Impaired Microsomal Oxidation of the Atypical Antipsychotic Agent Clozapine in Hepatic Steatosis

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ABSTRACT

Hepatic lipid infiltration (steatosis) is a complication of the metabolic syndrome and can progress to nonalcoholic steatohepatitis and severe liver injury. Microsomal cytochrome P450 (P450) drug oxidases are down-regulated in experimental steatosis. In this study we evaluated the separate and combined effects of lipid accumulation and P450 down-regulation on the microsomal oxidation of the atypical antipsychotic agent clozapine (CLZ), the use of which is associated with an increased incidence of the metabolic syndrome. Several important drug oxidizing P450s were down-regulated, and the formation of N-desmethyl-CLZ (norCLZ) and CLZ N-oxide was decreased in microsomal fractions from orotic acid-induced early steatotic rat liver. Inclusion of lipids extracted from steatotic, but not control, liver decreased the free concentration of CLZ in microsomes and suppressed norCLZ formation; CLZ N-oxidation was unchanged. Triglycerides increased in steatotic liver to 15-fold of control, whereas increases in the monounsaturated oleic acid to 10-fold of control and total polyunsaturated and saturated fatty acids to 4- and 5-fold of control also occurred. Addition of triglycerides containing esterified ω-6 and ω-3 fatty acids inhibited the microsomal formation of norCLZ but not that of CLZ N-oxide; triglycerides esterified with unsaturated and monounsaturated fatty acids were inactive. Thus, drug oxidation may be suppressed in steatosis by P450 down-regulation and the accumulation of polyunsaturated fatty esters. In contrast, the activity of the flavin-containing monoxygenase that mediates CLZ N-oxidation was unimpaired. Lipid deposition in livers of patients with the metabolic syndrome may necessitate dosage adjustments for toxic drugs, including CLZ.

Hepatocellular lipid accumulation, or steatosis, is a central feature of nonalcoholic steatohepatitis (NASH). NASH is the hepatic component of the metabolic syndrome that is associated with obesity and type II diabetes. The metabolic syndrome is becoming increasingly prevalent in Western society and is characterized by impaired glucose and lipid metabolism (Marchesini et al., 2001). Initially believed to be a benign lesion, it is now thought that early hepatic steatosis precedes the development of NASH, which may progress to cirrhosis in up to 25% of patients. Steatosis may also be induced by a number of hepatotoxic drugs (Berson et al., 1998). In recent studies it has become apparent that therapy with certain antipsychotic agents, most notably the atypical antipsychotic clozapine (CLZ), is associated with an increased risk of developing hypertriglycerideremia and other manifestations of the metabolic syndrome (Meyer and Koro, 2004; Lamberti et al., 2006).

Although the role of steatosis in the pathogenesis of chronic liver disease is now accepted, the detailed effects of lipid infiltration on important aspects of hepatic function, especially drug biotransformation, remain underexplored. P450 dysregulation has been well documented in animal models of steatosis, obesity, and NASH (Leclercq et al., 1998; Su et al., 1999, 2005). Suppression of important xenobiotic and steroid hydroxylating P450s from the 2C and 3A subfamilies was proportional to the extent of hepatic lipid deposition in rats (Su et al., 1999) and force-fed geese (Leclercq et al., 1998). Drug clearance may also be impaired in humans with obesity, early steatosis, and NASH (Fiatarone et al., 1991; Blouin and Warren, 1999; Cheymol, 2000). However, changes in the extrahepatic distribution of lipophilic drugs in obese subjects may alter their pharmacokinetic and pharmacodynamic profiles and necessitate dose adjustments (Casati and Putzu, 2005). Sequestration in adipose tissue of obese subjects may decrease the unbound concentrations of basic drugs that are available for biotransformation by P450 enzymes (McLure et al., 2000). This issue is of particular importance for drugs such as CLZ, which is associated with a high incidence of neutropenia, cardiotoxicity, and a range of other

ABBREVIATIONS: NASH, nonalcoholic steatohepatitis; CLZ, clozapine; P450, cytochrome P450; OA, orotic acid; norCLZ, norclozapine (N-desmethyloclzapine); CLZ N-oxide, clozapine N-oxide; HPLC, high-performance liquid chromatography.
organ toxicities (Mags et al., 1995; Pacher and Keskesmeti, 2004).

