Interleukin-6 Alters the Cellular Responsiveness to Clopidogrel, Irinotecan, and Oseltamivir by Suppressing the Expression of Carboxylesterases HCE1 and HCE2

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ABSTRACT

Carboxylesterases constitute a class of enzymes that play important roles in the hydrolytic metabolism of drugs and other xenobiotics. Patients with liver conditions such as cirrhosis show increased secretion of proinflammatory cytokines [e.g., interleukin-6 (IL-6)] and decreased capacity of hydrolysis. In this study, we provide a molecular explanation linking cytokine secretion directly to the decreased capacity of hydrolytic bio-transformation. In both primary hepatocytes and HepG2 cells, treatment with IL-6 decreased the expression of human carboxy-esterases HCE1 and HCE2 by as much as 60%. The decreased expression occurred at both mRNA and protein levels, and it was confirmed by enzymatic assay. In cotransfection experiments, both HCE1 and HCE2 promoters were significantly repressed, and the repression was comparable with the decrease in HCE1 and HCE2 mRNA, suggesting that transrepression is responsible for the suppressed expression. In addition, pretreatment with IL-6 altered the cellular responsiveness in an opposite manner of overexpression of HCE1 and HCE2 toward various ester therapeutic agents (e.g., clopidogrel). Transfection of HCE1, for example, decreased the cytotoxicity induced by antithrombogenic agent clopidogrel, whereas pretreatment with IL-6 increased the cytotoxicity. Such a reversal was observed with other ester drugs, including anticancer agent irinotecan and anti-influenza agent oseltamivir. The altered cellular responsiveness was observed when drugs were assayed at sub- and low-micromolar concentrations, suggesting that suppressed expression of carboxylesterases by IL-6 has profound pharmacological consequences, particularly with those that are hydrolyzed in an isoform-specific manner.

The lipophilic nature of drugs favors absorption and subsequent distribution to their target tissues (Parkinson, 2001). Metabolism of drugs, conversely, leads to increased polarity of drugs, and it favors excretion into urine and feces. The liver is the richest source of drug-metabolizing enzymes in terms of abundance and diversity, thereby playing a determinate role in drug metabolism (Parkinson, 2001). Although many factors may affect the hepatic capacity of drug metabolism, regulated expression of drug-metabolizing enzymes contributes the most to the alteration (Parkinson, 2001; Poso and Honkakoski, 2006). Transactivation by nuclear receptors such as the pregnane X receptor is largely responsible for the increased expression of these genes (Poso and Honkakoski, 2006). In contrast, the mechanisms of the down-regulation largely remain unclear. Cytokines such as tumor necrosis factor-α and interleukin-6 (IL-6) have been shown to down-regulate the expression of a variety of drug-metabolizing enzymes (Frye et al., 2002; Prandota, 2005; Charles et al., 2006). The most investigated mechanism related to the down-regulation is on the expression of the cytochrome P450 (P450) system. In addition to drug-metabolizing enzymes, many cytokines decrease the expression of drug transporters as well as nuclear receptors that support the transactivation of genes encoding drug-metabolizing enzymes or transporters (Pascussi et al., 2000; Blokzijl et al., 2007).

Carboxylesterases constitute a class of enzymes that hydrolyze drugs containing such functional groups as carboxylic acid ester, amide, and thioester (Satoh and...
The liver expresses two major carboxylesterases, including human carboxyl-esterases HCE1 and HCE2, whereas the gastrointestinal tract expresses predominantly HCE2 (Schwer et al., 1997; Satoh and Hosokawa, 2006). In addition to the difference in tissue distribution, these two enzymes differ markedly in the hydrolysis of certain drugs. For example, HCE1 but not HCE2 rapidly hydrolyzes antithrombogenic agent clopidogrel and anti-influenza agent oseltamivir (Shi et al., 2006; Tang et al., 2006). In contrast, HCE2 but not HCE1 rapidly hydrolyzes anticancer agent irinotecan (Wu et al., 2002). In the presence of ethyl alcohol, HCE1 catalyzes transesterification, which accounts for the formation of ethyl clopidogrel (Tang et al., 2006). Based on the Human Genome sequence, HCE1 has two closely related genes, namely, HCE1A1 (AB111997) and HCE1A2 (AB111998). These two forms differ by four amino acids in the signaling peptide (Tanimoto et al., 2007). It is noteworthy that the expression of HCE1A2 but not HCE1A1 mRNA is correlated better with the sensitivity to anticancer drug irinotecan, although the precise mechanism for such a phenomenon remains to be determined (Tanimoto et al., 2007). In addition, several sequences encoding HCE1 with one or more amino acid substitutions have been deposited into the GenBank, but they probably represent polymorphic variants of this carboxylesterase.

