THE ROLE OF CYP2A AND CYP2E1 IN THE METABOLISM OF 3-METHYLINDOLE IN PRIMARY CULTURED PORCINE HEPATOCYTES

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ABSTRACT:

The accumulation of 3-methylindole (3MI) in uncastrated male pigs (boars) is a major cause of boar taint, which negatively affects the quality of meat from the animal. Previously, CYP2E1 and CYP2A have been identified as cytochrome P450 P450 (P450) isoforms involved in the metabolism of 3MI using porcine liver microsomes. This study further examines the role of these isoforms in the metabolism of 3MI using a primary porcine hepatocyte model by examining metabolic profiles of 3MI after incubation with P450 inhibitors. Incubation of hepatocytes with 4-methylpyrazole resulted in a selective inhibition of CYP2E1 activity as determined by p-nitrophenol hydroxylase activity and an associated significant decrease in the production of the 3MI metabolites 3-hydroxy-3-methylindole and 3-methylindole. Furthermore, inhibition of CYP2A, as assayed by coumarin 7-hydroxylase activity, using 6-methoxypsoralen and diethyldithiocarbamate was not associated with any further significant inhibition of the production of 3MI metabolites. Treatment with general P450 inhibitors resulted in further decreases in CYP2E1 activity and a more dramatic decrease in the production of 3MI metabolites, suggesting that additional P450s may be involved in the phase 1 metabolism of 3-methylindole. In conclusion, CYP2E1 activity levels are more important than CYP2A activity levels for the metabolism of 3-methylindole in isolated pig hepatocytes.

3-Methylindole (3MI) is a pneumotoxin in several mammalian species including goats, cattle, and humans (Yost, 1989). In mature uncastrated male pigs (boars), 3MI causes a problem of boar taint, where high levels of the compound present in the adipose tissue release an unpleasant odor when the meat of boars is heated. Consequently, male pigs are routinely castrated for meat production. 3MI is produced from the bacterial degradation of tryptophan in the hindgut of the pig and is metabolized in the liver to more readily excretable forms (Bonneau, 1997). The two most important control points that affect the accumulation of 3MI include its production and subsequent absorption from the hindgut and the metabolism of 3MI in the liver to more readily excretable forms (Claus et al., 1994; Squires and Bonneau, 2004). The formation of particular 3MI metabolites has been shown to be an important factor in 3MI clearance (Friis, 1992). In addition, various environmental and management factors can also affect 3MI levels in the pig.

Many studies have investigated the role of cytochrome P450 in the hepatic metabolism of 3MI in various species (Thornton-Manning et al., 1996; Squires and Lundström, 1997; Lanza and Yost, 2001). Huijzer et al. (1989) demonstrated, using suicide substrates for P450s in goat microsomes, that bioactivation of 3MI and covalent binding resulting in toxicity is mediated by P450 enzymes. Pigs are not susceptible to 3MI toxicity, suggesting that pigs metabolize 3MI by different P450 enzymes than other susceptible species. In a study conducted by Diaz and Squires (2000a), the two isoforms of P450 suggested to play a key role in the biotransformation of 3MI in pig liver microsomes were CYP2A and CYP2E1. Before this study, CYP2E1 was the only P450 isoform that was shown to metabolize 3MI in pigs (Friis, 1995; Squires and Lundström, 1997; Babol et al., 1998). Doran et al. (2002) has used primary porcine hepatocytes to investigate the effect of 3MI and androstenone (the other major contributor to boar taint in pigs) on CYP2E1 activity. In this present study, we used the isolated porcine hepatocyte model to elucidate the relative importance of CYP2A and CYP2E1 and potential additional P450 involvement in the metabolism of 3MI.

Three-week-old male pigs were used as a source for hepatocytes because they have similar hormonal profiles compared with sexually mature adult males (Schwarzenberger et al., 1993). Given that castration decreases 3MI levels and essentially eliminates the problem of boar taint (Babol et al., 1996), it can be inferred that a testicular factor is responsible for either the production or metabolism of 3MI, and thus, hormone levels are very relevant in the animal model chosen for these experiments. Hepatocytes have the advantage over microsomes of being in an inducible in vitro system where enzyme protein and activity levels can be manipulated by genetic regulation.

