Involvement of vitamin D receptor in the intestinal induction of human \textit{ABCB1}

Shuko Tachibana, Kouichi Yoshinari, Tsubasa Chikada, Takayoshi Toriyabe, Kiyoshi Nagata, and Yasushi Yamazoe

Division of Drug Metabolism and Molecular Toxicology, Graduate School of Pharmaceutical Sciences, Tohoku University (S. T., K. Y., T. C., T. T., K. N., Y. Y.)

Drug Metabolism & Pharmacokinetics Research Laboratories, Daiichi-Sankyo Co., Ltd. (S.T.)

Current address: Tohoku Pharmaceutical University, 4-4-1 Komatsushima, Aoba-ku, Sendai, Miyagi 981-8558 Japan (K. N.)
Running title page

Running title: Intestine-selective role of VDR in human ABCB1 induction

Corresponding author: Yasushi Yamazoe
Division of Drug Metabolism and Molecular Toxicology, Graduate School of Pharmaceutical Sciences, Tohoku University
6-3 Aramaki-Aoba, Aoba-ku, Sendai, Miyagi 980-8578 Japan
TEL: +81-22-795-6827, FAX: +81-22-795-6826, E-mail: yamazoe@mail.tains.tohoku.ac.jp

The number of text pages: 34
The number of tables: 0
The number of figures: 7
The number of references: 39
The number of words in Abstract: 248
The number of words in Introduction: 648
The number of words in Discussion: 1313

List of nonstandard abbreviations:
PXR pregnane X receptor, RXR; retinoid X receptor, CAR constitutive androstane receptor, DR4; direct repeat separated by 4 bases, VDR; vitamin D receptor, 1,25-VD3; 1α,25-dihydroxyvitamin D3, LCA; lithocholic acid, VDRE; vitamin D receptor responsive element, ER6; everted repeat separated by 6 bases, DR3; direct repeat separated by 3 bases, DMSO; dimethyl sulfoxide, GAPDH; glyceraldehyde-3-phosphate dehydrogenase, TK; thymidine kinase, SEAP; secreted alkaline phosphatase, siRNA; small interfering RNA, NURREM; nuclear receptor responsive module.
Abstract

ABCB1 (P-glycoprotein) is an efflux transporter that limits the cellular uptake levels of various drugs in intestine, brain and other tissues. The expression of human ABCB1 has recently been reported to be under control of nuclear receptor NR1I subfamily members, pregnane X receptor (PXR; NR1I2) and constitutive androstane receptor (CAR; NR1I3). Here we have investigated the involvement of another NR1I member, vitamin D receptor (VDR; NR1I1), in the ABCB1 expression. In human colorectal adenocarcinoma cell line LS174T, which abundantly expresses VDR, both 1α,25-dihydroxyvitamin D₃ (1,25-VD3) and lithocholic acid (LCA) increased ABCB1 mRNA levels. Reporter gene assays in LS174T cells with constructs containing various length of the ABCB1 regulatory region revealed that the region containing multiple nuclear receptor binding motifs located at -7.8 kb (termed NURREM), to which PXR and CAR also bind, is essential for the VDR-mediated ABCB1 transactivation. Further reporter assays with constructs containing truncated NURREM and gel shift assays suggested simultaneous binding of multiple VDR/retinoid X receptor α heterodimers to NURREM. Furthermore, knockdown of VDR expression in LS174T cells blocked the LCA- as well as 1,25-VD3-induced transcription of ABCB1 reporter genes. In human hepatoma HepG2 cells, in contrast to LS174T cells, 1,25-VD3 activated the ABCB1 transcription only in the presence of ectopically expressed VDR. These results suggest that the NR1I subfamily members regulate the ABCB1 expression sharing the binding sites within NURREM and that the physiologically produced LCA and 1,25-VD3 may modulate the ABCB1 expression in human intestines, possibly associated with interindividual variations of ABCB1 expression.
Introduction

ABCB1 (P-glycoprotein) plays an important physiological role as an efflux transporter. It is highly expressed in the epithelial cells of gastrointestinal tract and renal tubules, the canalicular membrane of hepatocytes, the capillary endothelial cells of the brain, testes, and ovaries. In these tissues, ABCB1 functions as a biological barrier to the systemic exposure of chemical substances by effluxing a broad range of hydrophobic compounds from the intracellular to the extracellular compartment (Fromm, 2004). In the intestine, ABCB1 limits the oral bioavailability of drugs and mediates excretion of the drugs into the intestinal lumen (Hsing et al., 1992; Leu and Huang, 1995; Sparreboom et al., 1997). Intestinal level of ABCB1 expression shows wide inter-individual variability, which may contribute to the variation in pharmacokinetics of drugs (Lown et al., 1997; Lindell et al., 2003; Urquhart et al., 2007). However, the mechanism underlying the interindividual variations in the basal expression level of ABCB1 remains unclear.