Hydrolysis of many drugs is reduced in liver diseases such as hepatitis and cirrhosis (Thiollet et al., 1992; Gross et al., 1993). In these conditions, the production of various cytokines is markedly increased (Frye et al., 2002; Zhang et al., 2002; Eriksson et al., 2004; Prandota, 2005). For example, the hydrolysis of perindopril, a nonsulphydryl angiotensin-converting enzyme inhibitor, is decreased by as much as 50% in patients with cirrhosis (Thiollet et al., 1992). Likewise, the hydrolysis of cilazapril, another antihypertensive, is decreased by 45% in hepatitis patients (Gross et al., 1993). In mice, treatment with lipopolysaccharide (LPS) causes a 70% decrease in the serum level of cytokines is markedly increased (Frye et al., 2002; Zhang et al., 1993). In these conditions, the production of various cytokines is markedly increased (Frye et al., 2002; Zhang et al., 1993). In mice, treatment with lipopolysaccharide (LPS) causes a 70% decrease in the serum level of (Gross et al., 1993). In addition, several sequences encoding HCE1 with one or more amino acid substitutions have been deposited into the GenBank, but they probably represent polymorphic variants of this carboxylesterase.

In this study, we have demonstrated in both primary hepatocytes and HepG2 cells that treatment with proinflammatory cytokine IL-6 decreased the expression of HCE1 and HCE2. The decreased expression occurred at both mRNA and protein levels, and it was confirmed by enzymatic assay. Both HCE1 and HCE2 promoters were significantly repressed by IL-6, and the repression was comparable with the decrease in HCE1 and HCE2 mRNA. In addition, pretreatment with IL-6 altered the cellular responsiveness in an opposite manner of overexpression of HCE1 and HCE2 toward various ester therapeutic agents, including clopidogrel, irinotecan, and oseltamivir. The altered cellular responsiveness occurred at sub- and low-micromolar concentrations, suggesting that suppressed expression of carboxylesterases by IL-6 has profound pharmacological consequences.

Materials and Methods

Chemicals and Supplies. IL-6 was purchased from R&D Systems (Minneapolis, MN). Actinomycin D, 5,6-dichloro-ido-sidyl-benzeni-midaizole (DRB), irinotecan, p-nitrophenylacetate, Hanks’ balanced salt solution, and Williams’ E medium were purchased from Sigma-Aldrich (St. Louis, MO). Clopidogrel bisulfate was purchased from ChemPacific (Baltimore, MD). Oseltamivir was purchased from Toronto Research Chemicals (North York, ON, Canada). Eagle’s minimal essential medium, high-fidelity Platinum TaqDNA polymerase, and insulin-transferrin-selenium G supplement were purchased from Invitrogen (Carlsbad, CA). Dual-Luciferase reporter assay system was from Promega (Madison, WI). Fetal bovine sera were from Hyclone Laboratories (Logan, UT). The antibody against glyceradehyde-3-phosphate dehydrogenase (GAPDH) was from Abcam (Cambridge, UK). The goat anti-rabbit IgG conjugated with horseradish peroxidase was from Pierce Chemical (Rockford, IL). Nitrocellulose membranes were from Bio-Rad Laboratories (Her-cules, CA). Unless otherwise specified, all other reagents were purchased from Fisher Scientific (Fair Lawn, NJ).

Culture and Treatment of Human Primary Hepatocyte and HepG2 Cell Line. Plated human primary hepatocytes (in six-well plates) were obtained from the Liver Tissues Procurement and Distribution System (University of Minnesota, Minneapolis, MN) or the commercial source CellzDirect (Pittsboro, NC). In total, four donors were included: two males (21 and 48 years old) and two females (35 and 47 years old). Among the donors, three were white and one was African American (the 21-year man). None of them was a smoker. Upon arrival, media were replaced with rich Williams’ E medium containing insulin-transferrin-selenium supplement and 100 U/ml penicillin/10 μg/ml streptomycin (Yang and Yan, 2007). After incubation at 37°C with 5% CO2 for 24 h, hepatocytes were treated with 50 ng/ml IL-6 for 24 h. This type of study usually uses a concentration between 10 and 100 ng/ml (Pascussi et al., 2000; Gubbins et al., 2003). HepG2 hepatoma line was purchased from American Type Culture Collection (Manassas, VA), and cells were maintained in Eagle’s minimal essential medium containing 10% fetal bovine serum, penicillin/streptomycin, and 1× nonessential amino acids. HepG2 cells were usually seeded at a density of 2.5 × 10⁵ cells/well (12-well plates) in normal medium, and treatment with IL-6 was performed 12 h after seeding. The treated cells were cultured in 1% serum-reduced medium.

Quantitative Reverse Transcription-Polymerase Chain Reaction. Total RNA was isolated with an RNA-Bee (Tel-Test Inc., Friendswood, TX) according to the manufacturer’s manual, and the integrity of the RNA was confirmed by formaldehyde gel electrophoresis. Total RNA (1 μg) was subjected to the synthesis of the first-strand cDNA in a total volume of 25 μl with random primers and Moloney murine leukemia virus reverse transcriptase. The reactions were conducted at 25°C for 10 min, at 42°C for 50 min, and at 70°C for 10 min. The cDNAs were then diluted eight times, and amplification and quantification were done with the Applied Biosystems 7500 real-time PCR system.