Enzyme activities for CYP2A and CYP2E1 were measured in this study by the hydroxylation of specific substrates, coumarin and p-nitrophenol, respectively (Baranova et al., 2005; Skaanild and Friis, 2005), and inhibitors were used to determine the importance of these
P450 isoforms in 3MI metabolism. 8-Methoxysporalen (8-MOP) is used as both an in vitro and in vivo inhibitor of CYP2A6 activity in humans (Sellers et al., 2000; Zhang et al., 2001), whereas 4-methylpyrazole (4MP) has been used as a CYP2E1-specific inhibitor in several in vitro studies, including in rat liver microsomes (Turini et al., 1998), in primary cultured rat hepatocytes (Ferrara et al., 2001), human liver microsomes (Spracklin et al., 1997), monkey liver microsomes (Amato et al., 1998), and pig liver microsomes (Diaz and Squires, 2000a). In addition, diethylthiocarbamate (DDTC), a metabolite of disulfiram, has been used to inhibit CYP2E1 activity by irreversible, mechanism-based inhibition in microsomes of multiple species, including pigs (Court et al., 1997), but may also affect CYP2A levels because many CYP2E1 substrates can be oxidized by CYP2A6 (Pass and McLean, 2002). Disulfiram has been reported to inhibit CYP2A6 activity in humans after a single dose (Kharasch et al., 1998); however, the specificity of these P450 inhibitors has not been previously demonstrated in the pig. The involvement of additional P450 isoforms was also investigated by using general inhibitors that target total P450 activity. General inhibitors have previously been used to determine the effect of mono-oxygenation on the metabolism of 3MI in other species (Huijzer et al., 1989; Ruangyuttikarn et al., 1991). Our objective was to evaluate the effect of these inhibitors on the activity of CYP2E1 and CYP2A and the metabolism of 3MI in isolated porcine hepatocytes.

Materials and Methods

Chemicals. 4MP, 8-MOP, DDTC, ketoconazole (KCZ), 1-aminobenzotriazole (ABT), 3-methylindole, indole-3-carbinole, 2-aminoacetophenone (2AAP), and β-NADPH were obtained from Sigma (Oakville, ON, Canada). The 3MI metabolite standards 3methylxindole (3MOI) and 3-hydroxy-3-methylindoline (HMOI) were a gift provided by Dr. G. S. Yost, Department of Pharmacology and Toxicology, University of Utah (Salt Lake City, UT), and 5-hydroxy-3-methylindole was a gift provided by Jens Hansen Møller of the Danish Meat Research Institute (Roskilde, Denmark). Type I collagenase (activity 274 units/mg) was purchased from Worthington Biochemical Corporate (Lakewood, NJ). Iletin regular insulin (beef and pork) was purchased from Eli Lilly Company (Indianapolis, IN). All remaining reagents were acquired from Sigma.

Research Animals. All animals used for these experiments were obtained from Arkell Swine Research facility of the University of Guelph and used in accordance with the guidelines of the Canadian Council on Animal Care. Pigs were uncastrated Yorkshire males at 21 ± 1 days of age at the time of slaughter. Immediately after slaughter, livers were surgically excised and used for liver perfusions or frozen in liquid nitrogen and stored at −70°C for future microsomal analysis. For microsomal enzymatic activity assay, livers were obtained from sexually mature uncastrated Yorkshire males (boars) and from age-matched adult castrated males (barrows).

Microsomal Preparation. For microsomal analysis, frozen liver samples were homogenized in a Poltron homogenizer (Brinkmann Instruments, Rexdale, ON, Canada) in 2 × (w/v) homogenizing buffer containing 50 mM Tris-HCl, 150 mM KCl, 250 mM sucrose, and 1 mM EDTA, pH 7.4, for 1 min on ice. Samples were centrifuged at 9000g for 30 min at 4°C. The supernatant was then centrifuged at 105,000g for 60 min at 4°C. After ultracentrifugation, the microsomal pellet was suspended in 1 × (w/v) storage buffer containing 50 mM Tris-HCl, 20% glycerol, and 1 mM EDTA, pH 7.4. The microsomal protein content was then determined by the Bradford method using the BioRad Protein Assay Reagent (Bio-Rad Laboratories Inc., Mississauga, ON, Canada), and aliquots were frozen at −70°C until needed.