In the present study, we tested the impact of lipid accumulation in early steatotic liver induced by dietary orotic acid (OA) on P450 expression and the microsomal oxidation of the lipophilic antipsychotic drug CLZ. The principal findings to emerge were that several important drug-metabolizing P450s were down-regulated and the accumulated lipids in steatotic liver markedly decreased the formation of the P450-derived metabolite N-desmethyl-CLZ (norCLZ), whereas the formation of CLZ N-oxide by the flavin-containing monoxygenase was spared. The addition of triglycerides containing esterified polyunsaturated fatty acids, but not saturated or monounsaturated fatty acids, to microsomal incubations mediated these inhibitory effects on norCLZ formation. Thus, the accumulation of specific triglycerides in steatosis exerts differential effects on oxidative pathways of CLZ elimination in liver that may necessitate dosage adjustments during drug therapy in individuals with the metabolic syndrome.

Materials and Methods

Chemicals and Biochemicals. CLZ and its metabolites norCLZ and CLZ N-oxide, OA, 7-ethoxyresorufin, resorufin, and biochemicals were from Sigma-Aldrich (Castle Hill, NSW, Australia) or Roche Pty Ltd (Castle Hill, NSW, Australia). The authentic triglycerides triolein (which contains three esterified stearyl residues), triolein (three esterified oleyl residues), triarachidion (three esterified arachidonyl residues), and tridocosahexaenoin (three esterified docosahexaenoyl residues) were purchased from Lardodan Fine Chemicals AB (Malmo, Sweden). Reagents for electrophoresis were from Bio-Rad (Richmond, CA). HPLC-grade solvents were from Rhone-Poulenc (Baulkham Hills, NSW, Australia), and analytical reagents were from Ajax (Sydney, NSW, Australia). Hyperfilm-MP, Hybrid-N25 filters, and reagents for enhancedchemiluminescence were from Amersham Pharmacia Biotech (Castle Hill, NSW, Australia).

Animal Treatments. Dietary manipulation studies in rats were approved by institutional animal ethics committees and followed the guidelines of the Australian National Health and Medical Research Council. The control synthetic diet contained sucrose (600 g/kg), casein (200 g/kg), cellulose (110 g/kg), corn oil (40 g/kg), salt mixture (4179; ICN Biochemicals, Seven Hills, NSW, Australia; 40 g/kg), ICN vitamin fortification mixture (10 g/kg), α-tocopherol (20 mg/kg), and retinyl acetate (8.7 mg/kg). OA (1%) was added to the control diet for the induction of hepatic steatosis. Inbred male Wistar rats (11% (at 10 mg/kg), 97 ± 10% (at 1 µM), and 96 ± 2% (mean ± S.E.M. at 10 µM) and analyzed by nonlinear regression using Prism 4 (GraphPad Software, Inc., San Diego, CA).

Lipids extracted from control or steatotic liver were equilibrated with microsomes with gentle shaking at room temperature for 5 min and then precipitated at 37°C for 2 min before the estimation of CLZ oxidation as described above. Lipid was included in microsomal incubations at ratios of 1:1 and 25:1 with microsomal protein to reflect the proportions found in control and steatotic liver, respectively. In further experiments authentic triglycerides (100 µg and 1 mg of triolein (18:1), triarachidonin (20:4, ω6), or tridocosahexaenoin (22:6, ω3)) were added to microsomes, in combination with a control liver lipid extract (ratio 1:1) to directly assess the effect of augmentation with esterified fatty acids on CLZ oxidation.

7-Ethoxyresorufin O-deethylation activity was determined in a FLUOstar fluorescence plate reader (BMG LabTech, Mt. Eliza, VIC, Australia). Cytocrome c reductase activity was measured spectrophotometrically using methods described previously (Murphy et al., 1997).

Analysis of CLZ and Its Metabolites by HPLC. A solid-phase method using Oasis HLB solid-phase extraction cartridges (containing 60 mg of divinylbenzene and N-vinylpyrrolidone sorbent; Waters, Milford, MA) was developed for the extraction of CLZ metabolites from microsomal incubations. The cartridges were conditioned with 1 ml of methanol, followed by 1 ml of distilled water. After microsomal incubations, samples were diluted with 1 ml of 0.1% formic acid in water and applied to the cartridges, which were washed with 0.1% of formic acid in water (1 ml) and then two aliquots (0.5 ml) of 0.1% formic acid in methanol, followed by acetone (0.3 ml). The mean recoveries of norCLZ were 96 ± 2% (mean ± S.E.M. at 10 µM) and 97 ± 10% (at 1 µM), respectively, and for CLZ N-oxide were 96 ± 11% (at 10 µM) and 100 ± 8% (at 1 µM), respectively. Standard calibration curves were linear over the range 0.25 to 12.5 µM for both CLZ N-oxide (r = 0.999) and norCLZ (r = 0.998); interassay variability was < 10%.