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Reporter Constructs. The HCE2 promoter reporter (~1931/−/6) was kindly provided by Dr. M. E. Dolan (University of Chicago, Chicago, IL) (Wu et al., 2003). Three HCE1A2 promoter reporters were prepared to contain various lengths of HCE1A2 genomic se-
sequence: HCE1A2-9224-Luc, HCE1A2-8251-Luc, and HCE1A2-7851-Luc. The HCE1A2-9224-Luc reporter was prepared first, and it contained the genomic sequence from −9133 to −40 (relative to the translation initiation codon). Two fragments (−5155 to −40 and −9224 to −5049) were initially amplified by PCR with high-fidelity Platinum TaqDNA polymerase and human genomic DNA as the template. The sequence (−5155 to −5049) overlapped by these two fragments contains an EcoRV site. The fragment from −5155 to −40 was generated by primers forward, 5′-tcatgacctgtagctgagtcag-3′ and reverse, 5′-tagagataggcttgacgagtcagctcc-3′ (restriction endonuclease sites are underlined). The fragment from −9224 to −5049 was generated by primers forward, 5′-taacctgct-accagtgcg-3′ and reverse, 5′-tcctagat-ctctagag-3′. These two fragments were, respectively, subcloned into the pGL3 basic vector through MluI and BamHI sites. To prepare the HCE1A2-9224-Luc reporter, the fragment (−9224 to −5049) was released by MluI-EcoRV digestion, and it was ligated to the construct containing the fragment from −5155 to −40, which was pretreated with MluI-EcoRV. To prepare HCE1A2-8251-Luc and HCE1A2-7851-Luc reporters, the corresponding fragments were amplified by PCR with the same reverse primer, 5′-gtcagatatacaggtgctgcttcatgtgc-3′, but with different forward primers. The forward primer for HCE1A2-8251-Luc was 5′-cctagacgctctcgtccggccagtctt-3′, whereas the forward primer for HCE1A2-7851-Luc was 5′-agagacgctctcgtccggccagtctt-3′. These fragments were digested with SacI and EcoRV and ligated to the HCE1A2-9224-Luc reporter pretreated with the same restriction endonucleases. All reporter constructs were subjected to sequence analysis.

Co-transfection Assays. Cells (HepG2) were plated in 48-well plates in DMEM supplemented with 10% fetal bovine serum at a density of 6 × 104 cells/well. Transfection was conducted by FuGene HD (Roche Diagnostics, Indianapolis, IN). Transfection mixtures contained 100 ng of a reporter plasmid and 5 ng of thymidine kinase-Renilla reniformis luciferase plasmid. Cells were transfected for 12 h, and the medium was replaced with fresh medium supplemented with 1% fetal bovine serum with or without 50 ng/ml IL-6. The treatment lasted for 12 h, and then the cells were washed once with phosphate-buffered saline (PBS) and collected by scraping. The collected cells were subjected to two cycles of freeze/thaw. The reporter enzyme activities were assayed with a Dual-Luciferase reporter assay system. This system contained two substrates, which permitted enzyme activities were assayed with a Dual-Luciferase reporter enzyme activity, which was measured by adding an aliquot of lysates (10 μl) with Luciferase Assay Reagent II (Promega, Madison, WI). Then, the firefly luminescence signal was normalized based on the Renilla reniformis luminescence signal.

Western Analysis. Cell lysates (2–20 μg) were resolved by 7.5% SDS-polyacrylamide gel electrophoresis in a mini-gel apparatus (Bio-Rad Laboratories, Hercules, CA) and transferred electrothermally to nitrocellulose membranes. After nonspecific binding sites were blocked with 5% nonfat milk, the blots were incubated with an antibody against HCE1, HCE2, or GAPDH. The preparation of the antibodies against HCE1 and HCE2 was described previously (Zhu et al., 2000; Xie et al., 2002). The primary antibodies were subsequently localized with goat anti-rabbit IgG conjugated with horseradish peroxidase. Horseradish peroxidase activity was detected with a chemiluminescent kit (SuperSignal West Pico; Pierce Chemical). The chemiluminescent signal was captured by Kodak Image Station 2000 (Eastman Kodak, Rochester, NY), and the relative intensities were quantified by Kodak 1D Image Analysis software.

Enzymatic Assay. Primary hepatocytes or HepG2 cells were treated with IL-6 as described above. Cells were rinsed with PBS and harvested in 300 μl of 100 mM potassium phosphate buffer, pH 7.2. The cell suspension was sonicated by a sonifier (Branson Ultrasonics Corporation, Danbury, CT), and cell debris was removed by centrifugation at 12,000g for 15 min at 4°C. The supernatant was assayed for hydrolytic activity toward para-nitrophenylacetate as described previously (Yang and Yan, 2007). A sample cuvette (1 ml) contained 10 to 100 μg of microsomes in 100 mM potassium phosphate buffer, pH 7.4, and 1 mM substrate at room temperature. Reactions were initiated by adding para-nitrophenylacetate (10 μl of 100 mM stock in acetonitrile), and the hydrolytic rate was recorded from an increase in absorbance at 400 nm. The extinction coefficient (E400) was determined to be 13 mM−1 cm−1. Several controls were performed, including incubation without proteins.