Liver Perfusion and Hepatocyte Culture. Hepatocytes were prepared by a modification of a collagenase perfusion method described previously (Sinclair et al., 2005). Briefly, one hepatic lobe was immediately catherized by selecting the largest vessel at the cut end. Blood was then flushed from the liver by perfusion with 25 ml/min of medium containing 10 mM hydroxyethyl piperazine ethane (HEPES), 1 mM EGTA, and Hanks’ balanced salt solution, pH 7.4, delivered at 37°C. The lobe was then perfused for 5 min with the same medium without EGTA and then with Williams’ E media (pH 7.4) containing 10 mM HEPES and 0.7 mg/ml collagenase type 1 for approximately 15 min until the hepatocytes appeared to be fully dissociated.

All remaining experimental procedures were carried out under sterile conditions. The lobe was gently minced with a scalpel to dissociate cells in attachment medium containing 10 mM HEPES, 10% (v/v) fetal bovine serum, 1% (v/v) penicillin-streptomycin, and 50 units/ml insulin in Williams’ E media, pH 7.4, at 4°C. Cells were filtered through gauze and centrifuged at 15g for 3 min. The cell pellet was washed in attachment media, and cell viability was determined by trypan blue exclusion. Hepatocytes were only used if viability was greater than 80%. Hepatocytes were then plated on Primaria 60-mm tissue culture dishes (VWR International Ltd., Mississauga, ON, Canada) at a density of 2.25 × 106 cells in 3.0 ml of attachment media and kept in a incubator at 37°C supplied with 95% air and 5% CO2. After 4 h of attachment, the medium was replaced with serum-free medium that contained 10 mM HEPES, 10 mM pyruvate, 0.35 mM proline, 1% (v/v) penicillin-streptomycin, and 50 units/ml insulin in Williams’ E media, pH 7.4. Inhibitors used to treat the hepatocytes were dissolved in methanol and used at a final methanol concentration of less than 0.05%. After 1 h of preincubation with inhibitors, the P450 activity and 3MI metabolism studies were carried out. Cell mortality was assessed by cell detachment from tissue culture dishes (Simets et al., 2002).

p-Nitrophenol Hydroxylase Activity Assay. To determine the rate of p-nitrophenol (PNP) hydroxylase activity, primary hepatocytes were incubated with 500 μM PNP for 6 h. PNP hydroxylase activity was proportional to number of cells and linear with time over 8 h (r² = 0.99). After incubation, media were added to an equal volume of acetonitrile and frozen until analysis. After thawing, the samples were vortexed briefly and centrifuged at 15,000g for 20 min to remove precipitated protein before HPLC analysis. A 100-μl aliquot of the supernatant was injected using a Spectra-Physics model SP8880 (Spectra-Physics, San Jose, CA) autosampler into a Spectra Physics HPLC consisting of a model SP8800 Ternary HPLC Pump equipped with a Spectra-Physics 100 variable wavelength detector set at 345 nm and a Spectra-Physics model 4290 integrator. Compounds were separated on a Luna 5-μ 250 × 4.60-mm reverse-phase C-18 column (Phenomenex, Torrance, CA). Elution of the compounds was accomplished using the following step-wise gradient of 100% acetonitrile (buffer A) and 25% acetonitrile, 75% double-distilled water, and 0.1% trifluoroacetic acid (buffer B) at a flow rate of 1.0 ml/min: 0 to 10 min 100% buffer A, 11 to 16 min 100% buffer A, and 16.1 to 20 min 100% buffer B. Typical retention times for p-nitroacetaldehyde (PNC) and PNP were 12 and 17 min, respectively.

The PNP hydroxylase assay in microsomes was adapted from Jiang et al. (1998). In a total volume of 250 μl, 1.0 μg of microsomal protein was incubated with 200 μM PNP in 0.1 M potassium phosphate buffer (pH 6.8). The mixture was washed to equilibrate for 5 min at 37°C, and reactions were carried out with 1 mM NADPH for 30 min at 37°C. The reaction was terminated by the addition of 20 μl of 40% trichloroacetic acid. Tubes were centrifuged for 20 min at 15,000g for 15 min to precipitate the protein and 100 μl of the supernatant used for HPLC analysis of PNC. PNC concentration was determined with a standard curve of PNC of 0, 1, 5, 10, 20, and 40 nmol in assay buffer and activity was reported as picomole of PNC per minute per milligram microsomal protein.

