Repression of Phenobarbital-Dependent CYP2B1 mRNA Induction by Reactive Oxygen Species in Primary Rat Hepatocyte Cultures

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ABSTRACT

Xenobiotic-metabolizing cytochrome P-450 (P-450) enzymes not only play a pivotal role in elimination of foreign compounds but also contribute to generation of toxic intermediates, including reactive oxygen species, that may elicit cellular damage if produced excessively. Expression of several xenobiotic-metabolizing P-450 enzymes is induced by phenobarbital (PB). Pronounced induction is observed for the rat CYP2B1 isoform. A primary rat hepatocyte culture system was used to investigate whether reactive oxygen species might modulate PB-dependent CYP2B1 induction. In cells cultivated for 3 days with 1.5 mM PB, substantial CYP2B1 mRNA induction was observed (100%). Addition of H2O2 or of the catalase inhibitor 3-amino-1,2,4-triazole (AT) to the medium repressed induction to approximately 30% (at 1 mM H2O2 and 2 mM AT, respectively). Accordingly, treatment of hepatocytes with PB and the glutathione precursor N-acetylcysteine (NAC) led to enhanced PB-dependent induction (to over 1000% at 10 mM NAC). In primary hepatocyte cultures transfected with a CYP2B1 promoter-luciferase construct containing approximately 2.7 kilobase pairs of the native CYP2B1 promoter sequence, PB-dependent reporter gene activation was repressed by AT and stimulated by N-acetylcysteine. Furthermore, a 263-base pair CYP2B1 promoter fragment encompassing the phenobarbital-responsive enhancer module conferred suppression of PB-dependent luciferase expression by AT and activation by NAC in a heterologous SV40-promoter construct. In summary, these data demonstrate a regulatory mechanism that is dependent on the cellular redox status, which modulates CYP2B1 mRNA induction by PB on the transcriptional level, thus representing a feedback mechanism preventing further P-450-dependent production of reactive oxygen intermediates under oxidative stress.

The superfamily of cytochrome P-450 (P-450) proteins consists of enzymes involved in metabolism of an array of endogenous and xenobiotic compounds (Nelson et al., 1996). Processes mediated by P-450 enzymes include steroidogenesis and metabolism of cholesterol, vitamin D3, and fatty acids but also biotransformation of innumerable drugs, environmental chemicals, and pollutants. Four of the cytochrome P-450 families (CYP1, CYP2, CYP3, and CYP4) are of relevance in drug and xenobiotic metabolism. Expression of many members of xenobiotic-metabolizing P-450 isoforms is induced by their substrates, thus allowing adaptation of metabolism. The liver, constituting the major site of biotransformation of xenobiotics, exhibits abundant basal expression and induction of xenobiotic-metabolizing cytochrome P-450 isoforms. Phenobarbital (PB) is regarded as the prototype of a specific spectrum of genes (reviewed by Honkakoski and Negishi, 1998). Although members of several P-450 subfamilies are inducible by PB (CYP2A, CYP2B, CYP2C, CYP3A, CYP4B), phenobarbital-dependent induction of the rat CYP2B1 isoform is most pronounced [up to 100-fold or greater increase of CYP2B1 protein in rat liver microsomes (Waxman and Azaroff, 1992)]. Several laboratories recently demonstrated the pivotal role of a phenobarbital-responsive enhancer found in the distal region of the rat CYP2B2 promoter in conferring CYP2B2 gene activation by phenobarbital (Trottier et al., 1995; Park et al., 1996; Stoltz et al., 1998). The relevance of a homologous region in conveying PB-dependent CYP2B induction was later confirmed in the mouse Cyp2b10 promoter (Honkakoski and Negishi, 1997). The ability to confer induction has recently been localized to a 51-bp sequence in the mouse Cyp2b10 promoter, termed the phenobarbital-responsive enhancer module (PBREM; reviewed by Honkakoski and Negishi, 2000). Sequences highly homologous to the mouse PBREM are found in the human CYP2B6

ABBREVIATIONS: P-450, cytochrome P-450; PB, phenobarbital; bp, base pair(s); PBREM, phenobarbital-responsive enhancer module; AT, 3-amino-1,2,4-triazole; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; PCR, polymerase chain reaction; mdr, multidrug resistance transporter; ROS, reactive oxygen species; NAC, N-acetylcysteine; NF1, nuclear factor 1; XRE, xenobiotic-responsive element.
and the rat CYP2B1/CYP2B2 promoters (Sueyoshi et al., 1999).