In addition, some drugs and steroid hormones increase intestinal ABCB1 levels, which may result in drug-drug interactions (Schuetz et al., 1996; Kim and Benet, 2004). For example, oral bioavailability of β-blocker talinolol, which is a substrate for ABCB1 but not oxidized in humans, was decreased after co-administration of rifampicin or St John’s wort (Westphal et al., 2000; Schwarz et al., 2007). This induction of ABCB1 in the intestine resulted mainly from the activation of human ABCB1 gene expression. The rifampicin-mediated activation of the ABCB1 expression has been shown to be through the nuclear receptor, pregnane X receptor (PXR; NR1I2). PXR binds as a heterodimer with
retinoid X receptor α (RXRα; NR2B1) to the PXR-responsive element located at -7.8 kb upstream regions of ABCB1 (Geick et al., 2001). Recently, constitutive androstane receptor (CAR; NR1I3) has also been shown to bind the same motif, the direct repeat 4 (DR4) element of ABCB1 (Burk et al., 2005).

PXR and CAR also regulate the gene expression of drug metabolizing enzymes such as CYP3A4 (Lehmann et al., 1998; Goodwin et al., 2002). CYP3A4 and ABCB1 show similar profiles of tissue distribution and substrate specificity, and are often co-induced by PXR ligands. They are thus considered to cooperate the defense against the potentially harmful chemical substances (Zhang and Benet, 2001). In addition to PXR and CAR, the CYP3A4 expression is also enhanced by vitamin D receptor (VDR; NR1I1), which belongs to the same nuclear receptor NR1I subfamily as PXR and CAR (Thummel et al., 2001). VDR, forming a heterodimer with RXR, is activated by 1α,25-dihydroxyvitamin D3 (1,25-VD3) and a secondary bile acid lithocholic acid (LCA), and enhances the transcription of target genes through binding to VDR responsive elements (VDREs) in their promoter sequences. In CYP3A4, the proximal everted repeat separated by 6 bases (ER6) and distal direct repeat separated by 3 bases (DR3) motifs bind to VDR as well as PXR and CAR (Drocourt et al., 2002; Thompson et al., 2002). These facts raise the possibility that VDR is also involved in the expression of ABCB1. In fact, the mRNA level of ABCB1 was increased by treatment with 1,25-VD3 in human colorectal adenocarcinoma Caco-2 and LS180 cell lines (Schmiedlin-Ren et al., 1997; Thummel et al., 2001). However, little is known about the VDR regulation of the ABCB1 expression.
In the present study, we have tested our hypothesis of the VDR-mediated \textit{ABCB1} expression.

To this end, we have investigated the molecular mechanism of the transcriptional activation of human \textit{ABCB1} in response to 1,25-VD3 and LCA, known VDR ligands (Makishima et al., 2002; Jurutka et al., 2005; McCarthy et al., 2005), using reporter gene assays in human colon carcinoma LS174T cells and gel shift assays. Our results show that multiple VDR/RXR\textsubscript{\alpha} heterodimers simultaneously bind to the several VDR-responsive motifs within the regulatory cluster region located in the 5'-upstream of the \textit{ABCB1} gene, which is identical with that for PXR and CAR, suggesting the complex regulation of the human \textit{ABCB1} expression via NR1I subfamily members.
Materials and Methods

Materials

Rifampicin, LCA, and 1,25-VD3 were purchased from Sigma-Aldrich (St Louis, MO). Dimethyl sulfoxide (DMSO) was obtained from Wako Pure Chemical Industries, Ltd. (Osaka, Japan). Restriction endonucleases and DNA-modifying enzymes were obtained from Takara Bio (Ohtsu, Japan). Oligonucleotides were prepared by Nisshinbo Industries (Tokyo, Japan) and Fasmac Co., Ltd. (Atsugi, Japan). pSV-β-galactosidase was from Promega (Madison, WI).

Cell culture

LS174T cells were obtained from Institute of Development, Aging and Cancer, Tohoku University (Sendai, Japan) and cultured in Minimum Essential Medium containing 10% fetal bovine serum (Sigma-Aldrich or BioWest, Nuaillé, France), minimal essential medium nonessential amino acid (Invitrogen, Carlsbad, CA), and penicillin-streptomycin (Invitrogen). HepG2 cells were obtained from Riken Bioresource Center and cultured in Dulbecco’s modified Eagle’s medium containing 10% fetal bovine serum, minimal essential medium nonessential amino acid, and penicillin-streptomycin.

RNA isolation and Quantitative Real-time PCR analysis

Total RNA was extracted from LS174T and HepG2 cells using acid guanidine thiocyanate-phenol-chloroform method. Reverse transcription reactions were performed using
Ready-To-Go Your-Prime First-Strand Beads (GE Healthcare, Little Chalfont, UK) with oligo(dT) primer.

Quantitative real-time PCR was performed with TaqMan® Universal PCR Master Mix using ABI PRISM 7000 (Applied Biosystems, Foster City, CA). All samples were quantified using the comparative Ct method for relative quantification of gene expression, normalized to glyceraldehyde-3-phosphate dehydrogenase (GAPDH). The following primers and probe sets were used in this study: Human

\[
\begin{align*}
\text{ABCB1} & \quad (5'-\text{CTCAGACAGGATGTAGTTGTTTT-}3', \ 5'-'\text{ATTACAGCAAGCCTGGAACCTATAG-3'} \text{ and} \\
& \quad 5'-'\text{FAM-CACCACTGGAGCATTGACTACCAGGCTC-3'}); \\
\text{GAPDH} & \quad (5'-\text{AACAGCCTCAAGATCATCAGCAA-3'}, \ 5'-'\text{GACTGTGGTCATGAGTCCTTCCA-3'} \text{ and} \\
& \quad 5'-'\text{VIC-CCAAGGTCATCCATGACAACCTTTGGTATCG-3'}).
\end{align*}
\]

