Inflammation or infection down-regulates the activity and expression of cytochrome P450 enzymes in hepatic drug clearance, possibly altering drug effectiveness and leading to toxicity. The regulation of UDP-glucuronosyltransferases (UGTs) in inflammation and infection is less well characterized. To determine the response of hepatic and renal UGTs during inflammation and infection, mice were administered either saline or 1 mg/kg lipopolysaccharide (LPS) (16 h), or Citrobacter rodentium by oral gavage (6 days). Hepatic mRNA expression of UGT1A1, 1A9, and 2B5 was similarly down-regulated after LPS exposure and C. rodentium infection, whereas UGT1A2 and 1A6 mRNAs were unchanged. Effects of C. rodentium infection did not require a functional Toll-like receptor 4. Conversely, renal UGT isozymes were relatively unaffected, except for UGT2B5 induction after LPS treatment. Regulation of UGTs during the inflammatory response exhibits similarities to and differences from regulation of P450s, and may be cytokine-mediated.

**Materials and Methods**

**Chemicals, Animals and Treatments.** Unless otherwise specified, all chemicals were obtained from Sigma-Aldrich (St. Louis, MO). Adult female 129S1/SvImJ (Sv129) and C3H/HeOuJ (HeOu) mice were obtained from The Jackson Laboratory (Bar Harbor, ME) and acclimated to the animal facility for 1 week. In one experiment, Sv129 mice (7 weeks old) were provided rodent chow and water ad libitum. Escherichia coli LPS, serotype 0127:B8, was dissolved in sterile 0.9% saline, and Sv129 mice were injected intraperitoneally with either 1 mg/kg LPS or saline (n = 5). At 16 h, livers and kidneys were collected and stored at −80°C until RNA or microsome preparation. In a second experiment, 5-week-old HeOu mice were infected with C. rodentium (Serotype 0127:B8, a 2.0 × 10^8 colony-forming units). C. rodentium infection was confirmed by culture and visualization with ethidium bromide. Liver microsomes were prepared using the method described by Richardson et al. (2006). Control mice were administered saline by gavage without infection, and were pair-fed; i.e., they received the same amount of food eaten by the infected mice on the previous day. Mice were sacrificed 6 days after administration of saline or bacteria (n = 6), and livers and kidneys were collected. The Institutional Animal Care and Use Committee of Emory University approved all procedures.

**Preparation of Total RNA and Microsomes.** Total liver and kidney RNA was prepared using RNA-Bea isolation reagent (Tel-Test, Friendswood, TX). DNA contamination was verified spectrophotometrically at 260 nm, and RNA purity and integrity were confirmed by formaldehyde agarose gel electrophoresis and visualization with ethidium bromide. Liver microsomes were prepared as described by Richardson et al. (2006). The online version of this article (available at http://dmd.aspetjournals.org) contains supplemental material.
prepared by differential centrifugation (Haugen and Coon, 1976), and protein concentrations were determined using bovine serum albumin (Lowry et al., 1951).

Primer Sequences. Primers for mouse UGTs and glyceraldehyde phosphate dehydrogenase were designed using the Primer Select software program (DNASTAR, Inc., Madison, WI). All primers were submitted to the National Center for Biotechnological Information for nucleotide comparison by the basic local alignment search tool (BLASTn; Altschul et al., 1990). For UGT1A family members, the 5’-variable region was used as a target sequence to guarantee specific amplification of an individual isoform over similar ones within the same family. For UGT2B5, the entire sequence was used for primer design. Oligonucleotides with a high degree of similarity (>80%) to other mouse UGT mRNAs were eliminated. Primers were custom-synthesized by MWG Biotech, Inc. (High Point, NC), diluted to 100 μM in deionized water, and stored at −80°C. Primer sequences are as follows (UGT isoform, forward 5’-3’, reverse 3’-5’, annealing temperature): UGT1A1, ccagcagaaggggccagaagtt, 54.7°C; UGT1A2, ttgcaagctggagagatacagg, 55.4°C; UGT1A6, ctgctctgaggtggtgctgctg, 59.4°C; UGT2B5, accccagcaactttaggacacaat, tgatagatcgcctcgtagaca-tcccgcacaacatccctcatg, 59.4°C; UGT1A6, ctggctgatggtggctgactg, actgaggcc-agttg, tgaccacgcgcagcagaaaagaat, 56.9°C; UGT1A2, tgccccttcgaggaatctcagg, 55.2°C; UGT2B5, accccagcaactttaggacacaat, tgatagatcgcctcgtagacaccca, 54.7°C. Glyceraldehyde phosphate dehydrogenase primers were also designed for use at annealing temperatures corresponding to the various primer sets.

