STEROSELECTIVE METABOLISM OF ENDSULFAN BY HUMAN LIVER MICROSONES AND HUMAN CYTOCHROME P450 ISOFORMS

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ABSTRACT:

Endosulfan (6,7,8,9,10-hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,3,4-benzo(dioxathiepin-3-oxide) is a broad-spectrum chlorinated cyclodiene insecticide. This study was performed to elucidate the stereoselective metabolism of endosulfan in human liver microsomes and to characterize the cytochrome P450 (P450) enzymes that are involved in the metabolism of endosulfan. Human liver microsomal incubation of endosulfan in the presence of NADPH resulted in the formation of the toxic metabolite, endosulfan sulfate. The intrinsic clearances (CLint) of endosulfan sulfate from β-endo-sulfan were 3.5-fold higher than those from α-endo-sulfan, suggesting that β-endo-sulfan would be cleared more rapidly than α-endo-sulfan. Correlation analysis between the known P450 enzyme activities and the rate of the formation of endosulfan sulfate in the 14 human liver microsomes showed that α-endo-sulfan metabolism is significantly correlated with CYP2B6-mediated bupropion hydroxylation and CYP3A-mediated midazolam hydroxylation, and that β-endo-sulfan metabolism is correlated with CYP3A activity. The P450 isoform-selective inhibition study in human liver microsomes and the incubation study of cDNA-expressed enzymes also demonstrated that the stereoselective endosulfan sulfate formation from α-endo-sulfan is mediated by CYP2B6, CYP3A4, and CYP3A5, and that from β-endo-sulfan is mediated by CYP3A4 and CYP3A5. The total CLint values of endosulfan sulfate formation catalyzed by CYP3A4 and CYP3A5 were consistently higher for β-endo-sulfan than for the α-form (CLint of 0.67 versus 10.46 µl/min/pmol P450, respectively). CYP2B6 stereoselectively metabolizes α-endo-sulfan, but not β-endo-sulfan. These findings suggest that the CYP2B6 and CYP3A enzymes are major enzymes contributing to the stereoselective disposition of endosulfan.

In general, pesticides undergo extensive metabolic transformations in living organisms through various metabolic reactions. Microsomal mixed function oxidase is the primary enzyme for the phase I reactions that convert xenobiotics into more soluble products. Although these products are generally less toxic than the parent compound, more toxic metabolites may also occur, as in the cases of parathion (Chambers et al., 1991) and malathion (Buratti et al., 2005). Such in vitro studies with microsomal preparations provide specific details of the chemical identity of metabolites and intermediates, the pattern of their formation, and the metabolic pathways of xenobiotics (Liu et al., 2002; Liu and Kim, 2003; Kim et al., 2005a).

In recent years, a number of papers have been published on the activity of human P450s involved in the metabolism of some pesticides. It has been demonstrated with human liver microsomes and recombinant human P450s that CYP1A2, CYP2B6, and CYP3A4 are major metabolizing enzymes responsible for pesticide metabolism (Tang et al., 2001, 2002, 2004; Usmani et al., 2004a,b; Buratti et al., 2005). No information is available on the metabolism of endosulfan in humans, despite the fact that its widespread use makes the potential for human exposure high, both for agriculture workers and for the general population.

Endosulfan (6,7,8,9,10-hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,3,4-benzo(dioxathiepin-3-oxide) is a broad-spectrum chlorinated cyclodiene insecticide developed by Farbwerke Hoechst AG in Germany (Barnes and Ware, 1965). Because of its abundant usage and its potential for environmental transport, endosulfan contamination is found throughout the environment (Kullman and Matsumura, 1996). It is rapidly metabolized and excreted by chemical or biological systems in a living body as oxidation or hydrolysis products such as endosulfan sulfate, endosulfan alcohol, endosulfan ether, endosulfan lactone, and endosulfan-hydroxyether (Martinez Vidal et al., 1998). Endosulfan alcohol is a metabolite nontoxic to fish and other organisms; thus, hydrolysis producing endosulfan alcohol may be an important detoxification pathway of endosulfan. However, endosulfan sulfate is nearly as toxic as the parent chemical, and because it does not
undergo any further degradation, its residues tend to increase in the environment (Kennedy et al., 2001).

The technical grade of endosulfan contains two stereoisomers, α-endosulfan and β-endosulfan, in an approximate ratio of 7:3. Although the commercial product is applied as a 7:3 isomeric mixture, the fates of the α- and β-forms vary, and the observed ratio of the isomers is dependent upon the physical state of environmental components. The differences between the two isomers have been attributed to various factors, such as their differential volatilization, photodecomposition, and alkaline hydrolysis, as well as their biotic metabolism (El Beit et al., 1981).