Coumarin 7-Hydroxylase Activity. The 7-hydroxylation of coumarin was used to measure CYP2A activity by a procedure described for cell culture by Donato et al. (1998a). Primary hepatocytes were treated with 100 μM coumarin for 1 h. To determine the amount of 7-hydroxycoumarin produced, 70 μl of medium was collected from each culture dish into a 96-well plate. To each well, 20 μl of 0.1 M sodium acetate buffer (pH 4.5) containing 15 Fishman units of β-glucuronidase and 120 Roy units of arylsulfatase (Roche Applied Science, Laval, QC, Canada) was added and incubated for 1 h at 37°C. Then, 170 μl of 0.1 M Tris-HCl (pH 9.0) was added to each well, and fluorescence was measured at an excitation of 360 nm and emission at 460 nm using a Victor 3 plate reader (PerkinElmer Life Sciences, Woodbridge, ON, Canada) equipped with the Wallac 1420 (version 3.0) software (PerkinElmer Life Sciences). The coumarin 7-hydroxylase (COH) assays were linear with number of cells, microsomal protein content, and with time.

For the microsomal analysis, a total of 0.8 mg of microsomal protein was combined with 0.2 mM coumarin and 5 mM magnesium chloride in 50 mM Tris buffer (pH 7.4) in a volume of 200 μl. After 5 min of preincubation, the
reaction was started by the addition of 25 µl of 25 mM NADPH and incubated for 15 min at 37°C. The reaction was stopped by the addition of 100 µl of 20% trichloroacetic acid, followed by a 5-min centrifugation at 10,000 g to pellet protein. A total of 200 µl of the supernatant was added to 1.5 ml of 0.1 M Tris buffer (pH 9.0), and the fluorescence was determined using a Hitachi F2000 Fluorescence Spectrophotometer (Hitachi, Yokohama, Japan) with an excitation of 360 nm and emission at 460 nm. The concentration of 7-hydroxycoumarin formed was determined by interpretation of a standard curve and reported as picomoles of 7-hydroxycoumarin per minute per milligram microsomal protein.

3MI Metabolism Assay. To measure 3MI metabolism in primary cultured hepatocytes, cells were incubated with 500 µM 3MI for 6 h, after which 100 µl of medium was added to an equal volume of acetonitrile to stop the reaction. The extract was centrifuged at 15,000 g for 20 min to pellet protein, and a 100-µl aliquot was used for HPLC analysis using the chromatograph described previously, with the UV detector set at 250 nm and a SpectroSystem fluorescence FL3000 (Thermo Separation Products, Fremont, CA) detector with the excitation FL300 (detection FL300) wavelength setting at 285 nm excitation, 350 nm emission. Metabolites were separated on a Luna 5 µ 250 x 4.60-mm reverse-phase C-18 column (Phenomenex). The metabolites were eluted using the following gradient of 100% acetonitrile (buffer A) and 0.01 M potassium dihydrogen phosphate, pH 3.9 (buffer B) at a flow rate of 1.2 ml/min: 0.0 min 10% buffer A, 6.0 min 20% buffer A, 12.0 min 30% buffer A, 25.0 min 70% buffer A, 25.1 min 100% buffer A. A mixture of standards was used after every ninth sample on the HPLC for identification of metabolite peaks. Concentration curves for metabolites up to 300 ng/ml were used to calculate picomoles of metabolites produced. Standards, including their presence in cells, concentration of standards used, and typical retention times, are presented in Table 1.

Inhibition Experiments. Inhibitors were used to elucidate the role of the isoforms CYP2A and CYP2E1 in the metabolism of 3MI. To achieve inhibition of CYP2E1 and CYP2A, the inhibitors 4MP, 8-MOP, and DDTC were used as treatment groups. After attachment of hepatocytes, 50 µM 4MP, 200 µM 8-MOP, or 250 µM DDTC was added in 3 ml of serum-free medium. For general inhibition of P450s, the inhibitors KCZ and ABT at a concentration of 2.7 pmol/million cells/h (r2 = 0.96) were added to a concentration of 250 µM were used. After a 1-h incubation period with the inhibitors PNP and COH, activity assays and the 3MI metabolism assay were performed.