In addition to participating in elimination of xenobiotics, P-450 activity may also contribute to generation of potentially toxic products. Many procarcinogens are metabolically activated by P-450 isoforms to ultimate carcinogens. CYP2B isoforms in particular are involved in activation of aflatoxin B1 or cyclophosphamide to genotoxic metabolites (Chang et al., 1993). Furthermore, reactive oxygen species (ROS) are released during the catalytic reaction cycle of P-450 (Heinemeyer et al., 1980). It is assumed that activity of P-450 systems constitutes a major source of intracellular ROS in the liver (Bondy and Naderi, 1994; Puntarulo and Cederaum, 1998), indicating that excessive P-450 activity resulting from P-450 induction may lead to cellular damage caused by generation of noxious metabolites or ROS. Accordingly, adaptive mechanisms, repressing P-450 induction during cellular oxidative stress and thus lowering P-450-dependent production of active intermediates, would be expected to minimize cellular damage. Indeed, several lines of evidence suggest that ROS might play a negative regulatory role in CYP2B induction by phenobarbital. Induction of CYP2B isoforms by phenobarbital, as well as basal and induced expression of other P-450 isoforms, have been shown to be decreased by inflammatory processes in the liver (reviewed by Morgan, 1997), during which also enhanced liberation of ROS occurs. Several proinflammatory cytokines, including interleukin 6 and tumor necrosis factor-α, and also other cytokines (e.g., epidermal growth factor), that may lead to intracellular ROS production via physiological signaling (Bae et al., 1997; reviewed by Morel and Barouki, 1999), have also been identified as mediators of repression of phenobarbital-dependent CYP2B1 induction in rat hepatocytes (Aubrecht et al., 1995; Clark et al., 1995; Carlson and Billings, 1996).

To investigate whether ROS might affect CYP2B1 induction, we used as a model system primary rat hepatocyte cultures in which inducibility of CYP2B1 expression by phenobarbital is modulated in a redox-sensitive manner and therefore offers a system to study the role of redox signaling in CYP2B1 regulation (Seglen, 1976). Hepatocyte suspensions showed viabilities >90% as determined by trypan blue exclusion. Cells were plated onto culture dishes at a density of 8.6 × 10⁴ cells/cm² in MX-82 medium (Hoffmann et al., 1989) supplemented with 10% fetal calf serum. After an initial attachment period of 3 h at 37°C in a humidified atmosphere of 10% CO₂ and 90% air, the medium was replaced with serum-free MX-83 medium (Hoffmann et al., 1989) that lacked arginine, but contained 1 μM insulin and 20 μM hydrocortisone hemisuccinate. The cells were further cultured (37°C, humidified atmosphere of 10% CO₂/90% air) in the absence or presence of 0.75 or 1.5 mM PB, with or without oxidants (0.1–2 mM H₂O₂, or 0.5–5 mM 3-amino-1,2,4-triazole) or antioxidants (1–20 mM N-acetylcysteine or 100 μM tocopherol acetate), as indicated, for up to 3 days. Media changes were performed daily.

**Hepatocyte Culture and Induction Experiments.** Primary hepatocytes were isolated from adult male Wistar rats (180–220 g) by collagenase perfusion (Seglen, 1976). Hepatocyte suspensions showed viabilities >90% as determined by trypan blue exclusion. Cells were plated onto culture dishes at a density of 8.6 × 10⁴ cells/cm² in MX-82 medium (Hoffmann et al., 1989) supplemented with 10% fetal calf serum. After an initial attachment period of 3 h at 37°C in a humidified atmosphere of 10% CO₂ and 90% air, the medium was replaced with serum-free MX-83 medium (Hoffmann et al., 1989) that lacked arginine, but contained 1 μM insulin and 20 μM hydrocortisone hemisuccinate. The cells were further cultured (37°C, humidified atmosphere of 10% CO₂/90% air) in the absence or presence of 0.75 or 1.5 mM PB, with or without oxidants (0.1–2 mM H₂O₂, or 0.5–5 mM 3-amino-1,2,4-triazole) or antioxidants (1–20 mM N-acetylcysteine or 100 μM tocopherol acetate), as indicated, for up to 3 days. Media changes were performed daily.

