 1). In HLE cells, the mRNA and protein expression levels of OATP1A2 were significantly decreased by exposure to H2O2 for 6 h but were significantly increased by exposure for 48 h (Fig. 1A). The mRNA and protein expression levels of OATP1B1 were significantly increased by exposure to H2O2 for 6 h, but only the mRNA level was increased by exposure for 48 h (Fig. 1B). The mRNA and protein expression levels of OATP1B3 were significantly increased by exposure to H2O2 for 48 h but were not altered by exposure for 6 h (Fig. 1C). The mRNA level of OATP2B1 was significantly decreased by exposure to H2O2 6 h, though the protein expression level was not altered by exposure for either 6 h or 48 h (Fig. 1D). To evaluate effects of oxidative stress on the function of OATPs, uptake of [14C]CA, [3H]TCA or [3H]E3S by H2O2-exposed HLE cells was assessed (Fig. 2). Before the investigation of the effect of H2O2 on uptake of each compound, we determined the initial uptake rate of each compound in HLE cells from time course experiments, and we evaluated the initial uptake for 10 sec for [14C]CA, 30 sec for [3H]TCA and 1 min for [3H]E3S in HLE cells, respectively (data not shown).

The uptake of [14C]CA by HLE cells was found to be significantly decreased by exposure to H2O2 for 6 h but significantly increased by exposure for 48 h (Fig. 2A). The uptake of [3H]TCA
by HLE cells was significantly increased by exposure to H$_2$O$_2$ for 48 h but was not altered by exposure for 6 h (Fig. 2B). The uptake of $[^3]$H]E3S by HLE cells was significantly increased by exposure to H$_2$O$_2$ for 6 h but was not altered by exposure for 48 h (Fig. 2C).

In rat primary hepatocytes, the mRNA levels of Oatp1a1 and Oatp1a4 were significantly decreased by exposure to H$_2$O$_2$ for 12 h and 48 h (Figs. 3A and 3B). However, the protein expression levels were decreased only by exposure to H$_2$O$_2$ for 12 h (Figs. 3A and 3B). The mRNA and protein expression levels of Oatp1b2 were not altered by exposure to H$_2$O$_2$ for either 12 h or 48 h (Fig. 3C). The mRNA level of Oatp2b1 was significantly decreased by exposure to H$_2$O$_2$ for 12 h, though the protein expression level was not altered by exposure for either 12 h or 48 h (Fig. 3D). The initial uptake rate of $[^{14}]$CA, $[^3]$H]TCA and $[^3]$H]E3S in rat primary hepatocytes was determined by time course experiments, and we evaluated the initial uptake for 2 min for $[^{14}]$CA, 3 min for $[^3]$H]TCA and 3 min for $[^3]$H]E3S in rat primary hepatocytes, respectively (data not shown). The uptake of $[^{14}]$CA and that of $[^3]$H]TCA by rat primary hepatocytes were significantly decreased by exposure to H$_2$O$_2$ for 12 h but were not altered by exposure for 48 h (Figs. 4A and 4B). The uptake of $[^3]$H]E3S by rat primary hepatocytes was not altered by exposure to H$_2$O$_2$ for either 12 h or 48 h (Fig. 4C).

3.2. Effect of inosine-induced oxidative stress on lipid peroxidation in the liver
Activation of xanthine oxidase is one of the major pathways of oxidative stress in the body.

Inosine induces oxidative stress through activation of xanthine oxidase (Stirpe and Dellacorte, 1965). To confirm the generation of oxidative stress in rats fed powdery diet containing 2% inosine, we assessed oxidative stress by the level of MDA, which is a marker of lipid peroxidation, in the liver. During all periods, MDA levels in the livers of rats fed powdery diet containing 2% inosine were significantly increased compared with those in control rats (Fig. 5).