Quantitative Reverse Transcriptase PCR (Real-Time PCR). Purified total RNA was reverse-transcribed using the SuperScript First-Strand Synthesis System for the reverse transcription-polymerase chain reaction (PCR) kit (Invitrogen, Carlsbad, CA), according to the manufacturer’s protocol. Real-time reverse transcription-PCR was performed using the ABI PRISM 7000 Sequence Detection System (Applied Biosystems, Bedford, MA) and SyBr Green reagent, to determine UGT mRNA expression in mouse tissues by the method of Livak and Schmittgen (2001), as described previously in Richardson and Morgan (2005). Each primer set yielded a single PCR product of expected size by agarose gel electrophoresis, and specificity was monitored using product melting curves in each reaction well.

Western Immunoblotting. Hepatic UGT microsomal proteins were measured by sodium dodecyl sulfate-polyacrylamide gel electrophoresis and Western blotting, as described previously in Richardson and Morgan (2005). Antibody to the common region of rat UGT1A isozymes was diluted 1:5000, whereas UGT2B1 and UGT2B3 proteins to 50 to 60% of control. However, only UGT1A proteins were consistent with effects on mRNA expression. Effects of LPS on hepatic UGT proteins were consistent with effects on mRNA expression. LPS exposure significantly down-regulated hepatic UGT1A and 2B proteins to 50 to 60% of control. However, only UGT1A proteins were decreased in C. rodentium-infected mice (to 33% of control) (Fig. 2).

Results and Discussion

LPS-induced inflammation has been well studied with respect to its effects on hepatic P450s, but very little data exist on UGT expression during inflammation. As a live bacterial infection model, C. rodentium is the rodent equivalent of human enteropathogenic E. coli and a model of experimental colitis (Wales et al., 2005). Therefore, we investigated mouse hepatic and renal UGT mRNA expression in C. rodentium infection as well as in the well characterized LPS model. LPS administration significantly decreased mouse hepatic UGT1A1 (37% of control), 1A9 (13% of control), and 2B5 mRNAs (18% of control) (Fig. 1A). Similar responses were observed in mice infected with C. rodentium, with suppression of UGT1A1 (38% of control), 1A9 (25% of control), and 2B5 (46% of control) mRNAs (Fig. 1A). In contrast, UGT1A2 and 1A6 mRNAs were not affected during either LPS-induced inflammation or bacterial infection. Effects of LPS on hepatic UGT proteins were consistent with effects on mRNA expression. LPS exposure significantly down-regulated hepatic UGT1A and 2B proteins to 50 to 60% of control. However, only UGT1A proteins were decreased in C. rodentium-infected mice (to 33% of control) (Fig. 2).

Others have shown that hepatic UGT mRNAs are suppressed after exposure to an inflammatory stimulus. Strasser et al. (1998) reported down-regulation of hepatic UGT mRNAs from turpentine-treated rats, including UGT1A1 (16% of control) and UGT2B3 mRNAs (53% of control) during inflammation. As a live bacterial infection model, C. rodentium, E. coli, and a rodent equivalent of human enteropathogenic E. coli, and a model of experimental colitis (Wales et al., 2005). Therefore, we investigated mouse hepatic and renal UGT mRNA expression in C. rodentium infection as well as in the well characterized LPS model. LPS administration significantly decreased mouse hepatic UGT1A1 (37% of control), 1A9 (13% of control), and 2B5 mRNAs (18% of control) (Fig. 1A). Similar responses were observed in mice infected with C. rodentium, with suppression of UGT1A1 (38% of control), 1A9 (25% of control), and 2B5 (46% of control) mRNAs (Fig. 1A). In contrast, UGT1A2 and 1A6 mRNAs were not affected during either LPS-induced inflammation or bacterial infection. Effects of LPS on hepatic UGT proteins were consistent with effects on mRNA expression. LPS exposure significantly down-regulated hepatic UGT1A and 2B proteins to 50 to 60% of control. However, only UGT1A proteins were decreased in C. rodentium-infected mice (to 33% of control) (Fig. 2).