Statistical Analysis. The model used for the treatment effect of inhibitor on enzyme activity and 3MI metabolism production was as follows:

\[
Y_{ijkl} = \tau_i \times \pi_{pk} \times \beta_k \times \beta \times \tau_i \times \epsilon_{ijkl}
\]

where \(Y_{ijkl}\) is the chromatogram peak, \(\tau_i\) is the inhibitor treatment, \(\pi_{pk}\) is the plate nested within inhibitor and within liver, \(\beta_k\) is the liver, \(\beta \times \tau_i\) is the liver \(\times\) inhibitor interaction, and \(\epsilon_{ijkl}\) is the residual error of the experiment. Significant differences in PNP conversion, COH activity, and 3MI metabolism were determined using the Tukey’s test for pair-wise comparison in the Proc Mixed program of the Statistical Analysis Software v8.0 (SAS Institute, Cary, NC). Treatment-related differences were determined with inhibitor as fixed effects and liver (treated as a block), liver \(\times\) inhibitor interaction and plate within inhibitor within liver as random effects. The Satterthwaite approximation was used to calculate the denominator for the degrees of freedom given that variances were pooled for analysis. Activity and concentration of 3MI metabolite data were either loge or square root transformed to meet analysis of variance assumptions of residual normality and homogeneous variance. The resulting analysis was examined using the Shapiro-Wilkes’ test (Proc Univariate Normal) and by graphical interpretation of the residual plots. For all comparisons, a type I error rate of \(\alpha = 0.05\) was used unless otherwise stated. All results are presented as means \pm standard errors, whereas all graphs are presented using the normalized raw data for easier illustration, with statistical results and interpretations performed using the transformed data.

For microsomal enzyme activity analysis, significant differences were examined with a Tukey’s test using the Proc GLM program of the SAS program and a type I error rate of \(\alpha = 0.05\). All linear regressions were calculated using Microsoft Excel (Redmond, WA).

Results

CYP2E1 and CYP2A Activity in Microsomes. To determine the suitability of using hepatocytes from 3-week old male pigs as a model of the adult boar liver, we measured microsomal P450 activity levels. Figure 1 illustrates the activity level comparison in microsomes for CYP2A1 and CYP2E1 between sexually mature boars, adult castrated males, and uncastrated 3-week old males. CYP2E1 and CYP2A activities (as determined by PNP hydroxylase and COH activities, respectively) in 3-week old males were higher than the levels observed in boars and lower than barrows. All enzyme levels were significantly different from one another \((P < 0.0001)\). Thus, the 3-week old male pig represents a better model for investigating 3MI metabolism in the adult boar liver compared with the adult castrated male pig.

3MI Metabolite Profile in Primary Hepatocytes. Three metabolites were identified after incubation of hepatocytes with 3MI (Table 1). The time course for the production of metabolites was investigated after attachment of the cells by incubating 15 culture dishes with 500 µM 3MI in serum-free medium and sampling from three plates at 0-, 4-, 8-, 16-, and 24-h incubation time. The production of HMOI and metabolite data were either loge or square root transformed to meet analysis of variance assumptions of residual normality and homogeneous variance. The resulting analysis was examined using the Shapiro-Wilkes’ test (Proc Univariate Normal) and by graphical interpretation of the residual plots. For all comparisons, a type I error rate of \(\alpha = 0.05\) was used unless otherwise stated. All results are presented as means \pm standard errors, whereas all graphs are presented using the normalized raw data for easier illustration, with statistical results and interpretations performed using the transformed data.

For microsomal enzyme activity analysis, significant differences were examined with a Tukey’s test using the Proc GLM program of the SAS program and a type I error rate of \(\alpha = 0.05\). All linear regressions were calculated using Microsoft Excel (Redmond, WA).

P450 Inhibition Experiments. Although chemical inhibitors have previously been shown to have an affect on 3MI metabolism in microsomal assays, we wanted to determine whether these inhibitors would result in changes in the 3MI metabolism profile in primary cultured hepatocytes. The inhibition curves of CYP2E1 and CYP2A activity with the inhibitors 4MP, 8-MOP, and DDTC are presented in Fig. 2. The inhibitor 4MP decreased CYP2E1 activity to a maximum inhibition of 94% at 100 µM concentration, whereas there was no significant inhibition of CYP2A activity. Therefore, 4MP was considered a specific inhibitor of CYP2E1 activity with no effect on CYP2A. 8-MOP inhibited both CYP2E1 and CYP2A activity with a maximum inhibition of 93 and 91%, respectively, at a concentration of 500 µM 8-MOP. DDTC also decreased both CYP2E1 and CYP2A activity with a maximum inhibition of 72 and 77%, respectively, at a