3.3. Effect of inosine-induced oxidative stress on mRNA and protein expression levels of Oatps in the rat liver

The mRNA and protein expression levels of Oatp1a1 and Oatp1a4 were significantly decreased by feeding powdery diet containing 2% inosine for 1 day and 2 days (Figs. 6A and 6B). The protein expression level of Oatp1b2 was significantly decreased at 1 day and 2 days, though the mRNA level was not altered (Fig. 6C). The mRNA and protein expression levels of Oatp2b1 were not altered in any period (Fig. 6D).

3.4. Effect of inosine-induced oxidative stress on pharmacokinetics of pravastatin

The plasma concentration, biliary excretion and liver accumulation of pravastatin in rats fed powdery diet containing 2% inosine are shown in Fig. 7. The plasma concentration of
pravastatin at 1-5 min after intravenous administration was significantly increased by feeding powdery diet containing 2% inosine for 1 day. Moreover, liver accumulation of pravastatin at 60 min after intravenous administration and biliary excretion of pravastatin at each time point were significantly decreased by feeding powdery diet containing 2% inosine for 1 day. The pharmacokinetic parameters calculated as a 2-compartment model are shown in Table 2. In rats fed powdery diet containing 2% inosine for 1 day, the area under the blood concentration-time curve (AUC$_{0-\infty}$) of pravastatin was significantly increased, and total body clearance (CL$_{tot}$) of pravastatin was significantly decreased, but the distribution volume (V$_d$) of pravastatin was not altered. The pharmacokinetics of pravastatin recovered in rats fed powdery diet containing 2% inosine for 5 days.
4. Discussion

It is well known that P-gp expression is increased in oxidative stress-induced diseases, such as cancer and ischemia disease, and that this increase in P-gp expression is caused by ROS, which mainly cause oxidative stress (Ghanem et al., 2004; Wu et al., 2009). Recently, alteration in the expression of OATPs/Oatps in oxidative stress-related diseases has been demonstrated (Tanaka et al., 2006; Obaidat et al., 2012), but the effect of ROS on the expression of OATPs/Oatps has not been fully revealed. Furthermore, the effect of oxidative stress on the pharmacokinetics of clinical drugs that are transported by OATPs has not been demonstrated. In this study, we characterized ROS-induced alteration of the expression of OATPs/Oatps and alteration of pharmacokinetics of the clinical drug pravastatin in an oxidative stress-exposed state.

An in vitro study showed that the oxidative stress was induced by H2O2 and H2O2 exposure times were decided on the basis of results of MTT assays (Supplementary Fig. 1). HLE cells were more susceptible to H2O2 than were rat primary hepatocytes. The viability in HLE cells exposed to H2O2 for 6 h was the same as that of rat primary hepatocytes exposed to H2O2 for 12 h. Thus, HLE cells and rat primary hepatocytes were exposed to H2O2 for 6 h and 12 h, respectively, in this study. Moreover, to determine the effect of exposure time on alterations in the expression and function of OATPs/Oatps, both HLE cells and rat primary hepatocytes were exposed to H2O2 for
48 h. The mRNA levels of OATPs/Oatps in HLE cells/rat primary hepatocytes were altered by 1 mM H_{2}O_{2} (Figs. 1 and 3) but were not altered by 0-100 µM H_{2}O_{2} (data not shown). Moreover, H_{2}O_{2} at the concentration of 1 mM was previously shown to up-regulate the rat multidrug resistance mdr1b gene (Ziemann et al., 1999) in primary rat hepatocyte cultures. Thus, in this study, effects of oxidative stress on the expression level and function of OATPs/Oatps were evaluated by exposure to 1 mM H_{2}O_{2}. As a result, mRNA and protein expression levels of OATPs/Oatps were altered by exposure to H_{2}O_{2} (Figs. 1 and 3), and uptake of some organic anion compounds was also altered (Figs. 2 and 4). Alterations in the uptake of [^{3}H]CA (Fig. 2A), [^{3}H]TCA (Fig. 2B) and [^{3}H] E3S (Fig. 2C) in HLE cells were associated with alterations of OATP1A2 (Fig. 1A), OATP1B3 (Fig. 1C) and OATP1B1 (Fig. 1B) protein expression levels, respectively. In rat primary hepatocytes, [^{3}H]CA (Fig. 4A) and [^{3}H]TCA (Fig. 4B) uptake was decreased by exposure to H_{2}O_{2} for 12 h, being associated with decreasing Oatp1a1 (Fig. 3A) and Oatp1a4 (Fig. 3B) protein expression levels. It has been shown that bile acids are mainly transported by Oatp1a1 and Oatp1a4 in rats (Gartung and Matern, 1997). Thus, the decrease in the uptake of [^{3}H]CA and [^{3}H]TCA might be caused by the decrease in expression levels of Oatp1a1 and Oatp1a4 for hepatic uptake. The sodium-taurocholate cotransporting polypeptide (NTCP/Ntcp) is known to be various bile acids uptake transporter. However, NTCP mRNA in HLE cells was not detected RT-PCR (data not shown). Moreover, Ntcp mRNA level was not
altered by exposure to H₂O₂ for either 12 h or 48 h (data not shown). The alteration of
OATPs/Oatps expression did not completely parallel between HLE cells and rat primary
hepatocytes. There is no strict one-to-one relationship between human OATPs genes and rodent
Oatps genes (Hagenbuch and Meier, 2004). This might be one of the reasons for the difference of
alteration of OATPs/Oatps expression between HLE cells and rat primary hepatocytes.