The HPLC system consisted of an LC-10AT isocratic pump, SIL-10A VP autosampler, SPD-10A VP dual wavelength UV-visible detector and a C-R2A Chromatopac integrator (Shimadzu, Kyoto, Japan). Separations were achieved on a Synergy Fusion-RP polar embedded C18 column (250 × 4.6 mm, particle size 4 µm; Phenomenex Australia Pty Ltd, Pennant Hills, NSW, Australia) operating at 38°C (Shimadzu CTO-10 AC VP column oven). The mobile phase consisted of 3:2:5 acetone/methanol/ammonium acetate buffer (20 mM, pH 5.0), containing N,N-dimethylthylamide (0.4 ml/l); the flow rate was 1.0 ml/min, and the UV detector was set at 260 nm. The retention times of authentic norCLZ, doxepin (internal standard), and CLZ N-oxide were 11.4, 13.1, and 16.9 min, respectively.

Estimation of the Unbound Fraction of CLZ in Microsomal Systems. The effects of hepatic lipid on the unbound fraction (fus) of CLZ in microsomal fractions were assessed by ultrafiltration. Thus, lipid extracts from control or steatotic liver (0.05 or 1.25 mg of total lipid) were incubated with microsomal fractions (0.05 mg) and CLZ (100 µM) for 30 min. The incubate was transferred to the sample reservoir of a Microcon YM-10 device (10-kDa molecular mass cutoff,
Millipore Corporation, Bedford, MA), equilibrated for 10 min and then centrifuged at 8000g for 30 min. CLZ in the ultrafiltrate was measured by HPLC as described above. All final estimates were corrected for nonspecific binding of CLZ to the YM-10 device (19 ± 3%).

Sodium Dodecyl Sulfate-Polyacrylamide Gel Electrophoresis and Immunoblotting. Microsomes (5 μl/g) were incubated at 100°C for 5 min with 2% sodium dodecyl sulfate and 5% 2-mercaptoethanol and electrophoresed on 7.5% polyacrylamide gels (Laemmli, 1970) with minor modifications. Proteins were transferred to nitrocellulose (Towbin et al., 1979) and incubated with anti-P450 IgGs for 120 min (3.7 μl of protein/ml). The rabbit anti-CYP2E1 IgG, the anti-CYP2J2 IgG, and the goat anti-CYP1A2 antisera were provided by Dr. M. Ingelman-Sundberg (Karolinska Institute, Stockholm, Sweden), Dr. D. C. Zeldin (National Institute of Environmental Health Sciences, Research Triangle Park, NC) and Professor M. E. McManus (University of Queensland, St. Lucia, QLD, Australia), respectively, and the properties of the rabbit anti-CYP2C11 and anti-CYP3A IgGs were reported previously (Murray et al., 1992b). Immunoreactive proteins were detected by enhanced chemiluminescence (Hyperfilm-ECL film) and analyzed by densitometry (GS-7000; Bio-Rad).

Statistics. Data are presented as means ± S.E.M. from measurements in hepatic fractions from individual animals (n = 4–6/group), unless otherwise indicated. Differences between means of two groups were detected with the Student’s t test. Differences between multiple groups were detected by one-way analysis of variance and Fisher’s protected least significant difference test.

Results

Effect of an OA-Containing Steatotic Diet on Liver Weight, Hepatic Lipid Accumulation, Microsomal P450 Expression, and CLZ Oxidation in Rats. Consumption of diet was not different between rats that received the OA-steatotic or the OA-devoid control diet. Animals that received the OA-steatotic diet gained weight at rates that were slightly lower than the rates of those that received the control diet. Thus, rats that received the control and steatotic diets were 134 ± 5 and 120 ± 10% of starting body weights after 21 days of dietary manipulation (p < 0.05). Serum bilirubin and γ-glutamyltranspeptidase were increased in rats with early steatosis, consistent with impaired hepatocellular function (Su et al., 1999).