**Construction of plasmid DNA**

The human \textit{ABCB1} 5'-flanking fragment including bases from -14556 to +125 was amplified by PCR with human genomic DNA as a template and oligonucleotides,

5'-\text{cgacgcgtCTCAAGATAGCCTACATCCTGCAGG-3'} containing an MluI site and

5'-\text{gcgtcgaCGCTCCTTGGAACGGCCACCAAGACG-3'} containing an SalI site, using \textit{TAKARA LA Taq} (Takara Bio). The PCR fragment was subcloned into pCR-XL-TOPO (Invitrogen). The 15-kb DNA fragment obtained by digesting the plasmid with MluI and SalI was inserted into the pSEAP2-basic vector (Clontech, Mountain View, CA) at MluI and Xhol sites to obtain a reporter gene plasmid (p-14566). Constructs p-8935, p-7472, and p-4179 were prepared by digesting p-14556 with Ball or
SpeI and ligating themselves.

pSEAP2-TK plasmid was constructed by inserting the thymidine kinase (TK) promoter (Sueyoshi et al., 1999) between BgIII and HindIII sites of pSEAP2-basic plasmid. To construct p-7880/7810-TK plasmid, oligonucleotides,

5’-ACGTTACCTCATTGAACTAACTTGACCTTGCTCCTGGGAGAGAGTTCATTTGAGATTAAACAAGTTCAAAG-3’ and 5’-

CTTTGAACCTTGTATCTCAAATGGAACCTCTCTCCAGGAGCAAGGCTAAATGAGGTAACGTG-3’ were annealed and the double-strand oligonucleotide was ligated into the MluI and Xhol sites of pSEAP2-TK. For the construction of p-7880/7847-TK and p-7846/7810-TK, the oligonucleotides pairs, 5’- GTACCACGTTACCTCATTGAACTAACTTGACCTTGCTCCA-3’/5’-

GATCTGGGAGCAAGGTTAGTTCAATGAGGTAACGTG-3’ and 5’-

GTACCTGGGAGAGTTCATTGAGATTAACAAAGTGTTCAAGAGTA-3’/5’-

GATCTCTTGACTTGTTAATCTCAAATGGAACCTCTCTCCAG-3’, were annealed, respectively, and the double-strand oligonucleotides were ligated into the MluI and Xhol sites of pSEAP2-TK. The sequences of these constructs were confirmed by direct sequencing.

To construct human VDR mammalian expression plasmid (pT-hVDR), human VDR cDNA was amplified by PCR with primers, 5’- AGGGATGGAGGCAATGGCGGCCAG-3’ and 5’-

TAGTCAAGAGATCTCATTGCCAAC-3’, and cDNA from HEK293 cells (Riken Bioresource Center, Tsukuba, Japan) as the template using KOD-FX (Toyobo, Osaka, Japan), and ligated into pTarget
plasmid (Promega). The cDNA fragment obtained by digesting pT-hVDR with NcoI and MluI was
inserted into pTNT plasmid (Promega) to obtain pTNT-hVDR for in vitro transcription/translation.

pTNT-hRXRα for in vitro transcription/translation of human RXRα was constructed previously (Toriyabe et al., 2009).

**Transient transfection and secreted alkaline phosphatase (SEAP) assay**

One day before transfection, cells were seeded in 12-well or 24-well plates. Reporter plasmid and
pSV-β-galactosidase were transfected using Cellphtect Transfection kit (GE Healthcare) according to
the manufacturer’s protocol. pSV-β-galactosidase was used for the normalization of transfection
efficiency. For human VDR expression experiments, pT-hVDR or pTarget (as a control) was also
transfected. Six to twelve hours after transfection, the cells were washed with phosphate-buffered
saline and then treated with compounds or vehicle (0.1%(v/v) DMSO) for 48 h. Then, an aliquot of the
medium was collected and used for the determination of SEAP activity with Great EscAPe™ SEAP
Assay System (Clontech) or SEAP Reporter Gene Assay, chemiluminescent (Roche Applied Science,
Mannheim, Germany) according to the manufacturers’ protocols. The cells were harvested with
Reporter Lysis Buffer (Promega) and β-galactosidase activity was measured using β-galactosidase
Enzyme Assay System (Promega) or as described previously (Toriyabe et al., 2009). The reporter gene
(SEAP) activity was normalized to the corresponding β-galactosidase activity and the results are
expressed as normalized values. Fold induction (ratio of activities in compound-treated cells to those in
vehicle-treated cells) was calculated with the normalized values.