Cytotoxicity Assay. HepG2 cells were seeded into 96-well plates at a density of 5000 cells/well. After an overnight incubation, the medium was replaced with fresh medium with or without 50 ng/ml IL-6 in 1% serum (half of the wells with medium alone and half of the wells with IL-6-containing medium). After an additional 12-h incubation, the cells were washed with DMEM twice and treated with cldopiglord, irinotecan, or oseltamivir at various concentrations. After the cells were treated for 24 h, the medium was replaced with fresh medium containing 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium (MTT) at a final concentration of 0.5 mg/ml. After 2-h incubation at 37°C, the medium was gently decanted, and dimethyl sulfoxide (100 μl/well) was added to dissolve formazan product. The optical density (OD) was determined at 570 nm, and the final OD values were expressed by subtracting the background reading (no seeded cells).

Other Analyses. Protein concentrations were determined with BCA protein assay (Pierce Chemical) based on albumin standard. Data are presented as mean ± S.D. of at least three separate experiments, except where results of blots are shown, in which case a representative experiment is depicted in the figures. Statistical analysis was performed using SAS software (SAS, version 9.1; SAS Institute, Cary, NC). Significance was made according to one-way analysis of variance followed by Duncan’s multiple comparison test (p < 0.05).

Results

Primary Hepatocytes Treated with IL-6 Express Markedly Lower Levels of HCE1 and HCE2 mRNA. It has been reported that hydrolytic biotransformation is decreased in patients with liver conditions such as hepatitis and cirrhosis (Thiollet et al., 1992; Gross et al., 1993; Prandota, 2005). In these conditions, the production of various proinflammatory cytokines (e.g., IL-6) is markedly increased (Frye et al., 2002; Zhang et al., 2002; Eriksson et al., 2004). To link the increased production of cytokines to the reduced hydrolysis, we tested whether IL-6 suppresses the expression of carboxylesterases HCE1 and HCE2, two major hydrolytic enzymes in the liver. Primary hepatocytes were cultured and treated with IL-6. Total RNA was isolated, and the levels of HCE1 and HCE2 were determined by qRT-PCR with TaqMan probes. HCE1 has two closely related genes that encode almost identical transcripts, and the HCE1 TaqMan probe recognized both transcripts. The level of CYP3A4 mRNA was monitored to serve as a positive control, because many cytokines have been shown to decrease the expression of CYP3A4 (Pascussi et al., 2000).

As shown in Fig. 1, treatment with IL-6 consistently decreased the level of HCE1, HCE2, or CYP3A4 mRNA. However, the magnitude of the decrease varied depending on genes and donors. Overall, the most decrease was detected in CYP3A4 mRNA (Fig. 1C), and the least decrease was detected in HCE1 mRNA (Fig. 1A). The level of CYP3A4 mRNA decreased by 64 to 99%, the level of HCE2 mRNA decreased by 34 to 63%, and the level of HCE1 mRNA decreased by 20
to 40% (Fig. 1). It should be noted that a regular RT-PCR with primers specific to HCE1A1 or HCE1A2 detected comparable decreases of both transcripts (data not shown). Among individual donors, the least decrease was detected with donor 2 in HCE1 and CYP3A4 mRNA, whereas donor 4 showed the least decrease in HCE2 mRNA (Fig. 1). At the basal level, CYP3A4 mRNA exhibited the largest interindividual variation, whereas HCE1 mRNA exhibited the least interindividual variation (Fig. 1). We previously tested 19 human liver microsomal samples for the abundance of HCE1 and HCE2, and we detected a larger overall interindividual variation (3- to 4-fold), although the majority of the microsomal samples exhibited a lesser variation (Tang et al., 2006).

**IL-6 Reduces the Overall Hydrolytic Activity by Decreasing HCE1 and HCE2 Proteins.** We next examined whether the decreases of HCE1 and HCE2 mRNA translate into decreases in the hydrolytic activity. Primary hepatocytes were treated with IL-6, and cell lysates were prepared. The overall hydrolytic activity by the lysates was determined with standard substrate para-nitrophenylacetate. Both HCE1 and HCE2 have been shown to hydrolyze this ester (Xie et al., 2002). Consistent with the decreases in HCE1 and HCE2 mRNA, the hydrolysis of para-nitrophenylacetate was markedly decreased (Fig. 2A). To determine whether the decreased hydrolysis is due to decreased enzyme proteins, the lysates were analyzed by Western blotting for the abundance of HCE1 and HCE2. As expected, the levels of both HCE1 and HCE2 proteins were markedly decreased, and the decrease was comparable with the decrease in the hydrolytic activity (Fig. 2A, bottom). As expected, no decrease was detected in the level of GAPDH, a housekeeping gene.