<table>
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TABLE 1

3MI and metabolite standards used to identify peaks at specific retention times on HPLC

For microsomal enzyme activity analysis, significant differences were examined with a Tukey’s test using the Proc GLM program of the SAS program and a type I error rate of \(\alpha = 0.05\). All linear regressions were calculated using Microsoft Excel (Redmond, WA).
concentration of 1 mM. DDTCT initially increased both activities at the lower concentrations examined (1 and 10 μM DDTCT) with a sharp decrease observed at higher concentrations of the inhibitor. There was no visible cell mortality after 24-h exposure of cultured hepatocytes with these three inhibitors.

The activity of CYP2E1 in hepatocytes from three pigs averaged 1.09 ± 0.23 nmol/million cells/h. Treatments with 50 μM 4MP, 200 μM 8-MOP, and 250 μM DDTCT resulted in a significant similar decrease in CYP2E1 activity compared with controls of 74% (P = 0.0005), 72% (P = 0.0006), and 64% (P = 0.0017), respectively (Fig. 3). CYP2A activity averaged 14.72 ± 4.52 nmol/million cells/h in hepatocytes. CYP2A activity was significantly inhibited in the 8-MOP and DDTCT treatment groups by 59% (P = 0.0005) and 72% (P = 0.0005), respectively. Treatment with 4MP resulted in no significant change compared with controls (P = 1.0). The production of the two major 3MI metabolites HMOI and 3MOI averaged 2.25 and 1.26 pmol/million cells/h, respectively. The production of the metabolites HMOI and 3MOI were significantly inhibited by 24% (P = 0.044) and 21% (P = 0.025), respectively, when cells were treated with 50 μM 4MP. Treatment with 200 μM 8-MOP resulted in a decrease trend in production of 19% (P = 0.10) and a 28% decrease (P = 0.006) for HMOI and 3MOI, respectively. Treatment with 250 μM DDTCT resulted in a significant decrease in production of 36% (P = 0.007) and 36% (P = 0.001) for HMOI and 3MOI, respectively.

**General P450 Inhibition Experiment.** We next used inhibitors that are reported to decrease all P450 activity levels to investigate the potential involvement of additional P450s in the metabolism of 3MI (Fig. 4). Treatment of the cells with 250 μM KCZ and 250 μM ABT significantly inhibited (P < 0.0001) CYP2E1 activity compared with controls by 97 and 96%, respectively. This inhibition from KCZ and ABT represented a further 15% significant decrease (P = 0.044, P = 0.006) over the 81% inhibition from treatment with 4MP (Fig. 4). KCZ inhibited CYP2A activity by a significant 77% (P = 0.040), whereas ABT had a trend to decrease CYP2A activity by 63% (P = 0.094). Neither KCZ nor ABT showed signs of toxicity during the 7-h incubations; however, in a parallel experiment, KCZ showed signs of limited toxicity as ascertained by an increase in cell detachment from culture plates 24 h after exposure.

The two major 3MI metabolites HMOI and 3MOI were used as indicators of treatment-related changes in 3MI metabolism. There was a negative trend on HMOI production after KCZ treatment compared with both the controls and 4MP treatment group, although no significant effects were observed (Fig. 4). No results for HMOI could be obtained from ABT-treated cells, given that the peak from ABT could not be resolved from the HMOI peak on HPLC. For the metabolite 3MOI, KCZ significantly inhibited its production by 70% (P = 0.003) and by a significant further decrease of 41% (P = 0.015) over cells treated with 4MP. ABT significantly inhibited 3MOI production by 51% (P = 0.011) and a further 22% (P = 0.12) decreasing trend over cells treated with 4MP.
FIG. 3. Inhibition of PNP hydroxylase (CYP2E1) and COH (CYP2A) activity and the production of major 3MI metabolites (HMOI and 3MOI) in porcine hepatocytes treated with P450 inhibitors, 50 µM 4MP, 200 µM 8-MOP, or 250 µM DDTC. 3MI metabolites were measured by HPLC after treatment with 500 µM 3MI. A, CYP2E1 and CYP2A activity; B, production of HMOI and 3MOI. Each data point represents results obtained from three aliquots of cells from three different pig livers and all samples analyzed in duplicate on HPLC. The results were divided by the control average from five aliquots of cells for each liver and reported as percentage of control. Values are presented as means ± S.E with significant differences within the P450 isoform or 3MI metabolite indicated by different letters. Capital letters refer to CYP2E1 and HMOI, whereas lowercase letters refer to CYP2A and 3MOI.

