Active efflux and metabolic transformation are two mechanisms that help mammalian cells control entry of a range of compounds (Nelson et al., 1996). P-gp is the product of the human ABCB1 (formerly multidrug resistance 1) gene and a member of the ATP-binding cassette transporter family. This efflux protein transports recognized hydrophobic substrates from the inside to the outside of cells and is expressed at various sites that determine drug disposition such as intestinal enterocytes, blood-brain barrier endothelia, renal proximal tubular cells, and hepatic canalicular cells (Thiebaut et al., 1987; Cordon-Cardo et al., 1990). The cytochrome P450 superfamily, such as thyroid hormone receptor (TR), vitamin D receptor (VDR), and retinoic acid receptor (RAR) (reviewed in Yen, 2001), plays an important role in the oxidative metabolism of numerous endogenous and exogenous compounds. More than 60% of currently marketed therapeutics are reported to undergo significant metabolism by the human CYP3A4 isoform in the intestine and/or liver (Li et al., 1995).

Expression of both ABCB1 and CYP3A4 can be regulated by nuclear receptor PXR, which binds to the enhancer region located 8 kb upstream from the transcriptional initiation sites of ABCB1 (Geick et al., 2001) and CYP3A4 (Goodwin et al., 1999). PXR dimerizes with retinoid X receptor (RXR) and binds to direct repeats of AG(G/A)GGT(C/G)A, with a striking similarity to the PXR response element forms in various arrangements response elements for different members of the nuclear hormone receptor superfamily, such as thyroid hormone receptor (TR), vitamin D receptor (VDR), and retinoic acid receptor (RAR) (reviewed in Yen, 2001). Direct repeat arrangement of consensus hexamers has been described as the most common motif (Williams and Brent, 1995) (Table 1). These nuclear hormone receptors can act as monomers, or form homo- and heterodimers. In the latter scenario, they bind to RXR and form a complex, which is believed to be the most important entity (at least for some hormone receptors) in hormonal regulation of gene expression (reviewed in Yen, 2001). In a previous study (Siegmund et al., 2002), P-glycoprotein levels were increased in duodenal biopsy specimens from healthy human volunteers after administration of levothyroxine (L-T4). However, the increase in ABCB1 mRNA levels was not statistically significant. Results from this in vivo study cannot indicate whether the effect was due to a direct action of L-T4 on intestinal cells, and whether this effect was mediated through PXR. The similarities between the mechanisms resulted in elimination of PXR-mediated induction (Geick et al., 2001). Similarly, the CYP3A4 enhancer site contains two consensus hexamers in a DR3 arrangement, and elimination of the enhancer site prevented PXR-mediated induction (Goodwin et al., 1999). Additional factors such as hepatocyte nuclear factor 4α also appear to be important in PXR-mediated CYP3A4 activation (Tirona et al., 2003).

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of PXR and nuclear hormone receptor actions (dimerization with RXR and recognition of similar consensus motifs) prompted the present study of non-PXR-mediated mechanisms of CYP3A4 and ABCB1 induction, with a focus on establishing whether TR has a role in the regulation of these genes.

Materials and Methods

Cell Lines. We cultured LS180V and Caco-2 cells (both purchased from American Type Culture Collection, Manassas, VA) in American Type Culture Collection-recommended medium (Invitrogen, Carlsbad, CA) supplemented with 10% fetal bovine serum, 1 mM sodium pyruvate, 0.1 mM nonessential amino acids, and 1% penicillin/streptomycin solution. LS180V cells were selected and maintained as described previously (Sto¨ rmer et al., 2002). Over the course of the experiment, we passaged LS180V cells up to 14 times since the initial acquisition from the manufacturer; the passage number for Caco-2 cells varied between 28 and 32. After the cells reached confluence, they were fed for 7 days and subjected to 72 h of incubation according to the treatment protocol: 100 nM or 100 μM L-thyroxine sodium salt; 2 nM, 100 nM, or 2 μM 3,3',5-triiodo-L-thyronine sodium salt; and 10 μM rifampin (all from Sigma-Aldrich, St. Louis, MO), each dissolved in 0.5% dimethyl sulfoxide (Fisher Chemicals, Fairlawn, NJ).