To determine whether hepatoma cells respond to IL-6 sim-

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**Fig. 1.** Effect of IL-6 on the levels of HCE1, HCE2, and CYP3A4 mRNA in primary hepatocytes. Human primary hepatocytes were treated with 50 ng/ml IL-6 or the same volume of PBS for 24 h. Total RNAs were isolated and subjected to qRT-PCR analysis for the level of HCE1 mRNA (top), HCE2 mRNA (middle), or CYP3A4 mRNA (bottom) by TaqMan probes as described under Materials and Methods. The signals from each target were normalized based on the signal from GADPH, and data are expressed as mean ± S.D. of triplicate analyses.

**Fig. 2.** Effect of IL-6 on the hydrolysis of para-nitrophenylacetate in primary hepatocytes and HepG2 cells, and regulated expression of HCE1, HCE2, and CYP3A4 mRNA as a function of time in HepG2 cells. A, effect of IL-6 on the hydrolysis of para-nitrophenylacetate in primary hepatocytes. Human hepatocytes were treated with 50 ng/ml IL-6 or with the same volume of PBS for 24 h, and cell lysates were prepared. The hydrolysis of 25 μg/ml para-nitrophenylacetate was determined spectrophotometrically as described under Materials and Methods. To determine the abundance of HCE1 and HCE2 proteins, 2 μg of lysates was subjected to Western analyses with an antibody against HCE1, HCE2, or GAPDH. B, effect of IL-6 on the hydrolysis of para-nitrophenylacetate in HepG2 cell line. HepG2 cells were treated and analyzed as described in A. However, 100 μg of cell lysates was used for the enzymatic assay, and 20 μg of lysates was used for the Western analyses. C, regulated expression of HCE1, HCE2, and CYP3A4 mRNA by IL-6 as a function of time. HepG2 cells were treated with IL-6 as described above; however, total RNA was prepared at various times after the initial treatment. The level of HCE1, HCE2, and CYP3A4 mRNA was determined by qRT-PCR analyses. The mRNA levels were expressed relative to those in control cells (considered as 1). All experiments described in this figure were repeated at least three times, and data are expressed as mean ± S.D. *p ≤ 0.05, statistically significant decrease by IL-6 treatment.
arily to primary hepatocytes in terms of altered expression of carboxylesterases, HepG2 cells were treated with IL-6, and lysates were prepared and analyzed for the hydrolysis of para-nitrophenylacetate. Consistent with the results from primary hepatocytes, the hydrolysis of para-nitrophenylacetate was markedly decreased in HepG2 cells treated with IL-6 (Fig. 2B). Likewise, the protein levels of HCE1 and HCE2 were comparably decreased. It should be noted that HepG2 cells expressed a much lower HCE1 and HCE2 than primary hepatocytes, and more lysates were used for the Western analysis (2 versus 20 μg). Likewise, the overall hydrolytic activity of HepG2 cells was much less than that of primary hepatocytes (Fig. 2, A and B).

We next performed a time course study with HepG2 cells, and qRT-PCR was used to monitor the changes of mRNA levels. The mRNA levels from IL-treated cells were normalized based on the mRNA levels from the corresponding control cells processed at various time points (expressed as 1). As shown in Fig. 2C, some decreases were detected as early as 3 h after treatment in HCE2 and CYP3A4 mRNA, although the decrease was statistically insignificant compared with that of the nontreated cells. The maximal decrease was detected at 9 h after IL-6 treatment on the levels of HCE1 and HCE2 mRNA (Fig. 2C). Thereafter, the levels of both HCE1 and HCE2 mRNA were slightly increased (remaining a statistically significant decrease), although the overall levels remained significantly lower than the levels in control cells (Fig. 2C). In contrast, a continuous decrease was detected in CYP3A4 mRNA (Fig. 2C). It should be noted that a continuous decrease in HCE1 and HCE2 mRNA was detected when a repeated treatment with IL-6 was performed at 9 h after the initial treatment (data not shown).

**IL-6 Represses the Promoter of HCE1 and HCE2.** The comparable decreases between mRNA and protein levels suggest that IL-6 suppresses the expression of HCE1 and HCE2 through transcriptional repression, increased degradation of mRNA, or both. To decipher these possibilities, the effect of IL-6 on the HCE1 and HCE2 mRNA was studied in the presence of actinomycin D or DRB, two inhibitors of RNA synthesis. HepG2 cells were cotreated with IL-6 and actinomycin D or DRB for 9 h, and the levels of HCE1 and HCE2 mRNA were determined by qRT-PCR. As shown in Fig. 3A, cotreatment with an RNA synthesis inhibitor abolished the IL-6-mediated decreases on HCE1 and HCE2. It should be noted that DRB itself caused a slight decrease in HCE1 mRNA and that actinomycin D caused a moderate decrease in HCE2 mRNA. Therefore, the HCE1 data shown in Fig. 3A are from the cells treated with actinomycin D, and the HCE2 data are from the DRB treatment.