Metabolism may be an important determinant of pesticide toxicity. Hepatic metabolism of endosulfan in humans has not been previously investigated in vitro; nor have the contributions of P450 isoforms to metabolic pathways been elucidated. An understanding of the metabolic pathways and the varying contributions of specific P450 isoforms involved will enable a better understanding of the differences in metabolism among individuals; this will provide important information relative to the metabolic interactions of endosulfan with other chemicals. Therefore, the present study was carried out to elucidate the stereoselective metabolism of endosulfan in human liver microsomes and to identify the cytochrome P450 isozymes responsible for the formation of the metabolite.

Materials and Methods

Chemicals and Reagents. α-Endosulfan, β-endosulfan, endosulfan sulfate, endosulfan diol, endosulfan ether, and endosulfan lactone were purchased from Chem Service, Inc. (West Chester, PA). Coumarin, diethylthiocarbamate, 6β-hydroxytestosterone, α-naphthoflavone, ketocanozole, quercetin, quinidine, sulfaphenazole, testosterone, toluene-TETA, β-nicotinamide adenine dinucleotide phosphate (β-NADP), glucose-6-phosphate, and glucose-6-phosphate dehydrogenase were purchased from Sigma-Aldrich (St. Louis, MO). The solvents were HPLC grade (Fisher Scientific Co., Pittsburgh, PA) and the other chemicals were of the highest quality available. S-Benzylxanthinol, pooled and single-donor human liver microsomes (HLMs), and 10 different human recombinant P450s, CYP1A2, 2A6, 2B6, 2C8, 2C9, 2C19, 2D6, 2E1, 3A4, and 3A5 (Supersomes), were purchased from BD Gentest (Woburn, MA). All human P450 isoforms in Supersomes are coexpressed with human P450 reductase. The manufacturer supplied information regarding protein concentration and P450 content.

Metabolism of Endosulfan Isomers in Human Liver Microsomes or cDNA-Expressed P450 Isoforms. The optimal conditions for microsomal incubation were determined in the linear range for the formation of metabolites of endosulfan. In all experiments, endosulfan was dissolved and then serially diluted with acetonitrile to the required concentrations; the solvent was subsequently removed by evaporation to dryness under reduced pressure with an AES2010 SpeedVac (Savant Instruments Inc., Holbrook, NY).

The incubation mixtures, containing either 25 μl of microsomes (2 mg protein/ml of stock, prepared from two different human liver microsomal preparations) or 25 μl of cDNA-expressed P450 (diluted to 200 pmol/ml with phosphate buffer, pH 7.4), were preincubated in 100 μM phosphate buffer (pH 7.4) in the presence of a NADPH-generating system (including 1.3 mM NADP, 3.3 mM glucose-6-phosphate, 3.3 mM MgCl₂, and 1.0 unit/ml glucose-6-phosphate dehydrogenase) for 10 min at 37°C in a shaking water bath. The control incubations were conducted in the absence of the NADPH-generating system. The reactions were initiated by the addition of various concentrations of endosulfan isomer (0.5–100 μM), and the reaction mixtures (final volume of 250 μl) were incubated for 30 min at 37°C. The reactions were terminated by adding 10 μl of 85% phosphoric acid. The samples were extracted with ethyl acetate (0.5 ml) by vortexing for 1 min and were centrifuged at 15,000g for 5 min; this procedure was repeated once to increase the extraction efficiency. The combined organic phase was analyzed by gas chromatography. Analytical Procedures. The concentrations of endosulfan sulfate were measured by the gas chromatography (GC) method (Kaur et al., 1997). The system consisted of an Agilent 4890 GC (Agilent, Wilmington, DE) with an electron capture detector. The compounds were separated on a DB-1 bonded-phase fused silica capillary column (30 m × 0.25 mm i.d., df = 0.25 μm; J & W Scientific, Folsom, CA). The injector and detector temperatures were 260 and 320°C, respectively. The oven temperature was programmed from 100°C (3 min isothermal) to 280°C (held for 3 min at the final temperature) at 10°C/min. The flow rate of the nitrogen carrier gas was 1 ml/min at a split ratio of 1:100. Quantitative analysis was performed with an external standard calibration method. Working standard solutions of endosulfan sulfate were prepared at the concentration of 0.01, 0.05, 0.2, 0.5, 2.5, 10, and 50 μM by serial dilution with ethyl acetate. The calibration curve was fitted with high linearity (r² > 0.98).