RNA interference

Two different small interfering RNA (siRNA) duplexes to target human VDR were purchased from Invitrogen. Their sequences were 5'-UUUGGAUGCUGUAACUGACCAGGUC-3'

(VDR-HSS111273; hVDR-siRNA-1) and 5'-UAGCAUUGAACUGAAAGCCAGUGGC-3'

(VDR-HSS111272; hVDR-siRNA-2). Slicer® negative control siRNA (Applied Biosystems) was used as a control siRNA. LS174T cells were seeded in 24-well plate (1x10^5 cells/well) and transfected with 15 pmol of each siRNA using siPORT™ Neo FX™ Transfection Agent (Applied Biosystems) according to the manufacturer’s protocol. Two days after seeding and transfection, the cells were transfected with p-8935 (0.5 μg) and pSV-β-galactosidase (1 μg) as described above. Twelve hours later, the cells were washed with phosphate-buffered saline and treated with vehicle (0.1% DMSO), 100 nM 1,25-VD3, 10 μM LCA, or 10 μM rifampicin for 24 h. Reporter activities were determined as described above.

Gel shift assay

Human VDR and RXRα were synthesized in vitro from pTNT-hVDR and pTNT-hRXRα, respectively, using the TNT SP6 Coupled Reticulocyte Lysate Systems (Promega) following the manufacturer’s protocol. Double-strand oligonucleotide probes (shown in Fig. 4A) were labeled with [γ-32P]ATP (PerkinElmer, Waltham, MA) using T4 polynucleotide kinase and purified by NICK columns.
The binding reaction was carried out with a reaction mixture (15 μl) containing 10 mM Tris-HCl (pH 8.0), 5% glycerol, 100 mM KCl, 1 mM dithiothreitol, 1 μg of poly(dI-dC) (GE Healthcare), and 0.5 μl each of synthesized VDR- and/or RXRα-containing lysate, or control lysate. Reaction mixtures were preincubated on ice for 1 hr before the addition of 32P-labeled probe (105 fmol). The samples were kept on ice for additional 30 min and then separated on 4% polyacrylamide gel in 0.25 x Tris-boric acid-EDTA buffer at 20 mA. The gel was dried and exposed to an imaging plate to detect DNA-protein complexes with Imaging Analyzer FLA-3000 (Fuji Film, Tokyo, Japan). In some reactions, 2 μg of anti-human VDR polyclonal IgG (H-81X, Santa Cruz Biotechnology, Santa Cruz, CA) was added to the reaction mixture before preincubation.
RESULTS

Effect of 1,25-VD3 and LCA treatment on ABCB1 mRNA level in LS174T cells

To investigate the effect of VDR ligands on the expression of human ABCB1, the ABCB1 mRNA levels in LS174T cells were determined after treatment with 1,25-VD3 or LCA (Fig. 1). The levels of ABCB1 mRNA were increased 22-fold and 2.5-fold in the presence of 250 nM of 1,25-VD3 and 10 μM LCA, respectively. Rifampicin, a human PXR ligand, also increased the mRNA levels (2.9-fold) as expected. In contrast, 1,25-VD3 and LCA as well as rifampicin had no effect on the ABCB1 mRNA levels in HepG2 cells (Fig. 1).

Transcriptional activation of ABCB1 reporter genes by 1,25-VD3 and LCA

To analyze the molecular mechanism of the ABCB1 transcriptional activation by 1,25-VD3 or LCA, we constructed a reporter gene plasmid containing approximately 15 kb of the upstream region of ABCB1 (p-14556), which included the previously reported regulatory cluster region located at -7.8 kb. The reporter plasmid was transiently transfected into LS174T cells and SEAP activity was determined after 48-h treatment with 100 nM 1,25-VD3, 10 μM LCA or vehicle. As shown in Fig. 2A, treatment with either VDR ligand increased the reporter activity. Rifampicin treatment also enhanced the reporter activity of p-14556 as expected (Fig. 2B). These ligands, however, had no effect on the SEAP activity of pSEAP2-basic vector (data not shown). The results indicated that VDR responsive region was located within the 15 kb upstream of the human ABCB1 gene.
To identify the region responsible for the VDR-mediated transcriptional activation of human ABCB1, a series of deletion constructs were prepared and transfected into LS174T cells. A deletion construct containing about 9 kb of the ABCB1 promoter (p-8935) also responded to 1,25-VD3 and LCA, whereas shorter constructs lacking the regulatory cluster region at -7.8 kb (p-7472 and p-4179) were no longer transactivated by the VDR ligands (Fig. 2A). As expected, rifampicin response was observed only with the constructs containing the regulatory cluster region (p-7472 and p-4179; Fig. 2B). These results suggest that the regulatory cluster region at around -7.8 kb is necessary for the VDR ligand-induced ABCB1 transcription as an enhancer element.

Geick et al. (Geick et al., 2001) found that the regulatory cluster at -7.8 kb contains several potential nuclear receptor-responsive elements, including DR3, DR4(I), DR4(II), DR4(III), and ER6 between -7880 and -7810. This 71-bp sequence was essential for the PXR- and CAR-mediated expression of ABCB1 (Geick et al., 2001; Burk et al., 2005). To investigate a possible role of this region in the VDR-mediated transactivation, we constructed a reporter gene containing the 71-bp sequence fused to the thymidine kinase promoter (p-7880/7810-TK). As shown in Fig. 3A, this construct, but not the construct without the 71-bp sequence (pSEAP2-TK), was transactivated by treatment with either 1,25-VD3 or LCA in LS174T cells. Rifampicin response was also observed with p-7880/7810-TK (Fig. 3B). These results suggested that the 71-bp sequence is sufficient for the transcriptional activation of ABCB1 via VDR as well as other NR1I subfamily members, PXR and CAR. The 71-bp sequence was thus termed NURREM (nuclear receptor responsive module).
Multiple VDR/RXRα heterodimers bind to NURREM