The abolition of IL-6-mediated suppression by RNA synthesis inhibitors suggests that this cytokine decreases the expression of these carboxylesterases by repressing their promoters. To test this possibility, cotransfection was performed with an HCE1 or HCE2 promoter reporter. The HCE1 reporter contains the genomic sequence corresponding to HCE1A2 promoter (HCE1A2-9224-Luc). As shown in Fig. 3C,
treatment with IL-6 resulted in decreased activities of both HCE1 and HCE2 reporters by ~40%. To locate the sequence in the HCE1 promoter that supports the repression, two deletion mutants of the HCE1-reporter (5′ end) were prepared and tested for the responsiveness to IL-6. As shown in Fig. 3D, the repression was detected with the HCE1-8251-Luc reporter but not HCE1-7851-Luc, suggesting that the sequence responsible for the repression is located at the region between −8251 and −7851.

Alteration of Cellular Responsiveness to Clopidogrel, Irinotecan, and Oseltamivir. We next examined the pharmacological/toxicological consequences of the reduced expression of carboxylesterases by IL-6. It has been reported that HCE1 and HCE2 differ markedly in the hydrolysis of antiplatelet agent clopidogrel, anticancer agent irinotecan, and anti-influenza agent oseltamivir (Wu et al., 2002; Shi et al., 2006; Tang et al., 2006). HCE1 rapidly hydrolyzes clopidogrel and oseltamivir, whereas HCE2 rapidly hydrolyzes irinotecan. More importantly, hydrolysis of clopidogrel represents detoxication, whereas hydrolysis of irinotecan and oseltamivir increases cytotoxicity. It was assumed that IL-6 treatment would increase cytotoxicity of clopidogrel, and the opposite would be true with irinotecan and oseltamivir.

HepG2 cells were first treated with IL-6 for 12 h, washed twice, and then treated with a drug at various concentrations. After an additional 24-h incubation, cell viability was determined by MTT assay.

As shown in Fig. 4, IL-6 pretreatment alone caused no difference in the cell viability (no drug treatment); however, pretreatment followed by a drug treatment caused statistically significant changes with all drugs and all concentrations compared with nonpretreated cells (Fig. 4). When exposed to clopidogrel as low as 3 μM, for example, the cells pretreated with IL-6 exhibited a 40% decrease in cell viability (Fig. 4A). The decreased viability by IL-6 pretreatment was consistent with the observation that hydrolysis of clopidogrel represents detoxication (Tang et al., 2006). In contrast, IL-6 pretreatment protected against oseltamivir-induced cytotoxicity. For example, when oseltamivir was assayed at 3 μM, the IL-6-pretreated cells had a relative viability of 150% of the nontreated cells (Fig. 4D). Interestingly, oseltamivir at low concentrations (3 and 30 μM) caused a statistically significant increase in cell viability among IL-6-pretreated cells (Fig. 2B). Nevertheless, the increased viability in IL-6-pretreated cells (decreased oseltamivir hydrolysis) is consistent with the previous observation that the hydrolytic metabolite but not the parent drug of oseltamivir causes cell toxicity (Shi et al., 2006). Finally, irinotecan is an anticancer prodrug, and only the hydrolytic metabolite has anticancer activity (Wu et al., 2002). Irinotecan decreased cell viability by 45% or higher compared with nontreated cells (without IL-6 pretreatment), but IL-6 pretreatment completely blocked this effect on cell viability at 0.3 μM, and it attenuated the reduction in viability with higher irinotecan exposures (Fig. 4C). For clarity, some of the statistical significances, particularly those showing obvious differences, are not labeled in this figure. An example is the statistically significant difference between irinotecan-treated and nontreated cells that were not pretreated with IL-6 (Fig. 4C).

We next examined morphological changes in cells pretreated with IL-6 in response to a drug. Under bright field, cells pretreated with IL-6 were spread, and the projects were well extended when exposed to oseltamivir (Fig. 5, top right). In contrast, cells without IL-6 pretreatment were rounded, isolated, and swollen with the presence of vesicles in the cytoplasm (Fig. 5, top left). Conversely, when exposed to clopidogrel, cells pretreated with IL-6 exhibited profound morphological changes (e.g., aggregation), whereas cells without IL-6 pretreatment showed normal appearance (Fig. 5, middle). As for irinotecan, cells without IL-6 pretreatment were isolated and shrank, whereas cells pretreated with IL-6 were morphologically normal (Fig. 5, bottom).