Chemical Inhibition Studies with Human Liver Microsomes. The inhibitory effects of known P450 isom-selective inhibitors on the formation of endosulfan metabolites were evaluated to determine the P450 isoform(s) involved in the metabolic pathway. The formation ratio of endosulfan sulfate from α- and β-endosulfan was determined from the reaction mixtures incubated in the presence or absence of known P450 isom-selective inhibitors. The P450 isom-selective inhibitors used were α-naphthoflavone (10 and 100 μM) for CYP1A2, coumarin (100 and 1000 μM) for CYP2A6, thiop-TEPA (5 and 50 μM) for CYP2B6, quercetin (1 and 10 μM) for CYP2C8, sulfaphenazole (10 and 100 μM) for CYP2C9, S-benzylxanthinol (1 and 10 μM) for CYP2C19, quinidine (10 and 100 μM) for CYP2D6, diethylthiocarbamate (10 and 100 μM) for CYP2E1, and ketoconazole (1 and 10 μM) for CYP3A. Except for the addition of the P450 isom-selective inhibitors, the incubation conditions were similar to those described previously (Shin et al., 1999).

Correlation Experiments. Endosulfan isomers (10 μM) were incubated with microsomes from 14 different livers to test the correlation of endosulfan metabolism with the activity of individual P450s. The activities of each P450 isoform were determined using cocktail incubation and tandem mass spectrometry, as described previously (Kim et al., 2005b). Isoform-specific reaction markers were used to determine the activity of each P450: phenacetin O-deethylating activity (CYP1A2), coumarin 7-hydroxylation (CYP2A6), bupropion hydroxylation (CYP2B6), paclitaxel 6a-hydroxylation (CYP2C8), tolbutamide 4-methylhydroxylation (CYP2C9), S-mephenytoin N-deethylation (CYP2C19), dextromethorphan O-deethylation (CYP2D6), chlorzoxazone 6-hydroxylation (CYP2E1), midazolam 1'-hydroxylation (CYP3A), and testosterone 6β-hydroxylation (CYP3A). The correlation coefficients between the formation rates of endosulfan sulfate and the activity of each P450 isoform in the different HLMs were calculated by nonparametric regression analysis (SAS version 8.01; SAS Institute Inc., Cary, NC). A p value less than 0.05 was considered statistically significant.

Data Analysis. Results are expressed as means ± standard deviations (S.D.) of estimates obtained from two different human liver microsomes in triplicate experiments. In the microsomal incubation studies, the apparent kinetic parameters of endosulfan biotransformation (Vmax and Km) were determined by fitting a one-enzyme Michaelis-Menten equation or a Hill equation to the formation data. The conversion rates of endosulfan were best fitted to the Hill equation (V = Vmax · S/(Km + S)). The calculated parameters were the maximum rate of formation (Vmax), the Michaelis constant (apparent Km), the intrinsic cleavage (CLint = Vmax/apparent Km), and Hill coefficient (n). Calculations were performed using WinNonlin software (Pharsight, Mountain View, CA). The percentages of inhibition were calculated by the ratio of the amounts of metabolites formed with and without the specific inhibitor. In the incubation study of the cDNA-expressed P450 isoforms, a Hill equation was fitted to the unweighted data on the formation rate of endosulfan sulfate to estimate the enzyme kinetic parameters.

Contributions of each cytochrome to endosulfan sulfate formation were normalized for mean values of the relative abundance of individual cytochromes in the liver (Rodrigues, 1999). Briefly, the reaction rates measured with individual cDNA-expressed P450 isoforms were normalized with respect to the nominal specific content of the corresponding P450 in native human liver microsomes. In this study, we adapted the data of immunologically determined P450 isoform liver contents reported by other researchers (Wrighton et al., 1990; Shimada et al., 1994; Hanna et al., 2000); i.e., 1.7% for CYP2B6, 23.0% for CYP3A4, and 5.8% for CYP3A5. In turn, the normalized rates for each cDNA-expressed P450 were summed, yielding a “total normalized rate” (TNR = Σfi · Vi), and the normalized rate for each P450 isoform (fi = Vmax/Vi) was expressed as a percentage of the net reaction rate
Retention time (min)

Retained under GC/ECOD conditions, the retention time of 
endosulfan sulfate was determined for each sample.

Fig. 1. GC/ECOD chromatogram of endosulfan and its metabolites from in vitro incubation with human liver microsomes, and the proposed metabolic pathway of endosulfan by human liver microsomes. Endosulfan (30 μM) was incubated with HLMs (0.2 mg/ml protein) in the absence (—) or presence (—) of an NADPH-generating system for 30 min at 37°C. The appearances of metabolite peaks were monitored by GC with electron capture detection.