HPLC Assay. L-T4 was extracted from the cell culture medium with methanol, and its concentrations were determined by HPLC with ultraviolet detection at 230 nm. We used a reverse-phase C18 μBondapak column (Waters, Milford, MA), with the mobile phase containing methanol, water, and phosphoric acid (80:20:0.2).

RNA Isolation, Reverse-Transcription PCR, and Quantitative Real-Time PCR. RNA isolation procedures were performed as described previously (Vishnuvardhan et al., 2003). We isolated total RNA from LS180V and Caco-2 cells using an RNeasy Mini Kit (QIAGEN, Valencia, CA). After DNase treatment (Invitrogen), the samples were reverse-transcribed with SuperScript II (Invitrogen). cDNA dilutions ranging from 1:5 to 1:20 were subsequently used in real-time PCR according to the SYBR Green protocol on a GeneAmp II (Invitrogen). The relative amounts of ABCB1 mRNA we used primers 5’-GAGACAGCAGGAAATGAAGT-GTA-3’ and 5’-CATATACTCCTCAAAAGGAACTGGA-3’; and for CYP3A4 mRNA we used primers 5’-GAGAAGTGTCCTCCTGGAAGATTCGACG-3’ and 5’-TTCTCGAGGAGAATGTCCTAAGCT-3’. The relative amounts of ABCB1 and CYP3A4 mRNA in each treatment sample were compared with the amount of 18S mRNA which was amplified using primers 5’-CCCCCTCGAT-GCTCTTATGCTGATTG-3’ and 5’-CGCCGGTCCAAGAATTTCACCT-3’. The presence of TR isoforms α1, α2, and β1 mRNA in LS180V and Caco-2 cells was determined using the published primers (d’Amati et al., 2001).

Immunoblot Analysis of P-gp. Western blot procedures were performed as described previously (Cotreau et al., 2000; Perloff et al., 2001).

Enhancer Sequence Analysis. We used the Transcription Element Search System (TESS; URL: http://www.cbil.upenn.edu/tess) to analyze the sequences (−10,000 base pairs to +100 base pairs) of ABCB1 and CYP3A4 (GenBank accession numbers X58723 and AF185589, respectively) genes.

Statistical Analysis. We used the one-tailed paired t test to assess the increase in mRNA levels after treatment of cells with L-T4 versus treatment with dimethyl sulfoxide vehicle.

Results and Discussion

LS180V cells were induced for 72 h with two different concentrations of L-T4: 100 nM, which approximates the physiologic plasma levels of total L-T4 in normal individuals, and 100 μM, which approximates the intraluminal concentration in patients receiving oral levothyroxine. Rifampin (10 μM) was used as the known PXR-mediated inducer (Pfrunder et al., 2003) of both ABCB1 and CYP3A4. The LS180V cell line has been shown in our laboratory to have abundant PXR, while lacking constitutive androstanse receptor (unpublished data). Stability of L-T4 in the culture medium over this period was verified by HPLC analysis.

In LS180V cells, ABCB1 was induced in a concentration-dependent manner by L-T4 (p < 0.05), with EC50 determined at 3.6 μM, and by rifampin (Fig. 1A). Levels of CYP3A4 mRNA were undetectable in all conditions except in rifampin-induced cells. Default values for these conditions were assigned by the real-time PCR software, and rifampin-treated samples were compared. Consequently, the magnitude of the actual mRNA increase with rifampin is at least as great as reported, but may be higher. L-T4 did not produce a detectable increase in CYP3A4 mRNA.