**RNA Isolation and Northern Blot Analysis.** Total cellular RNA was isolated by guanidinium thiocyanate-phenol-chloroform extraction (Chomczynski and Sacchi, 1987) and separated through formaldehyde agarose gels (20 μg/lane). The gels were stained with ethidium bromide to ensure equal loading of lanes, and RNA was subsequently blotted onto Hybond N nylon membranes by capillary transfer. RNA blots were hybridized to the rat CYP2B1 gene-specific oligonucleotide probe 5’-GGTTGTGAGCCCGTTGGA-3’ (corresponding to bases 66–49 of exon 7 region, GeneBank L00318), which had been end-labeled by T4-polynucleotide kinase using γ⁻³²P-ATP (Omiecinski et al., 1985).

Control hybridizations were performed with a glyceraldehyde-3-phosphate dehydrogenase (GAPDH) oligonucleotide probe (5’-CAG-GATGCATTGTGACAACTTTGTA-3’, corresponding to nucleotides 520–496 of the rat GAPDH gene; European Molecular Biology Laboratory no. X02231). Mdr1b mRNA was detected by hybridization to a specific oligonucleotide probe as described previously (Ziemann et al., 1999). RNA expression was quantified with the use of the Fujix BAS 1500 Bio-Imaging Analyzer (Fujix, Tokyo, Japan).

**Hepatocyte Transfection and Luciferase Reporter Gene Assay.** Firefly and Renilla luciferase expression plasmids (pGL3-Basic, pGL3-Control, pGL3-Promoter, and pRL-CMV) were purchased from Promega. A fragment representing approximately 2.7 kilobase pairs of the native rat CYP2B1 promoter sequence was amplified by PCR from genomic rat hepatocyte DNA using primers corresponding to sites of the promoter sequence published by Shaw et al., 1996 (bases −2648 to −2623 and 29 to 4, respectively). To facilitate cloning, the primers contained an additional 5’ Nhel recognition site and a three-base overhang: 5’-AAAGTACGTCAGGTTCCCAACCATTTGGCCTACGGA-3’ (forward) and 5’-ATTCTAGACTCTGGTGTAAC-CAGCGTAGACTCTCA-3’ (reverse).

The obtained PCR fragment was digested with Nhel and ligated into the Nhel site of the pGL3-Basic vector. The sequence of the resulting promoter luciferase construct designated as pGL3C2B1 was verified by sequence analysis employing standard sequencing primers of the pGL3 plasmid and internal primers of the insert. A 263-bp CYP2B1 promoter fragment bearing the PBREM region was obtained by introduction of an EcoRI site into pGL3C2B1 by PCR and subsequent digestion with BamHI and EcoRI. This 263-kilobase-pair fragment, representing the CYP2B1 promoter sequence from −2413 to −2151, was treated with T4-DNA polymerase to yield blunt ends and further cloned into the Smal I site of the pGL3-Promoter vector containing the SV40 promoter, yielding the heterologous promoter construct pGL3CS1. Sequence and orientation of the insert were confirmed by sequencing using the standard pGL3 primers. Endotoxin-free maxi-prep kits (Macherey-Nagel, Düren, Germany) were employed for plasmid purification following amplification in Escherichia coli. Primary adherent rat hepatocyte cultures, plated at a density of 8.6 × 10⁴ cells/cm² onto six-well plates (Nunc), were transiently transfected 24 h after seeding with 0.5 μg of one of the firefly luciferase constructs (pGL3-Basic, pGL3-Control, pGL3-Promoter, pGL3C2B1, or pGL3CS1) and 0.08 μg of the Renilla luc-

**Experimental Procedures**

**Materials.** All chemicals were of reagent grade and purchased from commercial suppliers. Collagenase was obtained from Biochrom (Berlin, Germany) and fetal calf serum from PAA (Coelbe, Germany). Cell culture dishes were purchased from Nunc (Wiesbaden, Germany). T4 poly nucleotide kinase was from Roche Molecular Biochemicals (Mannheim, Germany). Hybond N nylon membrane and [γ⁻³²P]ATP were obtained from Amersham Pharma cia Biotech (Freiburg, Germany). The transfection reagent Effectene was purchased from Qiagen (Hilden, Germany). Firefly and Renilla luciferase expression plasmids as well as the Dual Luciferase Reporter Assay kit were obtained from Promega (Mannheim, Germany).