NURREM comprises several candidates of VDRE such as DR3, DR4(I), DR4(II), DR4(III), and ER6 (Fig. 4A). In order to identify a principal VDRE involved in the VDR-dependent transcription of ABCB1, we performed electrophoretic mobility shift assays with in vitro transcribed/translated human VDR and human RXRα proteins, and 32P-labeled double-strand oligonucleotide probes (Fig. 4A). As shown in Fig. 4B, a heterodimer of VDR/RXRα bound to the DR3, DR4(I), and ER6 motifs, and weakly to DR4(II). The interaction of VDR/RXRα with DR4(I) was strongest among the probes tested. In addition, VDR monomer, but not RXRα monomer, bound to DR4(II), although the complex was barely detected in the presence of both VDR and RXRα (Fig. 4B and data not shown). Bands indicated with asterisk in Fig. 4B were nonspecific because they were also observed with control lysate that contained neither VDR nor RXRα (data not shown). As shown in Fig. 4C, at least 2 protein-DNA complexes with different electrophoretic mobility were detected when NURREM probe was incubated with in vitro synthesized VDR and RXRα. Preincubation of VDR and RXRα with anti-VDR antibody before addition of NURREM probe resulted in the formation of multiple supershifted complexes. Addition of normal IgG did not affect the bindings (data not shown). These results suggested simultaneous bindings of VDR/RXRα heterodimers to the several VDRE motifs with in NURREM.

To verify whether several putative VDREs contribute to the activation of the ABCB1 gene, two distinct half-deleted constructs of p-7880/7810-TK-SEAP were prepared; the 3’-half-deleted NURREM
construct (p-7880/7847-TK) lacking DR4(II), DR4(III), and ER6, and the 5'-half-deleted NURREM construct (p-7846-7810-TK) lacking DR3 and DR4(I). After transfection of these constructs into LS174T cells, the cells were treated with 1,25-VD3 for 48h. As shown in Fig. 5, the reporter activities of both constructs were decreased by 40-50% compared to that of intact p-7880/7810-TK, suggesting that not only DR4(I)/DR3 in the 5’-half of NURREM, but ER6/DR4(III) in the 3’-half of NURREM are also involved in the VDR-mediated transcriptional of human \( ABCB1 \).

**LCA-induced transcription of \( ABCB1 \) reporter genes through VDR**

We demonstrated that LCA and 1,25-VD3 transactivate \( ABCB1 \) through the common regulatory region NURREM. LCA is known to interact with multiple nuclear receptors including PXR and FXR as well as VDR. Thus, we have examined the role of VDR in the LCA-induced \( ABCB1 \) transcription using siRNA technique (Fig. 6). LS174T cells were transfected with two distinct siRNA for human VDR and then with the \( ABCB1 \) reporter gene p-8935. Treatment with LCA as well as 1,25-VD3 increased reporter activities in the cells transfected with control siRNA. On the other hand, the transfection of either human VDR-targeting siRNA completely abolished the response to LCA and drastically reduced the response to 1,25-VD3. In contrast, rifampicin responses were clearly observed even in the presence of the VDR-targeting siRNAs (Fig. 6). These results indicate that the LCA-induced transactivation of \( ABCB1 \) is mediated through VDR.
VDR-dependent transcription of ABCB1 reporter genes in HepG2 cells

The VDR-dependent regulation of the ABCB1 expression was observed in LS174T cells. As mentioned above, 1,25-VD3 and LCA, however, had no effect on the ABCB1 mRNA levels in HepG2 cells. To assess the mechanism underlying the difference in responses to VDR ligands between these cell lines, the influence of the ectopic expression of human VDR on the ABCB1 reporter activities was investigated in HepG2 cells. A reporter plasmid containing the 9-kb upstream region of ABCB1 fused to pSEAP2-basic vector (p-8935) was transfected into HepG2 cells, with either human VDR expression plasmid (pT-hVDR) or empty plasmid (pTarget). As shown in Fig. 7A, without co-transfection of pT-hVDR, the treatment with 1,25-VD3 had no significant effect on the reporter activity of p-8935. However, with co-transfection of pT-hVDR, the reporter activity was increased significantly in response to 1,25-VD3. Similar results were obtained with the p-7880/7810-TK (Fig. 7B): Treatment of HepG2 cells with 1,25-VD3 significantly increased the reporter activity in the presence, but not in the absence, of ectopic human VDR.
Discussion

In the present study, we have demonstrated that endogenous mRNA levels and ABCB1 reporter activities are inducible in human colon cancer LS174T cells in response to 1,25-VD3 and LCA (Figs. 1, and 2A). In addition, the 71-bp sequence termed NURREM located in the upstream region from -7880 to -7810 of the ABCB1 gene is essential for the transactivation mediated by VDR in addition to PXR and CAR (Figs. 2A, 2B, 3A, 3B, and 5). Thus, the NR1I subfamily member VDR as well as PXR and CAR enhances the gene expression of human ABCB1.