Fig. 2. Stereoselective inhibition of known P450 isozyme-selective inhibitors on endosulfan sulfate formation from α-endosulfan (A) and β-endosulfan (B) in human liver microsomal incubations. Pooled human liver microsomes (0.2 mg/ml; BD Gentest) were incubated with 10 μM endosulfan isomers in the absence or presence of various chemical inhibitors at 37°C for 30 min. The chemical inhibitors used were as follows: α-naphthoflavone (10 and 100 μM) for CYP1A2, coumarin (100 and 1000 μM) for CYP2A6, thio-TEPA (5 and 50 μM) for CYP2B6, quercetin (1 and 10 μM) for CYP2C9, sulfaphenazole (10 and 100 μM) for CYP2C9, 3-benzylxirirninol (1 and 10 μM) for CYP2C19, quinidine (10 and 100 μM) for CYP2D6, diethyldithiocarbamate (10 and 100 μM) for CYP2E1, and ketoconazole (1 and 10 μM) for CYP3A. Data shown are averages of remaining activity relative to the control metabolite formation rate estimated from duplicate experiments.

![Image](https://via.placeholder.com/150)

\[=100\cdot f_i\cdot \frac{V_i}{V_0}\cdot \frac{V_i}{V_0}\text{ where }f_i\text{ indicates the fraction of each P450 isoform content in the human liver, and }V_i=V_{max_i}\cdot [S_i]/K_{m_i}+[S_i].\]

Results

Identification of the P450 Isoforms Involved in the Metabolism of Endosulfan. Human liver microsomal incubation of endosulfan in the presence of NADPH resulted in the formation of endosulfan sulfate (Fig. 1). The rates of formation of metabolite were proportional to incubation times up to 45 min and protein concentrations up to 0.3 mg/ml at 30 min. A P450 isoform-selective inhibition study was performed to evaluate which P450 isoforms are involved in the stereoselective metabolism of endosulfan in human liver microsomes (Fig. 2). Among the nine inhibitors tested, ketoconazole, a well known CYP3A-selective inhibitor, inhibited endosulfan sulfate formation from both isomers. The CYP2B6-selective inhibitor, thio-TEPA, inhibited only the metabolism of α-endosulfan. After treatment with various concentrations of ketoconazole and thio-TEPA, the formation rates of endosulfan sulfate decreased in a concentration-dependent manner (Fig. 3). After treatment with 1 μM ketoconazole, the level of endosulfan sulfate formation from β-endosulfan (5 μM) markedly decreased to 22.9% of that in the controls, compared with 59.2% from the α-form, indicating the stereoselective inhibitory effect of ketoconazole on the formation of endosulfan sulfate. Endosulfan sulfate formation from α-endosulfan was also inhibited by thio-TEPA as well as ketoconazole, suggesting that the stereoselective endosulfan sulfate formation from α-endosulfan is mediated by more than one enzyme.

Correlations between the rate of endosulfan metabolism and the activities of P450s in HLMs are summarized in Table 1. The formation rates of endosulfan sulfate from α-endosulfan was significantly correlated with the activity of CYP3A and CYP2B6, whereas that of β-endosulfan was significantly correlated with the activity of CYP3A (Fig. 4).

Endosulfan sulfate formation from endosulfan isomers was also studied using the human cDNA-expressed P450 isoforms, CYP1A2, CYP2A6, CYP2B6, CYP2C8, CYP2C9, CYP2C19, CYP2D6, CYP2E1, CYP3A4, and CYP3A5 (Fig. 5). The endosulfan sulfate formation rates from the β-endosulfan by rCYP3As were significantly greater than those from the α-form. The
The formation of endosulfan sulfate from human liver microsomal preparations (Fig. 6). The formation rates of endosulfan was clearly stereoselective in the incubation of enzymes exhibited no significant metabolic activity.

Experiments.

endosulfan isomers at 37°C for 30 min. Data shown are averages of duplicate experiments.

cDNA-expressed CYP2B6, however, catalyzed endosulfan sulfate formation with a higher formation rate from α-endosulfan than from β-endosulfan. Similar to the chemical inhibition study, the other P450 enzymes exhibited no significant metabolic activity.

Kinetics of endosulfan sulfate formation

The formation of endosulfan sulfate formation by CYP3A5 was 113.2-fold higher for V9251-endosulfan than from V9252-endosulfan, which resulted in 3.5-fold higher formation CLint values from β-endosulfan, compared with the α-form. The values of the formation CLint of the endosulfan sulfate were 0.20 and 0.69 μl/min/pmol P450 for α- and β-endosulfan, respectively, indicating the metabolic stereoselectivity.