Lipid deposition in the cytoplasm of rat hepatocytes was extensive after intake of the steatotic diet for 21 days. In contrast, steatosis was not evident in livers of animals that received the control diet from which OA was excluded. The pronounced deposition of lipid in steatotic liver led to an increase in relative liver weight (7.6 ± 0.4 versus 5.6 ± 0.2% relative to control; p < 0.001). In accord with this finding, total of esterified and free fatty acid content was 6-fold greater in steatotic liver than in control liver (212 ± 15 versus 35 ± 14 mg/g liver; p < 0.001). Triglycerides were strikingly increased by intake of the steatotic diet from 9 ± 1 to 135 ± 9 mg/g liver (p < 0.001), with lesser increases in cholesteryl esters (to 4.7-fold of control: 7.4 ± 1.1 versus 1.6 ± 0.2 mg/g liver; p < 0.001) and phospholipid esters (to 2.1-fold of control: 36.2 ± 4.3 versus 16.9 ± 1.9 mg/g liver; p < 0.001). Thus, proportionately greater quantities of triglycerides were present in steatotic liver.

Immunoblot analysis indicated that expressions of rat hepatic microsomal CYP1A, CYP2E1, CYP2C11, and CYP3A proteins were decreased in early steatosis to 27 ± 10% (p < 0.05), 68 ± 12% (p < 0.05), 53 ± 14% (p < 0.01), and 50 ± 6% (p < 0.001) of their respective controls (Fig. 1). In contrast, CYP2J4 protein expression was unchanged from control.

Consistent with previous reports, when tested over the 5 to 100 μM concentration range, CLZ was oxidized efficiently in rat liver microsomes to norCLZ and CLZ-N-oxide (Bun et al., 1999). K_m values for the formation of these metabolites were determined in control microsomes to be 41 ± 3 and 38 ± 5 μM, respectively, and V_max values were 1.08 ± 0.06 and 0.59 ± 0.10 nmol/mg of protein/min, respectively (Table 1). The V_max for norCLZ formation was decreased in microsomes from early steatotic rat liver (p < 0.05), whereas, in the case of CLZ-N-oxidation, the K_m was increased and the V_max was decreased. Intrinsinc clearances (V_max/K_m) were decreased to 44 and 33% of control for norCLZ and CLZ N-oxide, respectively (Table 1).

Impact of Hepatic Lipid Extracts on Microsomal P450-Mediated Oxidation of CLZ and 7-Ethoxyresorufin in Vitro. In the present study, the impact of hepatic lipids on microsomal CLZ oxidation was evaluated. Control liver contained 1.0 ± 0.2 mg of lipid/mg of microsomal protein (mean ± S.E.M., n = 6), which increased to 23 ± 5 mg of lipid/mg of microsomal protein in OA-steatotic liver. Thus, lipid/microsomal protein ratios in control and early steatotic liver were ~1:1 and ~25:1, respectively. As shown in Fig. 2 the addition of a control liver lipid extract, in the ratio with protein that is present in control liver (1:1), had minimal impact on the oxidation of CLZ (100 μM) in microsomes from control liver. In contrast, addition of steatotic liver extracts to control microsomal incubations at the ratio found in steatotic liver (~25:1) substantially decreased the formation of norCLZ to 27% of the activity in the absence of exogenous lipid (p < 0.001) (Fig. 2). In microsomes from early steatotic liver,
the addition of steatotic lipid extracts (at the 25:1 ratio) similarly decreased norCLZ formation from 0.34 ± 0.09 to 0.022 ± 0.005 nmol/mg of protein/min (p < 0.05).

In contrast with these findings, neither control hepatic lipid (ratio 1:1) nor steatotic liver lipid (ratio 25:1) inhibited microsomal CLZ N-oxide formation in hepatic microsomes from control or steatotic rats (Fig. 2). Thus, there was relative preservation of CLZ N-oxide formation over norCLZ. For comparative purposes the effects of control lipid extracts at the 25:1 ratio were evaluated and were found to decrease norCLZ and CLZ N-oxide formation to 70 ± 4 and 50 ± 5% of corresponding control. Thus, the nature of the accumulated lipid in early steatosis appears to be a significant determinant of the extent of inhibition. However, it is important to note that the accumulation of control lipids to these levels does not occur in liver.