In contrast to the results obtained in LS174T cells, the ABCB1 transactivation was not observed in human hepatoma HepG2 cells (Fig. 7). Furthermore, we did not observe an increase of the ABCB1 mRNA level in response to 1,25-VD3 in cryopreserved human hepatocytes, in spite of the significant increase after rifampicin treatment (Tachibana et al., unpublished results). These are probably due to the low or little expression of VDR in HepG2 cells and human hepatocytes. In fact, VDR mRNA was barely detected in HepG2 cells, whereas it was detected at much higher level in LS174T cells (Matsubara et al., 2008). In addition, VDR protein was detected in human intestine at much higher levels (approximately 320 fmol/mg protein) than in the liver (Berger et al., 1988; Ebeling et al., 1992; Stumpf, 1995). Interestingly we found that co-transfection of VDR expression plasmid into HepG2 cells conferred the transactivation of the ABCB1 reporter genes on the cells (Fig. 7). These results suggest that the expression level of VDR is a major determinant for the induction of ABCB1 in response to 1,25-VD3 and LCA in these cell lines and probably in human tissues. Consistently, previous studies
demonstrated increased \textit{ABCB1} mRNA levels after treatment with 1,25-VD3 in Caco-2 and LS180 cell lines, in which VDR is abundantly expressed (Thummel et al., 2001).

VDR, in addition to other nuclear receptors including PXR, CAR and FXR, has been recognized as a key regulator of bile acid homeostasis in the intestine. LCA, a secondary bile acid, is thought to activate the expression of VDR target genes in the gastrointestinal tract to protect intestinal cells from bile acid toxicity (Makishima et al., 2002). McCarthy et al. (2005) have suggested that the physiologically relevant site for the VDR-dependent regulation of \textit{Mrp3} expression is the gastrointestinal tract. In this study, we showed that the LCA-mediated activation of \textit{ABCB1} reporter gene was completely blocked with siRNA for human VDR in LS174T cells (Fig. 6), which express both PXR and VDR (Matsubara et al., 2008). Recently, we have also reported that LCA enhances the \textit{CYP3A4} expression in the intestine but not in the liver, which is mediated by VDR rather than PXR and FXR (Matsubara et al., 2008). Thus, VDR probably plays a critical role in response to LCA for the intestinal expression of human \textit{ABCB1} as well as \textit{CYP3A4}.

Similar to \textit{CYP3A4}, the intestinal levels of \textit{ABCB1} expression show large inter-individual variability (Lown et al., 1997; Lindell et al., 2003; Urquhart et al., 2007). Although genetic factors are thought to influence, in part, the expression level (Leschziner et al., 2007), the mechanism underlying the variation is still not fully understood. Based on our results, LCA and 1,25-VD3 could modulate \textit{ABCB1} expression levels in the intestine. As reported in the literatures, LCA levels in intestines could reach high enough to activate VDR (Batta et al., 1999). One of most important physiological roles of
1,25-VD3 is to stimulate the absorption of dietary calcium and phosphate in the intestine. Although the formation of 1,25-VD3 from 25-hydroxyvitamin D mainly occurs in the kidney, CYP27B1, which catalyzes the 1α-hydroxylation of 25-hydroxyvitamin D to form 1,25-VD3, is expressed at various extra-renal sites including the colonic epithelial cells (Zehnder et al., 2001). In these tissues, 1,25-VD3 is considered to act as a VDR autocrine signal. Therefore, 1,25-VD3 produced locally in the intestine might affect the VDR-mediated gene expression. These facts support the idea that at least in part LCA and 1,25-VD3 are possible factors causing the variable expression of ABCB1 in the intestine.

Induction of the intestinal ABCB1 may lead to drug-drug interactions, usually resulting in the reduced absorption of drugs and their AUC. Our results implicate in addition to PXR ligands that VDR ligands could cause such drug-drug interactions involving ABCB1. Recently, 1,25-VD3 and its synthetic analogs have been indicated for their potential applications to the treatment of osteoporosis, inflammation, dermatological indications, cancers and autoimmune diseases through activation of VDR (Takahashi and Morikawa, 2006). Thus, these drugs have potential risks of drug-drug interactions caused by the ABCB1 induction in the intestine.