The formation of endosulfan sulfate was best described by a Hill equation. CYP3A4 and CYP3A5 oxidized both endosulfan isomers to endosulfan sulfate, whereas CYP2B6 only catalyzed endosulfan sulfate formation from α-endosulfan (Table 3). The total CLint values of all three P450 isoforms were higher for β-endosulfan than for the α-form. The CYP3A4-catalyzed endosulfan sulfate formation of β-endosulfan showed a higher Vmax and Km than those of α-endosulfan, resulting in a higher formation of CLint from the β-form than from the α-form (4.80 versus 0.62 μl/min/pmol CYP3A4). The CLint value for endosulfan sulfate formation by CYP3A5 was 113.2-fold higher for β-endosulfan than for the α-form.

Contributions of P450 isoforms were determined after normalization for the predicted relative abundance of each P450. This simulation shows that CYP3A4 is the major P450 isoform responsible for endosulfan sulfate formation from both α- and β-endosulfan (Fig. 8). For α-endosulfan, the percentage of the net reaction catalyzed by CYP3A4 (around 85%) decreased with increasing substrate concentration, and reached about 70% at 100 μM. However, in the case of β-endosulfan, the percentage of the net reaction catalyzed by CYP3A4 (around 74%) increased slightly to 84% at 100 μM with increasing substrate concentration.

TABLE 2

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<td>Vmax (pmol/min/nmol P450)</td>
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CYP3A4-catalyzed endosulfan sulfate formation of β-endosulfan was best described by a Hill equation. CYP3A4 and CYP3A5 oxidized both endosulfan isomers to endosulfan sulfate, whereas CYP2B6 only catalyzed endosulfan sulfate formation from α-endosulfan (Table 3). The total CLint values of all three P450 isoforms were higher for β-endosulfan than for the α-form. The CYP3A4-catalyzed endosulfan sulfate formation of β-endosulfan showed a higher Vmax and Km than those of α-endosulfan, resulting in a higher formation of CLint from the β-form than from the α-form (4.80 versus 0.62 μl/min/pmol CYP3A4). The CLint value for endosulfan sulfate formation by CYP3A5 was 113.2-fold higher for β-endosulfan than for the α-form.

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The metabolism studies of endosulfan have been reported for various organisms, such as mammals, fish, insects, and some microorganisms (Barnes and Ware, 1965; Sutherland et al., 2000; Awasthi et al., 2003). As the result of previous research, different major metabolites were determined according to the organisms, and they were endosulfan ether, endosulfan hydroxyster, endosulfan sulfate, and endosulfan alcohol. In the present study, we determined that the major metabolite of human liver microsomal incubation was endosulfan sulfate. This metabolite has a toxicity comparable to that of the parent compound, endosulfan.

The present in vitro incubation studies using human liver microsomes and cDNA-expressed human P450s clearly demonstrate the stereoselective metabolism of α- and β-endosulfan in the endosulfan sulfate formation pathway. The mean metabolic intrinsic clearance rates obtained in human liver microsomes, as estimated by $V_{\text{max}}/K_m$, indicated that β-endosulfan was metabolized to endosulfan sulfate more efficiently than α-endosulfan. The $CL_{\text{int}}$ values of the β-endosulfan were 3.5-fold higher for enosulfan sulfate formation than those of the α-endosulfan (0.20 and 0.69 $\mu$L/min/pmol P450, respectively), indicating the metabolic stereoselectivity.