Fig. 4. Effect of IL-6 on the cellular responsiveness to clopidogrel (A), irinotecan (B), and oseltamivir (C). HepG2 cells were seeded into 96-well plates at a density of 5000 cells/well. After an overnight incubation, 50 ng/ml IL-6 in 1% serum medium was added to half of the wells, and the treatment lasted for 12 h. Thereafter, the cells were washed with DMEM, and then they were treated with clopidogrel, irinotecan, or oseltamivir at various concentrations. After an additional 24-h incubation, MTT was added to each well at a final concentration of 0.5 mg/ml. After 2-h incubation at 37°C, the medium was gently decanted, and dimethyl sulfoxide (150 μl/well) was added to dissolve formazan product. The OD was determined at 570 nm, and the final OD values were expressed by subtracting the background reading (no seeded cells). The data are from three independent experiments, and they are expressed as mean ± S.D. *, p ≤ 0.05, statistically significant difference between columns specified by lines.
Discussion

Carboxylesterases constitute a class of hydrolytic enzymes that play important roles in the metabolism of drugs and other xenobiotics. In patients with liver conditions such as cirrhosis, the secretion of proinflammatory cytokines (e.g., IL-6) is increased, and the hydrolysis of many drugs is decreased (Thiollet et al., 1992; Gross et al., 1993; Frye et al., 2002; Zhang et al., 2002). In this study, we have provided a molecular explanation linking cytokine secretion directly to the decreased capacity of hydrolytic biotransformation. In both primary hepatocytes and HepG2 cells, treatment with IL-6 causes significant decreases in the expression of HCE1 and HCE2, two major carboxylesterases in the liver. The decreased expression occurs at both mRNA and protein levels, and it is confirmed by enzymatic assay. In cells treated with IL-6, the transcriptional activity of both HCE1 and HCE2 promoters is markedly repressed.

In addition to decreased expression of carboxylesterases, IL-6 pretreatment profoundly alters the cellular responsiveness to various ester drugs, including clopidogrel, irinotecan, and oseltamivir. The alteration is clearly achieved by decreasing the expression of HCE1 or HCE2. Multiple washes are performed to remove any residual IL-6 before treatment with a drug. More importantly, pretreatment with IL-6 alters the cellular responsiveness in an opposite manner of overexpression of HCE1 and HCE2. For example, transfection of HCE1 decreases clopidogrel-induced cytotoxicity (Tang et al., 2006), whereas pretreatment with IL-6 increases cytotoxicity (Fig. 4A). Conversely, transfection of HCE1 increases the cytotoxicity of oseltamivir (Shi et al., 2006), and the cytotoxicity is abolished by IL-6 pretreatment (Fig. 4B). Likewise, hydrolysis of irinotecan by HCE2 leads to increased cytotoxicity (Wu et al., 2002), and IL-6 pretreatment protects against cytotoxicity (Fig. 4C). It should be noted that all ester drugs are tested at submicromolar or micromolar concentrations, and the majority of these concentrations are pharmacologically relevant.

IL-6 suppresses the expression of both HCE1 and CYP3A4, and it probably presents a complex scenario on the pharmacological behaviors of clopidogrel. This antithrombogenic agent undergoes hydrolytic and oxidative metabolism. The hydrolysis is catalyzed by HCE1 (Tang et al., 2006), whereas the oxidation is catalyzed by CYP3A4 and CYP3A5 (Savi et al., 2000). More importantly, the oxidized but not hydrolytic metabolite exerts antithrombogenic activity, and hydrolysis of the ester bond represents inactivation (Savi et al., 2000). It is assumed that decreased expression of HCE1 would increase the amount of the parent drug for oxidation and favor therapeutic outcome. Conversely, decreased expression of CYP3A4 would decrease the oxidative metabolism and reduce its therapeutic activation. The ultimate effect, however, probably depends on the relative magnitude of decreased expression between HCE1 and CYP3A4 and the relative rate between these two types of metabolism. In this study, we have shown that the expression of CYP3A4 is decreased more than HCE1 in IL-6-treated cells (Fig. 1, A and C), suggesting that the oxidation is affected to a greater extent. Alternatively, hydrolysis usually proceeds much faster than oxidation catalyzed by P450s (Parkinson, 2001); thus, decreased hydrolysis during IL-6 exposure would weigh more over decreased oxidation, and prolong the therapeutic effect of clopidogrel. In support of the second possibility, patients with liver cirrhosis (i.e., IL-6 exposure) show increased bleeding time accompanied by decreased formation of the hydrolytic metabolite (Slugg et al., 2000).

In contrast to clopidogrel, hydrolysis of oseltamivir is required for its antiviral activity (Oxford et al., 2003). The hydrolytic metabolite is a potent inhibitor of the neuraminidase of influenza virus, and this sialidase plays important roles in the process of viral entry and release (Wagner et al., 2002; Ohuchi et al., 2006). It is expected that decreased hepatic hydrolysis by IL-6 probably results in decreased therapeutic activity of oseltamivir. In patients with liver cirrhosis, both $C_{\text{max}}$ and area under the curve0– values are decreased almost by 20% (Snell et al., 2005), but the precise therapeutic significance of such a decrease remains to be determined. In contrast, decreased hepatic hydrolysis of oseltamivir may have toxicological significance. It has been reported recently that some flu patients taking oseltamivir show neurobehavioral changes (Food and Drug Administration, 2007). Although the precise involvement of oseltamivir in the neurotoxicity remains to be established, it is tempting to speculate that patients who develop neurological symptoms may have increased levels of oseltamivir in the brain, and decreased hepatic hydrolysis probably contributes to such an increase. In humans, there are several mechanisms that may support reduced hepatic hydrolysis of oseltamivir.