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ciferase construct pRL-CMV using the Effectene reagent (QIAGEN) according to the manufacturer’s instructions. Six hours later the medium was replaced with fresh MX-83 medium with or without 1.5 mM phenobarbital or modulators of induction (2 mM 3-amino-1,2,4-triazole, 10 mM N-acetylcysteine) as indicated. The medium was exchanged 24 h after transfection; 48 h after transfection, hepatocytes were lysed with 150 μl of lysis buffer (Dual Luciferase Reporter Assay kit, Promega) and firefly and Renilla luciferase activity were measured in 20 μl of cell lysate according to the Promega protocol using a Berthold Lumat LB 9501 luminometer (Berthold Technologies, Bad Wildbad, Germany). Renilla luciferase activity was used to normalize the transfection efficiency in all culture wells.

Results

In the present study, we addressed whether phenobarbital-dependent CYP2B1 induction might be subject to repression by reactive oxygen species. Experiments were performed with primary rat hepatocyte cultures in which induction of CYP2B1 by phenobarbital, a hepatocyte-specific function lost in hepatoma cell lines, was retained (Aubrecht et al., 1995). Maximal CYP2B1 mRNA induction was observed in hepatocyte cultures exposed to 0.75 or 1.5 mM PB for three days, which is consistent with previous reports (Aubrecht et al., 1995; Kietzmann et al., 1999). Therefore, primary hepatocytes were treated with PB and possible modulators of CYP2B1 mRNA induction for 3 days.

Repression by H₂O₂ of Phenobarbital-Dependent CYP2B1 mRNA Induction. To examine the possible role of oxidants in modulation of CYP2B1 mRNA induction by PB, hepatocyte cultures were treated with H₂O₂, a highly diffusible molecule that easily penetrates through cellular membrane structures. A H₂O₂ concentration of 1 mM was previously shown to up-regulate mRNA expression of antioxidant enzymes (catalase, Mn-superoxide dismutase; Röhrdanz and Kahl et al., 1998) as well as expression of the rat multidrug resistance mdr1b gene (Ziemann et al., 1999) in primary rat hepatocyte cultures. Thus, in the present study, initial concentrations of H₂O₂ from 0.1 to 2 mM were added to the medium once daily for 3 days. PB-dependent CYP2B1 mRNA induction was determined in Northern blot analyses. Induction, defined as the difference between PB-dependent CYP2B1 mRNA expression and basal CYP2B1 mRNA levels in the absence of PB, was set to 100% in cultures treated with PB in the absence of H₂O₂. Indeed, H₂O₂ elicited repression of PB-dependent CYP2B1 mRNA induction in a concentration-dependent manner (Fig. 1). This effect reached statistical significance at concentrations of 0.5 mM H₂O₂ and above, amounting to mRNA levels of about 37% at 0.5 mM H₂O₂, 30% at 1 mM H₂O₂, and 12% at 2 mM H₂O₂, respectively (Fig. 1, A and B). Expression of GAPDH mRNA in control hybridizations remained stable under H₂O₂ (Fig. 1B). On the other hand, we observed stimulation of mdr1b gene expression by H₂O₂ in the same culture system (shown for 0.5 mM H₂O₂ in Fig. 1C), with maximal stimulation at 0.5 to 1 mM H₂O₂ (Ziemann et al., 1999). Thus, H₂O₂ significantly repressed PB-dependent CYP2B1 mRNA induction at concentrations that did not result in a deleterious general repression of mRNA expression.

In an alternative approach to test the role of ROS in modulation of CYP2B1 induction, the catalase inhibitor AT, which increases intracellular ROS levels by interfering with decomposition of H₂O₂ (Starke and Farber, 1985) was employed. AT, applied to the culture medium at 0.5 to 5 mM concentrations, also led to a concentration-dependent repression of PB-dependent CYP2B1 mRNA induction, amounting to approximately 34% of control induction at 1 mM AT and 30% at 2 mM AT (Fig. 2). On the other hand, up to 5 mM AT...
stimulated mdr1b mRNA expression (data not shown). Thus, repression of CYP2B1 mRNA induction by the catalase inhibitor AT is consistent with the notion that ROS (H₂O₂) act as regulators of PB-dependent CYP2B1 mRNA induction.