The differences in stereoselective disposition between α- and β-endosulfan seem to be largely due to their characteristic stereoselective metabolisms. In the present study, the stereoselective metabolism of α-endosulfan was mediated by three P450 isoforms, CYP2B6, CYP3A4, and CYP3A5, and β-endosulfan was transformed by CYP3A4 and CYP3A5. Correlation analysis conducted on 14 single-donor HLM samples revealed significant correlations for CYP3A (midazolam 1'-hydroxylation) and/or CYP2B6 (bupropion hydroxylation). When testosterone was used as the other probe substrate of CYP3A (Maenpaa et al., 1993), the rates of formation of endosulfan sulfate from endosulfan isomers also correlated very well with the CYP3A activity, as shown in Table 1. Further verification of the importance of CYP2B6 and CYP3A in the metabolism of endosulfan was obtained by the P450 isoform-selective inhibition study. Ketoconazole (2 $\mu$M) inhibited up to 59.7% and 89.1% of endosulfan sulfate formation from α- and β-endosulfan, respectively. The remaining metabolic activity of α-endosulfan after ketoconazole inhibition may be attributed to CYP2B6 activity. After treatment with 25 $\mu$M thio-TEPA, the level of endosulfan sulfate formation from α-endosulfan decreased to 52.9% of that in the control, compared with 89.5% from the β-form, indicating the stereoselective inhibitory effect of thio-TEPA on the formation of endosulfan sulfate. In the inhibition study of efavirenz, in which CYP2B6-mediated efavirenz 8-hydroxylation was also weakly inhibited (~20%) by sulfaphenazole. This inhibition may be due to nonselective inhibition of CYP2B6 activity by sulfaphenazole. A similar inhibition of CYP2B6 activity by sulfaphenazole was observed in a metabolism study of efavirenz, in which CYP2B6-mediated efavirenz 8-hydroxylation was also weakly inhibited (~20%) by sulfaphenazole (Ward et al., 2003). Therefore, the slight inhibition of endosulfan sulfate formation from α-endosulfan might be a minor inhibitory effect of CYP2B6 by sulfaphenazole. The total formation $CL_{\text{int}}$ values either of all three or of two of these P450 isoforms were consistently higher for the β-endosulfan than for the α-endosulfan. The $CL_{\text{int}}$ of CYP2B6 for α-endosulfan (1.85 $\mu$L/min/pmol P450) was extremely high compared with those of CYP3A4 and CYP3A5, and the $CL_{\text{int}}$ of CYP3A4 for β-endosulfan was similar to that of CYP3A5 (4.80 and 5.66 $\mu$L/min/pmol P450). Taken together, these results suggest that CYP3A4 is the major enzyme involved in endosulfan sulfate formation from both endosulfan isomers at concentrations in the usual experimental range. These results are similar to those from metabolism studies of fipronil (Tang et al., 2004), omeprazole (Abelo et al., 2000), and lansoprazole (Kim et al., 2003), in which CYP3A4 was shown to have a high degree of
sulfoxidation activity. In addition, CYP2B6 is also an important P450 isoform responsible for endosulfan sulfate formation from α-endosulfan (Figs. 5 and 7). The percentage of the net reaction by CYP2B6 (around 15%) increased in a substrate concentration-dependent manner and reached 26% at 100 μM. Similarly, it is known that CYP2B6 is involved in the sulfoxidation of tazofphone (Surapenani et al., 1997) and S-methyl N,N-diethyldithiocarbamate (Pike et al., 2001). Expression of CYP3A4 and CYP2B6 has been shown to be highly variable among human liver samples (Wrighton et al., 1990; Shimada et al., 1994; Faucette et al., 2000; Lang et al., 2001). This variability is probably due to effects of genetic polymorphisms or exposure to drugs that are inducers or inhibitors of CYP3A4 (Neuvonen et al., 1998; Westlind et al., 1999; Hariparsad et al., 2004) and CYP2B6 (Gervot et al., 1999; Hesse et al., 2001; Lang et al., 2001). Therefore, the genetic polymorphisms may affect the stereoselective metabolism of endosulfan. Some researchers reported that CYP2B6 represents ~6% of the total liver P450 content (Stresser and Kupfer, 1999), in contrast to earlier estimates that it represented less than 1% (Shimada et al., 1994). Hence, subjects with a high liver CYP2B6 level would be expected to exhibit higher α-endosulfan oxidation by CYP2B6 than by CYP3A4.

In conclusion, our study clearly demonstrated stereoselectivity in the formation of endosulfan sulfates from α- and β-endosulfan; the intrinsic clearances of both metabolic pathways were consistently and significantly higher for β-endosulfan than for the α-form in human liver microsomal fractions. The P450 isoform-specific chemical inhibition study, correlation analysis, and incubation study of cDNA-expressed P450 enzymes demonstrated that CYP2B6 selectively oxidized α-endosulfan, but not β-endosulfan, and that CYP3A4 and CYP3A5 were responsible for the formation of endosulfan sulfate from both isomers. In addition, even though the intrinsic clearance rates for CYP2B6 were greater for α-endosulfan than those observed for CYP3A4, CYP3A4 could contribute substantially to the metabolism because of its high relative abundance in liver tissue.