To further determine the involvement H₂O₂-induced alterations in the expression and
function of OATPs/Oatps, the effect of co-exposure to PEG-catalase, which is an H₂O₂ scavenger,
was examined. The H₂O₂-induced alterations in expression and function of OATPs/Oatps were
diminished by co-exposure to PEG-catalase (Supplementary Figs. 2-5). These results confirmed
the effects of H₂O₂ on the expression of OATPs/Oatps and their transport activities. However, a
part of the alterations in expression and function of OATPs/Oatps was different from the above
results (Figs.1-4). PEG-catalase was stocked in 50% glycerol/water solution at 5,000 U/mL and
diluted with a medium to 100 U/mL. Therefore, we used a medium containing 1% glycerol in the
experiments with co-exposure to PEG-catalase. The difference between the alterations in
expression and function of OATPs/Oatps in the experiments may have been caused by the
presence or absence of 1% glycerol in the medium.

Alteration in expression of Oatps by oxidative stress also occurred in in vivo experiments.

Oatp1a1, Oatp1a4 and Oatp1b2 expression levels in the livers of rats fed powdery diet containing
2% inosine for 1 day were decreased (Fig. 6). Although a decrease in Oatp1b2 protein expression level occurred only in the *in vivo* experiment, the decreases in Oatp1a1 and Oatp1a4 expression levels were similar to the results of *in vitro* experiments. Pravastatin is a substrate of Oatp1a1 and Oatp1b2 but not of Oatp1a4 (Hsiang et al., 1999; Chen et al., 2008). Thus, the decreases in Oatp1a1 (61%) and Oatp1b2 (66%) expression by oxidative stress caused suppression of pravastatin uptake in the liver (61%) and resulted in high plasma concentration and low biliary excretion of pravastatin (Fig. 7). In Oatp1b2 knockout mice, liver concentration of pravastatin at 2 h after s.c. injection was decreased to 76% than that in wild-type mice (Chen et a., 2008). Moreover, the uptake of pravastatin by rat primary hepatocytes was decreased to 73% of the control level by the exposure to H$_2$O$_2$ for 12 h (Supplementary Fig. 6B), and then Oatp1a1 (51%) expression decreased, but Oatp1b2 expression not altered (Fig. 3A and 3C). These findings suggested that the decrease in Oatp1a1 expression level had a greater contribution than the decrease in Oatp1b2 expression level to the decrease in accumulation of pravastatin in the liver. On the other hand, the uptake of pravastatin by HLE cells was increased by exposure to H$_2$O$_2$ for 48 h (Supplementary Fig. 6A), being associated with OATP1B3 expression (Fig. 1C). It has been shown that pravastatin uptake is mainly mediated by OATP1B1 in cryopreserved human hepatocytes (Kusuhara and Sugiyama, 2009), though it is also mediated by OATP1B3 and OATP2B1 (Kalliokoski and Niemi, 2009). However, the increase in OATP1B1 expression by
exposure to H₂O₂ for 6 h (Fig. 1B) did not affect the uptake of pravastatin by HLE cells (Supplementary Fig. 6A). Contribution of OATP1B1 to uptake of organic anion compounds might have been underestimated in the study using HLE cells. It is known that MRP2/Mrp2, which is expressed in the canalicular membrane, has a predominant influence on the efflux of pravastatin from hepatocytes to bile. Mrp2 mRNA level was increased by feeding powdery diet containing 2% inosine for 1 day and 2 days (Supplementary Fig. 7). An increase in MRP2/Mrp2 expression was induced by exposure to H₂O₂ for 6 h and 12 h in HLE cells and rat primary hepatocytes, respectively (Supplementary Fig. 8). These findings suggested that the low biliary excretion of pravastatin was caused by decrease in the expression of Oatps not by alteration of Mrp2 expression.