Enhancement by N-Acetylcysteine of Phenobarbital-Dependent CYP2B1 mRNA Induction. Because H₂O₂ and 3-amino-1,2,4-triazole repressed PB-dependent CYP2B1 mRNA induction, it was hypothesized that an increase in hepatocyte antioxidant capacity might enhance CYP2B1 mRNA induction or counteract ROS-dependent inhibition of induction. Therefore, the effect of the antioxidant N-acetylcysteine (NAC), a precursor of glutathione, on PB-dependent CYP2B1 mRNA induction was examined. In hepatocytes concomitantly treated with PB and 1 to 20 mM NAC for 3 days, a dramatic concentration-dependent enhancement of CYP2B1 mRNA induction was observed that was maximal (approximately 1000%) between 10 and 20 mM NAC (Fig. 3, A and B). The incubation of hepatocytes with PB and a 100 μM concentration of the antioxidant tocopherol acetate (vitamin E), a membrane-bound radical scavenger, also led to a moderate increase (to approximately 200%) of PB-dependent CYP2B1 mRNA induction (Fig. 3C).

The marked enhancement of PB-dependent CYP2B1 mRNA induction by 10 mM NAC was abolished by 1 mM concentrations of the catalase inhibitor AT (Fig. 4), again supporting the conclusion that the extent of CYP2B1 mRNA induction by PB was regulated by the hepatocyte redox status.

Repression of PB-dependent CYP2B1 Promoter Activation by Aminotriazole and Enhancement of Promoter Activation by N-Acetylcysteine. To investigate whether the modulation of PB-dependent mRNA induction by ROS and N-acetylcysteine might be based on regulation of CYP2B1 transcription, a CYP2B1 promoter-luciferase re-
porter gene construct was generated, bearing the native CYP2B1 promoter sequence from +30 to −2648 (Fig. 5A). Primary rat hepatocyte cultures were transiently transfected with the original luciferase vector without the CYP2B1 promoter insert (pGL3-Basic) or with the CYP2B1 promoter-luciferase construct (pGL3C2B1) 24 h after seeding of hepatocytes and subsequently treated with 1.5 mM PB or with a combination of PB and AT and/or NAC for 48 h. Firefly luciferase activity was determined in hepatocyte lysates as a measure of promoter activation. Although AT or NAC alone did not influence promoter activation, PB significantly induced reporter gene expression (Fig. 5B). Mean promoter activation by PB alone was set to 100%. In accordance with modulation of PB-dependent CYP2B1 mRNA induction, 2 mM AT repressed PB-dependent promoter activation to approximately 25%, whereas 10 mM NAC enhanced promoter activation to about 900%. In combination with PB and NAC, AT counteracted enhancement by NAC of promoter activation (Fig. 5B). Thus, these results support the conclusion that modulation of CYP2B1 mRNA induction by AT and NAC occurs on the transcriptional level.

**Fig. 4.** Aminotriazole-dependent abolishment of enhanced CYP2B1 induction under N-acetylcysteine in primary rat hepatocyte cultures. Cells were cultured in the presence or absence of 1.5 mM PB with or without 1 mM AT or 10 mM NAC for 3 days. CYP2B1 mRNA expression was determined by Northern blot analysis. A, hybridization signals were quantified by a Bio-Imaging Analyzer. Induction was defined as the difference between expression under 1.5 mM PB and expression in the absence of PB. Induction with 1.5 mM PB in the absence of AT or NAC was set to 100%. Data represent mean values ± S.E.M. of five (PB/AT and PB/NAC/AT) or 12 (PB and PB/NAC) independent experiments. Significant difference between PB and PB + modulator of induction (***p < 0.001). t, significant abolishment by AT of NAC-dependent enhancement of CYP2B1 induction (p < 0.05), Student’s t-test. B, representative Northern blot. After hybridization to a CYP2B1-specific oligonucleotide probe, the blot was rehybridized to a rat GAPDH-specific probe.