Consistent with the decreased expression of CYP1A2, the microsomal O-deethylation of 7-ethoxresorufin was decreased in steatotic liver to 55 ± 11% of control (p < 0.05). Further decreases in resorufin formation were noted in hepatic microsomes from control and steatotic rats in the presence of steatotic liver extracts (25:1 ratio) to 31 and 37% of the respective activities in the absence of lipid; control liver lipid extracts (1:1 ratio with protein) were without significant effect. Rates of microsomal cytochrome c reduction were unimpaired by exogenous lipid extracts (not shown).

**Unbound CLZ Concentrations and CLZ Oxidation in Microsomal Systems Containing Hepatic Lipids.** It would be expected that only the unbound fraction (f_u) of CLZ would be available for oxidation by microsomal P450 enzymes. As part of the present study we evaluated the effect of hepatic lipid accumulation on the f_u of CLZ (determined at a concentration of 100 μM). In microsomes from control and early steatotic liver the CLZ f_u values were 0.88 ± 0.03 and 0.84 ± 0.01, respectively (Fig. 3). The f_u in control microsomes decreased in the presence of lipid extracted from control liver (tested at the 1:1 ratio found in control liver) to 0.70 ± 0.01 (p < 0.001). Steatotic liver extracts, in contrast, markedly decreased CLZ f_u values to 0.14 ± 0.01 and 0.10 ± 0.01 (p < 0.001) in control and steatotic microsomes, respectively. Thus, hepatic lipid accumulation in steatosis diminished the concentration of CLZ available for microsomal oxidation.

These f_u values were applied to the apparent K_m values that had been determined for microsomal norCLZ and CLZ N-oxide formation in the presence of liver lipid extracts. Thus, the measured K_m values in the presence of control liver lipid (1:1) were 29 ± 6 and 27 ± 3 μM, respectively, and application of f_u = 0.70 (as shown in Fig. 3) produced corrected values of 20 ± 4 and 19 ± 4 μM, respectively. K_m values of 880 ± 380 and 850 ± 350 μM were determined for norCLZ and CLZ N-oxide formation, respectively, in the presence of steatotic liver lipid (25:1 ratio); these values were decreased to 123 ± 53 and 119 ± 49 μM, respectively, after application of CLZ f_u = 0.14 that was determined previously (Fig. 3). Thus, f_u considerations partially corrected the pronounced effects of exogenous lipids, especially from early steatotic liver, on apparent K_m values for CLZ biotransformation.
Differential Accumulation of Fatty Acids in Control and Early Steatotic Rat Liver. Extracts from steatotic liver had been found to be relatively enriched in triglycerides, which was confirmed by \(^1\)H nuclear magnetic resonance spectroscopy (not shown). In further experiments, we identified the major fatty acids that accumulated in early steatosis. Intake of the steatotic diet for 21 days increased the total amounts of polyunsaturated, monounsaturated, and saturated fatty acids in liver. The most striking increase was in the monounsaturated fatty acid content, which increased 10-fold from 9.83 \(\pm\) 0.37 to 99.1 \(\pm\) 1.7 mg/g liver \((p < 0.001)\). A striking increase in the \(\omega-6\) linoleic acid to 8.6-fold of control was also noted, whereas the unsaturated palmitic acid was increased to 6.3-fold of control \((p < 0.001)\).

Major quantifiable fatty acids in control liver included palmitic (16:0), palmitoleic (16:1), stearic (18:0), oleic (18:1), elaidic (the 9-trans-isomer of oleic acid) (18.1), linoleic (18:2 \(\omega-6\)), arachidonic (20:4 \(\omega-6\)), and docosahexaenoic (22:6 \(\omega-3\)) acids (Table 2); several other fatty acids were minor constituents of liver extracts. Pronounced increases in the contents of the monounsaturated palmitoleic, oleic, and elaidic acids to 7-, 13- and 5.3-fold of respective control were observed in steatotic liver \((p < 0.001)\). A striking increase in the \(\omega-6\) linoleic acid to 8.6-fold of control was also noted, whereas the unsaturated palmitic acid was increased to 6.3-fold of control \((p < 0.001)\; \text{Table 2}\).