Several putative VDREs exist within NURREM, overlapping with the PXR- and CAR-responsive elements (Geick et al., 2001; Burk et al., 2005). Among these VDREs, DR4(I) was reported to be a high affinity element for PXR/RXRα heterodimers. As for the CAR-mediated transactivation of human ABCB1, DR4(I) and DR4(II) were important for the receptor binding as a heterodimer with RXRα or as a monomer, respectively (Geick et al., 2001; Burk et al., 2005). In the
present study, VDR monomer also bound to DR4(II) as CAR monomer (Fig. 4B). However, its physiological relevance is unclear because the binding was not observed in the presence of both VDR and RXRα (Fig. 4B). We also found the high affinity binding of VDR/RXRα to DR4(I) (Fig. 4B), suggesting that DR4(I) mainly contributes to the VDR-mediated ABCB1 transactivation. Our findings, however, show that in addition to DR4(I), DR3 and ER6 elements significantly contribute to the bindings of VDR/RXRα to NURREM (Fig. 4B), which is in contrast to the binding preference for DR4 by PXR and CAR as heterodimers with RXRα. Although the well-known VDREs are DR3 or DR4 (Haussler et al., 1998; Quack and Carlberg, 2000), ER6 is also functional in the promoter region of CYP3A4 (Drocourt et al., 2002). In the present study, gel shift assays demonstrated that multiple VDR/RXRα heterodimers could simultaneously bind to NURREM (Fig. 4C). Consistently, neither 5’- nor 3’-half deletion of NURREM could completely abolish the reporter activity (Fig. 5). Such a VDR-mediated regulation via multiple VDREs has been also described in other VDR target genes, such as rat CYP24 (Chen and DeLuca, 1995), human cyclin C (Sinkkonen et al., 2005), and CYP3A4 (Drocourt et al., 2002; Thompson et al., 2002). The significance of the multiple functional VDREs within a single gene is still unknown. The functional cooperation between other transcription factors and VDR/RXR heterodimers in one of two VDREs within rat CYP24 was demonstrated (Dwivedi et al., 2000). Whether other transcription factor(s) could stabilize a VDR/RXR heterodimer on each VDRE is an interesting issue for future studies. Nevertheless, our present results clearly indicate that each VDRE within NURREM of ABCB1 can serve as a specific binding site of a VDR/RXRα heterodimer, and that the multiple VDREs
may act synergistically.

During the preparation of this manuscript, Saeki et al., (Saeki et al., 2008) have demonstrated the activation of human \(ABCB1\) expression by 1,25-VD3 via VDR in Caco-2 cells. They have also reported that multiple VDR/RXR heterodimers bind to several VDREs within NURREM with DR4(I) showing the highest affinity. These are consistent with our present results. In addition to these results, we first demonstrate in this manuscript that LCA, an activator of multiple nuclear receptors, enhances the \(ABCB1\) expression through VDR in human colon cells (Figs 1, 2A, 3A, and 6).

In conclusion, we have demonstrated the VDR-dependent regulation of human \(ABCB1\) expression through the previously reported cluster of nuclear receptor binding motifs (termed NURREM in this study). Thus, the nuclear receptors in NR1I subfamily, namely VDR, PXR, and CAR, have overlapping functions in the detoxification and excretion of xenobiotics through regulating the expression of both \(ABCB1\) and \(CYP3A4\). Because the \(ABCB1\) expression was enhanced by LCA in addition to 1,25-VD3, our present results also imply novel mechanisms that may explain the interindividual variability of \(ABCB1\) levels in the human intestine.
Acknowledgements

We thank Masakiyo Ohya for his technical assistance.
References


Footnote

This work was presented in part at the 8th ISSX International meeting, Oct 9–12, 2007, Sendai, Japan. This work was supported, in part, by Grant-in-Aid from Ministry of Education, Culture, Sports, Sciences and Technology of Japan, Ministry of Health, Labor, and Welfare of Japan and Comprehensive Research and Education Center for Planning of Drug Development and Clinical Education, Tohoku University 21st Century “Center of Excellence” Program.
Legends for Figures

**Figure 1. Effects of 1,25-VD3, LCA, and rifampicin on ABCB1 mRNA levels in LS174T cells.**

LS174T and HepG2 cells were exposed to 250 nM 1,25-VD3, 10 μM LCA, 10 μM rifampicin, or vehicle (0.1% DMSO) for 48 h. Then total RNA was extracted from the cells and ABCB1 mRNA levels were quantified by quantitative reverse transcription PCR as described under Materials and Methods. The ABCB1 mRNA levels were normalized with those of GAPDH. Data are expressed as fold increase over vehicle-treated cells.

**Figure 2. Identification of VDR-responsive region in human ABCB1.**

Schematic structures of reporter gene constructs are shown on the left. The closed boxes represent the regulatory cluster region previously reported (Geick et al., 2001), which is termed NURREM in this study. LS174T cells (2 x 10^5 cell/well in 12-well plate) were transfected with each reporter plasmid (1 μg) with pSV-β-galactosidase (1 μg). Six hours after transfection, the cells were treated with vehicle (0.1% DMSO), 100 nM 1,25-VD3, or 10 μM LCA in A, or vehicle (0.1% DMSO), 100 nM 1,25-VD3, or 10 μM rifampicin in B for 48 h, and SEAP and β-galactosidase activities were determined as described under Materials and Methods. Values of SEAP activities were normalized with β-galactosidase activities. Data are expressed as fold activation over vehicle-treated cells for each construct. Data are the mean ± SD (n = 4).
Figure 3. Functional evaluation of NURREM as a VDR responsive region.

A. LS174T cells (2 x 10^5 cell/well in 12-well plate) were transfected with each reporter plasmid (2 μg) with pSV-β-galactosidase (1 μg). Twelve hours after transfection, the cells were treated with vehicle (0.1% DMSO), 10 μM LCA, or 100 nM 1,25-VD3 for 48 h. B. LS174T cells (1 x 10^5 cell/well in 24-well plate) were transfected with each reporter plasmid (0.5 μg) with pSV-β-galactosidase (1 μg). Twelve hours after transfection, the cells were treated with vehicle (0.1% DMSO), 100 nM 1,25-VD3, or 10 μM rifampicin for 48 h. Reporter activities were determined as described under Materials and Methods. Values of SEAP activities were normalized with β-galactosidase activities. Data are expressed as fold activation over vehicle-treated cells for each construct. Data are the mean ± SD (n = 4).