Despite the persistence of oxidative stress, Oatp1a1, Oatp1a4 and Oatp1b2 expression and function were recovered in rats fed powdery diet containing 2% inosine for 5 days (Fig. 5), resulting in recovery of the pharmacokinetics of pravastatin (Fig. 7). Recovery of the expression of Oatps with long-term exposure to H₂O₂ also occurred in in vitro experiments (Fig. 3). These results suggested that the effects of oxidative stress on the expression and function of OATPs/Oatps depended on oxidative stress loaded time. It has been shown that the effect of oxidative stress on physiological status in a body was changed by oxidative stress loaded time (Jendrach et al., 2008). On the other hand, Macias et al. (2011) reported that prolonged
obstructive cholestasis in rats for 8 weeks, which induces severely oxidative stress, Oatp1a1 and Oatp1a4 mRNA level in the liver were significantly decreased. These findings are not consisted our results in this study. However, their prolonged obstructive cholestasis induces high mortality (20%), suggesting that the rats have not function of the recovery of Oatps expression because the liver injury in prolonged obstructive cholestasis rats progresses to the irreversible stage. Indeed, Donner et al. (2007) reported that Oatp1a1, Oatp1a4 and Oatp1b2 expression levels were decreased as with the peak of 3 days followed by the gradual increased with time up to 7 days after obstructive cholestasis in rats. Response to oxidative stress in a body occurs for maintenance of homeostasis and/or recovery from oxidative damage. Since OATPs/Oatps transport biologically active substances, such as bile acids and thyroid hormones, they play an important role in homeostasis. Although details of the molecular mechanism remain unclear, our results suggested that recovery of the expression and function of OATPs/Oatps might be one mechanism for cellular protection when oxidative damage has occurred.

Recently, oxidative modifications of proteins and phospholipids are related with the alteration of protein function (Jacob et al., 2012; Ullery and Marnett, 2012). Unfortunately, to our knowledge, there are no reports describing the effect of oxidative modification on OATPs/Oatps but there is a possibility to modified OATPs/Oatps by oxidative stress. Although we could not elucidate the effect of oxidative modifications on OATPs/Oatps function in this study, the
comprehensive evaluation of the effect of oxidative modifications on the OATPs/Oatps function is the subject of future investigation.

In conclusion, oxidative stress induces alterations in the expression and function of OATPs/Oatps in hepatocytes, resulting in alteration in the pharmacokinetics of pravastatin. Moreover, the alterations in the expression and function of OATPs/Oatps were affected by oxidative stress loaded time. The newly found influence of oxidative stress on the expression and function of OATPs/Oatps may be a key to perform appropriate drug therapy.
References


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Figure legends

Fig. 1. Effects of H$_2$O$_2$ on mRNA and protein expression levels of OATPs in HLE cells.