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control). In addition, Congiu et al. (2002) correlated decreased human UGT1A4, 2B4, and 2B7 mRNA levels from liver biopsies with increased inflammation. Moreover, changes in hepatic UGT protein and/or activities during inflammation are also documented. Chen et al. (1992) showed significantly decreased rat UGT activities toward 1-naphthol and p-nitrophenol (UGT1A6), and testosterone (UGT2B3) after administration of LPS (to 77–83% of control). Strasser et al. (1998) found that glucuronidation of testosterone was decreased to 65% of control, whereas activity toward p-nitrophenol was unchanged in turpentine-treated rats.

Our data provide a more comprehensive analysis of hepatic UGT mRNA regulation after LPS exposure and bacterial infection (Fig. 1), and demonstrate that this regulation is isoform-specific. Furthermore, our hepatic protein data indicate significantly decreased UGT1A and 2B proteins in LPS-treated mice and UGT1A proteins in infected mice, comparable to mRNA effects. The lack of effect on UGT2B protein in infected mice may be the result of variability in individual protein samples (Fig. 2), as well as the simultaneous detection of multiple UGT2B proteins that may be differentially regulated.

Renal UGT mRNAs seem relatively unaffected by inflammation or infection, except UGT2B5, which was significantly increased after LPS administration (Fig. 1B). Decreased renal UGT1A2 in infected mice narrowly missed significance (p = 0.073). In contrast to a lack of effect on UGTs, renal CYP4A and 2E1 mRNAs are induced in rat kidney after injection of LPS or irritants (Sewer et al., 1997; Mitchell et al., 2001) and CYP4A in mouse kidney (Barclay et al., 1999). In addition, C. rodentium infection has variable effects on renal P450 mRNAs, depending on the mouse strain (Richardson et al., 2006, companion paper).

The effects on hepatic UGTs during inflammation may be cytokine-dependent, similar to cytokine-mediated P450 suppression after LPS treatment. We observed increased hepatic expression of IL-1β, IL-6, tumor necrosis factor α, and acute phase protein mRNAs during both LPS-mediated inflammation (Richardson et al., 2005) and C. rodentium infection (Richardson et al., 2006, companion paper). Other studies lend support to the idea that effects on UGTs are cytokine-dependent. In isolated pig hepatocytes, IL-1α and tumor necrosis factor α caused early inhibition of glucuronidation (>60% at 12 h), whereas glucuronidation was inhibited 51% by IL-6 at 24 h (Monshouwer et al., 1996). Moreover, treatment of rat hepatocytes with IL-6, but not IL-1β, suppressed expression of UGT1A1 and 2B3 mRNAs (Strasser et al., 1998). Out-derived cytokines could contribute to the effects observed during C. rodentium infection. Further investigation of UGT down-regulation is necessary to determine the role of cytokines in these effects.

Other studies in our laboratory with hepatic and renal P450 expression during LPS-induced inflammation and C. rodentium infection found striking differences in P450 regulation for each model (Richardson and Morgan, 2005; Richardson et al., 2006, companion paper). To the contrary, in this study, we observed similar regulation of UGT isoforms in both models, despite several notable experimental differences between them. The LPS model is essentially an acute exposure (16 h), whereas the C. rodentium infection model could be considered a chronic exposure (6 days). Also, different mouse strains and routes of administration were used for each experiment. To determine whether the effects of C. rodentium infection on hepatic and renal UGTs were dependent on bacterial LPS and Toll-like receptor 4 (TLR4) signaling, we investigated these effects in TLR4 mutant mice. Our data indicate that the effects of C. rodentium infection on UGT mRNAs are independent of TLR4 and bacterial LPS signaling, because the effects of C. rodentium in TLR4 mutant mice (C3H/HeJ) were similar to effects in HeOu mice (supplemental data). Therefore, it appears that LPS and C. rodentium infection achieve the same effects on UGT expression through different mechanisms.

In summary, these data indicate that two different models of inflammation, LPS exposure and C. rodentium infection, produce similar down-regulation of hepatic UGT isoforms. This could have important consequences for drug and bilirubin metabolism in disease states. In contrast to P450 enzymes and hepatic UGTs, renal UGT mRNAs were not significantly decreased during these exposures. In addition, the down-regulation of hepatic UGT mRNAs and proteins by C. rodentium infection is independent of TLR4.

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