The mechanism of ABCB1 induction by L-T4 was evaluated using the Caco-2 cell line, which lacks significant amounts of PXR (Thummel et al., 2001; T. Mitin, L. L. von Moltke, M. H. Court, and D. J. Greenblatt, unpublished data) and therefore should not demonstrate induction of PXR-regulated genes. Rifampin failed to increase levels of ABCB1 mRNA or protein, but L-T4 significantly increased ABCB1 expression in a concentration-dependent manner (p < 0.05) (Fig. 1, B and C).

These results suggest that L-T4 differs from rifampin in its ability to induce P-gp and regulates the expression of P-gp by a PXR-independent mechanism, perhaps through the TR. Both cell lines express the three major types of TR (TRα1, TRα2, and TRβ1) (Fig. 2), and L-T4 may therefore regulate P-gp expression by a mechanism involving binding to its endogenous receptor. TRα accounts for most of the thyroid hormone secreted by the thyroid gland. TRα is converted to TRβ by target tissues, and TRβ directly interacts with TR. TRβ also induced ABCB1 expression in LS180V cells in a concentration-dependent manner, with no effect on CYP3A4 expression (data not shown). Our data were generated in human carcinoma cell lines, and any extrapolation to normal cells must be made with great caution.

Our findings may relate to the effect of 1α,25-dihydroxyvitamin D3 (Vit D3) on CYP3A4 and ABCB1 induction. The regulation of intestinal CYP3A4 expression by VDR and Vit D3 was first suggested by observations that treatment of Caco-2 cells with vitamin D analogs led to significant enhancement of CYP3A4 mRNA and protein levels and increased midazolam hydroxylation activity (Schmiedlin-Ren et al., 1997). These findings were confirmed later in LS180 cells, and ABCB1 up-regulation by Vit D3 occurred in the same study (Thummel et al., 2001), as well as in subsequent studies (Pfrunder et al., 2003).

Although ABCB1 gene expression can be up-regulated by L-T4, L-T3, and Vit D3, CYP3A4 can only be up-regulated by Vit D3. The ABCB1 upstream enhancer contains a perfect DR4 and an overlapping DR3 with only one nucleotide substitution at the fifth position (C → A) (Fig. 3). The presence of both motifs could allow binding of
TR/RXR as well as VDR/RXR to the enhancer site. The CYP3A4 enhancer region also contains a perfect DR3 and a DR4 with two nucleotide substitutions at position five (C→T), as well as at a critical position three (G/T→A). The nucleotide at the third position may be critical for transactivation of DNA by hormonal receptors (Yen, 2001). The absence of effect by L-T₄ or L-T₃ on CYP3A4 induction therefore might be the result of this nonfunctional DR4, which lacks a specific hexamer recognizable by TR/RXR. L-T₄ and L-T₃ might also lead to mRNA stabilization, resulting in the observed increase in mRNA and protein levels.

To our knowledge, this is the first report of L-T₄- and L-T₃-mediated ABCB1 gene expression up-regulation in vitro. A recent clinical study demonstrated an increase in duodenal P-gp in human volunteers after administration of L-T₄ (Siegmund et al., 2002), but with no significant pharmacokinetic changes for the P-gp substrate talinolol in individu-
als with P-gp increases. Since this study included only healthy individuals under the age of 30, the potential functional relevance of P-gp induction by thyroxine remains unclear. In clinical reports, higher doses of digitalis (a prototypic P-gp substrate) were necessary to control the heart rate of patients with hyperthyroidism and atrial fibrillation (Frye and Braunwald, 1961), and this phenomenon was attributed in part to the lower plasma concentration of digoxin in hyperthyroid patients (O’Connor and Feely, 1987).

In addition, L-T4 is widely prescribed, with prescriptions for Synthroid (one commercial formulation of L-T4) alone ranking as number four among all drugs for 2002 (http://www.rxlist.com/top200.htm). Reports indicate that 6.9% of a sample U.S. population over 58 years of age are treated with L-T4 (Sawin et al., 1989). These conditions.


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