Effect of H$_2$O$_2$ on mRNA levels of OATPs in HLE cells (left side).

Effect of H$_2$O$_2$ on protein expression levels of OATPs in HLE cells (right side).

HLE cells were exposed to 1 mM H$_2$O$_2$ for 6 h or 48 h.

Band intensity was determined by densitometry using Scion image program.

Each column represents the mean with S.D. of 3-6 measurements.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

N.S.; not significant

Fig. 2. Effects of H$_2$O$_2$ on uptake of various compounds by HLE cells.

(A) Effects of H$_2$O$_2$ on uptake of [${}^{14}$C]CA.

(B) Effects of H$_2$O$_2$ on uptake of [${}^{3}$H]TCA.

(C) Effects of H$_2$O$_2$ on uptake of [${}^{3}$H]E3S.

HLE cells were exposed to 1 mM H$_2$O$_2$ for 6 h or 48 h.

HLE cells were incubated with uptake medium containing 1 µM [${}^{14}$C]CA for 10 sec, 50 nM [${}^{3}$H]TCA for 30 sec or 5 nM [${}^{3}$H]E3S for 1 min at 37°C and at pH 7.4.

Each column represents the mean with S.D. of 3-6 measurements.
Fig. 3. Effects of H$_2$O$_2$ on mRNA and protein expression levels of Oatps in rat primary hepatocytes.

Effect of H$_2$O$_2$ on mRNA levels of Oatps in rat primary hepatocytes (left side).

Effect of H$_2$O$_2$ on protein expression levels of Oatps in rat primary hepatocytes (right side).

Rat primary hepatocytes were exposed to 1 mM H$_2$O$_2$ for 12 h or 48 h.

Band intensity was determined by densitometry using Scion image program.

Each column represents the mean with S.D. of 3-6 measurements.

Fig. 4. Effects of H$_2$O$_2$ on uptake of various compounds by rat primary hepatocytes.

(A) Effects of H$_2$O$_2$ on uptake of $[^{14}$C]$CA$.

(B) Effects of H$_2$O$_2$ on uptake of $[^{3}$H]$TCA$. 
(C) Effects of \( \text{H}_2\text{O}_2 \) on uptake of \([\text{^3H}]\text{E3S}\).

Rat primary hepatocytes were exposed to 1 mM \( \text{H}_2\text{O}_2 \) for 12 h or 48 h.

Rat primary hepatocytes were incubated with uptake medium containing 1 \( \mu \text{M} \) \([\text{^14C}]\text{CA}\) for 2 min, 50 nM \([\text{^3H}]\text{TCA}\) for 3 min or 5 nM \([\text{^3H}]\text{E3S}\) for 3 min at 37\( \degree \)C and at pH 7.4.

Each column represents the mean with S.D. of 3-6 measurements.

**; significantly different from control (p<0.01)

N.S.; not significant

Fig. 5. Lipid peroxidation in the liver of rats fed powdery diet containing 2\% inosine.

MDA levels in the liver of rats fed powdery diet containing 2\% inosine for 1 day, 2 days or 5 days.

Each column represents the mean with S.D. of 4-5 measurements.

**; significantly different from control (p<0.01)

Fig. 6. Effect of inosine-induced oxidative stress on mRNA and protein expression levels of Oatps in the liver.

Rats were fed powdery diet containing 2\% inosine for 1 day, 2 days or 5 days.

Band intensity was determined by densitometry using Scion image program.
Each column represents the mean with S.D. of 3-5 independent experiments.

*; significantly different from control (p<0.05)

N.S.; not significant

Fig. 7 Plasma concentration, biliary excretion and liver accumulation of pravastatin after intravenous administration in rats under the condition of oxidative stress.

Rats were fed powdery diet containing 2% inosine for 1 day (A) or 5 days (B).

Pravastatin was injected at a dose of 10 mg/kg. Blood samples and bile samples were collected at specified times after injection. Liver samples were harvested at 60 min after injection.