**Fig. 5.** Modulation of PB-dependent CYP2B1 promoter activation by 3-amino-1,2,4-triazole and N-acetylcysteine. Primary rat hepatocytes cultured for 1 day were transiently cotransfected with the pRL-CMV Renilla luciferase vector and with the original pGL3-Basic vector (pGL3-Basic) or with the pGL3C2B1 construct, in which luciferase transcription was driven by the native CYP2B1 promoter sequence, respectively. Six hours after transfection, cells were incubated with 1.5 mM PB, 2 mM AT, or 10 mM NAC, as indicated, for an additional 48 h, and firefly luciferase activity was subsequently determined in cell lysates as described under Experimental Procedures. A, schematic representation of the CYP2B1 promoter fragment ligated into the pGL3-Basic luciferase vector, yielding the pGL3C2B1 construct. PBREM, phenobarbital-responsive enhancer module. The arrow indicates the transcription start site. B, relative firefly luciferase activity in lysates of transfected hepatocytes, standardized according to Renilla luciferase activity. Control, cells transfected with the pGL3C2B1 construct, but not treated with a modulator of CYP2B1 expression. Data represent mean values of five parallel culture wells ± S.D. of an experiment representative of three independent hepatocyte preparations. Significant difference from cells treated with PB (**p < 0.01,** *p < 0.05; Student’s t test). tt, significant abolishment by AT of the NAC-dependent enhancement of gene activation by PB, p < 0.01.
Further experiments were conducted to specify the promoter region possibly involved in conveying responsiveness to AT or NAC. The PB-responsive enhancer module (PBREM) and related sequences have been identified as the major PB-dependent regulatory regions in the mouse Cyp2b10 promoter and in CYP2B promoters of human and rat (reviewed by Waxman, 1999). A 263-bp fragment of the CYP2B1 promoter, containing the 51-bp region corresponding to the mouse PBREM (Fig. 6A), was linked to a heterologous promoter-luciferase expression plasmid, and its responsiveness to PB and to PB in combination with AT and/or NAC was examined in transiently transfected hepatocytes.

As expected, promoter activation by PB was retained with the heterologous construct (Fig. 6B), although basal promoter activity (control, without PB) was higher than with the reporter gene construct pGL3C2B1. Furthermore, AT elicited repression of PB-dependent activation, whereas NAC markedly enhanced PB-dependent luciferase expression (Fig. 6B). Again, AT significantly counteracted enhancement by NAC of promoter activation (Fig. 6B). Thus, these results demonstrate that the 263-bp CYP2B1 promoter region that contains the PBREM confers responsiveness to redox-dependent modulation of CYP2B1 gene induction.

**Discussion**

Extreme exposure to ROS is deleterious to the cell, resulting either in necrosis or apoptosis. A transient or moderate increase in ROS, however, may allow reconstitution of the cellular redox status, either by direct detoxification processes or by long-term adaptive alterations in gene expression (Morrel and Barouki, 1999). Thus, ROS-dependent repression of activation of genes encoding enzymes contributing to ROS production, as well as induction of proteins participating in ROS detoxification, may be regarded as part of a general defense response to maintain cellular redox homeostasis. In the present study, H2O2 and the catalase inhibitor 3-amino-1,2,4-triazole, which interferes with decomposition of intracellular H2O2, repressed PB-dependent induction of CYP2B1 mRNA.

Cytochrome P-450-dependent systems are regarded as a major source of intracellular production of free radicals in hepatocytes, even in the uninduced state (Bondy and Naderi, 1994; Puntarulo and Cederbaum, 1998). Under conditions of enhanced exposure to ROS (e.g., during inflammation), marked induction of P-450 enzymes, resulting in further P-450-dependent ROS production, would be expected to result in oxidant damage to the cell. Therefore, adaptive mechanisms by which ROS might prevent induction of several P-450 isozymes in the liver seem feasible. Indeed, the transcriptional suppression by H2O2 of basal expression of the CYP1A1 and CYP1A2 isozymes and of their β-naphthoflavone-dependent induction has been described previously (Barker et al., 1994). The present study demonstrates ROS-dependent repression of induction by a different type of inducer (phenobarbital) of a different P-450 isozyme (CYP2B1). At this point, the questions of whether PB-dependent induction of other xenobiotic-metabolizing genes apart from CYP2B1 might also be subject to regulation by ROS and whether overlapping mechanisms might be crucial in redox-dependent regulation of P-450 induction remain to be resolved.