Direct Effects of Triglycerides on Microsomal CLZ Oxidation in Vitro. The possibility that the fatty acid esters accumulating in early steatosis may contribute to the decrease in the microsomal formation of norCLZ was tested directly. In these studies microsomal incubations incorporating control lipid extracts (1:1 ratio) were augmented with authentic triglycerides that reflected the principal fatty acid classes detected in rat liver. The saturated lipid tristearin (18:0, which contains three esterified stearate residues; 100 and 1000 \(\mu\)g/incubation) and the monounsaturated triolein (18:1; 100 and 250 \(\mu\)g/incubation) produced minimal changes in the formation of norCLZ and CLZ N-oxide (Fig. 5). However, the \(\omega-6\) ester triarachidonin (which contains three arachidonate residues esterified to glycerol; 250 \(\mu\)g/incubation) (20.4) and the \(\omega-3\)-fatty acyl triglyceride tridocosahexaenoic acid (22:6) significantly decreased norCLZ formation. This was selective for norCLZ because the production of CLZ N-oxide was not significantly affected by any of the triglycerides (Fig. 5).

Discussion

Hepatic steatosis is an increasing health problem, especially in Western society because of its association with obesity and type II diabetes. Early steatosis can progress in a proportion of patients to NASH. However, the consequences of extensive lipid infiltration for many important hepatic functions, including drug disposition and biotransformation are unclear. The OA-fed rat is a model of extensive hepatic steatosis that is uncomplicated by the inflammatory activity...
that occurs later in the progression to NASH (Su et al., 1999). Accordingly, the model is useful for the study of the consequences of early lipid infiltration on hepatic drug metabolism.

In obesity, changes in drug pharmacokinetics are often observed as a result of altered drug distribution and biotransformation. Apart from the dysregulation of microsomal P450 enzymes, lipid accumulation in adipose tissue can increase the volume of distribution and decrease drug clearance (Blouin and Warren, 1999). In general, therapy with basic lipophilic drugs, such as benzodiazipines, anesthetics, and other central nervous system-active drugs, is complicated in obese subjects (Abernethy et al., 1983; Casati and Putzu, 2005). Dose adjustment may be required with drugs such as CLZ because it has a highly significant toxicity profile and because close monitoring of plasma concentrations during therapy is mandatory. Obesity is frequently associated with hepatic steatosis, which could also influence the hepatic distribution of CLZ and decrease its oxidative biotransformation by microsomal enzymes.

Intake of the OA+steatotic diet led to a pronounced increase in the hepatic content of triglycerides and to lesser increases in phospholipids and cholesteryl esters. Triglyceride accumulation in this model is due to increased fatty acid synthesis and impaired lipoprotein transport through the Golgi apparatus. Significant correlations had been observed previously between the extent of hepatic lipid deposition and suppression of P450-mediated substrate oxidation in models of fatty liver in the rat (Murray et al., 1992a; Su et al., 1999) and the force-fed goose (Leclercq et al., 1998). The present study showed significant decreases in CYP1A2, CYP2C11, CYP2E1, and CYP3A expression in steatotic liver; these are important drug metabolizing P450s in the rat. A number of nuclear hormone receptors have been shown to regulate P450 genes in human and rodent liver (Honkakoski and Negishi, 2000). Thus, the pregnane X-receptor and constitutive androstane receptor heterodimerize with the retinoid X-receptor to stimulate the transcription of several P450s. In previous studies, we have found that ingestion of the OA+steatotic diet by rats decreases the hepatic expression of the important transcription partner, the retinoid X-receptor (Su et al., 2000). Peroxisome proliferator-activated receptor-(a), another closely related member of the nuclear receptor superfamily, was also down-regulated in early steatosis. Similar alterations in the expression of other nuclear hormone receptors may contribute to P450 dysregulation in steatotic liver.

Decreased CYP1A2 and CYP3A4 expression has been noted in human liver microsomes and hepatic sections from subjects with steatosis and/or NASH (Weltman et al., 1998; Donato et al., 2006). Importantly, Donato et al. have demonstrated that several P450 mRNAs were down-regulated in hepatocytes, and the corresponding P450 activities were decreased, by inclusion of millimolar concentrations of a free fatty acid mixture containing oleate and palmitate (Donato et al., 2006). However, several studies have shown that the predominant lipids that accumulate in clinical and experimental steatosis are triglycerides, in which fatty acids are esterified with glycerol; the accumulation of phospholipids and cholesteryl esters and free fatty acids is somewhat less pronounced. The present study has identified triglycerides