Figure 4. In vitro binding of VDR and RXRα heterodimer to NURREM.

A. The sequences and positions of probes used are shown as double-headed arrows. B and C. Gel shift assays were performed as described under Materials and Methods with radiolabeled probes shown in A and in vitro synthesized human VDR and/or human RXRα. The complex of VDR/RXRα/probe (shifted complex), and the free probe are marked. An asterisk indicates nonspecific bindings. Polyclonal antibody against VDR was used for supershift assays in C.

Figure 5. Reporter assays with truncated NURREM-reporter gene constructs.

Schematic structures of reporter gene constructs are shown on the left. LS174T cells (1 x 10^5 cell/well
in 24-well plate) were transfected with each reporter plasmid (0.5 μg) and pSV-β-galactosidase (1 μg).

Twelve hours after transfection, the cells were treated with vehicle (0.1% DMSO) or 100 nM 1,25-VD3 for 48 h, and then reporter activities were determined. Values of SEAP activities were normalized with β-galactosidase activities. Data are expressed as fold activation over vehicle-treated cells for each construct. Data are the mean ± SD (n = 4).

**Figure 6. Influence of siRNA targeting VDR on the transcription of ABCB1 reporter gene.**

LS174T cells were transfected with 15 pmol of VDR-targeting siRNA or control siRNA when being seeded in 24-well plate (1x10^5 cells/well). Two days after seeding, the cells were transfected with p-8935 (0.5 μg) and pSV-β-galactosidase (1 μg). Twelve hours later, the cells were treated with vehicle (0.1% DMSO), 100 nM 1,25-VD3, 10 μM LCA, or 10 μM rifampicin for 24 h, and then SEAP and β-galactosidase activities were determined as described under Materials and Methods. Values of SEAP activities were normalized with β-galactosidase activities. Data are expressed as relative activities to those in the vehicle-treated cells transfected with control siRNA. Data are the mean ± SD (n = 4).

**Figure 7. Influences of ectopic expression human VDR in HepG2 cells on the activation of ABCB1 reporter genes.**

Schematic structures of reporter gene constructs are shown on the left. The closed box in the construct represents NURREM. LS174T cells (1 x 10^5 cell/well in 24-well plate) were transfected with each
reporter plasmid (0.5 μg) and pSV-β-galactosidase (1 μg) in the absence or presence of hVDR expression plasmid pT-hVDR (+; 0.25 μg, ++; 0.5 μg). Empty pTarget vector was used as the control for pT-hVDR. Twelve hours after transfection, the cells were treated with vehicle (0.1% DMSO) or 100 nM 1,25-VD3 for 48 h, and then reporter activities were determined as described under Materials and Methods. Values of SEAP activities were normalized with β-galactosidase activities. Data are expressed as relative activities to those in the vehicle-treated and pSEAP2-basic/pTarget-transfected (A) and vehicle-treated and pSEAP2-TK/pTarget-transfected (B) cells (the top bar in each figure). Numbers next to the closed bars represent the fold-activation of reporter activities over the corresponding vehicle-treated cells. Data are the mean ± SD (n = 4).
Fig. 1

Relative mRNA levels

**LS174T**

**HepG2**

- **Vehicle**
- **1,25-VD3**
- **LCA**
- **Rifampicin**

*Graph showing relative mRNA levels for LS174T and HepG2 cell lines under different conditions.*
Fig. 2A

Relative SEAP activity

-14566

-8935

-7472

-4179

Vehicle

1,25-VD3

LCA
Fig. 3

A

Relative SEAP activity

-7880  -7810

NURREM  TK  SEAP

TK  SEAP

Vehicle

1,25-VD3

LCA

B

Relative SEAP activity

-7880  -7810

NURREM  TK  SEAP

TK  SEAP

Vehicle

1,25-VD3

Rifampicin
Fig. 4A

5’-TGAACGTACCTCATTGAACTAACTTGGACCTTGCTCCTGGGAGAGAATTCTTTGGATTAACAAGTCAAGTCT-3’
3’-ACTTGCAATGGAGTAACTTGATTGAACTGGAACGAGGACCTCTCTCAAGTAAACTCTAATTTGGTTCAAAGTTTCAAGA-5’

DR3

DR4(I)

NURREM

DR4(II)

DR4(III)

ER6
<table>
<thead>
<tr>
<th>Probe:</th>
<th>DR3</th>
<th>DR4(I)</th>
<th>DR4(II)</th>
<th>DR4(III)</th>
<th>ER6</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDR:</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>RXRα:</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 4B

- VDR/RXRα/probe complex
- VDR/probe complex
- Free probe
Fig. 4C

<table>
<thead>
<tr>
<th>Probe</th>
<th>NURREM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RXRα</td>
<td>+ - + + +</td>
</tr>
<tr>
<td>VDR</td>
<td>- + + + +</td>
</tr>
<tr>
<td>anti-VDR</td>
<td>- - - + +</td>
</tr>
</tbody>
</table>

- Supershifted complex
- Shifted complex
- Free probe
Fig. 6

![Graph showing relative SEAP activity with categories: Vehicle, 1,25-VD3, LCA, Rifampicin.](image-url)