The xenobiotic-responsive elements (XREs), to which heterodimers of the aryl hydrocarbon receptor and the aryl hydrocarbon receptor nuclear translocator protein bind, play a pivotal role in conferring induction of CYP1A enzymes by aromatic hydrocarbons (Hankinson, 1995). The ability of AT and NAC in the present study to modulate promoter activation in CYP2B1 promoter-reporter gene constructs transiently transfected into primary hepatocytes supports the conclusion that regulation of CYP2B1 induction by ROS occurs on the transcriptional level. However, in contrast to CYP1A gene regulation, XRE regions have not been shown to be of relevance in mediating PB-dependent induction (Wax-
man, 1999); rather, the major PB-responsive region in CYP2B promoters is a PB-responsive enhancer (Trottier et al., 1995; Park et al., 1996; Stoltz et al., 1998), which has been delimited to the PBREM in the mouse Cyp2b10 promoter (reviewed by Honkakoski and Negishi, 2000). To further specify the CYP2B1 promoter region conveying modulation of PB-dependent gene activation by AT and NAC, a promoter construct was employed in which a 263-bp fragment of the CYP2B1 promoter, encompassing the 51-bp PBREM, was placed in front of the heterologous SV40 promoter (Fig. 6A). Responsiveness not only to PB but also to AT and NAC was retained in hepatocytes transfected with the heterologous promoter construct, which suggests that either the PBREM itself or functional synergism between the PBREM and a promoter region in the vicinity of the PBREM is involved in conferring redox-sensitive regulation of PB-dependent CYP2B1 promoter activation.

The cellular redox status may affect transcription by different pathways. First, ROS might lead directly to oxidation of sensitive motifs of transcription factors, (e.g., of thiol groups), thus resulting in possible alterations in transcription factor DNA binding, in translocation to the nucleus, or in trans-activation (reviewed by Morel and Barouki, 1999). The PBREM region contains a nuclear factor 1 (NF1) binding motif, flanked by two nuclear receptor binding sites (reviewed by Honkakoski and Negishi, 2000). Interestingly, studies conducted with hepatoma cells suggest that oxidation of NF1 protein binding to a proximal NF1 site in the CYP1A1 promoter, which acts in synergy with XRE regions, constitutes the basis of suppression of CYP1A1 induction by ROS: the NF1/CTF trans-activating domain was repressed by oxidative stress, mediated by a critical cysteine (Morel et al., 1999). On the other hand, a different study indicates that the H$_2$O$_2$-dependent suppression of CYP1A1 induction is linked to the potential of the XREs to confer transcriptional activation by aromatic hydrocarbons (Xu and Pasco, 1988). Further examples of redox-sensitive regulation have been provided for members of the nuclear receptor superfamily (Morel and Barouki, 1999). Although oxidation of a cysteine residue in the nuclear localization signal domain NLI of the glucocorticoid receptor interferes with nuclear translocation (Okamoto et al., 1999), thiol oxidation in the DNA binding domain of the estrogen receptor seems to constitute the major factor contributing to redox-dependent estrogen receptor regulation (Liang et al., 1998).

Alternatively, ROS may indirectly modulate the activity of transcription factors by leading to an alteration in their phosphorylation status. ROS (H$_2$O$_2$) have been shown to hyperphosphorylate transcription factors by leading to an alteration in their phosphorylation status and/or by interfering with translocation of a transcription factor into the nuclear compartment.

In summary, the present study demonstrates the regulation of PB-dependent CYP2B1 gene activation by the cellular redox status. Repression of CYP2B1 induction under oxidative stress may be interpreted as part of a general defense strategy that is activated under enhanced exposure to ROS or when the antioxidative status of the hepatocyte is compromised.

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References


Katagiri Y, Takeda K, Yu ZX, Ferrans VJ, Ozato K and Guroff G (2000) Modulation of CYP2B induction (Katagiri et al., 2000). Nuclear receptor dimers consisting of the constitutive androstane receptor and the retinoid-X-receptor are thought to play an essential role in PB-dependent transcriptional activation of CYP2B genes via the PBREM (reviewed by Honkakoski and Negishi, 2000). Nuclear translocation of the constitutive androstane receptor protein into the nucleus was shown to be inhibited by the protein phosphatase inhibitor okadacin acid (Kawamoto et al., 1999), indicating that either hyperphosphorylation of the nuclear receptor protein itself or hyperphosphorylation of a different protein essential for the translocation process interferes with nuclear translocation.

Thus, it may be hypothesized that ROS may repress PB-dependent transcriptional activation of CYP2B1 gene expression directly, by oxidation of redox-sensitive transcription factors, or indirectly, by leading to an alteration in transcription factor phosphorylation status and/or by interfering with translocation of a transcription factor into the nuclear compartment.


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