**TABLE 2**

Major fatty acids in rat liver after dietary manipulation

<table>
<thead>
<tr>
<th>Fatty Acid</th>
<th>Control</th>
<th>Steatotic</th>
<th>Relative Content (OA+/OA–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:0 (Palmitic)</td>
<td>8.88 ± 0.13</td>
<td>56.00 ± 2.14***</td>
<td>6.3</td>
</tr>
<tr>
<td>16:1 (Palmitoleic)</td>
<td>2.11 ± 0.06</td>
<td>14.71 ± 0.07***</td>
<td>7.0</td>
</tr>
<tr>
<td>18:0 (Stearic)</td>
<td>4.23 ± 0.13</td>
<td>8.63 ± 0.82**</td>
<td>2.1</td>
</tr>
<tr>
<td>18:1 (Oleic; cis)</td>
<td>5.38 ± 0.30</td>
<td>69.72 ± 0.39***</td>
<td>13.0</td>
</tr>
<tr>
<td>18:1 (Elaidic; trans)</td>
<td>2.25 ± 0.02</td>
<td>12.02 ± 0.14***</td>
<td>5.3</td>
</tr>
<tr>
<td>18:2 ω-6 (Linoleic)</td>
<td>3.83 ± 0.07</td>
<td>33.12 ± 0.94***</td>
<td>8.6</td>
</tr>
<tr>
<td>20:4 ω-6 (Arachidonic)</td>
<td>5.25 ± 0.21</td>
<td>6.22 ± 1.14</td>
<td>1.2</td>
</tr>
<tr>
<td>22:6 ω-3 (Docosahexaenoic)</td>
<td>1.09 ± 0.07</td>
<td>1.49 ± 0.64</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*** P < 0.01, different from control.

**Fig. 5.** Effects of authentic triglycerides on norCLZ and CLZ N-oxide formation in control rat microsomes. Microsomal fractions (0.05 mg of protein) were augmented with control liver lipid extract (0.05 mg) containing the indicated microgram quantities of triglycerides. Metabolite formation was monitored by HPLC as described under Materials and Methods. Different from control microsomes containing control liver lipid extract alone (1:1 ratio with protein): *** p < 0.001; * p < 0.05.
esterified with ω-3 and ω-6 polyunsaturated fatty acids as lipids with the potential to inhibit microsomal P450 oxidases. It is noteworthy that CYP1A2 and CYP3A4 have been shown to be important enzymes in norCLZ formation in human liver (Tugnait et al., 1999; Olesen and Linnet, 2001). These findings are also in accord with the decrease in antipyrine clearance that has been reported in NASH patients (Fiatarone et al., 1991). Indeed, antipyrine clearance in humans has been shown to depend on several P450s, in particular CYP1A2 and CYP3A4 (Engel et al., 1996).

In the present study, CYP2E1 expression was decreased in hepatic microsomes from rats with early steatosis. Studies in humans with NASH and in the methionine-choline-deficient rat model of NASH have reported an increase in the expression and function of this enzyme (Weltman et al., 1996, 1998; Emery et al., 2003). The reasons for these discrepancies are unclear, but it may be significant that inflammatory activity is a feature of NASH and methionine-choline deficiency, which is absent from OA+steatotic rat liver (Su et al., 1999). Indeed, microsomal activities mediated by CYP2E1 were also decreased in several other models of fatty liver, including the obese Zucker rat (Zaluzny et al., 1990), the choline-deficient rat, which exhibits steatosis but not NASH (Murray et al., 1988), and the intragastric high-fat dietary model in the mouse (Deng et al., 2005). Thus, CYP2E1 expression has emerged from a number of studies as a sensitive indicator of pathogenic processes in rat and possibly human liver (Leclercq et al., 1998).

Consistent with P450 down-regulation, the oxidation of CLZ to norCLZ was decreased in microsomal incubations from steatotic liver that were conducted in the absence of lipid. The inclusion of control lipid extracts at the level found in control rat liver (1:1 lipid/protein ratio) had minimal effects on CLZ oxidation. However, incorporation of lipid extracts from steatotic liver in microsomal incubations produced further suppressive effects on microsomal CLZ oxidation. Lipid extracts also decreased CLZ fα, which would diminish the concentration of the drug able to penetrate to the P450 active site. A partial correction of apparent Km values that had been determined in the presence of exogenous lipid was produced by application of fα values. Importantly, however, the inhibitory effects of steatotic liver lipids were restricted to P450-dependent norCLZ formation, whereas CLZ N-oxidation was spared. Rates of CLZ oxidation in early steatosis appear to be decreased because of the combined effects of P450 dysregulation and the accumulation of particular lipids. Indeed, considerations from P450 immunonquantitation data could underestimate the effect of steatosis on drug clearance.