Each point and column represent the mean with S.D. of 3-4 measurements.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

N.S.; not significant

Supplementary Fig. 1. Effect of H$_2$O$_2$ on viability of HLE cells and rat primary hepatocytes.

(A) Effect of H$_2$O$_2$ on viability of HLE cells.

HLE cells were exposed to 1 mM H$_2$O$_2$ for 6 and 48 h.

(B) Effect of H$_2$O$_2$ on viability of rat primary hepatocytes.

Rat primary hepatocytes were exposed to 1 mM H$_2$O$_2$ for 12 and 48 h.
Each column represents the mean with S.D. of 6-8 measurements.

Supplementary Fig. 2. Eliminative effects of catalase on H$_2$O$_2$-induced alterations in mRNA and protein expression levels of OATPs in HLE cells.

Eliminative effect of catalase on H$_2$O$_2$-induced alteration in mRNA levels of OATPs (left side).

Eliminative effect of catalase on H$_2$O$_2$-induced alteration in protein expression levels of OATPs (right side).

HLE cells were exposed to 1 mM H$_2$O$_2$ in the absence or presence of PEG-catalase (100 U/mL) for 6 h or 48 h. Each solution contained 1% glycerol.

Band intensity was determined by densitometry using Scion image program.

Each column represents the mean with S.D. of 3-6 measurements.

Statistical significance was evaluated using ANOVA followed by Tukey’s test.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

†; significantly different from H$_2$O$_2$ (p<0.05)

††; significantly different from H$_2$O$_2$ (p<0.01)

N.S.; not significant.
Supplementary Fig. 3. Eliminative effects of catalase on H$_2$O$_2$-induced alteration in uptake by HLE cells.

(A) Eliminative effect of catalase on H$_2$O$_2$-induced alteration in uptake of $[^{14}$C]$\text{CA}$.

(B) Eliminative effect of catalase on H$_2$O$_2$-induced alteration in uptake of $[^{3}$H]$\text{TCA}$.

(C) Eliminative effect of catalase on H$_2$O$_2$-induced alteration in uptake of $[^{3}$H]$\text{E3S}$.

HLE cells were exposed to 1 mM H$_2$O$_2$ in the absence or presence of PEG-catalase (100 U/mL) for 6 h or 48 h. Each solution contained 1% glycerol.

HLE cells were incubated with uptake medium containing 1 µM $[^{14}$C]$\text{CA}$ for 10 sec, 50 nM $[^{3}$H]$\text{TCA}$ for 30 sec or 5 nM $[^{3}$H]$\text{E3S}$ for 1 min at 37°C and at pH 7.4.

Each column represents the mean with S.D. of 3-6 measurements.

Statistical significance was evaluated using ANOVA followed by Tukey’s test.

*; significantly different from control (p<0.05)

††; significantly different from H$_2$O$_2$ (p<0.01)

N.S.; not significant.

Supplementary Fig. 4. Eliminative effects of catalase on H$_2$O$_2$-induced alterations in mRNA and protein expression levels of Oatps in rat primary hepatocytes.

Eliminative effect of catalase on H$_2$O$_2$-induced alteration in mRNA levels of Oatps (left side).
Eliminative effect of catalase on $\text{H}_2\text{O}_2$-induced alteration in protein expression levels of Oatps (right side).

Rat primary hepatocytes were exposed to 1 mM $\text{H}_2\text{O}_2$ in the absence or presence of PEG-catalase (100 U/mL) for 12 h or 48 h. Each solution contained 1% glycerol.

Band intensity was determined by densitometry using Scion image program.

Each column represents the mean with S.D. of 3-6 measurements.

Statistical significance was evaluated using ANOVA followed by Tukey’s test.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

†; significantly different from $\text{H}_2\text{O}_2$ (p<0.05)

††; significantly different from $\text{H}_2\text{O}_2$ (p<0.01)

N.S.; not significant.

Supplementary Fig. 5. Eliminative effects of catalase on $\text{H}_2\text{O}_2$-induced alteration in uptake by rat primary hepatocytes.