![Image](https://example.com/image.png)
First, certain drugs (e.g., clopidogrel) concurrently administered may profoundly inhibit oseltamivir hydrolysis (Shi et al., 2006). Second, people express polymorphic variants of HCE1 with marked decreases in the hydrolysis of oseltamivir (Shi et al., 2006). And finally, excessive production of cytokines (e.g., IL-6) down-regulates the expression of HCE1. In support of the last possibility, influenza viral infection has been shown to increase the secretion of various proinflammatory cytokines, including IL-6 (Aiba et al., 2001).

Like oseltamivir, irinotecan is an ester prodrug, and the hydrolytic metabolite exerts potent anticancer activity (Matsuura et al., 1996). In contrast to oseltamivir, irinotecan is hydrolyzed by HCE2 but not HCE1 (Wu et al., 2002). Although the liver expresses high levels of HCE2, it has been suggested that hydrolytic metabolite generated locally contributes significantly to its antitumor activity (Rowinsky et al., 1994; Kojima et al., 1998). In support of this notion, gallbladder carcinoma expresses little HCE2, and it does not respond to irinotecan (Alberts et al., 2002). Interestingly, several investigators have shown that the expression of HCE2 is decreased in tumors (Guichard et al., 1999; Xie et al., 2002). However, the precise mechanism on the tumor-associated decrease remains to be determined. In contrast, the expression of various proinflammatory cytokines, including IL-6, is elevated in tumor tissues (Nakano et al., 1999; Charles et al., 2006). In this study, we have demonstrated in hepatocytes and hepatoma cells treated with IL-6 a marked decrease in the expression of HCE2 (Figs. 1B and 2C). Whether increased expression of IL-6 is responsible for the tumor-associated decrease in HCE2 expression remains to be determined. CYP3A4 reportedly metabolizes irinotecan, and the oxidized metabolites can be converted to the active metabolite by HCE2. However, the conversion is much less effective than that of irinotecan (Sanghani et al., 2004). Therefore, the greater suppression of CYP3A4 than HCE2 expression (Fig. 1) probably increases the availability of parent drug for hydrolysis.

Proinflammatory cytokines such as IL-6 have been shown to suppress the expression of many drug-metabolizing enzymes, particularly P450 enzymes (Pascucci et al., 2000; Frye et al., 2002; Sunman et al., 2004). In this study, we have shown that IL-6 causes marked decreases in the expression of HCE1 and HCE2, further increasing the spectrum of repressed enzymes. Although IL-6 exerts a broad suppressive activity, the mechanisms supporting the suppression may vary from target to target. In fact, we have observed several major differences on the suppressed expression of carboxylesterases and CYP3A4. First, the suppression of CYP3A4 is much more profound than that of either HCE1 or HCE2 (Fig. 1). Second, the magnitude of suppression of carboxylesterases is similar between primary hepatocytes and HepG2 cells, whereas the suppression of CYP3A4 is much higher in primary hepatocytes than that in HepG2 cells (Figs. 1C and 2C). Third, a continuous decrease in CYP3A4 mRNA occurs during the full time course of the study (up to 24 h). In contrast, the maximum decrease in HCE1 and HCE2 mRNA occurs 9 h after the treatment (Fig. 2C). It should be noted that repeated treatment with IL-6 leads to more persistent decreases in HCE1 and HCE2 mRNA (data not shown).

It seems that suppressed expression of HCE1 and HCE2 is achieved primarily through transcriptional repression. We have presented several lines of evidence that directly support this possibility. First, the IL-6-mediated suppression is abolished by RNA synthesis inhibitors (Fig. 3A), excluding an involvement of post-transcriptional mechanism. Second, the promoters of HCE1 and HCE2 are markedly repressed in cells treated with IL-6 (Fig. 3B). More importantly, the repression of the promoters is comparable with the extent of decreased mRNA and proteins (Figs. 1–3), providing direct evidence that transcriptional repression is responsible for the suppressed expression of the carboxylesterases. And finally, we have located a genomic sequence in the HCE1A2 gene that supports the transcriptional repression. HCE1A2-Luc (−8213/−40) but not HCE1A2-Luc (−7813/−40) responded to IL-6 (Fig. 3C), suggesting that the sequence (−8213 to −7813) contains a response element(s) that supports the response to IL-6.

In summary, our work points to several important conclusions. First, we have shown that IL-6 causes marked decreases in the expression of HCE1 and HCE2, suggesting that proinflammatory cytokines exert a broad suppression on the expression of various types of drug-metabolizing enzymes. Second, we have observed several differences in the suppressed expression between carboxylesterases and CYP3A4, suggesting that multiple mechanisms support the action of IL-6 and that these mechanisms operate independently or cooperatively, depending on a target gene. And finally, pretreatment with IL-6 profoundly alters the cellular responsiveness to ester drugs such as oseltamivir, suggesting that suppressed expression of carboxylesterases has profound pharmacological and toxicological consequences, particularly with those drugs that are hydrolyzed in an isoform-specific manner.

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References


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