The relative preservation of CLZ N-oxide formation is consistent with the possibility that some microsomal enzymes may be less susceptible to the membrane-perturbing effects of polyunsaturated fatty acids esterified in triglycerides. It has been established that the activities of certain P450s, notably CYP3A enzymes in reconstituted systems, are sensitive to the nature of the lipid environment, possibly because of interactions with other microsomal proteins to facilitate electron transfer during substrate oxidation (Imaoka et al., 1992). Previous findings in this model of early steatosis suggest that CYP3A activity is highly susceptible to changes in hepatic lipid composition produced by dietary means (Su et al., 1999). However, there is little information on how lipids influence the flavin-containing monoxygenase that supports CLZ N-oxidation. In addition, in the present study we did not observe any effect of exogenous lipid or triglycerides on microsomal cytochrome c reduction. However, it remains a possibility that the spatial relationship of P450s and the flavoprotein NADPH-P450 reductase may be altered by accumulation of esterified polyunsaturated fatty acids in the vicinity of the endoplasmic reticulum and could result in altered electron flow from NADPH to P450s.

Quantification of major fatty acids in liver extracts indicated that the proportion of monounsaturated fatty acids increased markedly in early steatotic liver relative to polyunsaturated and saturated fatty acids. By 1H nuclear magnetic resonance spectroscopy, monounsaturated fatty acids have also been shown to accumulate in preference to polyunsaturated fatty acids in liver of patients with acute hepatic failure (Pollesello et al., 1996) and nonalcoholic fatty liver disease (Araya et al., 2004). The ratio of monounsaturated to polyunsaturated fatty acids also increased in liver extracts from obese Zucker rats (Serkova et al., 2006). Taken together, the accumulation of monounsaturated fatty acids observed in the present study appears to be common to several forms of hepatic steatosis in humans and experimental animals.

Although the proportion of polyunsaturated fatty acids decreased in steatotic liver, the 6-fold increase in total lipid deposition led to an increase in the hepatic content of ω-6 fatty acids to 4.3-fold of control. This was due principally to the marked accumulation of linoleic acid. Direct testing of authentic lipids indicated that triglycerides esterified with the ω-6 fatty acid arachidonic acid (triarachidonin), which was used as a model ω-6-containing triglyceride, selectively decreased the formation of norCLZ (and not that of CLZ N-oxide) by rat hepatic microsomes. The triglyceride tridocosahexaenoic acid, which contains three molecules of the ω-3 fatty acid docosahexaenoic acid esterified to the triacylglycerol backbone, was also inhibitory toward norCLZ formation in rat liver microsomes. In contrast, even the extensive augmentation of microsomal lipids with unsaturated (tristearin) and saturated (triolein) fatty acids had minimal impact on CLZ oxidation. These findings established the capacity of ω-6 polyunsaturated fatty acids esterified in triglycerides to selectively decrease P450 activity in rat liver.

Sequestration of drug substrates in subcellular compartments is increasingly recognized as a major limiting factor in rates of drug oxidation and elimination in vivo. Drug substrates entering the hepatocyte must permeate the cytoplasm to reach the endoplasmic reticulum and protein and lipid factors may sequester drug nonspecifically. Ultrastructural findings have indicated that after short-term OA feeding the accumulated lipids are in close proximity to the endoplasmic reticulum (Novikoff and Edelstein, 1977), which is the principal location of P450s in the hepatocyte. In the present study, it was found that lipids accumulating in early hepatic steatosis may decrease the fα of CLZ, which could decrease the availability of the drug for oxidation by P450s. Direct evaluation of the inhibitory actions of authentic triglycerides on CLZ oxidation suggested that ω-6 polyunsaturated fatty acyl esters may be potent inhibitory agents that accumulate in steatosis. The data also support the contention that the activity of certain microsomal enzymes may be refractory to the effects of these esterified fatty acids, because...
of the preservation of CLZ N-oxidation. In view of these findings, it is now important to evaluate in greater detail how lipid accumulation in human steatosis influences drug efficacy and safety.

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