Discussion

Improving the metabolism and subsequent clearance of 3MI has been suggested as a means of preventing 3MI accumulation in fat of pigs (Friis, 1995; Bæk et al., 1997). Therefore, it is essential to identify the role of biotransforming enzymes in the metabolism of 3MI. A role of CYP2E1 and CYP2A in the metabolism of 3MI has been suggested through the analysis of liver microsomes of pigs (Friis, 1995; Squires and Lundström, 1997; Babol et al., 1998; Diaz and Squires, 2000a). Herein, using a primary hepatocyte model, we provide evidence that CYP2E1 is of importance in the phase 1 metabolism of 3MI by the use of an inhibitor of CYP2E1 activity but not CYP2A activity, 4MP, and by the production of 3MI metabolites HMOI and 3MOI. Our results show that inhibition of CYP2A and CYP2E1 activity did not reduce the production of HMOI and 3MOI metabolites any further than the inhibition of CYP2E1 alone. In addition, a further reduction in the formation of HMOI and 3MOI metabolites in hepatocytes was observed upon treatment with the general P450 inhibitors ABT and KCZ, which was greater than the inhibition of CYP2E1 activity, suggesting that other P450 enzymes may be involved in the metabolism of 3MI.

Hepatocytes obtained from males at 3 weeks of age were used as a model to study 3MI metabolism, because these cells have a viability of greater than 80% upon isolation, whereas adult cells were typically less viable (unpublished data). The activities of CYP2E1 and CYP2A in microsomes from 3-week-old pigs were higher than in boars and lower than in castrated males. Thus, 3-week-old male pigs were determined to be a more appropriate model than castrated males to study 3MI metabolism.

Initially, Bæk et al. (1997) identified several metabolites of 3MI in the plasma and urine of pigs, including 6-hydroxy-3-methylindole (6-HO-3MI), HMOI, and the mercapturate adduct of 3MI, 3-[(N-acetylcyesteine-5-yl)methyl] indole. Seven metabolites were identified in incubations of 3MI with pig liver microsomes by Diaz et al. (1999) and include HMOI, 3MOI, 6-HO-3MI, 5-HO-3MI, 3-hydroxy-3-methylindolenine, indole-3-carbinol, and 2AAP. Herein, three of these metabolites, HMOI, 3MOI, and 2AAP, were found in incubations with primary porcine hepatocytes, which further supports their use as a model for the evaluation of the role of P450s in the metabolism of 3MI. However, the use of primary cultured hepatocytes is somewhat limited by changes in the expression of drug-metabolizing enzymes that can occur during the culture period.

This apparent lack of detection of some metabolites of 3MI in hepatocyte preparations can be explained by accounting for the phase 2 biotransformation of the metabolites. It is possible that those phase 1 products were conjugated by the time that sampling had occurred and that they might have been end products of the metabolism pathway, ready for excretion. For example, whereas Friis (1992) identified 5- and 6-HO-3MI as major excretory metabolites of 3MI, we were not able to detect them in intact hepatocytes. These metabolites can be readily sulfated by cytosolic sulfotransferase (SULT) enzymes. For example, we have previously shown that high levels of hepatic SULT1A1 (previously termed thermostable phenol-sulfotransferase, TS-SULT) are associated with the sulfation of 5-HO-3MI, and this is related to low levels of 3MI fat accumulation (Diaz and Squires, 2003). Furthermore, we have shown that the allelic variants...
of the SULT1A1 gene that decrease sulfation may account for the accumulation of 3MI (Lin et al., 2004). However, because of the very close retention times, we may have been unable to resolve any sulfated 6-OH-3MI produced from the large amount of 3MOI in the incubations. The metabolite 3-hydroxy-3-methylindolenine was also identified in porcine microsomes (Diaz et al., 1999) but was not observed in cultured hepatocytes. A likely reason for this outcome is that the cytosolic enzyme aldehyde oxidase is absent in microsomes but is present in intact cells and was responsible for rapidly converting 3-hydroxy-3-methylindolenine into HMOI (Smith et al., 1996; Diaz and Squires, 2000b).