References


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CORRECTION TO “STEREOSELECTIVE METABOLISM OF ENDOSELFAN BY HUMAN LIVER MICROSOMES AND HUMAN CYTOCHROME P540 ISOFORMS”


On page 1090, the sentence “The P450 isoform-selective inhibition study in human liver microsomes and the incubation study of cDNA-expressed enzymes also demonstrated that the stereoselective sulfonation of α-endosulfan is mediated by CYP2B6, CYP3A4, and CYP3A5, and that of β-endosulfan is transformed by CYP3A4 and CYP3A5” should be corrected to: “The P450 isoform-selective inhibition study in human liver microsomes and the incubation study of cDNA-expressed enzymes also demonstrated that the stereoselective endosulfan sulfate formation from α-endosulfan is mediated by CYP2B6, CYP3A4, and CYP3A5, and that from β-endosulfan is transformed by CYP3A4 and CYP3A5”.

On page 1090, the sentence “CYP2B6 enantioselectively metabolizes α-endosulfan, but not β-endosulfan” should be corrected to: “CYP2B6 stereoselectively metabolizes α-endosulfan, but not β-endosulfan”.

On page 1091, the sentence “Metabolism of Endosulfan Enantiomers in Human Liver Microsomes or cDNA-Expressed P450 Isoforms” should be corrected to: “Metabolism of Endosulfan Isomers in Human Liver Microsomes or cDNA-Expressed P450 Isoforms”.

On page 1091, the sentence “The reactions were initiated by the addition of various concentrations of endosulfan enantiomer (0.5–100 µM)” should be corrected to: “The reactions were initiated by the addition of various concentrations of endosulfan isomer (0.5–100 µM)”.

On page 1091, the sentence “Endosulfan enantiomers (10 µM) were incubated with microsomes from 14 different livers” should be corrected to: “Endosulfan isomers (10 µM) were incubated with microsomes from 14 different livers”.

On page 1091, the sentence “Contributions of each cytochrome to endosulfan sulfonation were normalized for mean values of the relative abundance of individual cytochromes in the liver” should be corrected to: “Contributions of each cytochrome to endosulfan sulfate formation were normalized for mean values of the relative abundance of individual cytochromes in the liver”.

On page 1092 (Fig. 2), the sentence “Stereoselective inhibition of known P450 isoform-selective inhibitors on sulfonation from α-endosulfan (A) and β-endosulfan (B) in human liver microsomal incubations” should be corrected to: “Stereoselective inhibition of known P450 isoform-selective inhibitors on endosulfan sulfate formation from α-endosulfan (A) and β-endosulfan (B) in human liver microsomal incubations”.

On page 1092 (Fig. 2), the sentence “Pooled human liver microsomes (0.2 mg/ml; BD Gentest) were incubated with 10 µM endosulfan enantiomers in the absence or presence of various chemical inhibitors at 37°C for 30 min” should be corrected to: “Pooled human liver microsomes (0.2 mg/ml; BD Gentest) were incubated with 10 µM endosulfan isomers in the absence or presence of various chemical inhibitors at 37°C for 30 min”.

On page 1092 (Table 1), the sentence “Correlation of formation rates of endosulfan sulfate from endosulfan enantiomers (10 µM) with the P450 marker activities in human liver microsomes (n = 14)” should be corrected to: “Correlation of formation rates of endosulfan sulfate from endosulfan isomers (10 µM) with the P450 marker activities in human liver microsomes (n = 14)”.

On page 1092, the sentence “Among the nine inhibitors tested, ketoconazole, a well known CYP3A-selective inhibitor, inhibited endosulfan sulfate formation from both enantiomers” should be corrected to: “Among the nine inhibitors tested, ketoconazole, a well known CYP3A-selective inhibitor, inhibited endosulfan sulfate formation from both isomers”.

On page 1092, the sentence “Endosulfan sulfate formation from α-endosulfan was also inhibited by thio-TEPA as well as ketoconazole, suggesting that the stereoselective sulfonation of α-endosulfan is mediated by more than one enzyme” should be corrected to: “Endosulfan sulfate formation from α-endosulfan was also inhibited by thio-TEPA as well as ketoconazole, suggesting that the stereoselective endosulfan sulfate formation from α-endosulfan is mediated by more than one enzyme”.

On page 1092, the sentence “Endosulfan sulfate formation from endosulfan enantiomers was also studied using the human cDNA-expressed P450 isoforms” should be corrected to: “Endosulfan sulfate formation from endosulfan isomers was also studied using the human cDNA-expressed P450 isoforms”.

On page 1093 (Fig. 5), the sentence “Representative plot of the formation of endosulfan sulfate from
endosulfan enantiomers by cDNA-expressed P450 isoforms” should be corrected to: “Representative plot of the formation of endosulfan sulfate from endosulfan isomers by cDNA-expressed P450 isoforms”.