(A) Eliminative effect of catalase on $\text{H}_2\text{O}_2$-induced alteration in uptake of $[^{14}\text{C}]\text{CA}$.

(B) Eliminative effect of catalase on $\text{H}_2\text{O}_2$-induced alteration in uptake of $[^{3}\text{H}]\text{TCA}$.

(C) Eliminative effect of catalase on $\text{H}_2\text{O}_2$-induced alteration in uptake of $[^{3}\text{H}]\text{E3S}$.
Rat primary hepatocytes were exposed to 1 mM H$_2$O$_2$ in the absence or presence of PEG-catalase (100 U/mL) for 12 h or 48 h. Each solution contained 1% glycerol.

Rat primary hepatocytes were incubated with uptake medium containing 1 µM [$^{14}$C]CA for 2 min, 50 nM [$^{3}$H]TCA for 3 min or 5 nM [$^{3}$H]E3S for 3 min at 37°C and at pH 7.4.

Each column represents the mean with S.D. of 3-6 measurements.

Statistical significance was evaluated using ANOVA followed by Tukey’s test.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

†; significantly different from H$_2$O$_2$ (p<0.05)

N.S.; not significant.

Supplementary Fig. 6. Effects of H$_2$O$_2$ on uptake of pravastatin by HLE cells and rat primary hepatocytes.

(A) Effect of H$_2$O$_2$ on uptake of pravastatin by HLE cells.

HLE cells were exposed to 1 mM H$_2$O$_2$ for 6 h or 48 h. HLE cells were incubated with uptake medium containing 10 µM pravastatin for 3 min at 37°C and at pH 7.4.

(B) Effect of H$_2$O$_2$ on uptake of pravastatin by rat primary hepatocytes.

Rat primary hepatocytes were exposed to 1 mM H$_2$O$_2$ for 12 h or 48 h. Rat primary hepatocytes
were incubated with uptake medium containing 10 µM pravastatin for 5 min at 37°C and at pH 7.4.

Each column represents the mean with S.D. of 3-6 measurements.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

N.S.; not significant

Supplementary Fig. 7. Effect of inosine-induced oxidative stress on Mrp2 mRNA level in the rat liver.

Mrp2 mRNA level in the liver of rats fed powdery diet containing 2% inosine for 1 day, 2 days or 5 days.

Each column represents the mean with S.D. of 3-5 independent experiments.

*; significantly different from control (p<0.05)

N.S.; not significant

Supplementary Fig. 8. Effects of H₂O₂ on MRP2/Mrp2 mRNA levels in HLE cells and rat primary hepatocytes.

(A) Effect of H₂O₂ on MRP2 mRNA level in HLE cells.
HLE cells were exposed to 1 mM H$_2$O$_2$ for 6 h or 48 h.

(B) Effect of H$_2$O$_2$ on Mrp2 mRNA level in rat primary hepatocytes.

Rat primary hepatocytes were exposed to 1 mM H$_2$O$_2$ for 12 h or 48 h.

Each column represents the mean with S.D. of 3-6 measurements.

*; significantly different from control (p<0.05)

**; significantly different from control (p<0.01)

N.S.; not significant
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Fig. 1
Fig. 2
Fig. 3

(A) Oatp1a1

(B) Oatp1a4

(C) Oatp1b2

(D) Oatp2b1
Fig. 4
Fig. 5
Fig. 6

(A) Oatp1a1

(B) Oatp1a4

(C) Oatp1b2

(D) Oatp2b1
Fig. 7
Table 2 Pharmacokinetic parameters of pravastatin after intravenous administration in rats fed powdery diet containing 2% inosine

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*: significantly different from control (p<0.05)
Supplementary fig. 1

(A) HLE cells

(B) Rat primary hepatocytes
Supplementary fig. 2
Supplementary fig. 3
Supplementary fig. 4
(A) CA  
(B) TCA  
(C) E3S  

Supplementary fig. 5
Supplementary fig. 6
Supplementary fig. 7
Supplementary fig. 8