The effectiveness of P450 chemical inhibitors on CYP2E1 and CYP2A activities was determined using specific enzymatic assays. The COH activity assay is an established method for estimating CYP2A6 activity in human microsomes and in hepatocytes isolated from human, rabbit, dog, and rat livers (Donato et al., 1998a). A porcine CYP2A that has COH activity has been described and characterized (Skaanild and Friis, 2005) and is referred to as CYP2A19, which is currently the only known porcine CYP2A. The PNP conversion to PNC has been used for in vitro estimation of CYP2E1 activity in rats and humans (Donato et al., 1998b; Jiang et al., 1998) and has been used in microsomes prepared from minipig liver (Baranova et al., 2005).

In the current study, the effect of P450 chemical inhibitors on CYP2E1 by inhibitors that are presumed to be specific for only one of the two enzymes.

Only the inhibitor 4MP was able to selectively inhibit CYP2E1 without affecting CYP2A, whereas 8-MOP and DDTC were inhibitors of both enzymes. The effect of CYP2A activity on 3MI metabolism was determined by subtracting the effect of inhibiting just CYP2E1 from inhibiting both enzymes concurrently. Treatment with the inhibitors 4MP, 8-MOP, and DDTC resulted in a decrease of 21, 28, and 36% of control in the production of 3MOI. Thus, treatment with 8-MOP and DDTC decreased levels of 3MOI by 7 and 15%, respectively, over the inhibition as a result of 4MP treatment. These differences were not significant from inhibition because of 4MP treatment (8-MOP, P = 0.54; DDTC, P = 0.08), which suggests that CYP2A is of minor consequence in the metabolism of 3MI to 3MOI. Likewise, there was a 24, 19, and 36% decrease in HMOI production by treatment with 4MP, 8-MOP, and DDTC, respectively. Compared with the inhibition due to 4MP treatment, DDTC and 8-MOP treatment resulted in no further significant inhibition. Thus, the patterns of HMOI and 3MOI inhibition suggest that CYP2E1 activity (PNP hydroxylase) seems to be of greater importance to the metabolism of 3MI in pig liver compared with CYP2A activity (COH).

In this study, the two general P450 inhibitors KCZ and ABT were also used to inhibit total P450 activity. ABT is a suicide substrate that has been used for prolonged P450 inhibition with both in vitro and in vivo studies in rats and humans (Ruangyuttikarn et al., 1991; Meschter et al., 1994). ABT has the advantage of being safe enough to be used in vivo, and therefore, its use in cultured hepatocytes showed no overt confounding toxicity. KCZ is a general inhibitor of P450s both in vitro and in vivo (Loose et al., 1983; Peehl et al., 2002). The results from KCZ treatment support the results obtained by ABT treatment but should be interpreted with caution because there was some sign of limited toxicity from KCZ after 24 h.

The general P450 inhibitor KCZ significantly decreased CYP2E1 and CYP2A activity, and ABT significantly decreased CYP2E1 activity compared with the control and inhibited CYP2E1 to a greater amount than the CYP2E1-specific inhibitor 4MP. KCZ was also able to further decrease the production of 3MOI compared with the specific CYP2E1 inhibitor 4MP. KCZ treatment caused a 16% decrease in CYP2E1 activity compared with 4MP treatment, along with a further 41% decrease in 3MOI production. Treatment with ABT resulted in a 16% additional decrease in CYP2E1 activity compared with 4MP treatment, along with a further 41% decrease in 3MOI production. These findings are not conclusive, the disproportionate decrease in the production of the 3MOI metabolite compared with the inhibition of CYP2E1 suggests that other P450 isoforms may be involved in 3MI metabolism in the pigs. This information is of specific relevance to the understanding of the problem of boar taint.

Genetic differences responsible for the variability in 3MI metabolism and accumulation in fat can be important molecular markers for breeding programs designed to reduce 3MI levels in fat, thereby reducing taint in boars. Here, we provide evidence in isolated hepatocytes that CYP2E1 is of major importance in the phase 1 metabolism of 3MI compared with CYP2A, and we suggest that other P450s may potentially be involved in the metabolism of 3MI. This research has also highlighted the benefits of using a cell-based system over microsomes to gain insight into the importance of considering phase 2 metabolism in the understanding of boar taint.

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