On page 1093 (Fig. 5), the sentence “Human cDNA-expressed CYP1A2, 2A6, 2B6, 2C8, 2C9, 2C19, 2D6, 2E1, 3A4, and 3A5 were incubated with 10 μM endosulfan enantiomers at 37°C for 30 min” should be corrected to: “Human cDNA-expressed CYP1A2, 2A6, 2B6, 2C8, 2C9, 2C19, 2D6, 2E1, 3A4, and 3A5 were incubated with 10 μM endosulfan isomers at 37°C for 30 min”.

On page 1093 (Fig. 6), the sentence “Kinetics for the formation rate of endosulfan sulfate from endosulfan enantiomers in human liver microsomes” should be corrected to: “Kinetics for the formation rate of endosulfan sulfate from endosulfan isomers in human liver microsomes”.

On page 1093, the sentence “The cDNA-expressed CYP2B6, however, catalyzed endosulfan sulfate formation with a higher formation rate from α-endosulfan than by CYP3A4” should be corrected to: “The cDNA-expressed CYP2B6, however, catalyzed endosulfan sulfate formation with a higher formation rate from α-endosulfan than from β-endosulfan”.

On page 1093, the sentence “CYP3A4 and CYP3A5 metabolized both endosulfan enantiomers to endosulfan sulfate” should be corrected to: “CYP3A4 and CYP3A5 oxidized both endosulfan isomers to endosulfan sulfate”.

On page 1093, the sentence “The cDNA-expressed CYP2B6, however, catalyzed endosulfan sulfate formation with a higher formation rate from α-endosulfan than by CYP3A4” should be corrected to: “The cDNA-expressed CYP2B6, however, catalyzed endosulfan sulfate formation with a higher formation rate from α-endosulfan than from β-endosulfan”.

On page 1094, the sentence “CYP3A4-catalyzed endosulfan sulfate formation of β-endosulfan showed a higher V_max and K_m than those of the α-enantiomer” should be corrected to: “CYP3A4-catalyzed endosulfan sulfate formation of β-endosulfan showed a higher V_max and K_m than those of α-endosulfan”.

On page 1094, the sentence “In the inhibition study with sulfaphenazole, a selective CYP2C9 inhibitor, α-endosulfan sulfonation was slightly inhibited (~30%) by sulfaphenazole” should be corrected to: “In the inhibition study with sulfaphenazole, a selective CYP2C9 inhibitor, endosulfan sulfate formation from α-endosulfan was slightly inhibited (~30%) by sulfaphenazole”.

On page 1094, the sentence “Therefore, the slight inhibition of α-endosulfan sulfonation might be a minor inhibitory effect of CYP2B6 by sulfaphenazole” should be corrected to: “Therefore, the slight inhibition of endosulfan sulfate formation from α-endosulfan might be a minor inhibitory effect of CYP2B6 by sulfaphenazole”.

On page 1094, the sentence “Taken together, these results suggest that CYP3A4 is the major enzyme involved in the sulfonation of both endosulfan enantiomers at concentrations in the usual experimental range” should be corrected to: “Taken together, these results suggest that CYP3A4 is the major enzyme involved in endosulfan sulfate formation from both endosulfan isomers at concentrations in the usual experimental range”.

On page 1094 (Fig. 7), the sentence “The formation of endosulfan sulfate from endosulfan enantiomers in recombinant human CYP2B6 (A), CYP3A4 (B), and CYP3A5 (C)” should be corrected to: “The formation of endosulfan sulfate from endosulfan isomers in recombinant human CYP2B6 (A), CYP3A4 (B), and CYP3A5 (C)”.

On page 1094 (Fig. 8), the sentence “Abundance-adjusted simulations of the relative contributions of three or two P450 isoforms to endosulfan sulfonation in relation to α- and β-endosulfan concentrations” should be corrected to: “Abundance-adjusted simulations of the relative contributions of three or two P450 isoforms to endosulfan sulfate formation in relation to α- and β-endosulfan concentrations”.

On page 1095, the sentence “In which CYP3A4 was shown to have a high degree of sulfonation activity” should be corrected to: “in which CYP3A4 was shown to have a high degree of endosulfan sulfate formation activity”.

On page 1095, the sentence “Hence, subjects with a high liver CYP2B6 level would be expected to exhibit higher α-endosulfan sulfonation by CYP2B6 than by CYP3A4” should be corrected to: “Hence, subjects with a high liver CYP2B6 level would be expected to exhibit higher α-endosulfan oxidation by CYP2B6 than by CYP3A4”.

The online version of this article has been corrected in departure from the print version.

The authors apologize for any confusion and inconveniences caused by these errors, and greatly appreciate the kind and valuable comments of Dr. Joseph Gal for correction of these errors.